Global and Planetary Change 254 (2025) 105021

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Short Communication

Editorial preface to special issue: Temporal and spatial patterns in Holocene floods under the influence of past global change, and their implications for forecasting "unpredecented" future events

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ARTICLE INFO

Keywords:
Flood hazard
Paleohydrology
Natural archives
Documentary sources
Multi-archive reconstruction
Integration model

ABSTRACT

Floods constitute the most significant natural hazard to societies worldwide. Population growth and unchecked development have led to floodplain encroachment. Modelling suggests that climate change will regionally intensify the threat posed by future floods, with more people in harm's way. From a global change perspective, past flood events and their spatial-temporal patterns are of particular interest because they can be linked to former climate patterns, which can be used to guide future climate predictions. Millennial and centennial time series contain evidence of very rare extreme events, which are often considered by society as 'unprecedented'. By understanding their timing, magnitude and frequency in conjunction with prevailing climate regime, we can better forecast their future occurrence.

This Virtual Special Issue (VSI) entitled *Temporal and spatial patterns in Holocene floods under the influence of past global change, and their implications for forecasting "unpredecented" future events* comprises 14 papers that focus on how centennial and millennia-scale natural and documentary flood archives help improve future flood science. Specifically, documentation of large and very rare flood episodes challenges society's lack of imagination regarding the scale of flood disasters that are possible (what we term here, the "unknown unknowns"). Temporal and spatial flood behaviour and related climate patterns as well as the reconstruction of flood propagation in river systems are important foci of this VSI. These reconstructions are crucial for the provision of robust and reliable data sets, knowledge and baseline information for future flood scenarios and forecasting. We argue that it remains difficult to establish analogies for understanding flood risk during the current period of global warming. Most studies in this VSI suggest that the most severe flooding occurred during relatively cool climate periods, such as the Little Ice Age. However, flood patterns have been significantly altered by land use and river management in many catchments and floodplains over the last two centuries, thereby obscuring the climate signal. When the largest floods in instrumental records are compared with paleoflood records reconstructed from natural and documentary archives, it becomes clear that precedent floods should have been considered in many cases of flood frequency analysis and flood risk modelling in hydraulic infrastructure. Finally, numerical geomorphological analysis and hydrological simulations show great potential for testing and improving our understanding of the processes and factors involved in the temporal and spatial behaviour of floods.

1. Flood disasters, society and global change

Floods constitute the most significant natural hazard to societies across the globe (UNISDR, 2022). Population growth and unchecked development have led to floodplain encroachment. Forecast climate change may regionally intensify the threat posed by future floods to societies, with more people in harm's way. Last year, in 2024, when we received the last manuscripts for this VSI, extreme flood episodes

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https://doi.org/10.1016/j.gloplacha.2025.105021
Received 7 August 2025; Received in revised form 9 August 2025; Accepted 9 August 2025
Available online 11 August 2025

affected some European regions once again, causing casualties and material damage:

i) On June 21st and July 29th/30th, 2024, in Valais (estimated return period 100–300 years) and in the Maggia Valley (estimated return period 50–100 years; press release from the Federal Office for the Environment, Switzerland, 16 July 2024).
ii) From September 8th to 23rd, 2024, in Austria, Germany, the Czech Republic, Poland, Slovakia, Hungary, and Romania. According to estimates by the Helmholtz Centre for Environmental Research - UFZ (press release in Oct. 2024) and the Czech National Institute of Hydrology (personal communication dated 18.09.2024), the return periods for this episode may vary locally between 50 and 1000 years, depending on the location.
iii) Finally, the floods of October 29, 2024, in the Valencia region (the third extraordinary flood in the region since 1957) triggered by an isolated high-level depression (DANA). The catastrophic flooding episode caused claimed the lives of 220 people. Based on the compilation of a historical series of floods of the Turia River reconstructed from 1321 to 2010 CE by Barriendos et al. (2019), the return period of the 2024 episode is around 100 years, whereas the worst flood episodes occurred between 1570 and 1620 CE.

These examples from Europe illustrate the relevance of flood impact on society and the urgent need to improve disaster risk reduction and achieving greater resilience of social and ecological systems. However, instrumental hydro-meteorological records are usually too short to include the very rare extreme events necessary for a precise Flood Frequency Analysis, which is required for the design of effective integrated hydrological risk management and climate resilience enhancement. In contrast, millennial and centennial time series include these rare extreme events, which society often considers ‘unprecedented’ (Baker, 2008). From a global change perspective, the spatio-temporal patterns of past flood events and climate variability are of particular interest as they can be used as a proxy for future climate predictions (for example, as analogues in a world that is 1.5–2 °C warmer).

Understanding their timing, magnitude and frequency in relation to the prevailing climate regime and human activities (attributions) enables us to forecast their future occurrence more accurately and to overcome our lack of information and disentangle the so-called “unknown unknowns”. Improving the estimation of return periods, mapping of flood areas and identification of relevant impact-determining factors, as well as better characterizing the climatic conditions associated with these events, will enhance our ability to identify situations of greatest risk and mitigate losses of life, property, services and heritage. The results, which are applicable in the short and medium term, could be useful and effective for regional and local water policymakers.

