Floods in the Pyrenees: A global view through a regional database

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Abstract. This paper shows the results of the analysis on the first systematic dataset of flood episodes referred to the entire Pyrenees massif, named PIRAGUA_flood, which covers the period 1981-2015 (available at http://hdl.handle.net/10261/270351). First, the structure of the database is detailed, so that it can be reproduced anywhere else in the world adapting to the specific nature of each situation. Subsequently, the paper addresses the spatial and temporal distribution of flood episodes and events (including trends) that affected the Pyrenees regions of Spain (Catalonia, Aragon, Navarre, the Basque Country), France (Nouvelle Aquitaine, Occitanie) and Andorra, as well as the massif as a whole, for a given period of time. In the case of the Spanish regions, it was also possible to analyse the compensation paid out made by the Spanish Insurance Compensation Consortium, and the number of deceased. The weather types associated with flood episodes were also classified based on sea level pressure and 500 hPa geopotential height from ERA5. The results show 181 flood events and 154 fatalities, some of which affected more than one region. In the Spanish part of the Pyrenees, between 1996 and 2015, there were a total compensation payout amounting to €142.5 million$_{2015}$. The eastern part of the area records more flood events than the western one, being Catalonia the community that registered the highest number of events, followed by Andorra and Occitanie. Associated weather types are dominated by southern component flow over the Pyrenees region, with a thalweg on the Iberian Peninsula and a depression in the vicinity, either in the Atlantic or in the Mediterranean. In terms of the entire massif, there is a slight positive trend of 0.84 events/decade, driven by the evolution of ordinary and extraordinary floods, but not significant at 95%. At a regional level, flood behaviour is more heterogeneous, although not significant for the most part. Nouvelle Aquitanie is the only region that shows a positive and significant trend of 0.34 events/decade.

1   Introduction

It is well known that floods in the Mediterranean area are usually flash floods (Gaume et al., 2009; Braud et al., 2014; Llasat et al., 2016), associated with very heavy rains with a short duration. , which generally go unnoticed in the databases. In general, they cause local damage in coastal populations or mountainous regions, which can sometimes be very serious. Other times they can affect large regions, as happened with the Gard floods (France) in 2002 (Braud et al., 2010). Most of these episodes

do not appear in the best-known flood databases such as EM-DAT (https://www.emdat.be/) or Munich Re's NatCatSERVICE (https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html)~~Most of these databases, such as the ones belonging to EM-DAT or Munich Reinsurance, also include other types of natural disasters and refer to what could be called very severe episodes. These databases, however~~, because the~~se databases~~~~y~~, are often based on indirect information (i.e.~~for example,~~ from the insurers that Munich Reinsurance reinsures) so many events are not included, either because the insurers are not aware of the events, or because they are not considered to have had sufficient impact (Llasat et al., 2013a; Wirtz et al., 2014). For example, there are very few such episodes that have affected the Pyrenees Mountain region on these databases. More systematic and precise studies are therefore necessary~~required~~, but the ~~. For example, there are very few such episodes that have affected the Pyrenees Mountain region on the databases. The~~ high workload required to elaborate these studies means that they are only available for few regions. This is the case of INUNGAMA (Llasat et al., 2014) that includes all the flood events that have affected Catalonia (NE Spain) between 1981 and 2020 (partial information available in the Flood Observatory of Catalonia, https://experience.arcgis.com/experience/484172e12fae4cbb934441203ee04e36/), and~~for~~ FLOODHYMEX (Llasat et al., 2013b), which currently includes all the catastrophic flood episodes (following the criteria of "catastrophic" introduced in Barriendos et al., 2003) that have affected Catalonia, Valencian Community and the Balearic Islands, in Spain, the former Languedoc-Roussillon region, Midi-Pyrénées and PACA (Provence-Alpes-Côte d'Azur) in France, Calabria, in Italy, and all Greece (available ~~. This dataset can be found~~ at https://mistrals.sedoo.fr/catalogue/~~—~~) https://mistrals.sedoo.fr/?editDatsId=1150&datsId=1150&project_name=HyMeX&q=flood.

On the other hand, c~~C~~oncern about the impact of climate change in mountainous regions, including natural hazards, has grown significantly in recent decades. Proof of this is the increase in publications on this topic (i.e. Beniston, 2003; Beniston and Stoffel, 2014; Zimmermann and Keiler, 2015; Steiger et al., 2022) including a cross-chapter devoted to Mountains in the Sixth Assessment Report of IPCC (2022). There are, however, few studies that address mountain massifs in their entirety from a climatic or meteorological perspective. This is the case of the Pyrenees, a cross-border mountainous region between Spain, France and Andorra. ~~, where an example of such studies would be the article by Amblar-Francés et al. (2020)~~. To facilitate the international management of a massif distributed between three countries, the Pyrenees Working Community (CTP) was created, which in turn founded the Pyrenean Climate Change Observatory (OPCC, https://www. opcc-ctp.org/en) that promotes the observation and research on climate change from a multidisciplinary approach. Given that the Pyrenees are key in the generation of water resources in the surrounding regions, where more than 20 million people live, as well as in the production of hydroelectric energy, the OPCC promoted the PIRAGUA project financed by the European call for projects POCTEFA (https://www.opcc-ctp.org/en/piragua) and whose results are available to the public in the OPCC Geoportal (https://www.opcc-ctp.org/en/geoportal) and the publications of Beguería et al. (2023a, 2023b). ~~–~~Among these results, noteworthy are those obtained from trend analysis. Clavera-Gispert et al. (2023) show that in autumn there is a predominance of significant negative trends throughout the mountain range, mainly in September, for low (P10) average (P50) and high flows (P90), for the period 1980-2013. A similar predominance is observed in summer, while only a relevant significant positive trend is observed in the

western part (Basque Country, Spain), in the month of March. The decrease in flow throughout the mountain range is more clearly manifested when the period is reduced to 1990-2013. This negative trend becomes more pronounced, even on an annual scale, when analyzing projections of annual precipitation for the middle and end of the century, especially in the western part of the Pyrenees, while in the eastern part, especially in Catalonia (Spain), an increase is observed, which will also be reflected in the average annual flows (Beguería et al., 2023a). CLIMPY, another project from OPCC, concluded that the projections for the next seventy years do not showed a significant trend in the heavy precipitation index (CP95) at the mountain range scale; only a certain decrease could be detected in the south-eastern slope (Catalonia, Spain) and a certain increase in the northern and western parts (French basins, and Navarre and the Basque Country in Spain) (Amblar-Rancés et al., 2020). In this context arises the question about extremes, and specifically, about floods.

Onepart. One of the objectives of PIRAGUA was the analysis of floods in the entire Pyrenean region, where In this context, floods, usually flash floods, can have a great direct impact on both the fixed and floating population, as well as on water services and energy resources. Some examples are An example is the catastrophe at Camping las Nieves, in Biescas (Aragón, Spain), on August 7, 1996, in which 87 people drowned (García-Ruiz et al., 1996); the June 2013 floods with catastrophic damages in Spain and France (https://hepex.org.au/flash-floods-in-the-french-western-and-central-pyrenees-17-19-june-2013/); or the floods produced on 7 November 1982 (Trapero et al., 2013) that affected the three Pyrenean countries. The recent death of two people who were canyoning in the Pyrenees of Aragón (Spain) on September 2, 2023, when a flash flood event occurred is another example of this type of event that most people are unaware of. The Pyrenees Mountain range has an area of 49,850 km² (W-E: 520 km; S-N: 150 km), and a maximum altitude of 3,404 m.a.s.l (Aneto), extending from the Atlantic Ocean to the Mediterranean Sea (Fig. 1). 43% of the Pyrenees is covered by forest, making it one of the richest regions in biodiversity in Europe. The number of inhabitants in the Pyrenean region is less than 1,200,000 people, but this figure can be doubled in summer. Although there is still notable agricultural and livestock activity, the service sector is the main source of income. Thus, in Andorra, the tourism sector constitutes more than 80% of the GDP. The Pyrenees are key in the generation of water resources in the surrounding regions, where more than 20 million people live, as well as in the production of hydroelectric energy, which exceeds 3,300 MW. In this context, floods, usually flash floods, can have a great direct impact on both the fixed and floating population, as well as on water services and energy resources. An example is the catastrophe at Camping las Nieves, in Biescas, on August 7, 1996, in which 87 people drowned. The recent death in September 2023 of two people who were canyoning when the flash floods occurred is another example of an increasingly frequent risk.

However, until now there is no database or flood catalogue that specifically covers the Pyrenean regions, and even less so, the Pyrenees massif as a whole. For this reason, iIn the same way that the final objective of FLOODHYMEX (Llasat et al., 2013) was to cover the entire Mediterranean region, it was decided to create a similar database for the Pyrenees, but that included all types of flood episodes. The aim of this article is to present the first systematic database of flood episodes covering the entire Pyrenees massif, for the period 1981-2015, analyze the trends in light of the most recent articles (Clavera-Gispert et al., 2023),

100 and characterize the weather types favourable to these flood events ~~that was created in the context of the Interreg POCTEFA project, PIRAGUA (https://www.opcc-ctp.org/en/piragua)~~. This database is available at http://hdl.handle.net/10261/270351 (Llasat et al., 2022). Following the introduction of the study area, the structure of the base ~~is shown~~, the criteria followed for its construction, and the sources of information used are shown. The spatial and temporal distribution of flood episodes, both in the massif and the administrative regions, as well as the weather types, are then analysed. The paper ends with conclusions

105 and discussion, where some adaptation measures are also commented.

2 Area of study and sources of information

2.1 Area of study

The Pyrenees Mountain range has an area of 49,850 km² (W-E: 520 km; S-N: 150 km), and a maximum altitude of 3,404 m.a.s.l (Aneto), extending from the Atlantic Ocean to the Mediterranean Sea (Fig. 1). 43% of the Pyrenees is covered by forest,

110 making it one of the richest regions in biodiversity in Europe. The number of inhabitants in the Pyrenean region is less than 1,200,000 people, but this figure can be doubled in summer. Although there is still notable agricultural and livestock activity, the service sector is the main source of income. Thus, in Andorra, the tourism sector constitutes more than 80% of the GDP.

The study area (Fig. 1) is exclusively comprised of the municipalities within the limits of the Pyrenees, as defined by the

115 Pyrenees Climate Change Observatory (Observatorio Pirenaico del Cambio Climático - OPCC), a subsection of the Pyrenees Working Community (Comunidad de Trabajo de los Pirineos - CTP), and which includes part of the Nouvelle Aquitaine and Occitanie regions of France, part of the Basque Country, Navarre, Aragon and Catalonia in Spain, and Andorra as a whole. In total, 1803 municipalities are included, of which 609 are in Spain, 1187 are in France and 7 are in Andorra (Table 1).

