



Recent flood disasters in Europe (2007–2025): comparative analysis and policy implications for climate-resilient governance

Ana Margarida Bento, Florian Cordier, Alan Cuthbertson, Benjamin Dewals, Michalis Diakakis, Cristiana Di Cristo, Gordon Gilja, Hossein Hamidifar, Stefan Haun, Janek Laanearu, Melissa Latella, P. Amparo López-Jiménez, Eda Majtan, Cristina Prieto Sierra, Elena Pummer, Paweł M. Rowiński, Kai Schröter, Anastasios I. Stamou & Laura Maria Stancanelli

To cite this article: Ana Margarida Bento, Florian Cordier, Alan Cuthbertson, Benjamin Dewals, Michalis Diakakis, Cristiana Di Cristo, Gordon Gilja, Hossein Hamidifar, Stefan Haun, Janek Laanearu, Melissa Latella, P. Amparo López-Jiménez, Eda Majtan, Cristina Prieto Sierra, Elena Pummer, Paweł M. Rowiński, Kai Schröter, Anastasios I. Stamou & Laura Maria Stancanelli (22 Jul 2026): Recent flood disasters in Europe (2007–2025): comparative analysis and policy implications for climate-resilient governance, International Journal of River Basin Management, DOI: [10.1080/15715124.2026.2694415](https://doi.org/10.1080/15715124.2026.2694415)

To link to this article: <https://doi.org/10.1080/15715124.2026.2694415>



View supplementary material [↗](#)



Published online: 22 Jul 2026.



Submit your article to this journal [↗](#)



Article views: 505



View related articles [↗](#)



View Crossmark data [↗](#)



Recent flood disasters in Europe (2007–2025): comparative analysis and policy implications for climate-resilient governance

Ana Margarida Bento ^{a,b}, Florian Cordier ^{c,d}, Alan Cuthbertson^e, Benjamin Dewals ^f,
Michalis Diakakis ^g, Cristiana Di Cristo^h, Gordon Gilja ⁱ, Hossein Hamidifar ^j, Stefan Haun^k,
Janek Laanearu ^l, Melissa Latella ^m, P. Amparo López-Jiménezⁿ, Eda Majtan ^o,
Cristina Prieto Sierra ^{p,q,r}, Elena Pummer ^s, Paweł M. Rowiński^t, Kai Schröter^u, Anastasios I. Stamou ^v
and Laura Maria Stancanelli ^w

^aCIIMAR/CIMAR LA, Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Matosinhos, Portugal; ^bHydraulics, Water Resources, and Environmental Division, Department of Civil Engineering, Faculty of Engineering, University of Porto, Porto, Portugal; ^cEDF R&D National Laboratory of Hydraulics and Environment, Chatou, France; ^dSaint-Venant Hydraulics Laboratory, Chatou, France; ^eFaculty of Science, Engineering and Business (Civil Engineering), University of Dundee, Dundee, UK; ^fResearch Group of Hydraulics in Environmental and Civil Engineering (HECE), University of Liège, Liège, Belgium; ^gFaculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Athens, Greece; ^hDepartment of Civil, Building and Environmental Engineering (DICEA), University of Naples Federico II, Naples, Italy; ⁱDepartment of Hydrosience and Engineering, Laboratory for River and Sediment Dynamics, University of Zagreb Faculty of Civil Engineering, Zagreb, Croatia; ^jPolish Academy of Sciences, Institute of Geophysics, Warsaw, Poland; ^kInstitute of Hydraulic Engineering and Water Resources Management, Graz University of Technology, Graz, Austria; ^lWater and Environmental Research Group, Department of Civil Engineering and Architecture, School of Engineering, Tallinn University of Technology, Tallinn, Estonia; ^mCMCC Foundation – Euro-Mediterranean Center on Climate Change, Venice, Italy; ⁿDIHMA, Universitat Politècnica de València, Valencia, Spain; ^oSchool of Engineering, University of Liverpool, Liverpool, UK; ^pIHCantabria – Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Santander, Spain; ^qDepartment of Environmental Systems Science, ETH Zürich, Zürich, Switzerland; ^rEawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland; ^sDepartment of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway; ^tPolish Academy of Sciences, Institute of Geophysics, Warsaw, Poland; ^uDivision Hydrology and River Basin Management (HYDRIV), Technische Universität Braunschweig, Leichtweiss-Institute for Hydraulic Engineering and Water Resources (LWI), Braunschweig, Germany; ^vDepartment of Water Resources and Environmental Engineering, Laboratory of Applied Hydraulics, School of Civil Engineering, National Technical University of Athens, Athens, Greece; ^wDepartment of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy

ABSTRACT

Flood disasters in Europe have become increasingly frequent and severe due to factors including rapid urbanisation, infrastructure vulnerabilities and climate change-related weather anomalies. This paper summarises lessons from major flood events since 2007 using a harmonised framework aligned with Integrated Flood Risk Management (IFRM). The analysis is based on multi-country datasets and case studies. Hazards characteristics, exposure, vulnerability and governance responses are examined in order to identify recurring patterns and systemic gaps. The results of the study highlighted five critical themes: (i) the growing prevalence of riverine and flash floods in urban areas; (ii) the amplifying effects of urbanisation and inadequate drainage; (iii) the shaping of hazard profiles by climate-induced extremes; (iv) the persistent shortcomings in the dissemination of early warnings and last-mile communication and (v) the regional variability in vulnerability and coping capacity. The insights gathered have informed a series of recommendations for policy and practice, the enhancement of early warning systems, investment in sustainable infrastructure, cross-border cooperation and community resilience. The objective of these findings is to inform adaptive strategies and strengthen Europe's capacity to manage evolving flood risks under increasing urbanisation, continuous economic development in flood-prone areas and climate variations.

ARTICLE HISTORY

Received 18 March 2026
Accepted 22 June 2026

KEYWORDS

Flood disasters; integrated flood risk management; climate-resilience; urban planning; early warning systems

1. Introduction

1.1. Context and significance

Floods are among the most recurrent and damaging natural hazards in Europe and the world, causing loss of life, economic disruption and infrastructure failure (Jonkman 2005, Barredo 2007, Bento et al.

2020, Prieto et al. 2020, 2024). In 2024, new hydrometeorological extremes were recorded (Reinert et al. 2025), with flood-related disasters causing more than 8700 deaths and economic losses exceeding 450 billion euros. Over the past decade (2014–2023), such events have produced cumulative global losses of approximately 2.7 trillion euros according to World

CONTACT Ana Margarida Bento  ana.mbento@outlook.com  CIIMAR/CIMAR LA, Interdisciplinary Centre of Marine and Environmental Research, University of Porto, University of Porto, Terminal de Cruzeiros do Porto de Leixões, Av. General Norton de Matos S/N, 4450-208 Matosinhos, Portugal; Hydraulics, Water Resources, and Environmental Division, Department of Civil Engineering, Faculty of Engineering of the University of Porto, 4200-465 Porto, Portugal

ASSOCIATE EDITOR: Michael Nones

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/15715124.2026.2694415>.

© 2026 International Association for Hydro-Environment Engineering and Research

Meteorological Organization (WMO) reports. Notwithstanding the advances achieved in the field of Integrated Flood Risk Management (IFRM), recent high-magnitude events have exposed persistent vulnerabilities driven by three main factors: (i) a change in both frequency and intensity of precipitation extremes resulting from climate change (IPCC 2023, Haslinger et al. 2025, Macdonald et al. 2026); (ii) rapid urbanisation and growing exposure of people and assets (Barredo 2009, Rodríguez Castro et al. 2022) and (iii) governance gaps, including under-maintained infrastructure and ineffective last-mile risk communication (European Environment Agency 2024, Schüttrumpf et al. 2025).

From a global perspective, many high-income regions in the Global North have experienced an increase in flooding frequency while recording a decline in mortality per event, largely due to strengthened early-warning systems, improved preparedness and broader access to risk-reduction infrastructure (Alfieri et al. 2020, Bento et al. 2020, 2023, Hamidifar and Nones 2023). This highlights the growing importance of resilience and adaptive capacity (Klör et al. 2025, Sairam et al. 2025, Schaum et al. 2025). IFRM represents a shift from traditional hazard-centred control towards integrated approaches that jointly consider hazard, exposure, vulnerability and residual risk across spatial and governance scales (European Commission 2021, Haun et al. 2023). Such approaches promote balanced portfolios of structural and non-structural measures, adaptive planning under uncertainty, including compound and cascading events, stakeholder participation and impact-oriented modelling (Stamou 2024). However, putting these frameworks into practice continues to be challenging, especially when it comes to integrating hydrological, engineering and socio-economic evidence into decision-making in urban settings (Stamou 2024). Strengthening a shared language and operational interface between research, policy and technical guidance remains essential (European Commission 2021, Macdonald et al. 2026) for effective flood governance, particularly for the consistent identification of hazards, exposure, vulnerability and feasible adaptation pathways.

The present paper addresses these gaps by analysing emblematic European flood disasters from the last two decades and examining how hazard characteristics, exposure, vulnerability and governance responses interact across contexts. The analysis adheres to the principles of IFRM and current European guidance on climate-proofing. Simultaneously, it recognises a significant methodological restriction: a 20-year timeframe provides merely a limited view of long-term climatic trends, given that the conventional definition of climate is based on observational periods of approximately 30 years. Consequently, while the selected timeframe captures significant and

well-documented flood events, it does not fully meet the conventional threshold for assessing climate-related trends, reinforcing the need for cautious interpretation (European Commission 2021, Hamidifar and Nones 2023, Haun et al. 2023, European Environment Agency 2024, Haslinger et al. 2025).

Notably, despite the occurrence of multiple floods across Europe in recent decades, this study deliberately focuses exclusively on extreme and catastrophic events. The selection of these cases was driven by their capacity to elucidate the upper-end behaviour of flood hazards, the breakdown of protection systems and the systemic vulnerabilities that become apparent only in high-impact conditions. By directing attention towards these exceptional events, it is possible to ensure that the analysis addresses the most critical threats to population safety, infrastructure resilience and governance performance. This is in contrast to routine or lower-magnitude floods, which fall outside the scope of this work.