However, historical and longer instrumental flood records are mainly limited to large cities (Wetter, 2017). In contrast, in catchments in more remote regions — particularly mountainous regions — instrumental data for calibration is often lacking, and historical sources are scarce. Therefore, the work package 2 of the international PAGES-Floods Working Group developed the theoretical concept of integrating multi-archive flood series (e.g. lake and floodplain sediments, tree-rings, lichenometry, archaeological evidence, historical sources, etc.), into a composite model, in which physical flood phenomena are interpreted using different types of records and scientific disciplines (Schulte et al., 2019b). To understand the climatic variability of flood episodes, sequences of atmospheric pressure maps were generated from paleoclimatic reconstructions (Twentieth Century Reanalysis) and simulations (Last Millennium Ensemble) (Peña and Schulte, 2020). This integrative approach has been successfully applied in the Swiss Alps, with the results published in the first Virtual Special Issue of the Floods Working Group.

Furthermore, paleo-perspectives on natural flood processes also provide a critical baseline that for identifying anthropogenic impacts (Notebaert et al., 2018) and determining tipping points in the fluvial systems. As flood-prone areas, particularly floodplains and wetlands, are hotspots of economic, social and cultural development in many regions, the historical role of human activity in altering flood frequencies, hydro-sedimentary and environmental processes is a priority topic.

2. This second VSI on global change and floods

Since 2015, the Past Global Changes Floods Working Group (PAGES-FWG) has been a global scientific platform bringing together scientists from different disciplines to conduct integrated research on past and present floods. In 2020 the PAGES-FWG published their first Virtual Special Issue (VSI) titled “Pluridisciplinary analysis and multi-archive reconstruction of paleofloods” in *Global and Planetary Change* (Schulte et al., 2019a, 2020). Even after closing the VSI, we still received numerous messages from interested researchers in 2020 expressing their desire to participate in a special issue.

Following the organization of several meetings and sessions on paleofloods, including the Paleoflood Conference in Palmerston North (2020), the OSM Conference in Agadir (2022), the INQUA Conference in Rome (2023) and the EGU Conference in Vienna (2024), the idea arose to launch a second Virtual Special Issue. Due to scientific challenges and social demand, this VSI focuses on understanding how existing natural and documentary flood archives can help overcome our lack of information on large flood disasters, which society has not expected. Thus, the VSI guest editors invited authors to share their innovative ideas and methods with a broader audience, to disseminate new solutions, and to improve our understanding of extreme floods and their consequences for societies in the context of global change.

Finally, this VSI collected 14 multidisciplinary research papers (Fig. 1; Table 1), integrating different sources of data, methodologies and research perspectives, and uniting experts in the field. The scope of the VSI is threefold:

i) to investigate temporal and spatial flood patterns and the associated climate drivers;
ii) to perform Flood Frequency Analysis in order to assess flood-of-record and recent large-scale flood disasters, with the aim of improving flood risk maps; and.
iii) to perform numerical modelling in order to simulate past and present flood behaviour.

These three foci are based on the assumption that reconstructing past floods is crucial for providing robust and reliable datasets, knowledge, and baseline information for future flood scenarios and forecasting.

Fig. 1 shows the global locations of research papers participating in the present VSI, articles published by the VSI in 2020 (Schulte et al., 2019a), and flood series compiled in the PAGES Flood Working Group (WG) meta-database since 2015. Most paleoflood research is conducted in the Northern Hemisphere; only 22 out of 379 studies are located in the Southern Hemisphere. In 2019, the number of studies in North America was similar to the number of studies in Asia, but since the VSI was published in 2020, the number of studies in Asia has increased significantly. Nevertheless, the majority of paleoflood series (219) were reconstructed in Europe. Interestingly, Spain leads Europe with 46 flood records. These numbers are, of course, only representative with restrictions because the series were collected from researchers who collaborate with the PAGES Flood WG. In any case, the map indicates that both researchers and the PAGES Flood WG need to make more efforts to integrate and support works on past floods in Africa, South America and Oceania.