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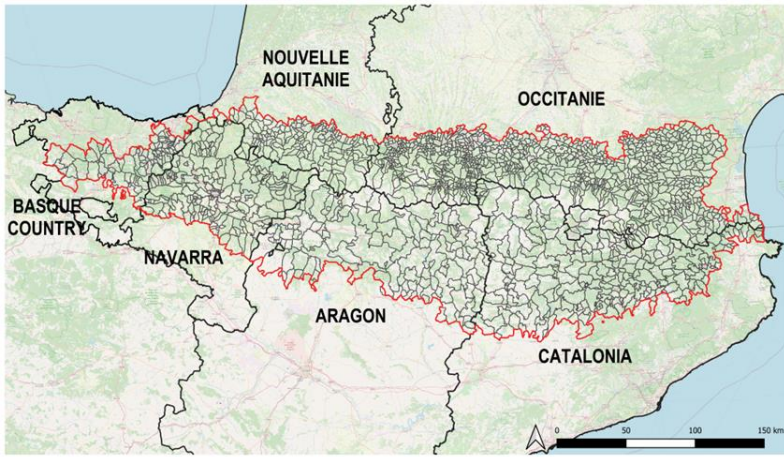
Figure 1: Map of the municipalities located within the area defined as the Pyrenees by the OPCC.
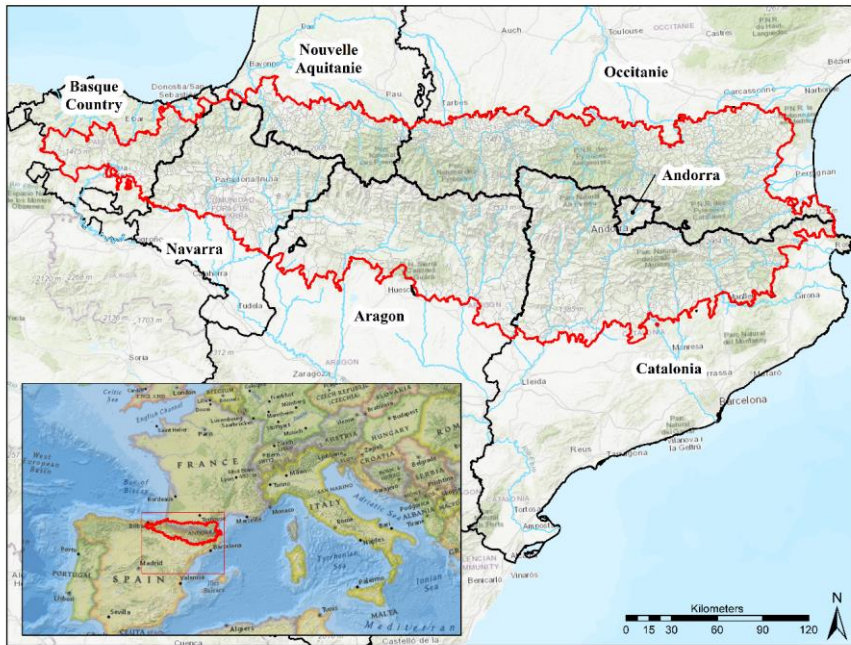
Figure 1: Map of the Pyrenean municipalities located within the area defined as the Pyrenees by the OPCC. The frontiers and names of the Pyrenean regions are also included.

2.2 Sources of information and identification of flood events

Table 1 shows the main physical and socioeconomic characteristics of the study area as well as the sources of information used to identify all the flood events that have affected de Pyrenean Region. FLOODHYMEX (Llasat et al, 2013) was used to recover the catastrophic events that have affected the Pyrenees in Catalonia and the part of Occitanie corresponding to the Languedoc-Roussillon. For the Spanish part of the Pyrenees, the National Catalogue of Historical Floods (Catálogo Nacional de Inundaciones Históricas - CNIH) and the information from the Spanish Insurance Compensation Consortium (CCS, 2021) were also used. The CNHI catalogue was published by the General Directorate of Civil Protection in Spain and contains the most important flood events (DGPC, 2022). It is made up of reports made for the different river demarcations into which Spain is divided, observing some heterogeneities, such as the fact that the same event can be in two reports associated with different dates, which requires careful contrast with other sources. The CCS provided, for the period 1996-2015, ~~that includes~~

the compensation paid to municipalities in the Pyrenees, ~~organized~~, organized by postal code ~~and date~~and date of the "claim",~~.~~ which may be different from the date of the flood. In order to resolve this, the postcode data was transformed to a municipality data (a municipality may have more than one postcode) and the damage caused by a flood event was considered to be the sum of the compensations due to floods between the initial day of the event and the final day, with an additional 7 days, as in Cortès et al. (2019). Data from CCS has been also useful to identify some minor flood events that haven't been found in the other sources of information. Finally, in the case of Catalonia, Aragón and Navarra, the information was completed based on news from ~~the~~ La Vanguardia, El Heraldo de Aragón and Diario de Navarra, newspapers, respectively. La Vanguardia had already been systematically consulted, day by day, for the construction of the INUNGAMA database (Llasat et al, 2014), part of which was included in FLOODHYMEX (Llasat et al., 2013)~~.~~ and PIRAGUA_flood (Llasat et al., 2022). Given that day-to-day consultation of newspapers is extremely slow, in the case of Aragon and Navarra only the cases identified from the rest of the sources cited above were consulted plus the government press releases and the days of rain that exceeded 40 mm (threshold fixed following the criteria of Cortés et al., 2019). This information was obtained from the precipitation field provided by the SAFRAN analysis (Quintana-Seguí et al., 2016). In the case of the Basque Country and Andorra, the project partners, through whom we obtained the information, confirmed that it was complete, so it was not necessary to consult the newspapers, since the creators of the respective episode lists had done so. ~~The part of PIRAGUA_flood corresponding to the Pyrenees of Catalonia has been created from INUNGAMA and expanded with cases identified through the other cited sources that did not constitute news in La Vanguardia. The Herald of Aragon was also consulted systematically day by day to complete the information on the Aragonese Pyrenees. Given that this process is extremely slow, in the case of the Diario de Navarra, the cases identified from the CNIH, the CCS, the press releases of the Government of Navarra were consulted and, to complete, the rainy days in which they were exceeded 40 mm, following the criterion used by Cortés et al. (2019). This information was obtained from the rainfall field provided by the SAFRAN analysis (Quintana Seguí et al., 2016). In the case of the Basque Country, consultation was difficult as the sources were written in Basque language, but it was possible to verify with the partners in the PIRAGUA Project, that the information indicated in table 1 was very complete, as it was also in the case of Andorra.~~

For Nouvelle Aquitaine (AQ) and Occitanie (OC), the databases of the Central Reinsurance Company (*Caisse Centrale de Réassurance* – CCR) and the National Observatory of Natural Risks (*Observatoire National des Risks Naturels* - ONRN) were used to create PIRAGUA_flood. In this case the information was completed in basis to the extreme rainfall records of Météo France. This ensured that all episodes that produced notable damage were included, although it is possible that some minor flood events with little damage have gone unnoticed~~.~~

Table 1. Main characteristics of the study area. N.munic.: number of municipalities; Total pop.: total population; GDP: mean Gross Domestic Product for the region for the year indicated in the table ; *: value relative to the part of the region that belongs to the Pyrenees. CNIH: Catálogo Nacional de Inundaciones Históricas (National Catalog of Historical Floods); INE: Instituto

170 Nacional de Estadística (National Institute of Statistics); PERICFN: Plan de Emergencia ante el Riesgo de Inundaciones en la Comunidad Foral de Navarra (Emergency Plan for the Risk of Floods in the Foral Community of Navarra) (https://gobiernoabierto.navarra.es/es/gobernanza/planes-y-programas-accion-gobierno/plan-emergencia-ante-riesgo-inundaciones-comunidad); EPRI: Evaluación Preliminar del Riesgo de Inundación (Preliminary Flood Risk Assessment of the 2nd Cycle of the Eastern Cantabrian Hydrographic Area); CCR: Caisse Centrale de Réassurance (Central Reinsurance Company) (https://catastrophes-naturelles.ccr.fr/); ONRN: Observatoire National des Risques Naturels (National Observatory of Natural Risks) (https://www.georisques.gouv.fr/articles-risques/onrn/acceder-aux-indicateurs-sinistralite#summary-target-1); INSEE: Institut national de la statistique et des études économiques (National Institute of Statistics and Economic Studies) (https://www.insee.fr); CENMA-IEA : Centre d'Estudis de la Neu i de la Muntanya d'Andorra-Institut d'Estudis Andorrans (Andorra Centre of Snow and Mountain Studies-Andorra Studies Institute). GDP data have been obtained from https://Datosmacro.Expansion.Com/Pib/Espana-Comunidades-Autonomas (Spanish regions), https://fr.statista.com/statistiques/479490/pib-par-habitant-selon-regions-france/ (French regions), https://datosmacro.expansion.com/pib/andorra (Andorra)

Region	Country	N.Munic.*	Area(km^2)*	Total pop.*	GPD(M€)	Information sources
Catalonia (CAT)	Spain	213	12,027.38	255,804	255,154 (2022)	INUNGAMA (Llasat et al, 2014); FLOODHYMEX (Llasat et al, 2013); CNIH (DGPC, 2022); CCS, 2021; La Vanguardia newspaper; INE.
Aragon (AR)	Spain	122	10,594.59	60,624	41,763 (2022)	CNIH (DGPC, 2022); CCS, 2021; El Heraldo de Aragón newspaper; INE.
Navarra (NA)	Spain	186	6,418.75	462,932	22,595 (2022)	CNIH (DGPC, 2022); CCS, 2021; PERICFN; Diario de Navarra newspaper; press releases from the Government of Navarre; SAFRAN (Quintana-Seguí et al., 2016), INE.
Basque Country (PV)	Spain	87	2,585.55	222,533	79,350 (2022)	CNIH (DGPC, 2022); CCS, 2021; EPRI (CHC and URA, 2018); INE.
Nouvelle Aquitaine (AQ)	France	162	3,697.2	104,568	189,300 (2021)	FLOODHYMEX (Llasat et al, 2013); CCR; Météo France; ONRN; INSEE.
Occitanie (OC)	France	1025	14,711.01	409,040	181,300 (2021)	FLOODHYMEX (Llasat et al, 2013); CCR; Météo France; ONRN; INSEE.
Andorra (AND)	Andorra	7	468	815,888	3,210 (2022)	CENMA-IEA; Database of the Ministeri d'Ordenament

						Territorial (Ministry of Territorial Planning) of the Government of Andorra.

In the case of Andorra, the information was obtained from the Andorra Snow and Mountain Studies Centre-Andorra Studies Institute (*Centre d'Estudis de la Neu i de la Muntanya d'Andorra-Institut d'Estudis Andorrans* -CENMA-IEA) database, which includes press information on floods in the media in Andorra. As the information in this database ends in 2002, information was also obtained from a register of the impacts caused by overflows of rivers and secondary streams provided by the Ministry of Territorial Planning of the Government of Andorra.

In some specific cases, precipitation maps were created from rainfall reanalyses provided by SAFRAN (Quintana et al., 2016), which allowed us to detect some municipalities that suffered flood damage where there was no other record. This was the case for Navarre, where possible cases not included in the CNIH were detected, which were later corroborated by the press.

3 Database structure and methodology

3.1 Development of the database

The database was built in ACCESS but to facilitate its use by any person interested in it, the public version is in EXCEL. It and is made up of two tables: a) Events; b) Affected municipalities that are linked throughout the event code (Fig. 2). The Events table aims to collect the most relevant data in as systematic a format as possible and contains the following fields: Identification of the event, meteorological and hydrological information indicators, impact indicators. In the second table, the municipalities affected by each event are entered. In case of victims, the information related to the victims is entered in the corresponding municipality. All fields are detailed in Appendix A. Tables 2 and 3 show the information and criteria used to create each one of these tables, that follows the example of FLOODHYMEX and INUNGAMA databases.

Figure 2. Structure of the PIRAGUA_flood database

Table 2. Information and criteria used to fill out the EVENTS table.

Event codes	**Integrated Event Code**: numerical code used to identify the event that have affected one or more regions. Indicates the first and last day on which the event has been registered in the entire Pyrenean region.
	Event: Numeric field composed of the start and end dates of the event in the specific region
Dates	**Start date**: Indicates the beginning of the episode in the specific region.
	End date: Indicates the end of the episode in the specific region. Criteria: -The event starts when the rain starts in the region. -The event ends when the flood ends. -A subsequent episode is considered a new episode when there is more than one day (at least) without any of the previous conditions occurring.
Location information	**Region**: Indicates the administrative region affected by the event: Aragon (AR), Catalonia (CAT), Navarre (NA), Basque Country (PV); Aquitaine (AQ); Languedoc-Roussillon (LR); Midi-Pyrénées (MP); Andorra (AND)
	Location 1: List of affected counties in the specific region
	Location 2: List of affected municipalities in the specific region
	Number of municipalities affected: number of municipalities that suffered damages in the specific region
	Affected area (Km²): Sum of the total area of the affected municipalities, in Km²
Meteorological and hydrological information	**Ptotal (Loc), Pmax (24 h) (Loc) o P (h) (Loc) (mm)**: It indicates the maximum cumulated precipitation in all the event or/and the maximum precipitation in 24h in mm or/and the maximum rainfall intensity in mm/h and its duration. In the three cases the station where the value was recorded is indicated.
	Other meteorological data: Optional field to add more hydrometeorological information.
	Other weather phenomena: Other adverse natural phenomena occurred in addition to floods: landslide, debris flow, hail, snow, windstorm, tornado, snow melting, lightning.
	Affected drainage basins: List of affected river basins
	Maximum flow (m³/s): Maximum instantaneous flow recorded indicating the river, gauging station and date, in addition to the average annual flow. If information is available for more than one river, it is included.