1.2. Overview of recent flood disasters in Europe

Over the past 20 years, Europe has experienced a series of catastrophic floods, including fluvial (riverine) and flash events, which collectively demonstrate recurring risk patterns (Barredo 2007, European Environment Agency 2024). A synthesis of selected events from 2007 onwards has been undertaken in order to highlight both geographical diversity and systemic vulnerabilities:

- **Austria (2024):** In 2023 and 2024, riverine floods caused severe damage to infrastructure and property. Sustained investment in flood protection measures has proven to be an effective strategy, as reflected in the reduction of fatalities to zero and the limitation of total damages to €1.4 billion in 2024, compared to €3 billion in 2002. These figures underline the effectiveness of proactive risk management in mitigating the economic impacts of flood events (European Environment Agency 2024, Haslinger et al. 2025).
- **Croatia, Bosnia and Herzegovina and Serbia (2014):** Several consecutive days of rainfall recorded between 14th and 18th May 2014 summed up to more than the long-term average of May monthly precipitation: 1.5–1.8 times in Croatia, >2 times in Bosnia and Herzegovina and >3 times in Serbia. This close to highest historical rainfall was preceded by a rainy month before, causing highly saturated soil in the Sava River Basin, with the soil moisture between 60% and 100% in parts of the basin. This combination caused flash floods, erosion and landslides along small

watercourses, but also disastrous flooding along the Sava River main course and its right tributaries.

- **France (2020–2023):** Notable examples of recurrent catastrophic floods include Storm Alex in 2020, which resulted in 663 mm of precipitation within a 24-h period, and the Aline storm in 2023, which led to estimated damages of 1.3 billion euros and impacted over 500,000 individuals. The presence of sediment in a river has been demonstrated to induce instability, thereby introducing a degree of complexity to the management of risk (European Environment Agency 2024).
- **Germany and Belgium (2021):** A sequence of extreme precipitation events over a period, culminating in the passage of Storm Bernd, which lasted multiple days, resulted in severe flooding in the tributaries of the Ahr, Erft and Meuse rivers. In addition to the hydrometeorological anomaly, failures in risk communication, underestimation of severity and limited institutional memory (despite historical precedents) served to amplify losses, including hundreds of fatalities and multi-billion-euro damages. This phenomenon underscores the critical importance of response systems, particularly in scenarios where exposure extends beyond designated zones and warning lead times are found to be inadequate (Hamidifar and Nones 2023).
- **Greece (2023):** The storm, named Daniel, resulted in unprecedented levels of rainfall in Thessaly, leading to significant inundation of prime farmland and causing disruption to critical infrastructure (European Environment Agency 2024).
- **Italy (2022–2023):** Catastrophic events that struck Marche in 2022 and Emilia-Romagna in 2023 resulted in severe flash and fluvial flooding, multiple fatalities and extensive damage to infrastructure, housing and agriculture. Discrepancies in international disaster databases, with some events being underreported, have been identified as a complicating factor in cross-country learning and trend assessment (Hamidifar and Nones 2023). This is a known limitation in multi-source datasets.
- **Poland (2010):** The impact of the 2010 flood was significant, with economic losses estimated at 2.5 billion euros and at least 16 fatalities. Rainfall-driven floods are the most prevalent type of flood, accounting for 60% of cases, while flash floods (e.g. Bogatynia, 144 mm/day) are increasing in frequency (Hamidifar and Nones 2023).
- **Portugal (2001–2010):** Notable incidents such as the Hintze Ribeiro bridge collapse (which resulted in 59 fatalities) and the 2010 Madeira flood serve to underscore the nation's exposure to both inland and coastal hazards.
- **Scandinavia (2023):** Storm Hans caused devastating flooding and landslides in southern Norway and other parts of Scandinavia, including the failure of a dam, necessitating the evacuation of 4,000 individuals. Two fatalities were reported, and the severe infrastructure damage underscores the necessity for adaptation measures (Solheim et al. 2025).
- **Spain (2024):** Notwithstanding a 17% decrease in rainfall, DANA-driven flash floods impacted regions that were not typically affected, thereby exposing approximately 2 million people to 100-year flood risk and 700,000 to 10-year events. It caused over 200 fatalities, displacing thousands and caused long-term livelihood losses as well as post-traumatic effects in a large proportion of the affected population.
- **Switzerland (2024):** The country witnessed a series of extreme precipitation events, leading to flash floods and debris flows, particularly in June (Ticino, Valais and Misoix) and August (Bern). Thirteen fatalities were reported, and the economic loss was estimated at CHF 905 million.
- **United Kingdom (2007 and 2015):** Several severe storms (named by the UK Met Office) during winter 2015/2016 produced record rainfall totals that triggered significant flooding across northern England, Scotland, north Wales and parts of Northern Ireland. In England alone, the winter storms resulted in approximately £1.6 billion in total economic damages and significant infrastructure failures. In December 2015 alone, around 16,000 properties were flooded and 2 fatalities were recorded. This was still considerably lower than the summer 2007 floods, when approximately 55,000 properties and 6000 businesses were affected, 13 fatalities occurred, and total economic losses reached approximately £3.2 billion. This reduction is partly attributable to the increased protection provided by flood defences built between these two flood events (Marsh et al. 2016, Environment Agency 2018, House of Commons Library n.d.).

These events emphasise (i) the heterogeneity of flood types and their causes (riverine vs. flash floods), (ii) the expansion of affected areas beyond 'known' risk zones; (iii) the critically of early warning performance and last-mile communication and (iv) the importance of infrastructure condition and adaptive operations. It is evident that the aforementioned factors serve to compound the challenges associated with conducting multi-country comparisons, as highlighted in the global analyses of the EM-DAT database (Hamidifar and Nones 2023). The aforementioned challenges pertain to coverage, classification and compound causality.

1.3. Research objectives

The purpose of this paper is to address the following overarching question: **What lessons can be learned**

from recent European flood disasters, and how can these lessons inform more resilient flood risk governance? The present endeavour is a continuation of the IAHR Leadership Team Europe initiative, and is in alignment with the IFRM paradigm and hazard–exposure–vulnerability analysis. The key elements of the present paper are outlined as follows:

- (1) The catalogue under consideration is emblematic of European flood disasters from 2007 to the end of 2025. It places particular emphasis on riverine and flash flood events in the Floods Directive era. The catalogue is drawn from a range of sources, including EM-DAT and complementary national and technical sources. However, it is important to acknowledge the limitations of the dataset.
- (2) The characterisation of each event should be undertaken via harmonised descriptors of hazard (intensity, duration, hydrologic response), exposure (populations, critical infrastructure, economic assets), vulnerability/early warning and communication, management/operations and impacts (fatalities, economic loss, sectoral damage).
- (3) A comparison of events should be made using qualitative indicators to identify cross-cutting patterns (e.g. short-duration extremes, out-of-zone exposure, warning usability, infrastructure condition) and these should be connected to IFRM consistent governance and design choices.
- (4) The synthesis of lessons into actionable recommendations for integrated flood risk governance and climate adaptation of water infrastructure should be undertaken, with the following perspectives being drawn upon: typologization and climate-proofing. The connection of research, standards and decision-making is to be facilitated.
- (5) Indicate some situations in which intense rains/flooding exert their effects on the vital infrastructure of the urban environment.

It should be emphasised that the catalogue underpinning this study was deliberately constructed to include only large-scale, high-impact and catastrophic flood events. The objective is not to provide an exhaustive inventory of all floods, but rather to extract lessons from the most severe cases, which carry the strongest implications for resilience planning, early warning performance and climate-adapted flood risk governance.

The present study aims to establish a robust knowledge base that integrates empirical evidence from recent catastrophic floods with institutional insights, operationalised through a comparative framework aligned with IFRM principles. By taking this approach,

it offers practical guidance to decision-makers, assisting them in designing adaptive strategies, strengthening early warning systems and implementing measures to ensure the resilience of water infrastructure in the face of climate change. The study contributes to the advancement of resilience planning and the support of European and global adaptation agendas in the face of evolving flood risk landscapes.

2. Methodology

2.1. Framework

A descriptive analysis of catastrophic flood events in Europe is adopted to identify trends and contributing factors. The methodology is structured around historical flood data, primarily from the EM-DAT (Emergency Events Database) database, and follows the principles of the Integrated Flood Risk Management (IFRM) to integrate hazard, exposure, vulnerability and governance dimensions. The insights derived from this study are intended to support improvements in flood risk management and inform future adaptation strategies. The ensuing subsections delineate the methodology's constituent elements (Figure 1).

2.2. Data sources and selection criteria

- The dataset utilised in this study is an extension of the compilation presented in Hamidifar and Nones (2025), which is principally based on the EM-DAT International Disaster Database (CRED 2024). EM-DAT is a compendium of standardised global records of natural disasters, from which flood events were selected according to the database's inclusion criteria. The database's inclusion criteria required that an event meet at least one of the following conditions:
- At least 10 fatalities (including missing persons);
- At least 100 people affected (through injury, displacement or economic loss);
- A state of emergency declaration or request for international assistance.

The analysis focuses on riverine and flash floods occurring between 2007 and the end of 2025, aligning with the implementation of the EU Floods Directive (2007). This timeframe is consistent with current European flood management policies and facilitates the evaluation of trends under contemporary climate and socio-economic conditions.

2.3. Event classification and scope

Flood events are categorised into riverine/fluvial and flash floods. This classification provides a basis for the

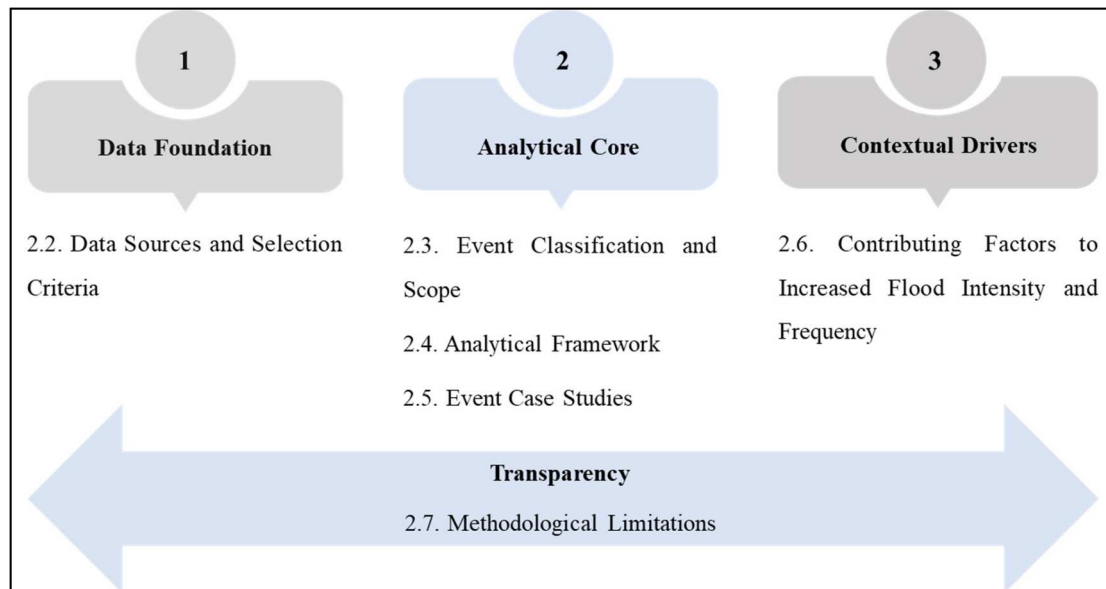


Figure 1. The methodological structure and phases adopted in this study.

comparative interpretation of flood regimes discussed in Section 4.1.6. For the former class, flooding is defined as the occurrence of inundation resulting from rivers exceeding their designated boundaries due to substantial precipitation, whether in the form of rain or snowmelt. Regarding the latter, rapid flooding is typically the result of intense rainfall occurring over a short period, and such events often have a significant adverse impact on urban areas. For each event, a compendium of descriptive attributes is compiled, encompassing its geographical location, date, magnitude, duration, return period and population affected. It is further acknowledged that additional contextual factors must be considered when assessing flood intensity and severity. These include infrastructural status, soil saturation levels, prevailing climatic conditions and topographical features.