3. Millennia-long flood series and climate change

The first group of articles examines how flood periods and episodes

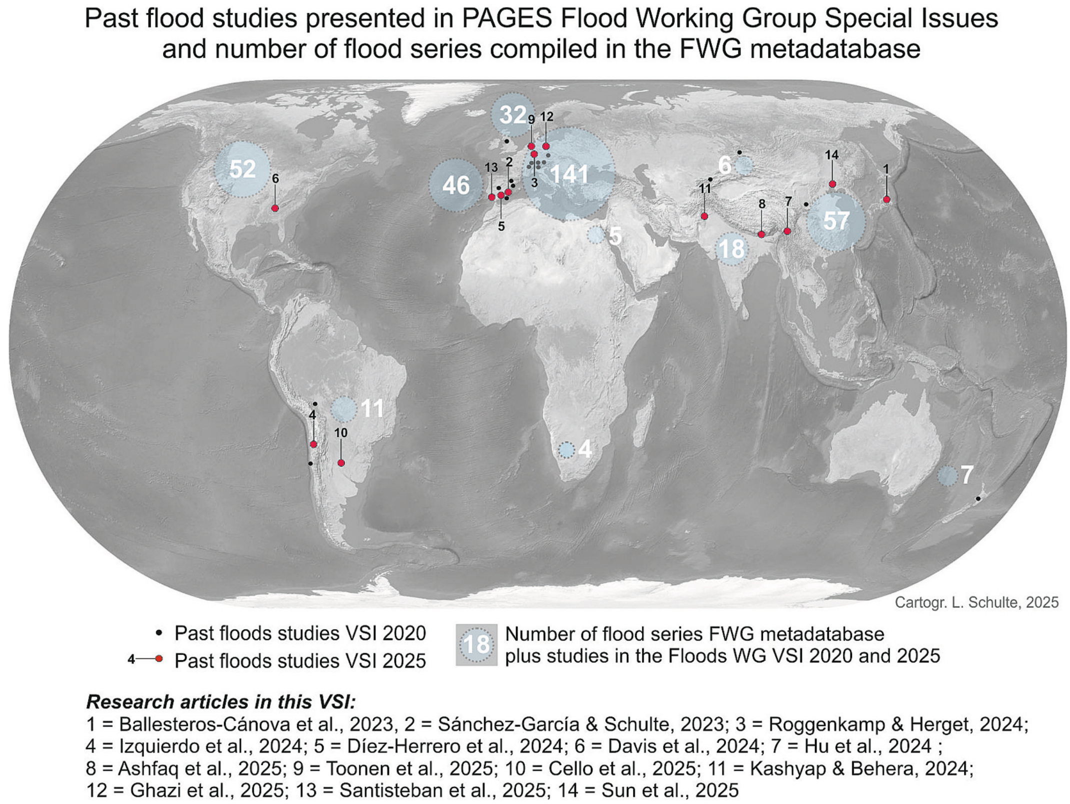

Fig. 1. Past flood studies presented in the two VSI in *Global and Planetary Change* (2020 and 2025) and number of flood series compiled in the PAGES Flood WG meta database.

Table 1
Summary of research articles of this VSI including study area, type of hazard and flood archive and reference period.

No	Study area	Hazard	Archive	Period	Reference
1	Japanese Alps	Debris flows	Tree rings, instrumental data	1800 CE – 2014 CE, 214 yrs.	Ballesteros-Cánovas et al. (2023)
2	Neogene basins of Southeast Spain	Floods	Documentary sources, instrumental data	1500 CE – 2018 CE, 518 yrs	Sánchez-García and Schulte (2023)
3	Ahr River, Germany	Floods	Documentary sources, flood marks, instrumental data	1450 CE – 2021 CE, 571 yrs	Roggenkamp and Herget (2024)
4	Copiapó River, Atacama, Chile	Floods	Fluvial sediments, historical documents, instrumental data	1600 CE – 2015 CE, 415 yrs	Izquierdo et al. (2024)
5	Guadix basin, Spain	Floods	Fluvial sediments, archaeological data, historical documents	1st century CE – present, 2 kyrs	Díez-Herrero et al. (2024)
6	Tennessee River Basin, United States	Floods	Slackwater deposits, instrumental data	6000 cal yr BP – present, 6 kyrs	Davis et al. (2024)
7	Upper Yangtze River, China	Outburst floods	Fluvial sediments, archaeological data	800 CE – present, 1.2 krs	Hu et al. (2024)
8	Khyber Pakhtunkhwa province, Pakistan	Floods	GIS data, remote sensing, instrumental data	present	Ashfaq et al. (2025)
9	Lower Meuse River, the Netherlands	Floods	Radiometric ages from fluvial geomorphological studies	12,000 cal vr BP, 12 kyrs	Toonen et al. (2025)
10	Pampa Plain, Argentina	Non-floodplain wetlands	Remote sensing, GIS data, instrumental data	Present	Cello et al. (2025)
11	Teesta catchment, Eastern Himalayas, India	Glacial Lake Outburst Flood	GIS data, remote sensing, instrumental data, seismicity data sets	2023 CE, one event	Kashyap and Behera (2024)
12	Poland	Floods	Flood database, documentary sources	1001 CE – 2010 CE, 1kyr	Ghazi et al. (2025)
13	La Janda basin, Gulf of Cádiz, Spain	Floods, sea level	Fluvial and marine sediments, geochemistry, pollen data	17,000 cal yr BP – present, 17 krs	Santisteban et al. (2025)
14	Daling River estuary, China	Floods	Fluvial sediments, documentary sources, pollen	1001 CE – present, 1kyr	Sun et al. (2025)

have responded to climate change over the millennia. They construct long flood series using environmental and sedimentary proxies in order to understand the role of climate as a driver, and to discuss the influence of climate forcing on flood variability (e.g. 20th century warming).

Ballesteros-Cánovas (2023, this VSI) examined the influence of climate on debris flows in the Japanese Alps since 1800 CE using tree rings. Their time series cover the last decades of the cooler climate pulses of the Little Ice Age and the warming of the 20th century. From correlation between sea surface temperature over the Pacific and the reconstructed debris flows at the Kamikochi area they found evidence that increased debris flows activity during the last decades occurred during La Niña events and furthermore, is related to the passage of typhoons. From the trend the authors assume that future debris flow activity may increase due to accelerating warming.

In southeast Spain, the driest region of Europe, Sánchez-Garcia and Schulte (2023, this VSI) reconstructed documentary flood series in four river systems. Processing the Poisson test, they determined flood trends and five flood periods since 1500 CE. Correlations with seven flood series from Atlantic and Mediterranean catchments of the Iberian Peninsula shows that the most intensive flood periods of the last 500 years (from 1554 to 1560 CE, from 1610 to 1650 CE and from 1860 to 1890) occurred during the Little Ice Age. Different to the debris flows in Japan there is no increasing trend recorded during the industrial period, but the magnitude of recent peak discharges is influenced by increased surface run off due to large scale land-use transformation in south-east Spain. Whereas flood periods occurred during negative and positive modes of North Atlantic Oscillation (NAOi) and Total Solar irradiance (TSI), the flood gaps are clearly related to minima of solar activity. Interestingly this pattern is reverse to the historical pattern of European Alp floods where floods are related mostly to solar minima. These different flood responses are likely related to different seasonality and regional impact of the atmospheric circulation system.