Event impact indicators	Category: The category of the flood event in the region according to the criteria described in section 3.1. There is a column for each category and supplementary category

Table 3. Information and criteria used to fill out the MUNICIPALITIES table.

Event codes	Integrated Event Code: numerical code used to identify the event that have affected one or more regions. Indicates the first and last day on which the event has been registered in the entire Pyrenean region.
	Event: Numeric field composed of the start and end dates of the event in the specific region. The same code that identifies the event in the "Events" table must be used.
Category	Event category: Category: The category of the flood event in the region according to the criteria described in section 3.1. There is a column for each category and supplementary category
Municipality and region identification	MunicipalityID: Code (NATCODE, INSEE or equivalent) of the municipality affected by the floods. Each row is for a municipality, which means an event can have more than one row.
	Location name: Name of the municipality.
	Region: region to which the municipality belongs
Information about victims	Deceased: Total number of fatalities in the municipality (if any).
	Gender and age of victims: When information is available, the gender and age of each victim is indicated.
	Causes: A brief description of the causes of death.
Other information	Other information: Supplementary information that is not covered in the other fields.

215 The category of flood events is based on the level of impacts and is divided into categories: 0 (ordinary), 1 (extraordinary), 2 (catastrophic), and 3 (major catastrophic), according to Figure 3, inspired by the criteria presented in previous publications (Barriendos et al., 2003; Llasat et al., 2013, 2016; Barrera-Escoda and Llasat, 2015). However, in these publications, the distinction between categories was purely subjective. In order to facilitate its reproduction by other authors, a table has been

220 designed to help decide in which category an event can be classified. Firstly, the "Damage indicators" have been selected based on literature (Petrucci, 2013; Boudou et al., 2016; Vinet et al., 2016). For each one of the indicators, the "Damage level" has been analyzed, where level 1 refers to possible minor damage (small floods in basements, breakdowns in traffic lights, etc.), level 2 refers to medium damages (it includes floods inside buildings and on communication routes which can cause traffic interruptions, partial damage to infrastructure, etc.), and level 3 refers to major impacts in the indicator (partial or total

225 destruction of buildings, roads, bridges, long lasting supply cuts, etc.). To classify flood episodes into categories, the level of damage in each of the seven indicators is taken into account, as shown in Figure 3. Fatalities are not included in Figure 3 as they can occur in any flood event category, although they are more likely to occur in catastrophic floods. The same applies to vehicles, as they can be swept away if they are parked on a creek where there is normally little water flow, without the river breaking its banks. This is why additional information has been included in the database, with the code of "0.5" if the episode

230 swept away cars and "5" if there were fatalities. Since the category of the episode may be different for each affected Pyrenees municipality, the highest occurring level determines the category of the episode.

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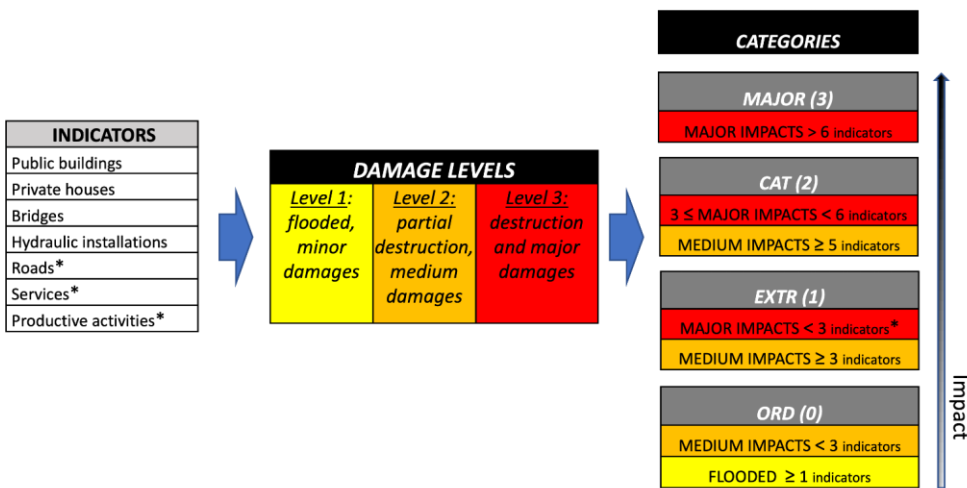
250 Figure 3: Criteria for categorizing flood events based on impacts. ORD (0): Ordinary flood event; EXTR (1): extraordinary flood event; CAT (2): catastrophic flood event; MAJOR (3): major catastrophic event. The level of damage is estimated from the direct impacts experienced, and a color scale is used (level 1: yellow; level 2: orange; level 3: red).

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Table 1: Criteria for categorizing flood events based on impact (0: Ordinary: one or more indicators at level 1; 1: Extraordinary: most of the indicators at level 2, with up to two at level 3; 2: Catastrophic: three or more indicators at level 3; 3: Major Catastrophe: seven or more indicators at level 3).

3.2 Spatial analysis

260 The number of flood events was represented at a municipal level using Geographic Information Systems (GIS), ArcGIS 10.4 and QGIS 3.10. Spatial analysis was carried out for all categories of flood episodes. To do this, for Catalonia it has been used the database of municipalities in shapefile format provided by the Cartographic and Geological Institute of Catalonia (ICGC) (https://www.icgc.cat/es/Administracion-y-empresa/Descargas/Capas-de-geoinformacion/Divisiones-administrativas). For the other regions, the database of municipalities and regions in the Geographic Information System of the European Commission (GISCO) has been used, which is part of Eurostat (Eurostat https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries). Regarding the study area, it has been used the defined delimitation in PIRAGUA (OPCC) in shapefile format (https://www.opcc-ctp.org/en/geoportal).

270 **3.3 Temporal analysis**

~~The temporal analysis includes a climatological aspect that makes it possible to characterise the seasonality of the events, and, also, a study of the possible annual trends. These analyses were carried out for the Pyrenees as a whole, as well as for the regions of Catalonia, Andorra, Aragon, the Basque Country, Navarre, Aquitaine and Occitanie. Likewise, for the severity of flood events, their evolution was studied considering the total number of events on a yearly basis, both by category (0, ordinary;~~
275 ~~1, extraordinary; 2, catastrophic; or notable -combined number of extraordinary and catastrophic), as well as by their total aggregate (i.e. evolution of the annual number of flood events in the Pyrenees).~~ The temporal analysis includes the monthly evolution of the events, in average, and the study of the possible annual trends. These analyses were carried out for the Pyrenees as a whole, as well as for the regions of Catalonia, Andorra, Aragon, the Basque Country, Navarre, Aquitaine and Occitanie. Likewise, for the severity of flood events, their evolution was studied considering the total number of events of each category
280 per year (0, ordinary; 1, extraordinary; 2, catastrophic; or notable -combined number of extraordinary and catastrophic).

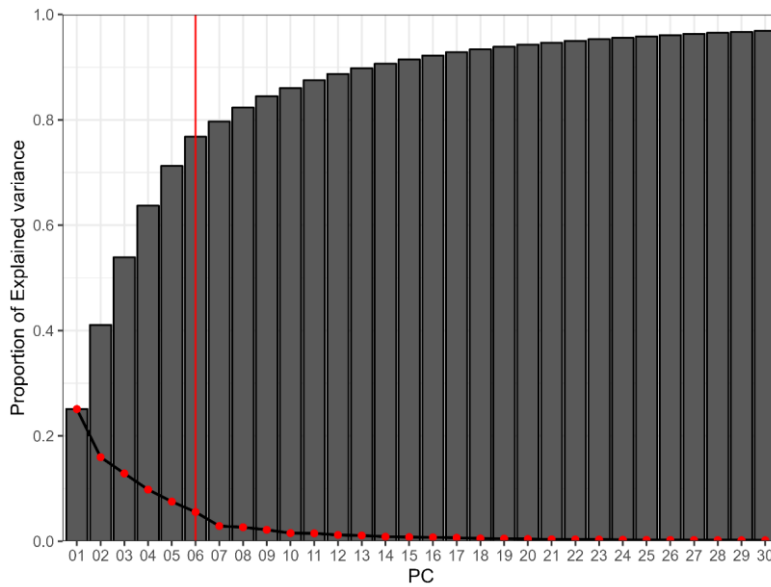
A linear regression was used to obtain the trend, while Mann-Kendall test was implemented~~used~~ to check its significance (Mann, 1945; Kendall, 1975). The Mann-Kendall test states as a null hypothesis (H0) that there is no monotonic tendency in the series, while the alternative hypothesis (Ha) is that there is trend (positive or negative). This is a non-parametric test, and
285 it can therefore be applied to all types of data regardless of the underlying probability density function. In the present study, it was established that a trend is significant when the p-value of the Mann-Kendall statistic is below 0.05 ($p < 0.05$).

~~These analyses were carried out for the Pyrenees as a whole, as well as for the subregions of Catalonia, Andorra, Aragon, the Basque Country, Navarre, Aquitaine and Occitanie. Likewise, for the severity of flood events, their evolution was studied by~~
290 ~~categories (0, ordinary; 1, extraordinary; and 2, catastrophic), as well as their total aggregate.~~

3.4 Weather types

The weather types associated with each flood episode have been classified using the mean sea level pressure (mslp) and the geopotential height at 500 hPa (z500), obtained from the ERA-5 reanalysis (Hersbach et al., 2020) in its native resolution (0.25°) for the geographical domain 20°W-20°E, 30°N-60°N~~., which was then averaged on a daily basis~~. The original hourly
295 data spanning from 1981 to 2015 were averaged on a daily scale to compute the synoptic classification described below.

To synthesise all the dates that comprise the flood episodes, a principal component analysis (PCA) was applied to the mslp and z500 matrices in mode T. Mode T configures the data matrix to which the PCA is applied as follows: the variables (columns) of such matrices are the days in which flooding occurs, while the cases (rows) are the grid points of ERA-5. Once
300 the PCA had been applied to the standardised data matrix, new variables were obtained: the principal components (PC), which

are linear combinations of the original variables. Subsequently, the PCs that explain a greater variance of the original data were identified using ~~a screen test (Cattell, 1966).~~ the scree~~n~~ test plot (Cattell, 1966), shown in Figure 4.

305   Figure 4. Scree test for the first 30 principal components (PCs). The red dots show the explained variance (%) for each principal component, while the grey bars show the cumulative explained variance. The red vertical line indicates the cut off PC. Thus, 6 PCs were retained accounting for the 78% of the total variance.

Once the most explanatory PCs had been retained, a Varimax rotation was applied to them to readjust the orthogonal
310   combination of each PC and obtain a greater variance explained by the initially less-explanatory PCs (Richman, 1986). Using the rotated PCs, the factor loads (i.e. the correlation matrix) were obtained, indicating the degree of correlation of each day with respect to each PC. In this sense, the allocation of each day to each of the PCs is based on the value of the maximum positive correlation and the minimum negative correlation. For example, day 1 is assigned to the absolute maximum correlation, but subsequently retains the correlation symbol. As a result, PC1 can be divided into two groups, one for days with
315   the maximum positive correlation (PC1+) and another for days with the lowest negative correlation (PC1-). This means that, if 6 PCs are retained, up to 12 weather types can be obtained. This type of classification has already been widely used to classify extreme events (with few samples), such as tornadic events (Rodriguez & Lemus-Canovas, 2023), torrential precipitation events (Martin-Vide et al., 2008; Lemus-Canovas et al., 2021) and heat waves and cold waves (Serrano-Notivoli

et al., 2022). To calculate the classification, the synoptReg R package was used (Lemus-Canovas et al., 2019a). This package
320   is available at https://github.com/lemuscanovas/synoptReg.