2.4. Analytical framework

The descriptive analysis is organised into four dimensions. First, the hazard, by recording information on precipitation intensity, duration and peak discharge rates, paying attention to climatic and topographical influences. Second, the exposure, relating data populations, infrastructure and economic assets at risk, including urban density and critical facilities. Third, the vulnerability, including socio-economic determinants (e.g. housing quality and health infrastructure), early warning systems and regional preparedness. This dimension also considers broader socio-economic factors, including economic capacity (e.g. GDP per capita), which influence preparedness, response capability and recovery potential across countries. These three dimensions directly refer to the risk definition.

A fourth is constituted by risk management practice, thus integrating a review of flood management strategies, including infrastructure maintenance, early warning systems and cross-border coordination.

The impacts of different events are compared in terms of fatalities, economic losses and recovery efforts to provide insights into the evolving patterns of flood consequences.

2.5. Event case studies

The depiction of selected flood events is structured in tabular form, ensuring a methodical and comparable description. Each case study includes the following attributes:

- Location and date of the event;
- Return period and key severity indicators (e.g. fatalities, economic losses and affected population);
- Early warning systems and their effectiveness;
- Response strategies, including transboundary coordination where applicable;
- Role of scientific and research communities in event analysis and response.

This format facilitates a systematic comparison of events across multiple dimensions relevant to flood risk management.

2.6. Contributing factors to increased flood intensity and frequency

The present study examines the main drivers behind the recent escalation in flood intensity and frequency, focusing particularly on the increasingly complex ways in which these factors interact. Urbanisation is one of the

most clearly evidenced contributors: as impermeable surfaces increase and drainage systems become overloaded, runoff rises and the local area becomes more vulnerable (Keenan-Jones et al. 2025). Unlike other contributing factors, the impact of urban development can generally be evaluated with a high degree of confidence, as it is supported by long-term records of land-use change and well-documented hydrological responses.

Climate change is also considered, though its influence requires careful interpretation. While shifts in precipitation patterns and an increasing number of short-duration, high-intensity rainfall events suggest that climate-related extremes are playing a role (Granata et al. 2025), the available evidence is often limited. Many regions have only a small number of extreme events on record, and observational datasets cover relatively short time periods. This restricts the number of robust comparisons that can be made and reduces the degree of confidence with which long-term trends can be identified. Consequently, attributing changes in flood behaviour to climate drivers is inherently more complex and uncertain than assessing the effects of urbanisation.

Finally, the study also highlights the role of infrastructure performance. Aging or inadequate drainage systems and limited flood storage capacity often reduce the effectiveness of response measures (Azhar et al. 2025). When these constraints coincide with rapid urban expansion or evolving climatic pressures, their combined influence can significantly amplify flood impacts.

2.7. Methodological limitations

Whilst the methodology adopted ensures a structured and comprehensive descriptive analysis, it is important to acknowledge the limitations of the approach:

- Data completeness: EM-DAT records may contain inconsistencies or be incomplete, particularly for smaller-scale events or regions characterised by limited reporting capacity.
- Temporal scope: The focus on events from 2007 onwards aligns with the EU Floods Directive, yet it omits earlier events that could offer insights into long-term trends.
- Event heterogeneity: Variability in event documentation (e.g. differences in severity indicators or socio-economic data) may affect comparability across cases.
- Qualitative approach: This descriptive study does not incorporate predictive modelling or statistical inference; it remains non-quantitative, which limits the ability to establish causal relationships.

These limitations are addressed in the interpretation of findings and discussed in the corresponding sections (Sections 3 and 4).

3. Recent flood disasters in Europe

3.1. Catalogue of emblematic flood disasters across Europe

Table A.1 presents a harmonised catalogue of emblematic flood disasters that occurred in Europe between 2007 and the present. This catalogue integrates event-level descriptors from multi-country sources, including hazard metrics (e.g. intensity, duration, return period), exposure indicators and observed impacts such as fatalities, affected population and economic losses. The presence of contextual drivers, including early warning performance and infrastructure condition, is also noted when available. The dataset under consideration constitutes the basis for the comparative analysis that is developed in the following subsections.

3.2. Comprehensive compilation of event attributes at the country scale

As demonstrated in Table A.2, a thorough examination of the characteristics of flood events at the national level is presented. The study encompasses typology, temporal occurrence, intensity and affected regions for each selected country. This structured compilation facilitates systematic comparison across diverse geographical and socio-economic contexts, thereby supporting the identification of patterns and country-specific vulnerabilities.

In order to enhance the interpretation of the data presented, Figure 2 provides a visual representation of the spatial distribution of the analysed flood events across Europe during the period 2007–2025. The cartographic representation provides a clear geographical overview of the selected case studies, highlighting their spatial coverage and supporting the identification of regional patterns in flood occurrence and impacts.

3.3. Descriptive flood event analysis, lessons learned and policy implications

The purpose of this subsection is to present harmonised descriptors of selected flood events. The intention is to enable cross-country comparison and to extract policy-relevant insights. The analysis addresses key dimensions of flood risk, including hazard characteristics, exposure, vulnerabilities and observed impacts, alongside institutional and governance responses.

Tables A.3–A.11 consolidate these descriptors and integrate lessons learned from each event, highlighting implications for future flood risk governance. This approach facilitates the identification of recurring patterns, systemic challenges and critical gaps across countries, forming the basis for actionable

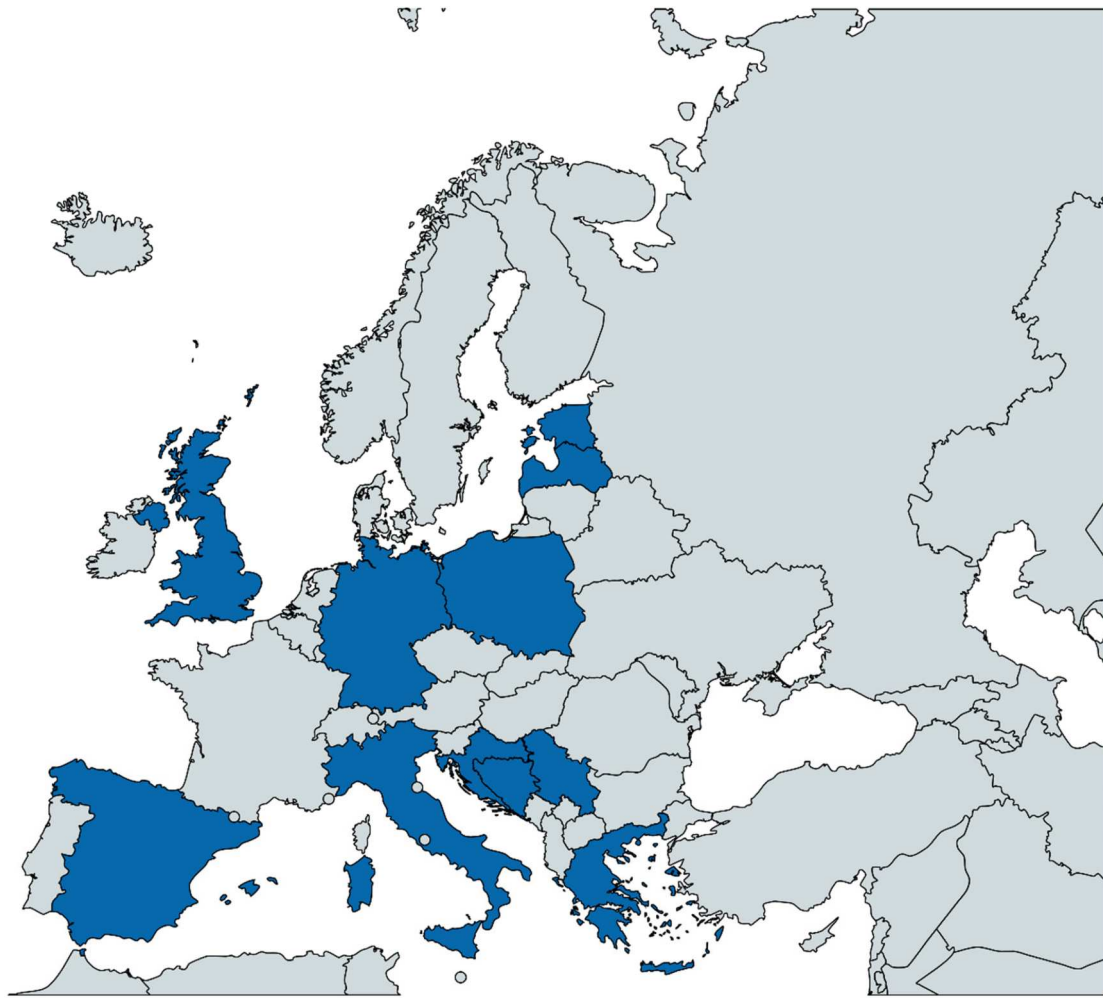


Figure 2. Spatial distribution of analysed flood events across Europe (2007–2025).

recommendations to strengthen integrated flood risk management and climate adaptation strategies.

4. Analysis and discussion

This section synthesises the findings presented in Section 3 (Tables A.1–A.11) to identify recurring patterns, extract cross-cutting lessons and discuss implications for Integrated Flood Risk Management (IFRM) in Europe. The analysis employs a logic model that progresses from hazard to exposure to vulnerability to governance, providing illustrative country-specific examples to support generalisable insights (see Tables A.1–A.11).