Approximately 100 km to the northwest of the Almería catchments, Díez-Herrero et al. (2024, this VSI) report millennium catastrophic floods from sedimentological and geoarchaeological studies in the Guadix basin. Radiocarbon and Optical Luminescence dating of three stratigraphical flood units. Two flood units date to the *Pax Romana* Empire (1st c. CE) and a third to the Islamic Almohad period, end of the 12th c., occurring during warm climate periods. The authors suggest that these flood episodes can provide analogies for understanding flood risk in the current warming period, which is a key point that should be considered. However, the paleoclimatic interpretation of the three well-dated individual events in the highly human-disturbed geomorphological context of a city such as Guadix is subject the fact that the record does not provide continuous paleo flood proxies, which also include minor floods. Undoubtedly, geoarchaeological studies such as those conducted in Guadix provide valuable geological evidence that can be used to improve risk maps based on modelled flood return periods, ultimately benefiting urban planning and civil protection.

Santisteban et al. (2025, this VSI) reconstructed a 17,000-year flood series from estuarine deposits in a former restricted embayment in the La Janda basin in the Gulf of Cádiz, southwest Spain. They employed a multiproxy approach, integrating sedimentological, stratigraphical, geochemical and palynological data. The authors emphasise that climate change influences floods in coastal areas through not only precipitation and the thawing process, but also sea-level changes. These changes determine the base level of coastal river stretches, consequently affecting the frequency of avulsion and overbanking. Correlating the flood deposits and frequencies with paleoclimate records of the southern Iberian Peninsula revealed that low-frequency floods during the Pleistocene were associated with meltwater pulses. During the early Holocene, flood frequency increased, reaching a maximum during the Holocene Thermal Maximum. In contrast, during the mid- to late Holocene, flood frequency was clearly lower than in the early Holocene. The authors suggest that changes in insolation control atmospheric moisture and therefore flood dynamics on a millennial timescale, whereas shorter-term flood episodes are related to centennial-scale changes in irradiance. These findings contribute to our fundamental understanding of the external drivers of paleoflood trends.

Toonen et al. (2025, this VSI) used a cumulative probability density function derived from sediments and radiometric dates to reconstruct the timing of fluvial changes, including deposition and stability, throughout the Holocene for the Meuse River in the Netherlands. As in the study of the Gulf of Cádiz, the paleoflood data series from the Netherlands indicates limited deposition during the Early Holocene. The authors attribute this to the entrenched river setting at that time. Over the past six millennia, human impact on land cover has increased clastic deposition. In the last millennia, clastic input has become a limiting factor in the formation of organic deposits. These trends were superimposed by the intensification of floods during colder climate periods; however, no specific, systematic correlations could be established with solar activity or the timing of volcanic eruptions. The Spanish and Dutch studies can both be useful tools for understanding changes in the flood regime and providing important baseline information for current and future flood risk analysis.

A different approach to understanding a 1000-year history were employed by Ghazi et al. (2025, this VSI). They created a new comprehensive database of floods in Poland using quality-controlled documentary evidence from the 11th to the 18th century as well as reviewing literature regarding floods in the 19th and 20th centuries. A total of 1680 floods were recorded in Poland in the last millennium, with summer being the most flood-prone season. Comparing the Polish data with flood data series from Germany, the Czech Republic and Austria from 1000 to 1800 CE reveals differences in the timing and frequency of floods. Notably, the 16th and 18th centuries were the most flood-prone periods in Poland, whereas during the warming period of the 20th century, negative flood-poor periods were slightly more numerous than positive flood pulses. However, river management and flood mitigation measures improved during the industrial period, thus positively affecting both ordinary and extraordinary floods.

Sun et al. (2025, this VSI) reconstructed a 1000-year record of extreme flooding in the semi-arid mountainous Daling River estuary catchment in Northeast Asia. They achieved this by exploring primary historical archives and analysing sedimentary records. Their data show that extreme flooding mainly coincided with periods of climate aridification on a centennial timescale. Periods of climate aridification coupled with increased rainstorms and reduced vegetation coverage increased flood erosion in the mountain catchment. However, human activities such as reservoir construction and vegetation restoration have noticeably reduced the amount of coarse sediment reaching the estuary, a phenomenon commonly observed along Asian coastlines.

4. Flood frequency analysis and assessment of large flood disasters

The starting point of the second group of research papers is the social demand to understand a specific extraordinary flood events or disasters in terms of flood magnitude, return periods, hydro-meteorological processes and causes. As with the papers in the first group, a historical-geological perspective is fundamental to providing baseline information on flood dynamics. As extreme floods frequently destroy gauges and peak flow data in large inundated areas may be inaccurate, past maximum discharges must be modelled using flood level reconstruction. Particular attention is given to the geographic characteristics of catchments and the spatial modelling of floods.