4   Regional distribution of flood events and impacts

4.1 Distribution of floods on a scale of the entire Pyrenean massif

~~Table 4 has been provided in order to synthesise the information that will be analysed in this section. It should be noted that~~
~~the same event can affect more than two regions. This is why we have calculated the total number of times that the different~~
325   ~~Pyrenees regions have been affected by floods, TOTAL, and the total number of episodes that have affected the massif, TOTAL~~
~~ep (considering that an episode that affects more than one region is counted only once). In this article, itis consider that those~~
~~floods that occur on the same day are related to the same meteorological synoptic situation, and, therefore, it is the same~~
~~episode that has produced floods in different points. This clarification is necessary because in other articles (i.e. Barriendos et~~
~~al, 2019; Gil Guirado et al., 2019) the criterion used is based on the sum of all the locations where flooding has occurred. If~~
330   ~~the number of times the regions have been affected by flood events is added, the figure of 242 is obtained, but if the criteria~~
~~just explained is taken into account, it is concluded that the Pyrenees massif was affected by 181 episodes of flood episodes~~
~~between 1981 and 2015. Of these events, 128 affected the Spanish part, 43 affected the French part, and 46 affected Andorra.~~
~~Some of the events were common to two or all three countries or they affected different regions from the same country, with~~
~~a total of 41 "transregional" episodes.~~

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Pyrenees regions have been affected by floods, TOTAL, and the total number of episodes that have affected the massif, TOTAL
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those floods that occur on the same day are related to the same meteorological synoptic situation, and, therefore, it is the same
340   episode that has produced floods in different places. This clarification is necessary because in other articles (i.e. Barriendos et
al, 2019; Gil-Guirado et al., 2019) the criterion used is based on the sum of all the locations where flooding has occurred. If it
would be considered the number of times the regions have been affected by flood events, the figure of 242 would be obtained,
but if the criteria just explained is taken into account, it is concluded that the Pyrenees massif was affected by 181 flood
episodes between 1981 and 2015. Of these events, 128 affected the Spanish part, 43 affected the French part, and 46 affected
345   Andorra. Some of the events were common to two or all three countries or they affected different regions from the same
country, with a total of 41 "transregional" episodes. One example was the flood event that occurred between June 17 and 19,
2013, that affected Spain and France. In Catalonia, the municipalities with the greatest damage due to the 2013 event were
Salardú, Arties, Escunhau, Vielha, Bossòst, and Les; in Aragon, it was Cerler, Castejón de Sos and Benasque; in Aquitaine,
there was catastrophic damage in Lourdes and Arreau (Hautes-Pyrénées), Nay (Pyrénées-Atlantiques) and Saint-Béat (Haute-
350   Garonne). Some towns were isolated due to road damage, landslides or rock falls. Numerous bridges, some buildings and

campsites were totally or partially destroyed by the violent floods that carried rocks and remains of vegetation. Numerous houses and crop lands were flooded, causing cuts in all types of supplies. It was, therefore, a flood event of category 3 (major).

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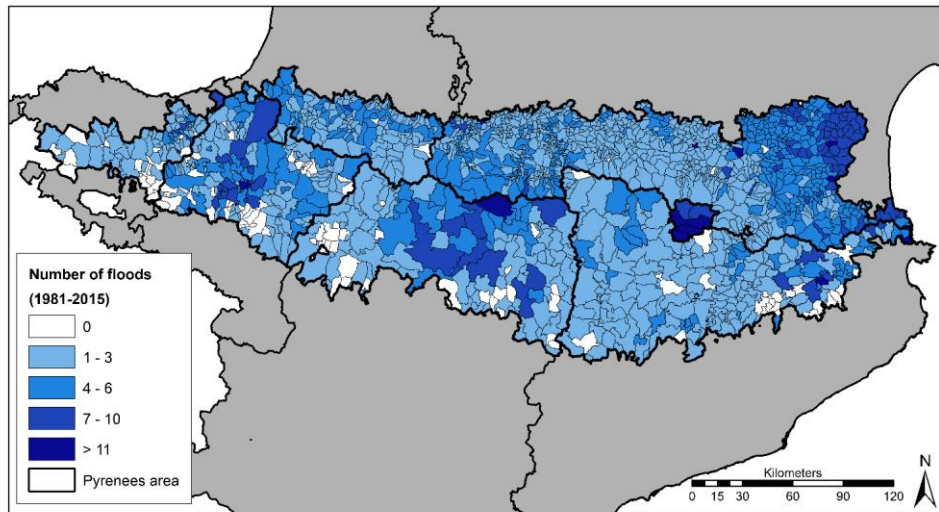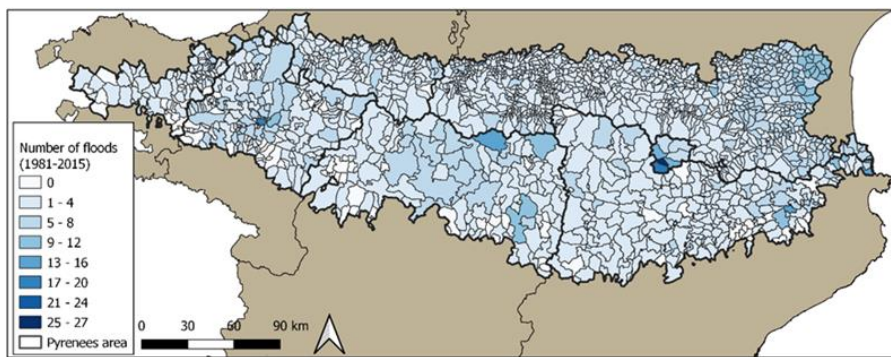
Figure 54²: Number of flood events that affected each municipality in the Pyrenees between 1981 and 2015.

Figure 2 shows an apparently uniform distribution throughout the region, highlighting only a greater frequency in some municipalities, which is why Fig. 3 has been constructed, which also allows us to distinguish the category of flood episodes. It shows that the region with the highest number of flood events was Catalonia, with 66 flood events, followed by Andorra, with 46, while the region with the lowest number of flood events is the Basque Country, with 16 flood events. This difference may be related to both the orography and the meteorological disturbances causing intense rains, which will be discussed later. But it should also be considered that for Andorra and Catalonia there is more systematized information available, which allows all ordinary floods to be included. In fact, Andorra is the region that records the highest percentage of ordinary floods (67.4%).

Figure 54 shows that the highest concentration of flood episodes occurs in Andorran municipalities and in the easternmost area of Occitanie and Catalonia. Some municipalities in Aragón and Navarra also stand out, while in the Basque Country and Nouvelle Aquitanie, no municipality have recorded more than 7 episodes of flooding. The region with the highest total number of flood events was Catalonia (66), followed by Andorra (46), while the lowest number was recorded in the Basque Country (16) (Fig. 6). Andorra is the region that records the highest percentage of ordinary floods (67.4%) although the absolute maximum corresponds to Catalonia (Fig.5). This regional difference may be related to both the orography and the meteorological disturbances causing intense rains, which will be discussed later. The highest number of catastrophic flood events was recorded in Nouvelle Aquitaine, followed by Occitanie and Aragón.

We cannot forget, however, that it is possible that some ordinary floods in France have gone unnoticed, as we have explained in section 2.2. This is why figure 7 6 has been constructed. It Figure 4 shows the distribution by municipality of flood events with notable damage (that is, they were extraordinary or catastrophic). The distribution hardly changes with respect to figure 54, and only the maxima of some municipalities are smoothed out. Of the 181 flood events, 52% produced notable damages in one or more of the Pyrenean regions. It is observed that notable flooding events are concentrated above all in the municipalities of the Pyrenees closest to the Mediterranean, both on the Spanish and French sides. The central part of the Spanish Pyrenees also stands out, located at the foot of the highest mountains. The highest number of catastrophic flood events was recorded in Nouvelle Aquitaine, followed by Occitanie and Aragón. It is observed that notable flooding events are concentrated above all in the municipalities of the Pyrenees closest to the Mediterranean, both on the Spanish and French sides. The central part of the Spanish Pyrenees also stands out, located at the foot of the highest mountains. Pamplona (Aragón) and Llançà (Catalonia) have been the municipalities with the major number of flood events (17 and 16, respectively). For the period 1996-2015, the number of flood episodes in both regions becomes 9 and 11, respectively, with a compensation paid by the CCS that amounts to 18 M€$_{2015}$ and 1.1M€$_{2015}$, respectively. In the same period, Vielha (Catalonia), which after Pamplona is the municipality to which the CCS has paid the most, collected €9.9 M€$_{2015}$ in compensation for one episode. This difference is consequence of the major exposure of Pamplona, with a population of 195,853 inhabitants, in front of the 5,450 inhabitants in Vielha and 4,985 inhabitants in Llançà (year 2015). In the case of Vielha, the GDP is 170.2 M€$_{2015}$, practically double that

the GDP of Llançà, with 91.9 M€$_{2015}$ that partially explains the different impacts between both Catalan villages, added to the fact that the 2013 flood in the Garonne River was catastrophic in Catalonia and Occitanie.

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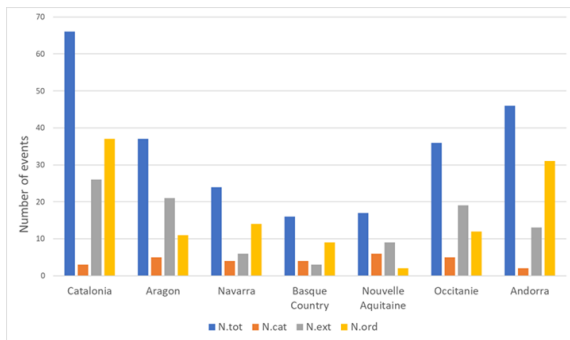
Figure 65: Distribution of the total number of flood events (blue) and the number of flood events by categories (catastrophic, orange; extraordinary, grey; and ordinary, yellow) in the different communities that make up the POCTEFA Pyrenees region, for the period 1981-2015.
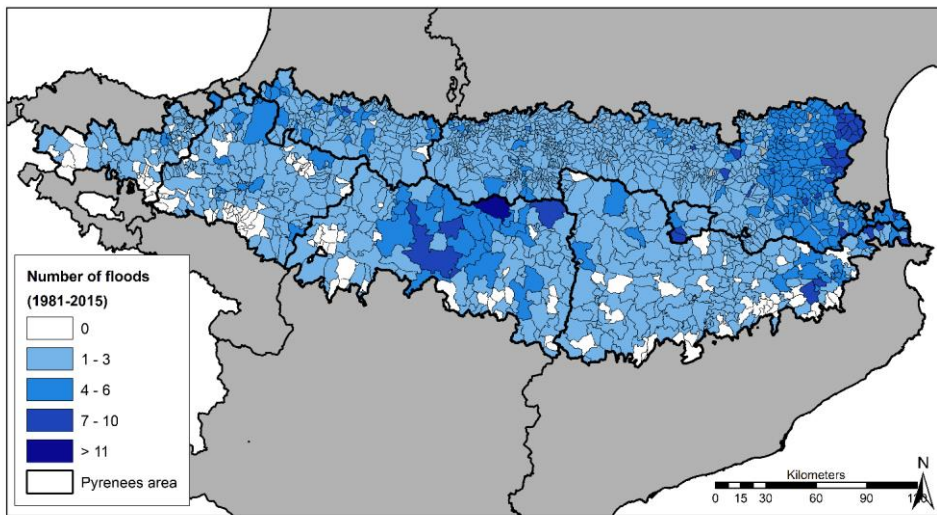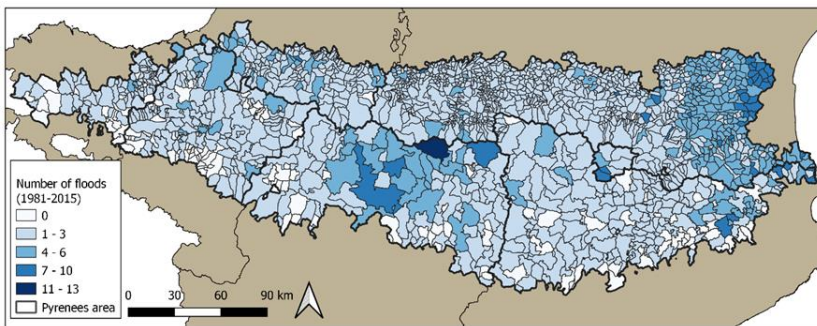
Figure 764: Number of notable flood events (of catastrophic and extraordinary floods (non-ordinary episodes) that affected each municipality in the Pyrenees.