4.1. Common themes and patterns across cases

The analysis of a series of selected flood events reveals several recurring themes and patterns that shed light on the evolving nature of flood disasters in Europe. The most significant themes are outlined and discussed in detail in the following subsections. In addition to the thematic analysis presented below, a cross-cutting interpretation in terms of flood regimes and regional variability is introduced to provide a

more comprehensive explanation of the differences in flood behaviour across Europe.

4.1.1. Flood type and urban amplification

Catastrophic events are characterised by riverine floods and rapid-onset flash floods, with escalating impacts in urban environments. Evidence of flash-flood-type behaviour has been observed in small headwaters and urbanised plains in West Germany (Ahr/Erft 2021; >150 mm/48 h; >180 fatalities; >30 billion euros in damages), in Mandra, Greece in 2017 (~300 mm in 13 h; 25 fatalities) and in Valencia, Spain in 2024 (422 mm in 8 h, affecting >60,000 people and major road/rail assets). The United Kingdom experienced a significant weather event in 2007, characterised by prolonged rainfall (414 mm over the May–July period) and widespread urban pluvial flooding. In contrast, the 2015 floods following Storm Desmond brought record-breaking rainfall in Cumbria, with 341.4 mm recorded in 24 h and up to 405 mm over 48 h (Marsh et al. 2016).

The presented examples offer indisputable evidence of the role of urban amplification in shaping flood impacts. It is evident that highly urbanised areas (e.g. Mandra, Valencia, Ahr/Erft) are distinguished

by a combination of high impervious surface ratios, limited drainage capacity and dense concentrations of exposed assets. This characteristic triad, when considered collectively, has been shown to accelerate runoff generation and increase peak flows. In such contexts, even relatively short-duration rainfall events can have disproportionately high impacts compared to similar events occurring in less urbanised or predominantly rural basins.

A juxtaposition with basin-scale events such as the Sava (2014) or Poland (2010) illuminates this discrepancy. While these events were driven by prolonged precipitation over large areas and produced widespread flooding, their impacts were more strongly controlled by basin hydrology and antecedent conditions rather than by rapid urban runoff processes. Conversely, flash-flood-type events in urban environments have been shown to exhibit faster response times, limited warning windows and higher damage concentration per unit area, particularly where drainage systems are undersized or poorly maintained.

These observations are consistent with the patterns discussed in Section 4.1.2, where urbanisation and drainage limitations are identified as key amplifying factors. Collectively, these findings underscore the notion that urbanisation does not merely augment exposure; it brings about a fundamental shift in the dynamics of flooding, culminating in elevated peak discharges, a more precipitous onset and a heightened severity of impact.

4.1.2. Urbanisation, drainage capacity and the safe-development paradox

The combination of rapid development, the occupation of alluvial fans and floodplains and inadequate drainage has the effect of repeatedly magnifying the flood impacts. In Mandra, the combination of clogged inlets and the presence of industrial and urban development on an alluvial fan resulted in exacerbated inundation and an increased frequency of bridge failures. During the 2023 Emilia-Romagna flood, the presence of a dense hydraulic network over semi-flat terrain and very permeable soils, compounded by months of drought, led to the occurrence of swift peaks and multiple river overflows. In the UK during the 2007 flood, approximately two-thirds of flooded properties were linked to inadequate sewer and drainage capacity, highlighting the need for improved spatial planning and the implementation of urban drainage upgrades. Although measures were introduced following the 2007 floods, the extreme short-term rainfall intensity during the 2015 floods nonetheless posed significant challenges, overwhelming urban drainage systems in areas such as Cumbria. It should be noted that the urban infrastructure and its reorganised functioning may be very vulnerable to unexpected rain events in locations where rebuilding works are

temporarily taking place. There exist some cases in the Tallinn area (Estonia), where building construction and main-road usage are adversely affected/flooded due to intensive rains occurring during their reconstruction periods. This underlies the need for an impact-oriented modelling of urban infrastructure to avoid hazardous consequences.

4.1.3. Persistent synoptic patterns and climate-driven extremes

A correlation has been identified between several events and specific atmospheric configurations, characterised by the presence of moisture-rich lows. The Omega blocking associated with the 2023 Daniel flood (Greece) delivered approximately 750 mm in 24 h (return period approaching approximately 1000 years); Genoa lows (e.g. Boris, Petar) delivered up to approximately 500 mm over a 72-h period across Central Europe; the 2024 Orinoco flood (Germany) produced locally approximately 300 mm over a 96-h period, resulting in damages exceeding 4.1 billion of euros and the 2015 Cumbria flood (UK) experienced extreme rainfall with 341 mm recorded in 24 h increasing to 405 mm over 48 h. The cyclones of 2014, namely Tamara and Yvette, resulted in unprecedented levels of water flowing through the Sava River basin. This phenomenon led to extreme water levels being recorded on five tributaries and the lower Sava River in Croatia, Bosnia and Herzegovina, and Serbia. The total direct damage incurred amounted to 3.8 billion euros, with 300,000 people being affected and 79 casualties being reported. These dynamics serve to reinforce the necessity of incorporating compound/serial extremes and persistent anomalies into design and operations.

4.1.4. Early warning usability and last-mile communication

Notwithstanding technological advances, failures in the final mile persist. In Germany, 35% of residents in the Erft region and 29% in the Ahr region reported no warning, and 85% of those who were warned did not anticipate severe flooding. In the aftermath of the event, cell broadcasting and sirens were introduced or reactivated. Following the 2023 trial and subsequent implementation of IT-alert in Italy, Greece proceeded with the deployment of the 112 system during the Ianos and Daniel events. In the UK (England and Wales), the Flood Forecasting Centre was established in 2009 for the warning service but lacked dedicated coverage for surface water (pluvial) flooding, resulting in urban centres being underwarned. Similar flood forecasting services are also provided in Scotland and Northern Ireland.

It is important to note that such challenges are not uniform across Europe, as countries operate with markedly different levels of early warning system

(EWS) maturity, institutional capacity and technological penetration. These asymmetries contribute to deficiencies in the final-mile communication chain and partly explain why evacuation routes were ineffective or absent in several affected areas, where the severity and type of flooding were not anticipated. Furthermore, even in regions with developed systems, existing public–private compensation schemes and insurance consortiums are unable to cover all damages, leaving significant residual losses and highlighting the need for broader risk-transfer and risk-reduction strategies.

4.1.5. Regional variability in vulnerability and coping capacity

The concept of vulnerability is complex and varies significantly across individuals, regions and socio-economic contexts. In Emilia-Romagna, approximately 10% of the population resides in 20–50-year risk zones, and around 60% in 100–200-year zones, with some provinces reaching 80–100% land at risk. In Thessaly (Greece), factors such as agricultural dependence and limited insurance penetration have been identified as contributing to extended recovery times and public health impacts. During the 2021 Germany flood, it was observed that insurance penetration (37–47%) was associated with a reduction in private losses. In the 2007 UK flood, analysis of damage profiles highlighted vulnerabilities in critical infrastructure, communications and agriculture.

The economic capacity of a nation has been demonstrated to have a significant impact on the disparities in vulnerability and coping capacity that are evident across different countries. These differences are closely linked to economic capacity, often approximated through indicators such as GDP per capita. Countries with higher GDP levels generally benefit from stronger institutional frameworks, broader insurance coverage and greater investment in flood protection and early warning systems, supporting more proactive and anticipatory approaches to flood risk management.

Conversely, transition and lower-income contexts (e.g. countries in the Sava River Basin) encounter limitations in sustaining infrastructure, implementing preventative measures, and ensuring effective last-mile communication, frequently engendering more reactive responses and protracted recovery processes. While GDP is not a comprehensive indicator of resilience, it serves as a valuable proxy for understanding the structural differences in preparedness, response capacity and recovery across the analysed cases.

These findings are consistent with broader global evidence indicating that, while high-income countries tend to accumulate a greater share of economic exposure, lower-income regions often demonstrate higher vulnerability and slower recovery processes

due to weaker infrastructure, limited social protection and reduced insurance coverage (Rentschler et al. 2022).

4.1.6. Flood regimes and regional variability

Flood events across Europe exhibit distinct hydrological and meteorological characteristics that can be interpreted in terms of contrasting flood regimes. Whilst the present study adopts a descriptive and comparative framework as opposed to a formal hydrological frequency analysis, the classification of events into broad regime types provides a useful lens for interpreting differences in hazard behaviour, impacts and regional vulnerability.

The initial regime is characterised by brief, intense precipitation events, often precipitated by convective storms or Mediterranean systems (e.g. DANA events). These events are commonly associated with flash flooding, particularly in small catchments and urban environments. Examples of this phenomenon include Mandra (Greece, 2017), Messina (Italy, 2009) and Valencia (Spain, 2024), where extreme rainfall intensities over a few hours generated rapid runoff, limited warning lead times and high localised impacts. Such events are frequently distinguished by precipitous hydrograph responses, pronounced sensitivity to land use and drainage capacity, and a considerable potential for cascading effects in densely urbanised areas.

A second regime corresponds to precipitation events of a longer duration, often associated with large-scale atmospheric circulation patterns (e.g. Atlantic storms, Genoa lows or persistent blocking situations). These events have a tendency to affect large river basins and result in widespread riverine flooding. Exemplary cases in point are the Central European floods of 2013, the Sava River Basin floods of 2014 and the UK events of 2007 and 2015. In such instances, antecedent soil saturation, cumulative rainfall over several days and basin-scale hydrological processes are found to be the dominant factors. This results in a slower onset of flooding, but often with extensive spatial impacts and significant economic losses.

Beyond these two dominant regimes, several events analysed in this study highlight the role of persistent synoptic configurations, such as Omega blocking patterns or moisture-rich cyclonic systems. These atmospheric drivers have the capacity to engender extreme precipitation over extended periods or to repeatedly impact the same region, thereby amplifying flood severity. Storm Daniel (Greece, 2023) and Storm Desmond (UK, 2015) are illustrative cases of the manner in which large-scale atmospheric persistence contributes to the exacerbation of compound and high-impact flood events across diverse hydro-climatic regions.

It is imperative to acknowledge the significant correlation between flood regimes and regional variability in exposure, vulnerability and coping capacity. It is evident that southern European regions, particularly those within the Mediterranean basin, are more susceptible to short-duration convective extremes and flash floods, particularly in steep or highly urbanised catchments. In contrast, Central and Northern Europe experience more frequent prolonged precipitation events associated with large river systems, although recent events indicate increasing overlap between regimes. These differences influence not only hazard dynamics but also the effectiveness of early warning systems, emergency response and risk management strategies.