Roggenkamp and Herget (2024, this VSI) performed a paleohydrological assessment of the devastating 2021 flood in the River Ahr valley in Germany. According to flood level indicators and measurements of the maximum water level along the river, the peak discharge of the July 2021 flood was five times higher than previously measured discharges. This exceptional magnitude can be put into context by comparing the 2021 flood to 53 historical Ahr River floods, mostly reconstructed from written sources. However, the flood recorded in July 1804 during the Little Ice Age was similar to the 2021 flood in terms of its destructive power and peak discharge. Their findings suggest that this flood was not unprecedented which provides valuable contributions for the discussion regarding the impact of recent anthropogenic-driven climate change on flooding.

Davis et al. (2024, this VSI) conducted an improved flood frequency analysis of the Lower Tennessee River Basin by sampling and analysing slackwater deposits in a rock shelter located on a limestone bluff and a river terrace to assess the flood-of-record in 1867 CE. This flood is a reference flow for the dams built and managed by the Tennessee Valley Authority. According to their results the 1867 flood-of-record was the largest flood within the last 2000 years and coincided with the final cool climate pulse of the wetter Little Ice Age. The three largest extreme floods occurred during a peak of the mid-Holocene Thermal Maximum. These Holocene flood results suggest that flood frequency models may underestimate design flows if historic-floods-of-record are assumed to be the most extreme floods within these analyses.

Ephemeral streams in desert environments are mostly ungauged catchments. As flash floods in these streams can be highly destructive, understanding flood dynamics in the context of climate change is crucial. Izquierdo et al. (2024, this VSI) investigated historical catastrophic floods in the southern Atacama Desert using a multi-archive reconstruction to assess the most recent extreme hydrometeorological event, which occurred in 2015. According to their findings, the 2015 flood was as one of the three largest of the last 400 years. Most extraordinary and catastrophic floods of the Copiapó River are caused by heavy rainfall linked to positive phases of the Pacific Decadal Oscillation and El Niño–Southern Oscillation (ENSO). The authors suggest that this knowledge could help communities to anticipate flood hazards during periods of stronger rainfall modulated by ENSO and ENSO-like conditions, thereby improving their resilience.

Hu et al. (2024, this VSI) analysed paleo-outburst flood events in the upper Yangtze River by applying sedimentological, geochronological and geoarchaeological studies. This region, where floods during historic times have remained largely undocumented, is a key for the development of hydroelectric power. An outburst flood event dated to 1200–1300 cal yr BP, during China's Tang Dynasty (618–907 CE), may reached according to 2D hydraulic modelling a peak flow of 55,300 m^3/s which is three times greater than the 10,000-year flood assumed for the hydroelectric power station nearest to the study area. The study clearly demonstrated the importance of paleoflood hydrology studies in understanding both the latent catastrophic flood risks in alpine mountain areas.

5. Morphometric analyses and hydrologic-hydraulic models to simulate flood behaviour

The third group of papers focuses on numerical geomorphological analysis and hydrological simulations in order to reconstruct and anticipate the temporal and spatial behaviour of floods. A new area of research is investigating the causal relationships between the physical drivers that cause floods. The methodological strength of these approaches lies in their systematic integration of the spatial component, which provides not only a compilation of maps, but also the identification of thresholds, internal hydrological controls, and external drivers.

Kashyap and Behera (2024, this VSI) performed a landscape analysis of the Teesta catchment in the Eastern Himalayas, using topographic metrics to understand the geomorphic response to the South-Lohnak Lake outburst flood of 2023, which caused high-magnitude peak flow and substantial socioeconomic disruption downstream. The authors used the channel steepness-weighted discharge metric as an event characteristic to investigate changes to the river channel morphology resulting from the flooding. Furthermore, the causal relationship between glacio-hydrological drivers in the upstream Zemu sub-catchment were quantified in order to understand the spatial links between the physical drivers that triggered the outburst flood. The results suggest that, regarding the event duration, precipitation intensity and surface temperature had a significant direct causal influence on snowmelt and snow depth with 5-day and 1-day lag composites.

Ashfag et al. (2025, this VSI) conducted a flood susceptibility assessment in the Khyber Pakhtunkhwa province in Pakistan and created a map using a GIS-based Analytical Hierarchy Process and Frequency Ratio Models. The study analysed hydro-geomorphological flood conditioning factors, including elevation, slope, distance from the river, rainfall, drainage density, land use and land cover, topographic wetness index, height above the nearest drainage point, normalised difference vegetation index, distance from the road, curvature and soil type. The study demonstrates how these factors interact to influence flood susceptibility. The multi-criteria integration and statistical approaches, as well as the generated flood susceptibility maps, are crucial for the accurate mapping of flood risk and offer valuable guidance to civil protection authorities, planners, researchers and related agencies.

Finally, the article by Cello et al. (2025, this VSI) investigates the influence of groundwater on non-floodplain wetlands in an upstream basin of the Pampa Plain in Argentina during hydro-climatic extremes, examining the importance of geomorphological thresholds controlling hydrodynamics. The integrated approach encompasses geomorphic and morphometric analyses based on remotely sensed satellite imagery in a GIS platform, as well as fieldwork and 2D hydrological-hydraulic simulations, in order to capture the behaviour of the system during recent rainfall events that caused widespread flooding. The sub-basin exhibits a notable delay in hydraulic response and pond overflow downstream, as the system must first exceed the storage capacity of both groundwater and surface water. Despite the presence of artificial drainage channels, the authors demonstrated that geomorphological thresholds further control hydrodynamics by increasing surface water storage and limiting channel conveyance. Knowledge of these critical thresholds and levels of hydrological connectivity contributes to better inundation management.