Table 42 also shows the number of fatalities per region. Of the 154 victims, 97 died in floods in August, 87 of which correspond

to the flash flood that destroyed Las Nieves campsite of Biescas on August 7, 1996. This makes Aragon the region with the

highest number of deaths, with a total of 97. The remaining ten deaths, as well as the other victims, were recorded in July or

September and are associated with mountain sports or ravine crossings. In contrast, the 39 victims recorded in November were

mostly a result of more organised and extensive episodes of heavy rainfall (i.e. 6-8 November 1982), and a major part of them died at home or they were in a car that was swept away by the flood.

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Table 4: Synthesis of information on flood events that have affected the Pyrenees-POCTEFA region in the period 1981-2015. It indicates total number of events (N.tot); number of catastrophic episodes (N.cat.); number of extraordinary episodes (N.ext.); number of ordinary episodes (N.ord); the municipality most affected (munic. max) and the number of cases it recorded (N.tot munic. max); the total number of fatalities (N.vict.), the compensation paid by the CCS to the municipalities in the Spanish

415 Pyrenees for floods that took place between 1996 and 2015, adjusted to 2015 (CCS tot); the municipality that received the most amount (munic. max CCS) and the amount (CCS munic. max); the three months that recorded the greatest number of events; and the trend of the number of events per decade (* means a significant trend at 95%). The sum of episodes that affected the various study regions (TOTAL) and the number of episodes that affected the Pyrenees region (TOTAL ep) is indicated. In the latter addition, events common to two or more regions have been included only once.

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4.2 Regional flood events distribution

In the study period (1981-2015) there were 66 episodes in the Catalan Pyrenees in which the number of victims amounted to 21. Three episodes were catastrophic and 26 were extraordinary (Table 4). Figure 5 shows that the highest number of floods took place in the coastal foothills of the Pyrenees (16 episodes in the coastal municipality of Llançà, of which 62% were extraordinary) that confirms the strong role played by the entrance of Mediterranean air masses In Aragon there were a total of 37 flood events, of which 13.5% were catastrophic. In 4 of them there were flash floods that led to the evacuation or death of several people who were canyoning. The number of victims amounts to 97, 87 of whom died at the Las Nieves campsite (Biescas) in August 1996 (Ayala Carcedo, 2002). Aragon has the county with the highest number of flash floods in the Pyrenees and it is Sobrarbe, where 26 events have taken place in 35 years. These are mainly events associated with thunderstorms in which the orography forces the rise and hinders the advance of convective systems, which can remain stationary in the same place (i.e. the Biescas case). The large number of torrents and dejection cones favors the production of flash floods. Given that these are very attractive mountain areas, it is possible that there are campsites, hikers or high-risk sportsmen and sportswomen, which increases vulnerability and exposure. The Navarre Pyrenees were affected by 24 events (17%, catastrophic) in which there was one victim. In this case, the damage is usually due to urban and peri-urban flooding, affecting its capital, Pamplona (203,418 inhabitants) that is the Pyrenean city with the largest number of recorded events (17). However, the most catastrophic episodes in Navarra have occurred in the Baztan valley, where numerous villages and small industries extend around the river. During the period 1981-2015 only 6 episodes of flooding (25% catastrophic) affected the Basque Pyrenees, with two victims. Most of them were concentrated in the eastern part of the region, near the Baztan valley. Although it is true that the costliest flood event recorded in Spain in that period took place in the Basque Country, in August 1983, the greatest damage occurred around the coastal estuaries, outside the Pyrenean region. Precisely, if the economic costs are taken into account, the CCS paid a total of €33.4 million$_{2015}$ (M$_{2015}$) in flood compensation in the Catalan Pyrenean Region in the period 1996-2015, with the Val d'Aran being the most compensated region (a recreation and ski area with luxurious urbanizations near the river), mainly due to the June 2013 event that also affected Aragón and the French Pyrenees (Table 7). For the same period, the CCS paid a total of €15.2 M$_{2015}$ in flood compensations in Aragón, mainly due to the flood events of August 1996 (the Biescas case), that also affected Andorra, and the flood event of June 2013. The CCS paid a total of €65.8 M$_{2015}$ in flood compensation in Navarra, of which about €18 M$_{2015}$ went to Pamplona and €5.5 M$_{2015}$ went to Baztan. The CCS paid a total of €28.1 M$_{2015}$ in flood compensation in the Basque Pyrenees, of which the largest amounts went to Tolosa (19.525 inhabitants, the most important city in the region).

A total of 46 flood events were recorded in Andorra in the period 1981-2015, of which only 4.55% were catastrophic. It is a country of 79,824 inhabitants with a very high risk of flooding, especially because the most important towns and villages are surrounding the Valira River in a very narrow valley. The most important heavy rainfall events are usually due to Mediterranean perturbations that also affect Catalonia and/or Aragón (Table 7). The maximum number of flood events

occurred in the municipality of Andorra la Vella (27), followed by Sant Julià de Lòria (18). In total, 43 episodes of floods affected the French side of the Pyrenees, of which Nouvelle Aquitaine recorded 17 events and Occitanie recorded a total of 36 events, with a percentage of catastrophic episodes of 35.3% and 13.9%, respectively. Ten of these episodes were common to the two regions. In Occitanie, the municipality with the most flood episodes was Montgaillard, with 13, while in Nouvelle Aquitaine the maximum was lower, with 7 events in Mauleon-Licharre. Both populations are located closer to the Atlantic than the Mediterranean, being exposed above all to disturbances from the west and northwest. As a whole, however, the municipalities located further east in Occitanie stand out, where floods are mainly associated with disturbances such as those affecting Catalonia and Andorra. It is noteworthy that all the municipalities in the French Pyrenees have recorded at least one catastrophic flood event, with the maximum recorded in the northeastern part, close to the Mediterranean.

The CCS paid a total of €33.4 million$_{2015}$ in flood compensation in the period 1996-2015, with the Val d'Aran being the most compensated region, mainly due to the June 2013 event (Fig. 5b).

a   b
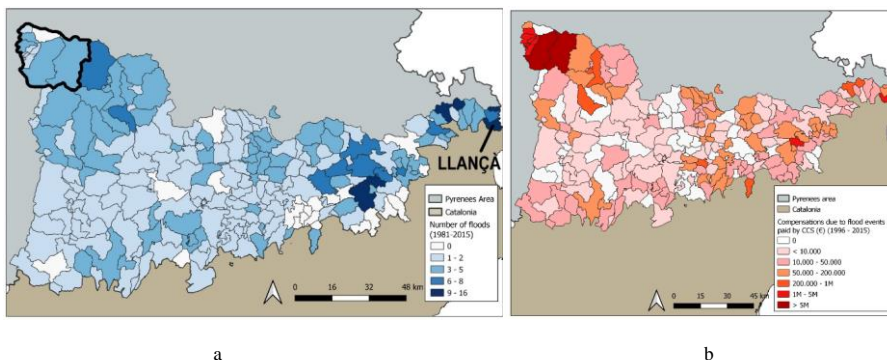
Figure 5: a) Number of flood episodes that affected each municipality in the Catalan Pyrenees between 1981 and 2015. The location of Val d'Aran (marked with a black line) and Llançà is shown; b) Compensation paid by the CCS for floods between 1996 and 2015.

In Aragon there were a total of 37 flood events, of which 13.5% were catastrophic. In 4 of them there were flash floods that led to the evacuation or death of several people who were canyoning. The number of victims amounts to 97, 87 of whom died at the Las Nieves campsite (Biescas) in August 1996 (Ayala Carcedo, 2002). Aragon has the county with the highest number of floods in the Pyrenees and it is Sobrarbe, where 26 events have taken place in 35 years (Fig. 6a). Its capital, Bielsa, recorded 15 flood events. The CCS paid a total of €15.2 million$_{2015}$ in the period 1996-2015 (Fig. 6b), mainly due to the flood events of August 1996 and June 2013 that also affected Catalonia, Occitanie and Nouvelle-Aquitaine.

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During the study period, there were a total of 16 episodes of flooding (25% catastrophic) in the Basque Pyrenees, with two victims. Most flood events are concentrated in the eastern part of the Basque Pyrenees, with a maximum of 8 events in Oiartzun (Fig. 8a), although the municipality with the highest number of catastrophic events is Itsasondo, with three events. The CCS paid a total of €28.1 million$_{2015}$ in compensation, of which the largest amounts went to Toulouse and Oiartzun, which received €3.1 million$_{2015}$ and €3 million$_{2015}$ respectively (Fig. 8b).

a   b
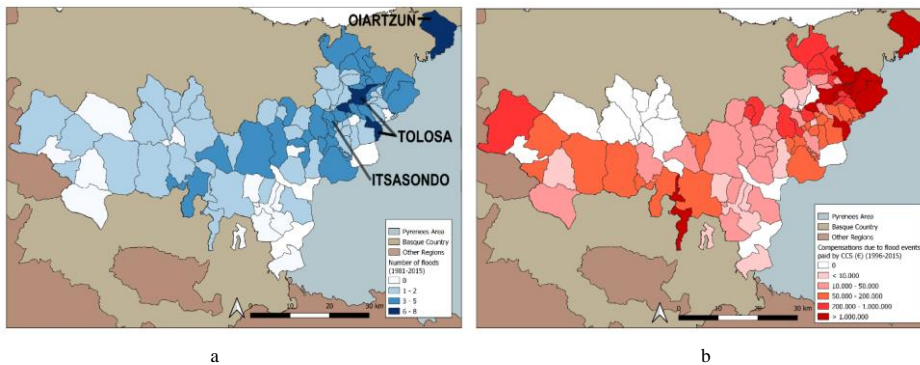
Figure 8: (a) Number of flood episodes that affected each municipality in the Basque Pyrenees between 1981 and 2015. The location of Oiartzun, Toulouse and Itsasondo is shown; b) Compensation paid by the CCS for floods between 1996 and 2015.

In total, 43 episodes of floods affected the French side of the Pyrenees, of which Nouvelle Aquitaine recorded 17 events (Fig. 9) and Occitanie recorded a total of 36 events, with a percentage of catastrophic episodes of 35.3% and 13.9%, respectively. Ten of these episodes were common to the two regions. In Occitanie, the municipality with the most flood episodes was Montgaillard, with 13 (Fig. 10), while in Nouvelle Aquitaine the maximum was lower, with 7 events in Mauleon-Licharre. It is noteworthy that all the municipalities in the French Pyrenees have recorded at least one catastrophic flood event, with the maximum recorded in the northeastern part, close to the Mediterranean.

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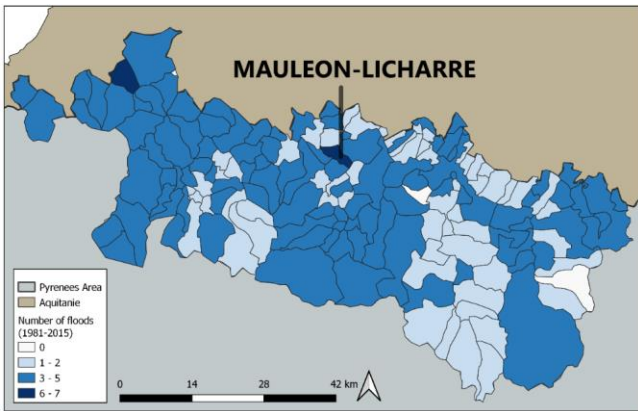
Figure 10: Number of flood episodes affecting each municipality in the Occitanie Pyrenees. The location of Montgaillard is shown.

A total of 46 flood events were recorded in Andorra in the period 1981–2015, of which only 4.55% were catastrophic. This percentage is very similar to that of Catalonia. Both regions are mainly affected by Mediterranean perturbations coming from
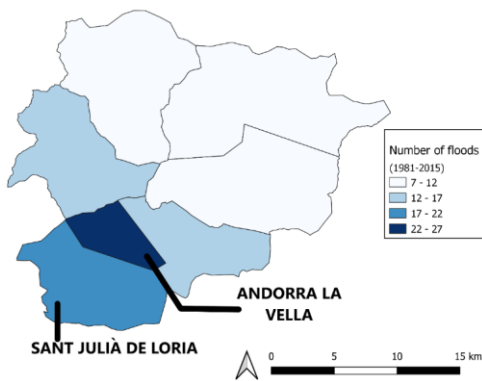
Figure 11: Number of flood episodes that affected each municipality in Andorra between 1981 and 2015. The location of Andorra la Vella and Sant Julià de Lòria is shown.