While this study does not undertake a formal statistical assessment of flood frequency, the inclusion of return periods and recurrence information in Tables A.1–A.11 allows for a qualitative comparison of hazard rarity and severity across regions. The combination of regime classification, observed recurrence patterns and spatial distribution of events supports an improved understanding of how flood risk varies across Europe under different climatic and socioeconomic contexts.

The utilisation of the concept of flood regimes in the analysis of the events in question serves to reinforce the comparative interpretation of the dataset, thereby elucidating the manner in which diverse combinations of atmospheric forcing, catchment response and human factors give rise to the heterogeneity of flood disasters observed across Europe.

4.2. Key lessons and cross-cutting insights from country examples

Based on the analysed cases (A.2–A.11), several key lessons emerge. These are consistent with the flood regime distinctions outlined in Section 4.1.6, which reinforces the need for context- and hazard-specific flood risk management strategies. In particular:

- **IFRM in urban planning and river corridors:**

- **Germany** (2013–2021): The implementation of measures such as the strengthening of the ‘room for the river’, the updating of risk maps, the introduction of new design levels for critical infrastructure, the promotion of inter-municipal cooperation and the reactivation of sirens and cell broadcasting.

- **Greece:** Post-Mandra legal reforms have been implemented, with the aim of clarifying responsibilities, establishing building codes, and managing river channels. Additionally, a master plan for Daniel has been devised, and new flood risk zones have been published.

- **Italy** (Emilia-Romagna in 2023): The implementation of measures such as the integration of PGRA/

PAI into spatial planning, the adoption of IT-alert, the implementation of pre-emptive evacuations for landslides and the mobilisation of national and EU funds for resilient reconstruction.

- **Latvia:** A major municipal levee project was initiated in 2023 in Jēkabpils, Latvia, at a cost of approximately €16.93 million, with 85% of the budget being allocated from the European Regional Development Fund (ERDF). The project also involved the implementation of targeted prevention and recovery instruments.

- **Sava River Basin,** after the floods, the advances to policy and regulatory frameworks were implemented, including the transposition of the EU Floods Directive into the national legal framework. The key role has the International Sava River Basin Commission, which provides recommendations and coordinates the development and implementation of joint and/or integrated Plan(s) on the management of the water resources of the Sava River Basin, preparation of the development programmes, establishment of integrated systems and the development of protocols for regulating specific aspects of the Framework Agreement on the Sava River Basin (FASRB), the unique international agreement, which integrated all aspects of the water resources management.

- **United Kingdom:** The Pitt (2008) review was instrumental in the formulation of a national Flood and Coastal Erosion Risk Management (FCERM) strategy, Exercise Watermark Review Team (2011) and the subsequent augmentation of investment. The recent National Flood Risk Assessment (NaFRA; Environment Agency 2024), updated in 2025, indicated that approximately 6.3 million properties in England are currently located in flood risk areas, a figure projected to increase to around 8 million by the middle of the century. Following the assessment, the UK government confirmed a record £10.5 billion investment programme of flood defences to protect around 900,000 properties in England. Updated flood maps for planning are currently in use, while further enhancements to flood forecasting and early warning services are under development.

- **Early warning and risk literacy:** Germany’s 2021 event exposed gaps in warning usability (reach, message clarity, actionable guidance), prompting redundant channels and civil-protection training. It is evident that Italy has successfully consolidated IT-alert; conversely, Greece has increased 112-based alerts. Moreover, the UK has established flood maps for planning in England that delineate flood zones where rainfall-related early warnings are available, while further enhancements to early warning systems for surface water and associated flooding are currently under development as a part of the FCERM strategy ambition.

- **Portfolios of measures (structural + nature-based):** In situations where infrastructure is aged or undersized, as evidenced by cases such as Mandra, UK drainage, or Poland's embankment-centric strategy, it is recommended that portfolios incorporate a combination of reinforced levees, reservoirs and bridges, complemented by nature-based solutions such as wetland restoration, permeable pavement and green roofs. Furthermore, the restoration of river corridors should be a key consideration.
- **Transboundary cooperation in river basins:** The modifications made to the Elbe (IKSE) and Danube (ICPDR) plans illustrate the significance of basin-scale coordination, while storms such as Boris/Petar underscore the necessity for shared data platforms and interoperable protocols.
- **Community preparedness and operational resilience:** The provision of spontaneous volunteer aid was found to be a pivotal element in the German and Spanish context (e.g. THW, fire brigades); however, formal integration has been demonstrated to enhance effectiveness. In the United Kingdom, post-event actions included the deployment of flood ambassadors and the organisation of public advisory clinics. In Greece and Italy, civil-protection drills were conducted, with the objective of increasing response capacity.

4.3. Implications for future flood risk management (IFRM)

The findings have direct implications for policy and practice:

- **Policy integration:** strengthen the alignment between the EU Floods Directive and urban/climate planning to ensure that risk maps are translated into actionable guidance for households, businesses and operators;
- **Technology and data:** scale up the aggregation of multiple sources of data (e.g. radar, satellite and citizen reports), near-real-time hydrological and hydraulic modelling, ensemble forecasting and AI-enabled nowcasting for urban pluvial contexts;
- **Multifaceted risk reduction:** adopt mixed portfolios to reinforce structural defences (e.g. levees, polders and reservoirs), restore river space ('room for the river') and deploy nature-based measures in hotspots. Update design standards to acknowledge residual risk and compound extremes;
- **Climate adaptation:** embed scenarios of persistent blocking and moisture-rich lows (Omega/Genoa) and compound sequences in planning and operations with explicit trigger points and cross-sector contingency plans;

- **Financing and territorial equity:** expand structural funds and national programmes (e.g. PNRR-type initiatives and ERDF) that prioritise vulnerable people, regions and critical lifelines. These programmes should have metrics for service continuity and rapid recovery, as well as transparent tracking of avoided losses. Funding mechanisms must also account for behavioural responses during crises. Individuals in vulnerable situations often prioritise life-saving actions over protecting property, which is a natural psychological reaction that can increase losses when evacuation is sudden or unplanned. Recognising this human factor is essential for designing fair financial instruments and recovery schemes that do not disadvantage the most vulnerable populations.

4.4. Comparing flood realities

Flood events in several European countries between 2007 and 2025 show recurring patterns, including episodes of extreme precipitation and/or atmospheric blockages, high exposure due to critical infrastructure and occupation of risk areas, and institutional responses ranging from legal reforms and map/plan revisions to improvements in warning systems (e.g. cell broadcasting and sirens). Despite these advances, there are still gaps in the final stage of warnings and in the robustness of infrastructure, particularly in scenarios involving flash floods and levee/embankment failures.

• Austria (2024 flood):

Austria experienced a series of weather events that were comparable in intensity to those that occurred in Italy, with precipitation levels reaching up to 266 mm within a 48-h period in the south-eastern region, and 160 mm over a 96-h period in the western and southern regions. Additionally, the storm known as Boris resulted in accumulations of 300–400 mm within a 72-h period in specific local areas. The financial repercussions of these events ranged from €0.5 to €1.0 billion per occurrence. However, the implementation of existing risk mitigations successfully circumvented approximately €100 million in one particular instance. Vienna and Lower Austria, on the other hand, have recorded direct losses amounting to approximately €0.7 billion and production losses of around €0.6 billion.

• Croatia, Bosnia and Herzegovina, and Serbia (2014 flood)

Sava River floods are a result of coinciding flood waves on the Sava River and its tributaries, exceeding

the conventional approach to floods of a certain return period. Across the basin, record daily rainfall was measured, inducing simultaneous high flows on the right-hand tributaries and consequently flooding along the Sava River. This event was unprecedented, but indicated by more frequent and reoccurring high flows in the years leading up to the event (Gilja et al. 2018, Leščešen et al. 2022). The post-flood period resulted in stronger cross-boundary cooperation and significant investments in structural and non-structural flood mitigation measures in all three countries, as well as a change in policies.

- **Estonia (2024 Tartu flood; 2025 Surju flood):**

The floods in Estonia, while less extensive, have given rise to governance and liability concerns. The occurrence of fluvial flooding in Surju resulted in the initiation of legal debates, while the incident of pluvial flooding in Tartu led to the isolation of 64 households and the potential evacuation of a nursing home. In contrast to the situation in Latvia, the context in Lithuania encompasses high urban density ($\sim 2440/\text{km}^2$) and peri-urban areas, along with ongoing mitigation funding and remote-sensing initiatives. Trans-boundary issues of flooding may arise within the shared urban areas, where the vital infrastructure of the city is integrated for the use of both EU states. The shared river (in Estonian Pedeli and in Latvian Pedele), whose upstream and downstream courses are located in Estonian territory, and the middle course of the river is on the Latvian side, is an example. The Pedeli River demonstrates hazardous flooding conditions seasonally near the border between southern Estonia and northern Latvia, and it flows through the twin town of Valga-Valka, where it has been transformed into several reservoirs with surrounding recreational areas.

- **Germany (flood events in 2013, 2017 and 2021):**

Flood events in Germany have demonstrated contrasting hazard mechanisms over time. In 2013, a large-scale event occurred under a blocking low combined with significant rainfall in the previous 30 days (100–150 mm) and dike breaches. In contrast, in 2017, the Harz headwaters experienced intense, short-duration rainfall (306 mm in 50 h), with local peaks reaching HQ5000. Similarly, in 2021, the Ahr and Erft basins recorded over 150 mm of rainfall within 48 h, coupled with non-exceedance probabilities of up to ~ 0.998 , indicating an extremely rare event.

The 2021 event resulted in disproportionately higher exposure and vulnerability, with more than 180 fatalities, estimated losses of around 33 billion euros, and damage to over 19,000 buildings. Insurance penetration remained limited (37–47%), and warning

systems showed critical gaps: 35% of people in the Erft area and 29% in the Ahr area received no warning, while 85% of those who were warned did not anticipate the severity of the event. Unlike in previous years, governance responses included the introduction of cell broadcasting and sirens, revised maps and plans, strengthened inter-municipal cooperation and new design standards for critical infrastructure.

- **Greece (2017 Mandra flood; 2020 Ianos storm; 2023 Daniel storm):**

Evidence from Greek events indicates a divergent hazard profile, characterised by a preponderance of convective storms and medicanes. For instance, Mandra (2017) recorded approximately 300 mm in 13 h (return period 200–500 years), whereas Ianos (2020) brought extreme rainfall (~ 769 mm) and winds up to 54.2 m/s. In contrast, the 2023 flood event, termed ‘Daniel’, occurred under the influence of Omega blocking, resulting in the inundation of approximately 8,500 km² of farmland. The vulnerability patterns exhibited during the events in question also demonstrated variability. The initial impact of Ianos resulted in 25 fatalities in Mandra, a dike collapse and damage to over 20 bridges. In the aftermath of Daniel, the number of bridges damaged increased to 79, in addition to 70.2 km of roads. The insurance coverage remained limited, and post-flood public health impacts were reported. The governance responses underwent a progressive evolution, characterised by budgetary increases and legal reforms in the aftermath of Mandra, the formulation of a comprehensive master plan for Daniel, the emergence of novel risk zones, and the augmentation of the utilisation of the 112 emergency alert system.