6. Concluding remarks

Progress in all main topics of this VSI will contribute to unravelling the 'unknown unknowns' of floods by: i) improving our understanding of the climatic drivers of flooding; ii) considering how flood behaviour is modified by land use; iii) performing more accurate flood frequency analysis, including the rarest flood episodes; and iv) improving our understanding of the processes and factors involved in the temporal and spatial behaviour of floods.

- The articles presented in this VSI demonstrated that the reconstruction of past floods is crucial for providing robust and reliable data sets, knowledge and baseline information for future flood scenarios and forecasting. Sedimentary flood archives from the Holocene retrieved from the Gulf of Cádiz (Santisteban et al., 2025, this VSI) and the Tennessee River Basin (Davis et al., 2024) indicate that the largest floods occurred during the Holocene Thermal Maximum. This flood dynamic was likely driven by insolation-controlled atmospheric moisture. However, other past flood studies from different regions show that flood trends are not necessarily aligned. The periods, frequencies and magnitudes of floods during the Late Holocene respond to the climate variability depending on the region. Ballesteros et al. (2023, this VSI) and Diez-Herrero et al. (2024, this VSI) suggest that there was increased flood activity during warmer climate periods in Japan and southern Spain (Fig. 2). However, Sánchez-Garcia and Schulte (2023, this VSI), Santisteban et al. (2025, this VSI), Toonen et al. (2025, this VSI), Ghazi et al. (2025, this VSI), and Davis et al. (2024, this VSI) report higher flood frequencies during cool climate pulses e.g. of the Little Ice Age (LIA) in catchments of southeastern Spain, Netherlands, Poland, Germany, Czech Republic, Austria and eastern USA (Fig. 2). These results align with the LIA flood pulses reconstructed by seven studies published in the first Floods WG Virtual Special Issue in 2019 (Schulte et al., 2019a), as well as with the continent-wide study of historical floods in Europe of the last 500 years (Blöschl et al., 2020). Roggenkamp and Herget (2024, this VSI) and Sun et al. (2025, this VSI) identified significant flooding events in the Ahr River in Germany and the Dalian River in China during both the Little Ice Age and the current warming period.

- Aside from the different characteristics of catchments, thresholds and sensitivities to hydro-meteorological extreme events (Schulte et al., 2019b), a key factor is the human impact. A large proportion of catchments and floodplains have been significantly altered by land use and river management, thereby obscuring the climate signal in flood patterns. According to Toonen et al.'s (2025) findings, human

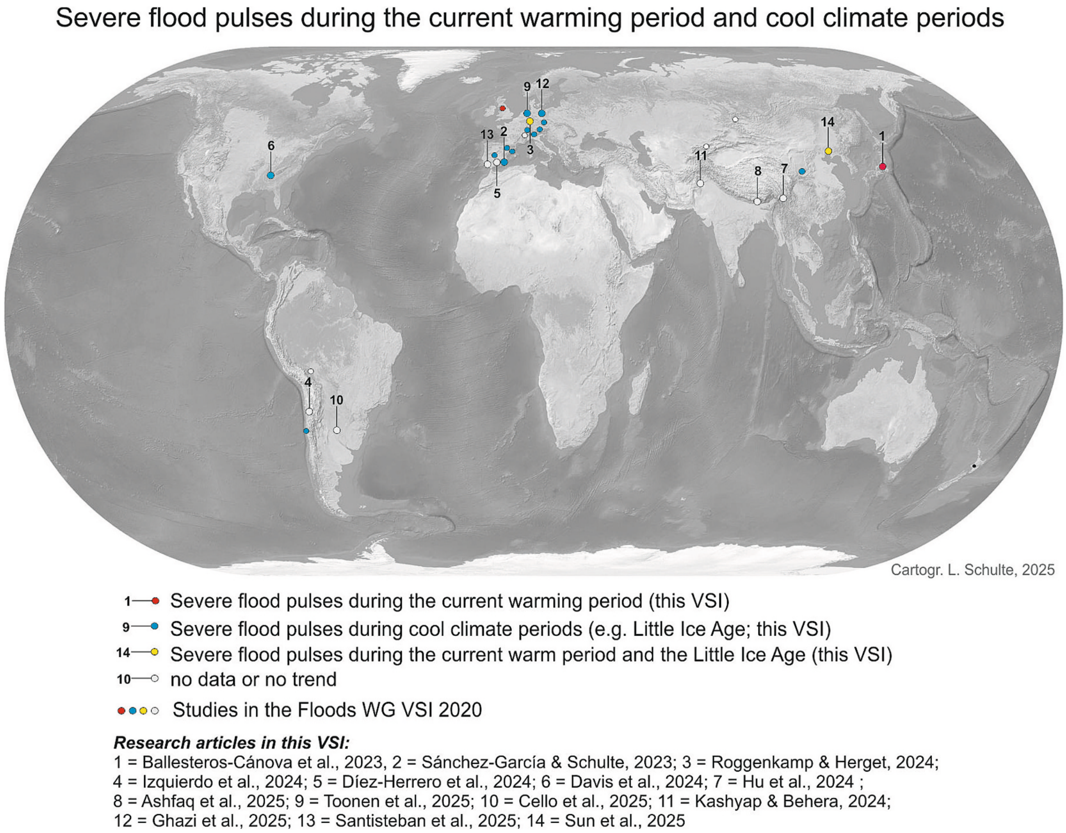

Fig. 2. Distribution of severe flood records occurring during relatively warm and cool climate periods of the Late Holocene published in the Floods WG VSI 2020 and 2025.