535 **5   Temporal analysis**

Figure 8712 summarises the monthly distribution of the number of flood events for each of the regions. In the case of the Catalan Pyrenees, most events are concentrated between September and November, while in Occitanie the October-November period stands out. In the Aragon Pyrenees, the August maximum stands out, extending the flood period until November. The summer season is also very significant in Andorra, with maximahighs in July and August. In Navarrae, the events they are
540   distributed throughout the October-July period, with no remarkable month. This distribution differs from that of Aquitaine, with a greater concentration from May to June, and from that of the Basque Country, with two different periods: June-August and January-March. This distribution leads us to believe that the regions with maxima in autumn are due to Mediterranean disturbances, while the maxima in spring and winter are associated with cold fronts, and summer encompasses convective events. In the same figure the solid line shows how the monthly evolution in the total number of episodes (an episode that
545   affects several regions is considered as a single episode) is unimodal, with a maximum in summer (42% of the total number of annual events) that would be associated with flooding by very intense and local convective rains. This is confirmed by the intra-eraannual evolution of the number of flood episodes excluding ordinary ones (see the dashed line in Figure 8712), in which the summer maximum disappears to give way to a bimodal distribution with maxima in June and October. The unimodal distribution bears a considerable resemblance to the distribution of the percentage of convective precipitation throughout the
550   year obtained for the Spanish Mediterranean region (Llasat, 2001; Llasat et al., 2021). In these 36 years, the highest number

of victims occurred in August. Generally, these are individuals who engage in risky sports, although the high number of deaths is due to the Biescas disaster. The number is also relatively high in November and is associated with longer-duration events."

The evolution of the flood events that have produced notable damages (extraordinary and catastrophic ones) in the different regions of the Pyrenees, shows high variability (Fig. 12). The trend analysis on a regional scale is only significant at 95% according to the Mann-Kendall test for Nouvelle-Aquitaine, which shows an increase of 0.34 events/dec., that is due to the increase of extraordinary events. For information purposes, although they are not significant at 95%, positive trends were also observed in Catalonia, Navarre, Occitanie and Andorra, although 0.1 ev./dec. is only exceeded in Catalonia and Occitanie. On the contrary, in Aragon and the Basque Country, the trend is negative, but it does not reach -0.1 ev/dec. Taking the Pyrenees massif in its entirety, the trend of notable flood events is positive and equal to 0.5 ev./dec., but it is not significant at 95% or 90% (Fig. 13). On the other hand, if ordinary episodes are also considered, the trend of flood events for the entire Pyrenees increases until 0.845 ev./dec. but if the confidence level is lowered to 90%, the trendit is still not only significant at 90% (Fig. 98).
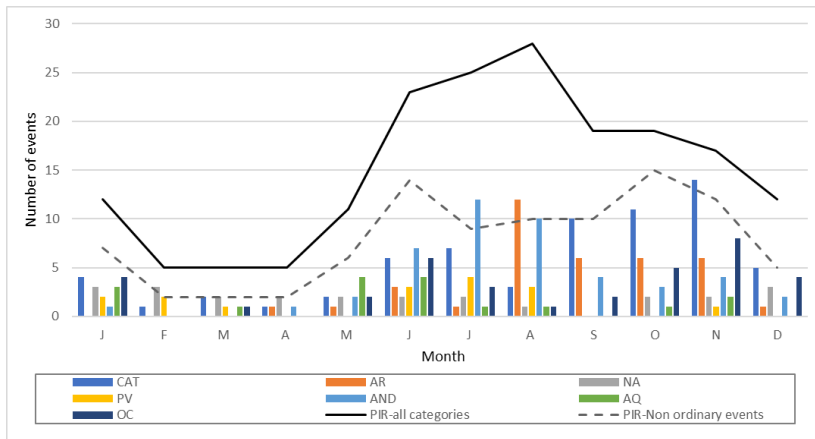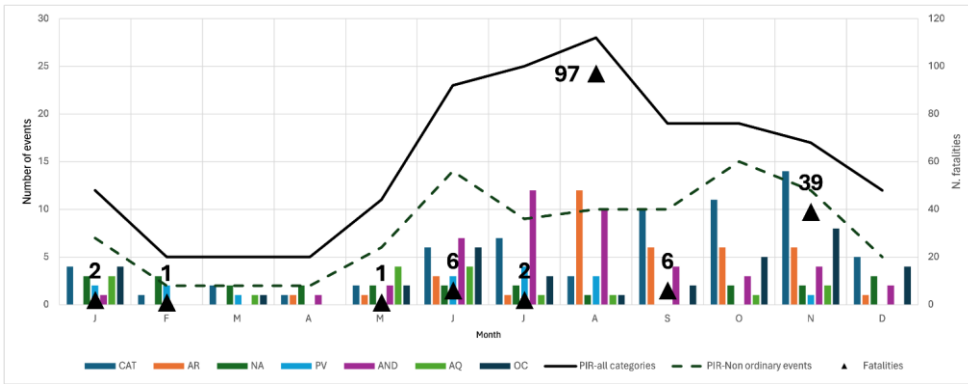
Figure 8712: Monthly distribution of the total number of flood cases for the different regions. The solid line shows the entire Pyrenees-POCTEFA region, and the dashed line shows the number of ~~significant~~ notable events (period 1981-2015). The triangles indicate the total number of casualties in the entire study area for each month, the value is included next to the symbol.

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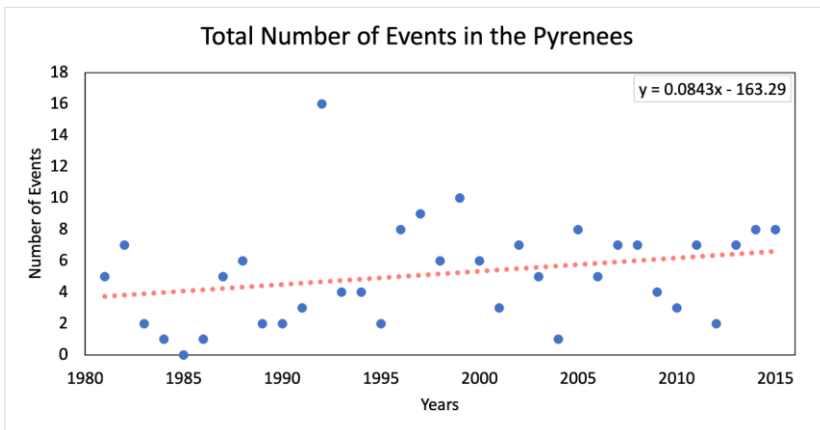
Figure 9813: Evolution of the total number of flood events (including ordinary and non-repeated events in the different regions) for the period 1981-2015.

6   Cross-border flood episodes

575   Of all the recorded flood events, 41 affected two or more Pyrenean regions (Table 63). Of these, 34 were international cross-border, highlighting the episodes that affected Spain and France (71%), while 24% affected Spain and Andorra simultaneously, and 5% affected all three countries (Table 6). The most frequent are episodes that simultaneously affect two or more of the regions of Catalonia, Aragon, Occitanie and Andorra: 41% of the transregional episodes took place between Catalonia and Occitanie, while 24% were between Catalonia and Aragon and another equal percentage between Occitanie and Nouvelle

580   Aquitaine (Table 6). They occur mainly in autumn (Fig. 10), which is consistent with the fact that it is in this season when the entry of organized Mediterranean disturbances is produced, usually associated with the presence of a depression in the Mediterranean and favored by a warm sea (Llasat, 2009). On the contrary, between January and April practically no transnational episodes are recorded, and none has been recorded in February, which points to more localized events.

~~Although the month of November recorded the most cross-border episodes, such episodes can occur at any time of the year~~

585   ~~(February is the only month with no cross-border episodes were recorded). It is important to note that, in general, in summer, such episodes do not usually last more than one day.~~

~~4 of which did not exceed the category of ordinary in any of the countries, 23 of which were extraordinary in at least one of the countries, and 7 of which were classified in at least one of the countries as catastrophic. The episodes from 6-8 November 1982 and from 3-7 July 2001 affected the three countries, 8 affected Spain and Andorra and 24 affected Spain and France.~~

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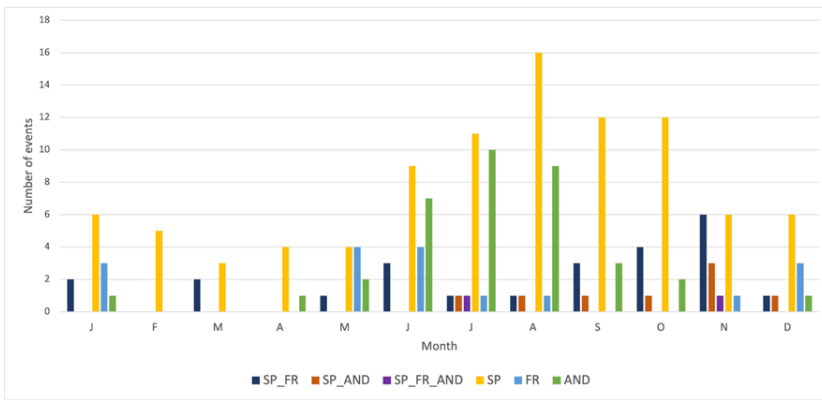
Figure 10. Monthly total number of flood events recorded in the Pyrenean Region (1981-2015), for each country (SP: Spain; FR: France; AND: Andorra) and for cross-border events.

Although the month of November recorded the most cross-border episodes, such episodes can occur at any time of the year (February is the only month with no cross-border episodes were recorded). It is important to note that, in general, in summer, such episodes do not usually last more than one day.

Month	Sp-Fr	Sp-And	Sp-And-Fr	Sp	Fr	And
January	2	0	0	6	3	1
February	0	0	0	5	0	0
March	2	0	0	3	0	0
April	0	0	0	4	0	1
May	1	0	0	4	4	2
June	3	0	0	9	4	7
July	1	1	1	11	1	10
August	1	1	0	16	1	9
September	3	1	0	12	0	3
October	4	1	0	12	0	2
November	6	3	1	6	1	0
December	1	1	0	6	3	1
TOTAL	24	8	2	94	17	36

Table 3: Monthly distribution of the number of episodes that affected the Pyrenees-POCTEFA region in the period 1981-2015, differentiating between the episodes that only affected one of the countries or, in the case of cross-border episodes, the countries affected. Sp: S pain, Fr: France, And: Andorra.

Table 6. Number of events that have affected each Pyrenean region and number of events that have affected each pair of regions indicated by the intersection by them. The diagonal shows the total number of events in each region.

	CAT	AR	NA	PV	AND	OC	AQ
CAT	66						
AR	10	37					
NA	0	1	24				
PV	1	1	3	16			
AND	7	8	0	0	46		
OC	17	8	2	2	2	36	
AQ	3	4	5	4	1	10	17

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Table 74: Flood events that affected more than one of the countries of the Pyrenees-POCTEFA region in the period 1981-2015. Affected countries in blue.