- **Italy (2009 Messina flood; 2013 Sardinia flood; 2023 Emilia-Romagna flood):**

The Italian floods illustrate the occurrence of both short-duration extremes and multi-day accumulations. Messina flood in 2009 recorded about 250 mm of rainfall in 9 h (Stancanelli et al. 2017), while Sardinia flood in 2013 received over 450 mm in 12 h, with winds approaching 100 km/h. By way of comparison, Emilia-Romagna flood in 2023 experienced two peaks (1–4 and 15–17 May), with a maximum of 300 mm in 48 h and totals surpassing 450 mm across several areas. Exposure levels are notably high, with 11.6% of the territory facing a 20–50-year risk and 45.6% facing a 100–200-year risk. This is further compounded by the fact that provinces have been identified where 80–100% of the land is at risk. In the context of Italy, governance responses have encompassed the implementation of compensation programmes, the adoption of IT-alert systems,

the mainstreaming of PGRA/PAI plans, the mobilisation of civil-protection resources and the allocation of funds from both the EU and national sources for the purpose of resilient reconstruction.

- **Latvia (2023 Jēkabpils flood):**

The event in Latvia was characterised by a combination of heavy rainfall and a mid-winter thaw, leading to a significant rise in the water level of the Daugava river, reaching levels not observed in the past 40 years. In view of the prevailing circumstances, the implementation of evacuation procedures and the augmentation of mobile communication infrastructure were deemed imperative measures. The governance strategy was centred on the construction of levees, with an estimated expenditure of 16.93 million euros, of which 85% was funded by the European Regional Development Fund (ERDF). The allocation also encompassed supplementary prevention and recovery funds.

- **Poland (2010 flood):**

In contrast to the short-duration extremes experienced in Spain, the hazard in Poland stemmed from prolonged rainfall (daily totals up to 185 mm) over saturated soils, compounded by reliance on embankments and floodplain development. The consequences of the hurricane were relatively moderate, with one fatality, 150 people affected and damages of approximately US\$142 million. However, the hurricane did reveal systemic weaknesses. The fundamental lesson to be drawn from this analysis is that an approach that focuses exclusively on embankments, without incorporating integrated flood risk management strategies (including land use, drainage and redundancy measures), results in residual vulnerabilities.

- **Spain (Valencia flood in 2024):**

In contrast to the multi-day events that have been observed in Italy, Valencia experienced a flash flood of a more traditional nature (DANA/Gota Fría), which resulted in 490 mm of precipitation falling (locally registered) in a period of 8 h. The impacts were severe: The disaster affected over 60,000 people, and approximately 3,906 buildings were damaged. In addition, around 531 km of roads and 15 km of rail have been disrupted, resulting in estimated losses of approximately 10.7 billion euros. Despite the availability of high-resolution meteorological forecasts, the event exposed persistent gaps in last-mile communication, impact anticipation and infrastructure robustness, highlighting the challenges of translating hazard-focused forecasts into effective impact passed emergency responses for convective flash flood events.

This case illustrates that, for short-duration convective extremes, improvements in spatial resolution alone are insufficient without probabilistic guidance and explicit communications of spatial uncertainty.

- **United Kingdom (floods in 2007 and 2015):**

Analogous to Poland, the UK experienced prolonged periods of rainfall (414 mm from May to July 2007), yet the repercussions were significantly more pronounced: The impact of the flooding is significant, affecting approximately 370,000 individuals, 48,000 residences and 7300 commercial establishments. The disruption to essential utilities has resulted in substantial financial implications, with estimated costs reaching approximately £3.164 billion. The governance responses encompassed the Pitt Review recommendations, which included the establishment of a national FCERM strategy, Exercise Watermark 2011, and augmented investment. Government interventions helped to mitigate the impacts of the 2015 flash floods in Cumbria, despite record-breaking rainfall of 341.4 mm within 24 h and up to 405 mm over 48 h. Compared with the 2007 floods, which resulted in approximately £1.6 billion in economic damages, the flooding of around 16,000 properties, and two fatalities, the 2015 event demonstrated improved resilience. Building on these lessons, the UK Government confirmed further investment for flood and coastal defences and early warning services (HM Government 2025).

Across the cases analysed, comparable hazard intensities often produced markedly different impacts depending on the level of urbanisation, confirming the role of urban amplification in increasing economic losses and infrastructure disruption. This underscores the assertion that hydrometeorological conditions, despite their similarity, can yield divergent outcomes contingent on exposure, urbanisation, governance capacity and prevailing socio-economic conditions.

These variations can be further interpreted through economic capacity, which is often approximated through GDP per capita. This economic capacity influences both the implementation of preventive measures and the effectiveness of response and recovery (Hallegatte et al. 2017, Rentschler et al. 2022). While the case studies demonstrate broadly comparable hazard drivers, the resulting impacts and recovery trajectories differ substantially between countries. In higher-income contexts (e.g. Germany, the United Kingdom), stronger institutional capacity, wider insurance coverage and more developed early warning systems support more proactive and integrated flood risk management approaches.

Conversely, in lower-income or transition contexts (e.g. countries in the Sava River Basin), financial and institutional constraints frequently result in more

reactive responses, with recovery processes exhibiting greater reliance on public intervention and external support. Consequently, comparable hazard intensities can engender considerably disparate social and economic consequences, underscoring the pivotal function of socio-economic circumstances in determining flood risk and resilience.

4.5. Synthesis of flood risk drivers and operational pathways

This section synthesises the key findings within an Integrated Flood Risk Management (IFRM) framework, linking hazard, exposure, vulnerability and governance dimensions to operational implications. The flood hazard is increasingly characterised by short-duration extreme events occurring under blocked synoptic regimes, such as Omega and Genoa patterns, often combined with intense moisture advection. These dynamics call into question established design return periods and underscore the necessity to revise design standards and to explicitly account for compound-event scenarios.

Exposure remains a critical driver of flood impacts, as ongoing urban expansion and the siting of critical lifelines (including bridges, hospitals, energy and telecommunications infrastructure) within flood-prone corridors substantially increase indirect and intangible losses. In particular, urban environments demonstrate a disproportionate sensitivity to short-duration extreme rainfall, reflecting the combined effects of elevated exposure, infrastructure constraints and modified hydrological responses. The amplifying impact of vulnerability is further compounded by socio-economic heterogeneity, including limited insurance coverage in certain regions of Southern Europe, reliance on agricultural livelihoods and variability in building and asset quality. Collectively, these factors influence the depth and duration of post-event recovery.

Significant advancements in governance, including the implementation of IT-alert systems, cell broadcast technologies and transboundary flood management plans, are indicative of noteworthy progress (Hamidifar and Nones 2025). However, these advancements frequently coexist with persistent deficiencies in last-mile communication and a limited translation of flood risk maps into actionable and operational measures. For instance, the 2021 floods in Germany exposed critical shortcomings in the dissemination and interpretation of warnings, while the subsequent reintroduction of sirens and implementation of cell broadcasting illustrate how such gaps can be addressed. In a similar manner, the implementation of IT-alert in Italy exemplifies the function of national-scale systems in enhancing the reach of warnings and the efficacy of responses. In order to address

these challenges, there is a necessity for institutionalised training programmes, harmonised operational protocols and the systematic use of performance-based indicators. These indicators include warning lead time, population reaches and action uptake rates.

It is evident that, upon further consideration of the aforementioned synthesis, a number of operational priorities have been identified. Early warning and risk communication systems should rely on redundant, multimodal channels to deliver location-specific and actionable messages supported by clear performance benchmarks. Such channels should combine cell broadcast, sirens, mobile applications and traditional media. The efficacy of such systems has been demonstrated in post-2021 Germany and through the implementation of IT-alert in Italy (Dipartimento della Protezione Civile 2023, Thieken et al. 2023).

The implementation of Urban IFRM necessitates a more robust integration between flood risk maps and spatial planning instruments, encompassing permitting processes, building codes and land-use zoning. These challenges are exemplified by events such as Mandra (Greece), where urbanisation on alluvial fans amplified flood impacts; the 2023 Emilia-Romagna floods, where drainage capacity and land-use interactions influenced flood dynamics; and the UK floods of 2007 and 2015, which highlighted the vulnerability of urban drainage systems to both prolonged and short-duration rainfall events. In this context, risk-informed planning should be complemented by private-sector guidance on temporary protection measures, equipment elevation, evacuation routes and the deployment of nature-based solutions in identified hotspots.

In order to enhance critical infrastructure resilience, it is imperative that updated design standards and contingency planning are implemented, particularly in the case of vital infrastructure such as dams, bridges and hospitals. The implementation of these measures should be accompanied by systematic post-event audits, with the objective of prioritising retrofitting interventions. Examples of this include transboundary cooperation frameworks, such as those implemented in the Sava River Basin, and national-scale investments, such as levee reinforcement in Latvia. These illustrate the need for combined structural and non-structural portfolios that are tailored to diverse socio-hydrological contexts.

At the basin scale, enhanced cooperation through transboundary frameworks, improved data interoperability and the integration of remote sensing and crowdsourced observations are essential, particularly to capture blocked-pattern and compound-event dynamics. Finally, financing mechanisms should combine European and national instruments with explicit equity criteria, ensuring continuity of critical lifelines

in vulnerable regions while systematically tracking avoided losses to support evidence-based investment decisions. The effectiveness of these strategies is, however, strongly conditioned by economic capacity, which is often approximated through GDP per capita. This, in turn, determines the ability of countries to invest in and sustain both structural and non-structural measures over time.

Higher-income countries are generally better positioned to implement comprehensive and anticipatory portfolios of measures. By contrast, lower-income or transition contexts more often face constraints that require prioritisation, external support and phased implementation. In circumstances where losses exceed the resources available at the national and EU levels, recovery processes may become selective, delayed and characterised by social inequality. This underscores the importance of incorporating distributive-justice principles within future funding frameworks and of adopting context-specific approaches to flood risk management.

5. Conclusions

The present study analysed major flood disasters across Europe between 2007 and 2025 using a comparative framework aligned with Integrated Flood Risk Management (IFRM). A thorough examination of hazard characteristics, exposure, vulnerability and governance responses was undertaken, leading to the identification of recurring patterns. These patterns elucidate both the increasing impacts of flood events and their variability across regions.