impact on land cover in the hinterland has increased clastic deposition in the Lower Meuse River over the past six millennia, intensifying during the last millennium and thus masking the climate signal. In the catchments of south-east Spain, this trend is more recent. The highest peak discharges in recent decades have been influenced by increased surface runoff due to large-scale land use transformation and destruction of traditional dry farming and irrigation systems (Schulte, 2002; Sánchez-García and Schulte, 2023, in this VSI). Conversely, in other regions human activities such as reservoir construction, river correction and vegetation restoration have noticeably reduced flooding and the amount of coarse sediment reaching the estuary. This phenomenon is commonly observed not only along Asian coastlines (Sun et al., 2025, this VSI), but also on many other coasts around the world.

- The articles in this VSI also highlight the importance of flood frequency analysis (FFA) for accurate flood risk assessment. Davis et al. (2024, this VSI) argue that millennia-long flood series often demonstrate that flood frequency models may underestimate the design flows of hydraulic infrastructure (e.g. reservoirs and embankments) if historic-floods-of-record are assumed to be the most extreme within these analyses. When historic-floods-of-record are compared with large historical floods reconstructed by natural and documentary archives, it becomes clear that there are precedent floods that should have been considered in flood frequency analysis and flood risk modelling in catchments (Roggenkamp and Herget, 2024, this VSI). Hu et al. (2024, this VSI) have illustrated, using the upper Yangtze River as an example, that paleoflood research can provide key data on millennium floods, which can exceed the assumed reference flow of 10,000-year floods for hydroelectric power stations by several magnitudes. Izquierdo et al. (2024, this VSI) suggest that this knowledge could help communities anticipate flood hazards, particularly when flood episodes can be linked to teleconnections such as the Pacific Decadal Oscillation (PDO), the El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and their related rainfall and temperature patterns.
- Finally, numerical geomorphological analysis and hydrological simulations show great potential for testing and improving our understanding of the processes and factors involved in the temporal and spatial behaviour of floods. Kashyap and Behera (2024, this VSI) determined the causal relationships between the physical drivers that trigger Glacier Lake Outburst floods (GLOFS). The methodological strength of GIS-based models lies in their systematic integration of the spatial component. This produces not only a compilation of maps, but also identifies thresholds, internal hydrological controls and external drivers (Ashfag et al., 2025, this VSI). Cello et al. (2025, this VSI) demonstrated the importance of groundwater to flooding by applying hydrological-hydraulic simulations, as well as showing the connectivity of subbasins that define storage capacity, thresholds, and response time lags.

7. Some final thoughts and outlook of the PAGES Floods Working Group

In recent years, we have observed with some concern that societies and decision-makers may have a biased understanding of natural disasters. In previous decades, many decision-makers reflexively evaluated natural disasters as ‘unforeseeable’ or ‘unprecedented’. However, investigations by the research community have shown the opposite: according to the analysis of natural flood archives (e.g. river and lake sediments, tree rings) and historical sources, these rare extreme events, which are not recorded in instrumental series, have indeed occurred frequently over the last few centuries and millennia (Baker, 2008; Glaser, 2001; Schulte et al., 2019b; Blöschl et al., 2020).

Since around the year 2000, this societal-political reflex to comment on flood disasters has been replaced and/or supplemented by a new dominating cause: climate change. Nowadays, global warming per se is often identified as the main cause, pushing integrated spatial causal research and thus the implementation of suitable measures into the background. But, natural disasters such as flooding of settlements are always social disasters and, moreover, the result of a chain of events, processes, (omitted) measures, causes and dispositions (Dikau and Weichselgartner, 2022; Felgentreff and Glade, 2008). For example, if recent, but also historical, settlements on the low river terraces, floodplains or paleo-meander are built without adequate protective measures, it is ultimately a matter of time before the next extreme flood causes personal and material damage. These are the fundamental processes of fluvial geomorphology and hydrology in non-stationary systems. In addition, a significant number of studies show an increase in flooding during cool climate periods.

However, also the social responses to natural hazards are fundamental to understanding the scale of the different magnitudes of impact. The perception, the spatial planning and actions to improve resilience to flood disasters can be summarized under the term ‘natural hazards culture’ or ‘flood culture’. The mentioned examples of 2024 floods in section 1 differ very clearly in their economic and social effects. On one hand, the catastrophic flooding episode of Valencia caused on 29 October 2024 by the DANA claimed the lives of 220 people. In contrast, although the rainfall that caused the floods in East Central Europe was locally classified by the Helmholtz Centre for Environmental Research (UFZ) as a millennial event and the number of people affected in the Danube and Elbe River plains was two million people, the number of human casualties was estimated at ‘only’ 28 people.

Of course, there are multiple factors that are involved in the course of a disaster and comparing numbers is simplistic. But, nevertheless, the human is a key component. For example, a culture of risk and resilience as developed (and conserved!) by local Swiss communities during hundreds of years by learning from nature is a key factor to keep human losses low such as during the flooding and massive aggradation in the villages of Brienz on August 12th 2024 and in Blatten on May 28th 2025 (Fig. 3A). Humans in the Alps have always been exposed to extreme events and processes. Communities have had to cope with floods, flash floods, debris flows, landslides, boulder falls, snow and ice avalanches, etc. This centuries-old learning, without having current mitigation technologies at their disposal, should therefore be reflected in a passive land-use strategy. In other words, communities had to avoid the geographic space at risk and build their homes in the safest locations, thus defining settlement development.