Event dates	SP	FR	AND	Event dates	SP	FR	AND
4-10/11/1982	■	■		3-7/7/2001	■	■	■
25-28/8/1983	■			16/7/2002	■		■
8-11/11/1984	■		■	3-4/12/2003	■	■	
12-15/10/1986	■	■		12-15/11/2005	■	■	
28/9-5/101987	■	■	■	9-1/3/2006	■	■	■
10-11/10/1987	■		■	3-4/5/2007	■	■	
14-18/11/1989	■	■		22-28/1/2009	■	■	■
8-9/9/1992	■	■	■	10-13/10/2010	■	■	
26-28/9/1992	■	■		1-10/11/2011	■	■	
21-26/9/1993	■	■		19-22/11/2011	■	■	
18-20/10/1994	■	■		18-21/10/2012	■	■	
4/11/1994	■		■	12-16/1/2013	■	■	■
2-3/8/1996	■		■	4-7/3/2013	■	■	■
5-7/11/1997	■	■	■	17-20/6/2013	■	■	■
16-20/12/1997	■	■		4/7/2014	■	■	
10-15/11/1999	■	■		27/11-1/12/2014	■	■	■
10/6/2000	■			10/6/2015	■	■	

Table 74 shows the list of cross-border flood events. As an example, Figure 1114 shows the municipalities that were affected by the floods of November 1982. The heavy rains began on 6 November in Spain, and extended to Andorra and France on 7 November, ending the following day. They had a particular impact on the Eastern Pyrenees. The maximum total rainfall was

615   610 mm in Py (France), 556 mm in La Molina (Spain) and 203 mm in Soldeu (Andorra) (Figure 12). As a result of the floods, 14 fatalities were recorded in Catalonia, with damages valued at €994 million$_{2015}$ (Catalonia), €88 million$_{2015}$ (Aragon) and €132 million$_{2015}$ (Andorra). This flood event is one of the most extensive and intense of the 20th century in southwestern Europe. In it, the mountains played a very relevant role, favoringfavouring the orographic ascent and the release of instability (Trapero et al., 2013). The large amount of precipitation that occurred was due to the feeding of water vapor from remote

620   sources, such as the subtropical Atlantic (Insua-Costa et al., 2019).
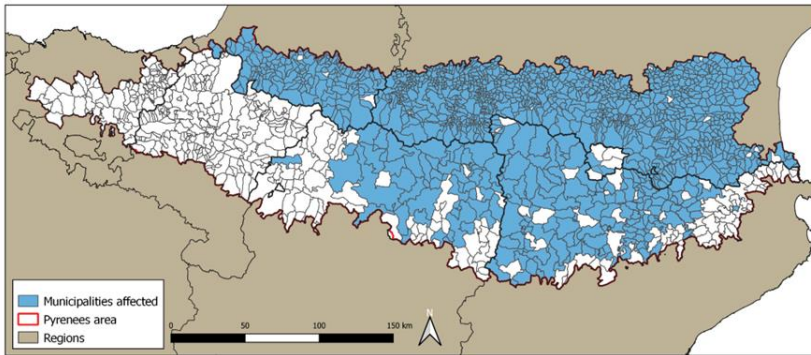
Figure 1̶1̶4: Municipalities of the Pyrenees affected by the floods of 6-8 November 1982.

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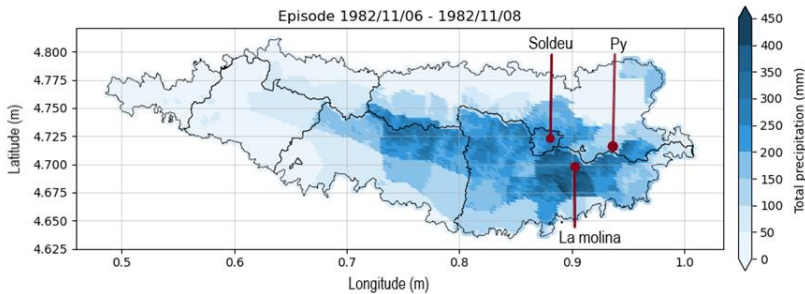
Figure 1̶2̶5: Precipitation collected between 6 November at 06:00 UTC and 9 November 1982 at 06:00 UTC from SAFRAN reanalysis.

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7   Weather types

Figure 1̶3̶6 shows the 12 weather types (WT) obtained from the combination of mslp and z500, and explaining practically 80%

630   of the variance, corresponding to the flood episodes that affected the Pyrenees between 1981 and 2015. First of all, it should

be noted that there is no significant trend in any of the WTs. The WT 1-, characterised by a marked depression to the NW of

the Iberian Peninsula and a t̶h̶alweg is the most characteristic of the episodes affecting the Eastern and Central Pyrenees (Fig.

1̶4̶7a) in autumn (Fig. 1̶4̶7b). This favours the advection of warm and humid air from the Mediterranean in low levels, and

feeds humidity from remote sources. This was the case during the November 1982 episode (Llasat, 1987), and is the case in a

635   large number of the episodes of intense rainfall that take place in the Western Mediterranean (Insua-Costa et al., 2022; Miró

et al., 2022). Note in Figure 1~~3~~7b that this type of weather shows its maximum frequency in the month of October, the month with the most episodes of flooding in the Pyrenees.

~~The WT 3+ shows the formation of a mesoscale depression off the coast of Catalonia that results in instability and the E-SE air flow over the Eastern Pyrenees (Fig. 17a). The highest frequency is recorded in spring, specifically in June, a month that, as we have already seen, comes after October in terms of flood frequency (Fig. 17b). An example of this would be the floods of June 2014. These northern movements are usually associated with summer floods and can affect any area in the Pyrenees.~~ The WT 1+ favours the entry of Atlantic air over the Western Pyrenees and, like the WT 1-, can lead to the passage of highly organised disturbances typical of winter or autumn (Fig. 1~~4~~7b), with notable rainfall accumulations in the western and northern part~~half~~ of the Pyrenees (Lemus-Canovas et al., 2019b) where most of the floods are recorded (Fig. 1~~4~~7a). In fact, the highest frequency is recorded in January (Fig. 1~~4~~7b). On the other hand, the dominant weather type in summer is WT 2- (Fig. 1~~4~~7b), which shows in the slight wave over the Iberian Peninsula, while on the surface the situation is relatively unclear. It would therefore be a situation favourable to isolated convection or poorly organised weather systems, typical of that time of year, but which can also result in some episodes of very intense rainfall, as also described in Lemus-Canovas et al. (2021). This is the situation that characterised the episode of Biescas (Aragon), which occurred on 7 August 1996, and the floods that affected the Basque Country and Aquitaine in August 1983, mainly concentrated in the southern half of the Pyrenees (Fig. 1~~4~~7a). The WT 3+ shows the formation of a mesoscale depression off the coast of Catalonia that results in instability and the E-SE air flow over the Eastern Pyrenees (Fig. 1~~4~~7a). The highest frequency is recorded in spring, specifically in June, a month that, as we have already seen, comes after October in terms of flood frequency (Fig. 1~~4~~7b). An example of this would be the floods of June 201~~3~~4. These northern movements are usually associated with summer floods and can affect any area in the Pyrenees. Finally, it can be observed that in November the WT 4+ and WT 5+ dominate (Fig. 14b), both with a very marked groove over the Iberian Peninsula that will favour the vorticity to the east and the contribution of air flow from the Atlantic that feeds intense rainfall, especially in the easternmost sector of the mountain range (Lemus-Canovas et al., 2018). These WT are mainly associated with floods in the Eastern part of the Pyrenees (Fig. 14a). An example is the episode of November 2005, which had a serious impact on Catalonia.

The types of weather associated with cross-border episodes depend on the time of year in which they occur. Of the eight cases recorded between June and August (Fig. 10), seven have been characterized by WT 2-. In September, types WT 2- and WT 3- dominate. In October and November, which have recorded 16 common episodes, there is no dominant type of weather, and it is even the case that unusual types appear, such as WT 4-, characterised by a deep depression to the west of the British Isles that extends up to 500 hPa and even more, with a talweg~~groove~~ that crosses the Peninsula from northwest to southeast.
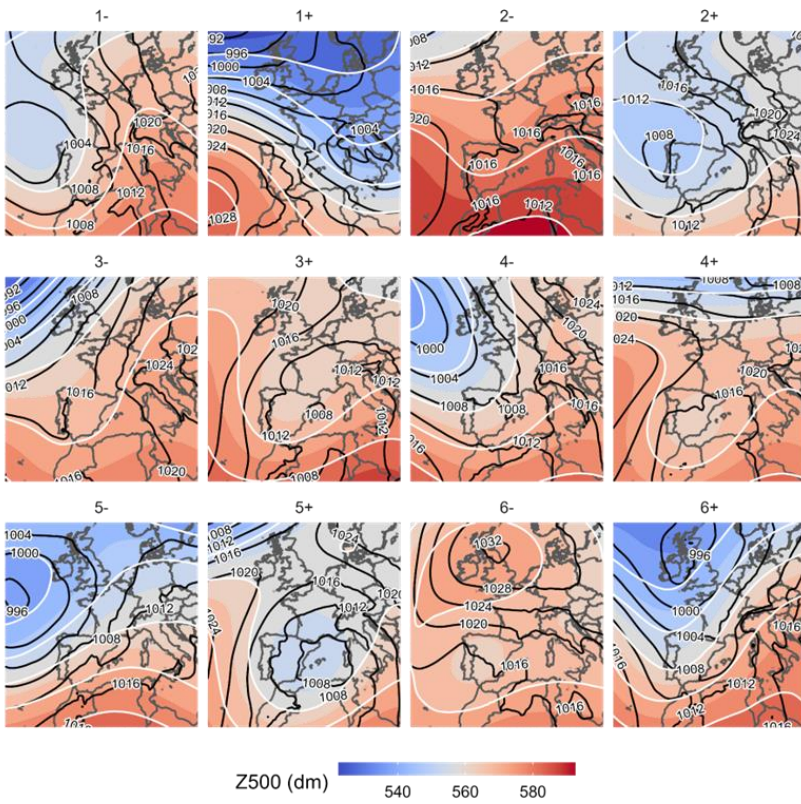
Figure 136: Types of wWeather types that characterise flood episodes in the Pyrenees.

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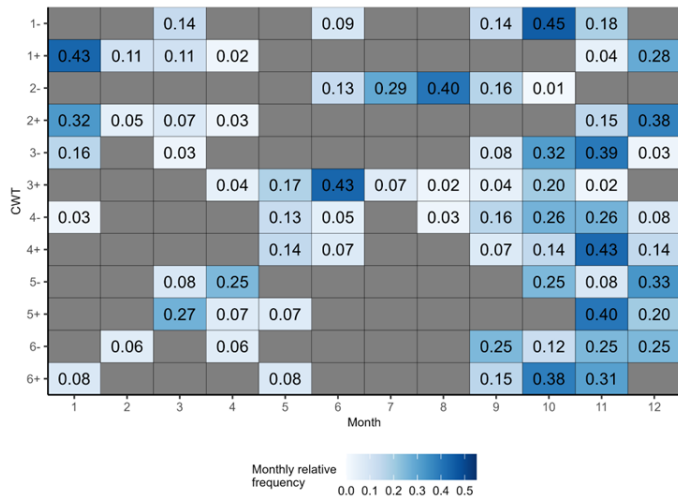
Figure 17: Monthly distribution of the frequency with which each weather type is recorded.
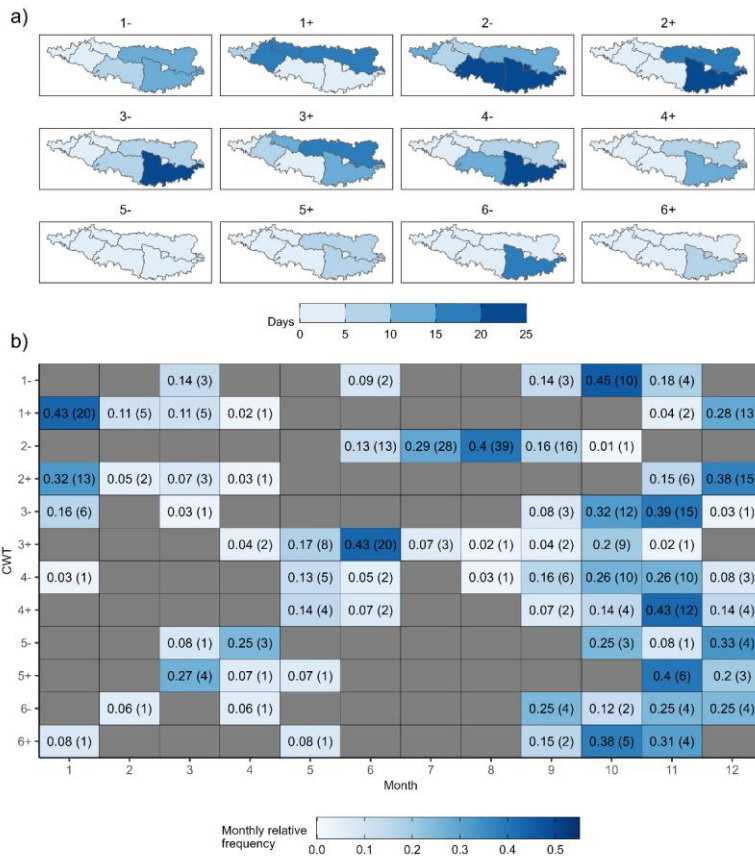
Figure 17. a) Number of flood days by weather type (WT) and Pyrenean region. b) Monthly relative frequencies of flood days by weather type and month. Between parenthesis absolute values are shown in flood days per month.