Firstly, the results indicate an increase in both the diversity and complexity of flood types throughout Europe. There is mounting evidence for both short-duration, high-intensity events (which are often associated with flash floods) and prolonged rainfall events affecting large river basins. Across the cases analysed, flood impacts are consistently amplified by urbanisation, infrastructure limitations and exposure beyond traditionally recognised flood-prone areas. In a multitude of instances, deficiencies in the dissemination of early warnings and last-mile communication have played a pivotal role in shaping outcomes, frequently outweighing the influence of hazard intensity itself.

Secondly, the findings highlight clear regional differences in flood regimes, vulnerability and response capacity. The southern and Mediterranean regions are more frequently affected by short-duration, high-intensity events with rapid onset. In contrast, Central and Northern Europe are more exposed to large-scale riverine flooding driven by prolonged precipitation. These variations are not solely driven by physical processes but also by differences

in socio-economic conditions, infrastructure resilience and institutional preparedness. Across the cases analysed, comparable hazard intensities often produced markedly different impacts depending on exposure, urbanisation, governance capacity and economic conditions. In particular, economic capacity, often approximated through indicators such as GDP, emerges as a key factor shaping both vulnerability and recovery trajectories. It is evident that higher-income contexts generally exhibit stronger institutional frameworks, wider insurance coverage and more developed early warning systems. These factors support more proactive and integrated flood risk management approaches. Conversely, in lower-income or transition contexts, financial and institutional constraints tend to favour more reactive responses, with recovery processes more dependent on public intervention and external support. Consequently, analogous hazard events can result in markedly disparate social and economic consequences across nations.

Thirdly, the findings emphasise significant implications for flood risk management. The effective reduction of risk necessitates integrated approaches that combine structural measures, risk-informed spatial planning, robust and multi-channel early warning systems, and strengthened cross-border coordination. The results also highlight the need to improve the usability of warning information, address residual risks in highly urbanised areas, and adopt flexible portfolios of measures capable of addressing both flash flood dynamics and large-scale basin processes. It is imperative to recognise the pivotal role of economic capacity in facilitating the implementation and sustained maintenance of these measures over time.

It is important to note that the present study is not without its limitations. The analysis is based on a 20-year time window and on heterogeneous data sources, including EM-DAT, which may contain inconsistencies across countries and events. Moreover, the study employs a descriptive and comparative approach, eschewing the undertaking of formal statistical or frequency-based analyses. These limitations must be considered when interpreting the results, particularly with respect to long-term trends and climate attribution.

Overall, the study shows that recent European flood disasters are shaped by the interaction between evolving hazard regimes, increasing exposure and uneven governance and economic capacities. Therefore, enhancing resilience requires advanced technical solutions and context-specific approaches that integrate socio-economic conditions, strengthen institutional capacity and support sustained investment in flood risk management across Europe.

Acknowledgements

The first author (A.M.B.) gratefully acknowledges financial support from national funds through FCT – Portuguese Foundation for Science and Technology, under the Scientific Employment Stimulus program (2023.09258.CEECIND), <https://doi.org/10.54499/2023.09258.CEECIND/CP2848/CT0011>.

Disclosure statement

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

Funding

This work was supported by Fundação para a Ciência e a Tecnologia: [Grant Number 2023.09258.CEECIND].

Notes on contributors

Dr Ana Margarida Bento is a postdoctoral researcher at the Interdisciplinary Centre for Marine and Environmental Research (CIIMAR) at the University of Porto in Portugal. She is also the principal investigator of the BriSK project, which is funded by the Portuguese Foundation for Science and Technology (FCT). She is also an Invited Assistant Professor and serves on the IAHR Europe Division Leadership Team. Her research interests include flood risk management, climate change adaptation, hydraulic engineering, infrastructure resilience, hydrological modelling and data-driven approaches to water-related hazards. She holds a PhD in Civil Engineering from the University of Porto.

Dr. Florian Cordier holds a PhD in Fluid Mechanics, specialising in numerical modelling of sediment transport, river morphodynamics and riverine vegetation. He works as an Environmental Research Engineer and Project Manager on Hydraulic Structures Safety at EDF R&D LNHE and LHSV in Chatou (France) and is also a member of the IAHR.

Dr Alan Cuthbertson is a Reader in Civil Engineering at the University of Dundee, United Kingdom. His main research interests include environmental fluid mechanics, river, coastal and marine hydrodynamics and sediment transport processes. He obtained his PhD in the latter from the University of Glasgow in 2002.

Prof. Benjamin Dewals is a Professor of Water Engineering at the University of Liège, Belgium. His research focuses on flood risk modelling and management, with particular expertise in developing innovative methods to assess and mitigate flood impacts. He serves as principal investigator of several European research projects and leads transdisciplinary research addressing flood impact modelling across multiple sectors, flood damage assessment, early-warning systems, and climate change adaptation strategies.

Dr. Michalis Diakakis is an Assistant Professor of Extreme Events and Natural Hazards at the National and Kapodistrian University of Athens, Greece. His research interests include natural hazards, flood risk assessment, climate change adaptation, disaster risk reduction, and critical infrastructure resilience. He holds a PhD in Flood Hazard Assessment from the National and Kapodistrian University of Athens.

Prof. Cristiana Di Cristo is a Full Professor of Hydraulics at the University of Naples Federico II, where she also earned her PhD in Hydraulics. Her research focuses on fluvial hydraulics, sediment transport and river morphodynamics, flow instabilities (including roll waves), granular and debris flows, modelling of Newtonian and non-Newtonian fluids, and the impact of mudflows and flood waves on rigid structures and erodible beds. She is a member of the leadership team of the European Division of the International Association for Hydro-Environment Engineering and Research (IAHR).

Gordon Gilja is an Associate Professor at the University of Zagreb Faculty of Civil Engineering, Croatia. He is a founder and head of the RISED laboratory, with research interests that include sediment transport, bedform dynamics, and bridge scour, combining experimental research and remote sensing methods. He is a contributing member of the International Association for Hydro-Environment Engineering and Research and the European Geosciences Union.

Hossein Hamidifar is a researcher at the Institute of Geophysics, Polish Academy of Sciences in Warsaw, Poland. He is an expert in river hydraulics, sediment dynamics, and flood processes. His work has integrated physical and numerical modelling to investigate flow-sediment interactions, flood modelling, and water quality processes in rivers. He has contributed to advancing process-based and data-driven approaches for understanding hydro-morphodynamic systems and improving predictive tools for river management.

Dr. Stefan Haun is a Full Professor and, since 2025, Head of the Institute of Hydraulic Engineering and Water Resources Management at Graz University of Technology, Austria. His research focuses on river morphodynamics, reservoir management, flood risk management, and the sustainable development of hydropower systems. Since 2025, he has served as Chair of the Flood Risk Management Committee and, since 2026, as Vice Chair of the IAHR Europe Division. He has been an Associate Editor of the Journal of River Basin Management since 2022. His work integrates experimental, field-based, and numerical approaches to advance resilient and sustainable water resources management.

Dr. Janek Laanearu is a Tenured Associate Professor at the Tallinn University of Technology in Estonia. Since 2022, he has been leading the Water and Environmental Engineering Research Group at the Department of Civil Engineering and Architecture at TalTech. He received his PhD in Environmental Physics from the University of Tartu in 2001 and his PhLic in Atmospheric Sciences/Physical Oceanography from Stockholm University in Sweden in 2000. His professional strengths are related to civil and environmental engineering and fluid mechanics teaching, which are reflected in his publications in transnationally recognised scientific journals and conference proceedings.

Melissa Latella is a junior scientist at the Euro-Mediterranean Center on Climate Change (CMCC Foundation). She holds a PhD in Civil and Environmental Engineering from the Polytechnic University of Turin, Italy. Her research focuses on monitoring and modelling interactions among sediments, water, and vegetation using remote sensing data and diverse modelling approaches. At CMCC Foundation, she develops services for soil erosion assessments and decision support tools for land and water resource management. Melissa is the co-founder and vice chair of the IAHR working group on Remote Sensing.

Dr. P. Amparo López-Jiménez is a Professor at the Universitat Politècnica de València. Her research interests include water systems modelling, urban hydraulics and sustainability. She holds a PhD in Hydraulic Engineering from UPV, Spain.

Dr. Eda Majtan is an Assistant Professor at the University of Liverpool, UK. She received her PhD from the University of Manchester, UK, where she investigated the behaviour of masonry arch bridges under flood flow and floating-debris impact. Her main research interests include fluid-structure interaction, sensing technologies, flood risk management, flood resilience of hydraulic structures, particularly masonry arch bridges, and smoothed particle hydrodynamics.

Dr. Cristina Prieto Sierra holds an International PhD in Civil Engineering and is a Ramón y Cajal Research Fellow at the University of Cantabria and IHCantabria, Spain. Her research focuses on hydrological modelling, probabilistic streamflow prediction and uncertainty quantification. She is an Associate Editor of Hydrology and Earth System Sciences, a member of the IAHR Europe Regional Division Leadership Team, and Science Officer for Hydrometeorological Hazards at the European Geosciences Union. She also contributes to international initiatives within the World Meteorological Organization and the International Association of Hydrological Sciences.

Prof. Elena Pummer is a professor in the Hydraulic Engineering Group at the Norwegian University of Science and Technology (NTNU) in Norway. She specialises in advancing the understanding of complex hydraulic processes, including flow dynamics, air entrainment, particle transport and ice-related phenomena. She combines fundamental research with a holistic systems perspective to develop innovative, sustainable solutions for hydraulic structures. Driven by the challenges posed by climate change, ageing infrastructure, sustainability demands and technological advances in computing and measurement, her work is helping to improve the design, safety and resilience of future hydraulic engineering systems.

Prof. Paweł M. Rowiński is the Director of the Institute of Geophysics of the Polish Academy of Sciences. Since June 2024, he has served as President of the European Federation of Academies of Sciences and Humanities (ALLEA). His research focuses on environmental hydrodynamics and mathematical modelling of hydrological processes. He served as Chair of the European Division of the International Association for Hydro-Environment Engineering and Research (IAHR) until June 2026.

Prof. Dr. Kai Schröter is a full Professor of Hydrology and River Basin Management at the Leichtweiß Institute for Hydraulic Engineering and Water Resources Engineering at the Technische Universität Braunschweig. His research focuses on the integrated analysis of water quantity and water quality in the context of hydrological extreme events and associated risks. Together with his team, he develops methods, simulation models, and tools for the sustainable and adaptive management of future water resources systems.