Finally, we, as individuals and but also as a whole society, also should accept that we cannot adequately protect ourselves against the most extreme events. One thing that can help besides the spatial avoidance strategy is the ultimately the timely evacuation. For example, a few weeks ago, the Swiss authorities demonstrated the significance of evacuation as the ultimate recourse when the massive landslide and debris flows buried on May 28th 2025 the village of Blatten in the Lötschen Valley (Fig. 3B and C). Eleven million m^3 of rocks and ice blocked the Lötschen valley inundating many of the few houses that survived the landslide and causing risk of outburst floods.

However, one disturbing finding emerged alongside this Lötschen Valley disaster: the historical and topographical maps since the end of the 18th century suggest that the historical centre of the village of Blatten with buildings date back to the 16th century, was located at a relative safe location regarding debris flows, floods, landslides and snow avalanches thanks to the centennial-long observations and experience of the local community. But the event on May 28th 2025 was the largest in the Lötschen valley since the Last Glacial Maximum!

Once again: as society and individuals we should internalize that we cannot adequately protect ourselves against the most extreme events, like against the small- and mid-magnitude flood events. But we can evacuate, we can take responsibility, we can develop spatial planning using paleoflood records for hazard maps, and finally create, support, conserve and – very important - live a ‘flood culture’. This is one of the key topics of our Floods Working Group Meeting in Prague in September 2025 and next Virtual Special Issue on past floods.

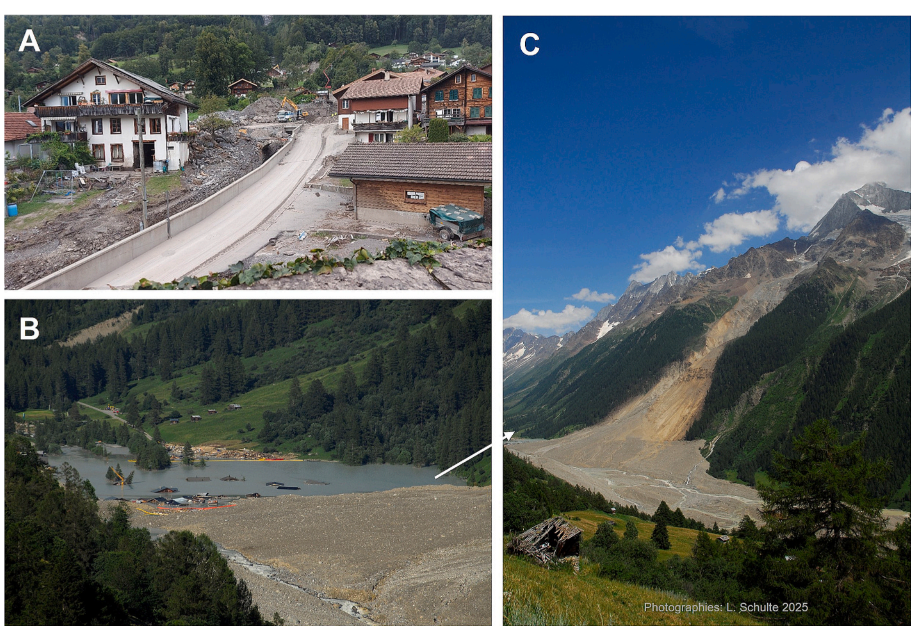

Fig. 3. Examples of recent flood, debris flow and landslide disasters in Switzerland. (A) The impact and aggradation of the debris flow in the Millibach in Brienz on 12 August 2024. Photograph taken on 21 August 2024 during fieldwork. The Birch glacier landslide (C) involved 11 million m^3 of debris and ice, which blocked the Lonza River and inundated the few intact houses of the buried village of Blatten (B). The risk of outburst floods remained weeks after the event. This photograph was taken on 4 July 2025 during fieldwork.

CRediT authorship contribution statement

Lothar Schulte: Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Juan I. Santisteban:** Writing – review & editing, Conceptualization. **Ian C. Fuller:** Writing – review & editing, Conceptualization. **Juan Antonio Ballesteros-Cánovas:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Jed O Kaplan, Editor-in-Chief of *Global and Planetary Change*, for his advice on how to focus this VSI. We would also like to express our gratitude the other Editors-in-Chief Alan Haywood, Fabienne Marret-Davies, Liviu Matenco, Shilong Piao, Aparna Shukla, Trude Storelvmo, Jimin Sun, and Maoyan Zhu for accepting our VSI proposal. We would also like to thank Howard Falcon-Lang, Managing Editor for his help in editing the VSI and his endless patience when we have not kept to the deadlines. We are also grateful to the many reviewers of the 14 research papers for their expertise and judgement. The authors of this introductory paper and guest editors of this VSI are members of the Past Climate Change (PAGES) Floods Working Group 2016-2018, 2019-2023 and 2024-2026. The VSI is part of the agenda of the PAGES Floods WG community and is co-funded by the Spanish Ministry of Economy and Competitiveness (PID2023-148210OB-I00), and the Catalan Institution for Research and Advanced Studies (ICREA Academia 2019).

Data availability

No data was used for the research described in the article.

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