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8   Discussion and conclusions

In this article, the first flood database integrating the entire Pyrenees massif and available to the public has been presented (http://hdl.handle.net/10261/270351). This database, PIRAGUA_flood, includes, at a municipal scale, all flood events that

have affected each of the 1803 municipalities comprising this cross-border region between 1980 and 2015, of which 609 are Spanish, 1187 are French, and 7 are Andorran. Each event is characterized based on a scale that considers the impacts, providing information on these, including the number of victims, and in the Spanish case, compensations paid by the Insurance Compensation Consortium. Hydro-meteorological information is also included. The database has been constructed using information from press sources, official lists provided by various public agencies, scientific studies, and rainfall analyses. In the case of Catalonia and Andorra, systematic daily-scale information on all types of flood events, including those with lesser impact, has been available. For other regions, it is possible that some of these minor events may have gone unnoticed. However, since this information is typically difficult to obtain from any other source, it has been decided to maintain it. Additionally, these types of floods are becoming more common due to urbanization of the territory.

If we take into account that some events can affect more than one region, the number of events that have produced floods in the Pyrenees between 1980 and 2015 has beenis 181, of which 128 affected Spain, 43 affected France and 46 affected Andorra. Of these, 34 were cross-border. The November 1982 catastrophic flood event episode was the most extensive and in fact affected the three countriesmuch of Spain and France, in addition to Andorra. The other very extensive episode took place in June 2013 and affected Spain and France. From the analysis of the flood episodes recorded in the Pyrenees massif between 1981 and 2015, it can be concluded that Tthe region with the greatest number of flood events episodes ishas been Catalonia (66 episodes), although only 4.5% produced catastrophic damage to the massif. Andorra follows, with a total of 46 events, of which 4.3% were catastrophic. However, the one that records the most serious events in terms of percentage is Nouvelle Aquitaine, since, of the 17 events recorded, 35% were catastrophic. Note that, if the ordinary events are not taken into account, Catalonia is still the one with the most events (29), followed by Aragon (26) and Occitanie (24). It follows that the eastern part of the Pyrenees wasis the most affected by flood episodes, some which had catastrophic impacts. If we take into account that some events can affect more than one region, the number of events that produced floods in the Pyrenees is 181, of which 128 affected Spain, 43 affected France and 46 affected Andorra. Of these, 34 were cross-border. The November 1982 episode was the most extensive and in fact affected much of Spain and France, in addition to Andorra. The other very extensive episode took place in June 2013.

The economic impacts are not available in France and Andorra, and in the case of Spain, only the compensation paid by the Insurance Compensation Consortium between 1996 and 2015 are known. In total, the CCS paid €142.5 million$_{2015}$ for flood damage in the Spanish Pyrenees. For this period, and despite being in third position in terms of the number of events, Navarrae is the region that received the most compensation in terms of damage for events, with a total of €65.8 million$_{2015}$. This high amount compared to Catalonia, which recorded more than twice as many events, is explained as Pamplona (the capital of Navarra) is within the Pyrenees region, and received payments worth €18 million$_{2015}$ in 2015. In this case, the risk of flooding is greater due to the high exposure and vulnerability, despite a moderate hazard compared to other Pyrenees regions. Something similar could take place in Catalonia on a regional and municipal scale. Although the Val d'Aran was not as affected by floods

as other Catalan regions, it is a very rich region, with a municipality, Vielha, to which the CCS paid more than €5 million$_{2015}$ for damage caused by floods from 17-20 June 2013. The latter was the most expensive episode since 1996, with an amount worth €27 million$_{2015}$ claimed in the Spanish Pyrenees. However, including the non-Pyrenees part of Aragon and Catalonia, this amount rose to €31 million$_{2015}$, and in France (mainly Occitanie) it rose to €240 million$_{2015}$ in insurance compensation alone (public works are considered to have exceeded this amount). The most expensive episode in Spain since 1981 however, if we take into account all of the autonomous communities affected, was 25-28 August 1983, which resulted in a total of €2.9 billion$_{2015}$ in compensation paid out in the Basque Country, Navarre and Cantabria. This high amount is a consequence of the serious damage suffered in the Basque Country, mainly in industrial areas.

The number of victims is closely linked to specific cases, such as the floods of August 1996 in Biescas and the flooding of November 1982, in which the majority of the deceased were swept away by water in their home or summer residence. The Biescas case is an example where all components contributing to the risk were high. It involved a camping site located in a debris cone at the foot of a dam in an area prone to storms (high hazard), with numerous people (high exposure) who took shelter in tents or trailers, and there was no early warning system (high vulnerability). Apart from these cases, fatalities are normally people who tried to cross a river, usually in a vehicle, or people doing adventure sports. The total number of victims in the Spanish Pyrenees was 121, with 13 in Andorra and 20 in the French Pyrenees.

The flood season starts in May in the Atlantic region and progresses to reach a maximum in autumn in the Mediterranean regions. Catalonia, Aragon, Navarrae and Occitanie all share the month of October among the months that record the highest number of events. The Basque Country and Nouvelle Aquitaine share the month of June in common, while in Andorra is summer.

If we only take into account events that caused notablesignificant damage (extraordinary and catastrophic episodes according to the nomenclature agreed here), in order to unify the criteria—since it is possible that the information for all the ordinary episodes is not always available—a positive trend can be observed across the entire massif of 0.5 ev./dec., although it is not significant. at 90%. However, if the ordinary episodes are included, the trend becomes 0.84 ev/dec., and it is significant at 905%. When analysing in terms of communities, Nouvelle Aquitaine is the only region with a significant positive trend at 95% (0.34 ev./dec.). It is striking that this level is not recorded in the Basque Country or in Navarre, which share an administrative—although not strictly geographical—border with Nouvelle Aquitaine. This positive trend in Nouvelle Aquitaine cannot be justified by the trend in the 90th percentile discharge, nor the lower percentiles, as shown in the study by Clavera-Gispert et al. (2023). To attribute this trend accurately, it would be necessary to conduct a study on more extreme discharge events and land use to associate it with an increase in vulnerability, exposure, or hazard. On average, projections also do not indicate an increase in intense precipitation in the Pyrenees (Amblar-Francés et al., 2020), but a recent study (Poncet et al., 2024) including the Mediterranean part of Occitania shows that the magnitude of the most intense floods will intensify.

From the classification of weather types, it can be concluded that most are dominated by southern component flow over the Pyrenees region, with a thalweg on the Iberian Peninsula. There is a frequent depression in the vicinity, either in the Atlantic or in the Mediterranean, which is in line with the studies carried out on intense rains in the Mediterranean region (according to the IPCC classification (2022), the Pyrenees massif would be included in the region) (Jansà et al., 2014). This type of configuration favours vorticity advection at the medium and upper part of the troposphere and the consequent instability at low levels, the advection of warm and humid air and, occasionally, the contribution of humidity from remote sources. No specific weather type is observed for cross-border episodes.

Apart from generating knowledge about floods in a mountainous region like the Pyrenees, This study also has an important social objective. The aim is to make the population living in the Pyrenees and who practice hiking or any other mountain sport aware that floods are also very important in this region and cause serious damage and even fatalities. This study was carried out in the context of the Interreg PIRAGUA project, and the meetings with the stakeholders showed that the awareness regarding floods in the Pyrenees was very low. Finally, Appendix A has been added detailing the fields of the database so that if desired it can be reproduced on another site. As it has been shown in the paper, many flood episodes are transnational, which calls for cooperation in the prevention and mitigation of flood risk between regions and countries. This is more relevant considering the United Nations call "Erly Warning for All" to ensure that everyone on Earth is protected from hydrometeorological hazard, including flood events through life-saving early warning systems by the end of 2027. Furthermore, in Europe there is a strong collaboration framework, both thanks to the ESA Copernicus observation program, Meteoalarm and within the Euromed Program of Prevention, Preparedness and Response to Natural and Man-made Disasters, in which all European Civil Protection agencies participate. However, it is necessary to land it in the interborder region of the Pyrenees.

Data availability. The dataset of flood episodes in the Pyrenees massif showed and analysed in this paper is available at http://hdl.handle.net/10261/270351.

Author contribution. MCLL contributed with the funding acquisition, conceptualized, and conducted the research, and prepared the manuscript with contributions from all co-authors as well as the revised versions; MLLB was responsible of data curation; RMM and MLC did de formal analysis and software; EP was responsible of the maps visualization.

Competing interests. One of the authors is members of the editorial board of journal NHESS.

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Appendix A

The database was built in EXCEL and is composed of two linked tables: a) Events; b) Affected municipalities.

    a) Events

920 Identification of the episode:

- Integrated Event Code: the numerical code used to identify the global event, when episodes that have affected more than one region belong to an event. If the episode only affected one region, it will be the same as the corresponding event code.
- Event: Numeric field composed of the start and end dates of the event. In events that occurred across several municipalities, the dates are unified on the common basis of all regions (resulting in the integrated event code), but the original date is maintained on the individual basis of each region.
- Start date: Start date in date format. Indicates the beginning of the episode.
- End date: Date of the end of the episode in date format. Indicates the end of the episode.

    Criteria:

930   o The event starts when the rain starts in the region.
      o The event ends when the flood or tangible damage ends.
      o The event lasts while heavy rain, damage or floods are occurring and ends when they cease to occur. A subsequent episode is considered a new episode when there is more than one day (at least) without any of these points occurring.

935 - Region: Indicates the administrative region affected by the event: SPAIN: Aragon (AR), Catalonia (CAT), Navarre (NA), Basque Country (PV); FRANCE: Aquitaine (AQ); Languedoc Roussillon (LR); Midi Pyrénées (MP); ANDORRA (AND)
- Location 1: List of affected counties or departments

- Location 2: List of affected municipalities
940
- Number of municipalities affected: number of municipalities that suffered damage
- Affected area (Km^2): Sum of the total area of the affected municipalities, in Km^2

Meteorological and hydrological information indicators for the episode:
- Precipitation: Data included when the information is available. Maximum total precipitation during the episode in
945
mm and location of the rainfall station where it was recorded; maximum precipitation in 24h in mm and location of the rainfall station where it was recorded; maximum rainfall intensity in mm/h and duration of this, and location of the station where it was recorded.
- Other meteorological data: Optional field to add rainfall data from other sources, or other data, as deemed appropriate.
- Other weather phenomena: Field to indicate if other adverse natural phenomena occurred in addition to floods. The
950
following are included:
  - Rock slide/landslide
  - Hail
  - Snow
  - Wind storm
955
  - Tornado
  - Thawing
- Affected drainage basins: List of affected river basins.
- Flow rate: Maximum instantaneous flow recorded in m^3/s indicating the river, rainfall station and date, in addition to the average annual flow in m^3/s. If information is available for more than one river, it is included.
960

Episode impact indicators:
- Category: The Category of the event according to the criteria described in section 3.1.
965

b) Municipalities
Fields:
- Integrated Event Code: this is the numerical code described above.
970
- Event: An event code that allows you to link this table with the "Events" table; the same code that identifies the event in the "Events" table must be used.
- Event category: the event category.
- MunicipalityID: Code (in NATCODE and/or equivalent, which allows you to locate it with GIS) of the municipality affected by the floods. Each row is for a municipality, which means an event can have more than one row.

975   • Location name: Name of the municipality.

    • Deceased: Total number of fatalities in the municipality (if any).

    • Gender and age of victims: When information is available, the gender and age of each victim is indicated.

    • Causes: A brief description of the causes of death.

    • Other information: Necessary information that is not covered in the other fields.

980   • Region: region to which the municipality belongs