Prof. Anastasios I. Stamou is a professor of computational methods in environmental fluid mechanics and the design of environmental hydraulic works at the National Technical University of Athens (NTUA) in Greece. He is the Director of the Laboratory of Applied Hydraulics and has served as a visiting professor at the Technical University of Munich. His research focuses on computational fluid dynamics (CFD), water resources management, hydraulic and

environmental engineering, ecohydraulics, coastal processes and the impact of climate change. He has extensive experience in leading and participating in research projects, in authoring scientific publications, and in contributing to engineering studies as a consultant and project coordinator.

Dr. Laura Stancanelli is currently Assistant Professor at the University of Padova. Her expertise lies in hydraulic modelling. Her research spans cross-scale analysis, from the engineering scale to the micron scale, focusing on geophysical processes such as debris flow propagation, density current mixing, and coastal hydrodynamics, as well as fluid mechanics aspects like wall shear stress analysis for drag reduction measures.

ORCID

Ana Margarida Bento  <http://orcid.org/0000-0002-8386-807X>

Florian Cordier  <http://orcid.org/0000-0001-8612-2532>

Benjamin Dewals  <http://orcid.org/0000-0003-0960-1892>

Michalis Diakakis  <http://orcid.org/0000-0001-6155-6588>

Gordon Gilja  <http://orcid.org/0000-0002-8796-5264>

Hossein Hamidifar  <http://orcid.org/0000-0001-9054-0120>

Janek Laanearu  <http://orcid.org/0000-0001-9176-8573>

Melissa Latella  <http://orcid.org/0000-0003-3678-6992>

Eda Majtan  <http://orcid.org/0000-0002-5623-3263>

Cristina Prieto Sierra  <http://orcid.org/0000-0002-9300-6967>

Elena Pummer  <http://orcid.org/0000-0002-0255-4715>

Anastasios I. Stamou  <http://orcid.org/0000-0002-8650-4175>

Laura Maria Stancanelli  <http://orcid.org/0000-0001-9725-9964>

References

- Alfieri, L., et al., 2020. Global modeling of seasonal mortality rates from river floods. *Earth's Future*, 8, e2020E-F001541. doi:10.1029/2020EF001541.
- Azhar, M. et al. 2025. Comprehensive portfolio of adaptation measures to safeguard against evolving flood risks in a changing climate. *Communications Earth & Environment*, 6 (1), 824. doi:10.1038/s43247-025-02779-z
- Barredo, J. I., 2007. Major flood disasters in Europe: 1950–2005. *Natural Hazards*, 42 (1), 125–148. doi:10.1007/s11069-006-9065-2.
- Barredo, J. I., 2009. Normalised flood losses in Europe: 1970–2006. *Natural Hazards and Earth System Sciences*, 9 (1), 97–104. doi:10.5194/nhess-9-97-2009.
- Bento, A. M., et al., 2020. Risk-based methodology for scour analysis at bridge foundations. *Engineering Structures*, 223, 111115. doi:10.1016/j.engstruct.2020.111115.
- Bento, A. M., et al., 2023. Improved assessment of maximum streamflow for risk management of hydraulic infrastructures. *International Journal of River Basin Management*, 21 (3), 489–499. doi:10.1080/15715124.2021.2016783.
- Centre for Research on the Epidemiology of Disasters (CRED), 2024. *EM-DAT: The international disaster database*. Université catholique de Louvain (UCLouvain). <https://www.emdat.be/>
- Dipartimento della Protezione Civile, 2023. *Almost 800,000 questionnaires completed after the first 5 tests*. IT-Alert.

- <https://www.it-alert.it/en/notizia/almost-800000-questionnaires-completed-after-first-5-tests/>
- Environment Agency, 2018, January 5. *Costs of the winter floods 2015 to 2016: summary*.
- Environment Agency, 2024, December 17. *National assessment of flood and coastal erosion risk in England 2024*. <https://www.gov.uk/government/publications/national-assessment-of-flood-and-coastal-erosion-risk-in-england-2024>
- European Commission, 2021. *Commission notice – technical guidance on the climate proofing of infrastructure in the period 2021–2027*. Publications Office of the European Union. <https://op.europa.eu/en/publication-detail/-/publication/23a24b21-16d0-11ec-b4fe-01aa75ed71a1>
- European Environment Agency, 2024. *European climate risk assessment*. EEA Report No 1/2024.
- Exercise Watermark Review Team, 2011. *Exercise watermark: final report (PB13673) [PDF]*. Department for Environment, Food & Rural Affairs.
- Gilja, G., Ocirk, E., and Kuspilić, N., 2018. Joint probability analysis of flood hazard at river confluences using bivariate copulas. *Journal of the Croatian Association of Civil Engineers*, 70 (4), 267–275. doi:10.14256/JCE.2173.2017.
- Granata, F., Zhu, S., and Di Nunno, F., 2025. Hydrological extremes in the Mediterranean basin: interactions, impacts, and adaptation in the face of climate change. *Regional Environmental Change*, 25 (3), Article 100. doi:10.1007/s10113-025-02432-7
- Hallegatte, S., et al., 2017. *Unbreakable: building the resilience of the poor in the face of natural disasters*. Washington, DC: World Bank.
- Hamidifar, H., and Nones, M., 2023. Spatiotemporal variations of riverine flood fatalities: 70 years global to regional perspective. *River*, 2 (2), 222–238. doi:10.1002/rvr.245.
- Hamidifar, H., and Nones, M., 2025. Integration of the EM-DAT dataset and Google Trends to depict river floods across Europe. *International Journal of River Basin Management*, 1–14. doi:10.1080/15715124.2025.2516745
- Haslinger, K., et al., 2025. Increasing hourly heavy rainfall in Austria reflected in flood changes. *Nature*, 639, 667–672. doi:10.1038/s41586-025-08647-2.
- Haun, S., et al., 2023. *The role of hydraulic engineering in support of flood mitigation and resilience*. Madrid: International Association for Hydro-Environment Engineering and Research (IAHR). <https://www.iahr.org/index/detail/944>
- HM Government, 2025, October 14. *Deprived communities to get new flood defences faster*. <https://www.gov.uk/government/news/deprived-communities-to-get-new-flood-defences-faster>
- Intergovernmental Panel on Climate Change (IPCC). 2023. *Climate change 2021: The physical science basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. doi:10.1017/9781009157896
- Jonkman, S. N., 2005. Global perspectives on loss of human life caused by floods. *Natural Hazards*, 34 (2), 151–175. doi:10.1007/S11069-004-8891-3.
- Keenan-Jones, D. C., et al., 2025. Urban development and long-term flood risk and resilience: experiences over time and across cultures. Cases from Asia, North America, Europe and Australia. *Urban Studies*, 62 (3), 469–486. doi:10.1177/00420980231212077.
- Klör, T., et al., 2025. Factors influencing mental burden caused by flooding: insights from the 2021 flood in the Ahr valley (Germany). *Journal of Flood Risk Management*, 18 (4), e70116. doi:10.1111/jfr3.70116.
- Leščešen, I., et al., 2022. Regional flood frequency analysis of the Sava River in South-Eastern Europe. *Sustainability*, 14 (15), 9282. doi:10.3390/su14159282.
- Macdonald, E., et al., 2026. Future climate change assessment in flood risk management: a synthesis of practices in Germany and the BeNeLux countries. *Journal of Flood Risk Management*, 19 (1), e70173. doi:10.1111/jfr3.70173.
- Marsh, T. J., et al., 2016. *The winter floods of 2015/2016 in the UK: a review*. Wallingford, UK: Centre for Ecology & Hydrology.
- Pitt, M., 2008. *Pitt Review: Learning lessons from the 2007 Floods*. London, UK: Cabinet Office.
- Prieto, C., et al., 2024. Preface: Advances in pluvial and fluvial flood forecasting and assessment and flood risk management. *Natural Hazards and Earth System Sciences*, 20 (4), 1045–1048. doi:10.5194/nhess-24-3381-2024.
- Prieto, C., Patel, D., and Han, D., 2020. Preface: advances in flood risk assessment and management. *Natural Hazards and Earth System Sciences*, 20, 1045–1048. doi:10.5194/nhess-20-1045-2020.
- Reinert, J., Klopries, E.-M., and Schüttrumpf, H., 2025. Meteorological and hydrological data as a basis for issuing flood warnings during the July Flood 2021 in Rhineland-Palatinate and North Rhine-Westphalia (Germany). *Journal of Flood Risk Management*, 18 (2), e70078. doi:10.1111/jfr3.70078.
- Rentschler, J., Salhab, M., and Jafino, B. A., 2022. Flood exposure and poverty in 188 countries. *Nature Communications*, 13 (1), 3527. doi:10.1038/s41467-022-30727-4.
- Rodríguez Castro, D., et al., 2022. Key drivers of flash flood damage to private households. *Journal of Flood Risk Management*, 13 (3), e70088. doi:10.1111/jfr3.70088.
- Sairam, N., et al., 2025. Evacuating flash flood victims: key drivers and psychological burden. *Journal of Flood Risk Management*, 18 (3), e70065. doi:10.1111/jfr3.70065.
- Schaum, S., et al., 2025. An overview of long-term temporaries after flood disasters. *Journal of Flood Risk Management*, 18 (3), e70109. doi:10.1111/jfr3.70109.
- Schüttrumpf, H., et al., 2025. The flood event in July 2021 in Europe—observations, conclusions, challenges. *Journal of Flood Risk Management*, 18 (1), e70175. doi:10.1111/jfr3.70175.
- Solheim, N., Pummer, E., and Lia, L., 2025. Oblique approach flow on a model spillway inlet: physical measurements. In: E. Pummer and I. Albayrak, eds. *Proceedings of the 10th IAHR International Symposium on Hydraulic Structures*. Zurich, Switzerland: ETH Zurich. doi:10.3929/ethz-b-000727196.
- Stamou, A. I., 2024. The typologization of water research as a possible means to improve the technical guidelines on the adaptation of water infrastructure to climate change. *Hydrolink Magazine*, 3, 4–8. International Association for Hydro-Environment Engineering and Research (IAHR).
- Stancanelli, L. M., et al., 2017. A combined triggering-propagation modeling approach for the assessment of rainfall-induced debris flow susceptibility. *Journal of Hydrology*, 550, 130–143. doi:10.1016/j.jhydrol.2017.04.038.
- Thieken, A. H., et al., 2023. Performance of the flood warning system in Germany in July 2021 – insights from affected residents. *Natural Hazards and Earth System Sciences*, 23, 973–990. doi:10.1016/j.jhydrol.2017.04.038. <https://nhess.copernicus.org/articles/23/973/2023/>