Nones and Guo *Geoenvironmental Disasters* (2023) 10:20
https://doi.org/10.1186/s40677-023-00250-9

Geoenvironmental Disasters

RESEARCH

Open Access

Can sediments play a role in river flood risk mapping? Learning from selected European examples

Michael Nones[1*] and Yiwei Guo[1]

Abstract

Background Climate change and increasing anthropogenic pressure are two of the major drivers of increasing extreme events like droughts and floods. To deal with the increasing number of flooding events hitting Europe in the last few decades, around twenty years ago the European Commission started to develop ad-hoc legislation to reduce flood risk by mapping flood hazard and risk areas, such as the Directive 2007/60/EC on the Assessment and Management of Flood Risk. This Directive looks to identify regions where flood management strategies should be prioritized. Despite this holistic approach, flaws connected to the consideration of sediment transport and morphological changes in rivers exist, leading to potential underestimations of the impact of floods affecting active watercourses or areas subjected to frequent morphological changes.

Results By discussing six examples related to European lowland and mountain watercourses affected by significant floods in the last 20 years, the present mini-review aims to provide additional evidence on the need for a rethinking of flood risk mapping, moving from a "clear water" perspective to a more integrated approach, where the interactions between all the fluvial components (water, sediment, biota, and humans) are adequately considered.

Conclusions The examples reported here show the importance of considering sediment and wood in flood risk management, suggesting the need for integrating flood-related studies with other disciplines like geomorphology and ecohydrology.

Keywords Europe, Flood risk mapping, Floods directive, River morphology, Sediment transport, Water framework directive

Legislative background

In Europe, the quality of watercourses is one of the major concerns for the future. This is also pointed out in one of the more important directives developed during the last two decades: the Water Framework Directive (WFD), which was issued at the beginning of this century (Directive 2000; Jager et al. 2016). Despite having more than twenty years, this Directive still represents a holistic, integrated approach to water protection, as it requires, among other obligations, the classification of watercourses looking at how the actual situation, in terms of biological, hydromorphological and physicochemical quality elements, compares with reference conditions. However, some discrepancies appear when speaking about river morphology, given that the Directive assumes that only watercourses classified in high status must achieve hydromorphological characteristics totally or nearly totally corresponding to undisturbed conditions when sediments are considered (Nones et al. 2017; Newson et al. 2006). Indeed, as per the WFD Annex V (Directive 2000) and the subsequent CIS Guidance 13

---

*Correspondence:
Michael Nones
mnones@igf.edu.pl
[1] Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland

(European Commission Common Implementation Strategy for the Water Framework Directive 2000), European Member States can classify surface waterbodies like rivers in good, moderate, poor or bad ecological status only by considering biological monitoring. In the case of rivers and streams that are not already classified in a high status, Water Authorities can prepare river basin management plans by disregarding other aspects such as river morphology and sediment transport (Nardini et al. 2008; El Hourani et al. 2022; Stefanidis et al. 2022). The WFD somehow accounts for the presence of sediments and their fluxes, as it mentions river continuity not only for biota but also for sediments, even though the evaluation and improvement of such continuity is still a challenging topic for scientists and water managers (Habersack et al. 2016; Heckmann et al. 2018), in particular when speaking about river restoration and rehabilitation projects (Thomas 2022; Nones and Gerstgraser 2016). Though, as pointed out by a growing number of studies (Gurnell et al. 2016; Wohl et al. 2015; Fryirs and Brierley 2012; Brils 2008), morphological variability, sediments and associated transport mechanisms in flowing waters are paramount to guaranteeing dynamic and healthy aquatic ecosystems.

An incomplete or inadequate consideration of the impact of fluvial morphology and sediment transport can have significant implications not only in the WFD implementation, but also in the case of the Directive 2007/60/EC on the Assessment and Management of Flood Risk (Floods Directive-FD) (European Community Directive 2007). This Directive was developed in 2007, following the WFD requirements (Segovia 2021) and to complement this previous directive. The FD aims to manage the risks that flooding events have on human health, the environment, cultural heritage, and socio-economic activities. However, methods and tools that should be applied to achieve these goals are not strictly defined in the Directive, while ample room is given to the various Member States (Mysiak et al. 2013; Nones 2015; Albano et al. 2017; Simonelli et al. 2022), eventually leading to improper and dissimilar implementation, such as in the case of transboundary river basins. In terms of morphological alterations and sediment transport, very few details are provided on that. Only Article 6.5d of the FD suggests including additional information regarding the impact of sediments and debris floods in the preparation of flood maps (European Community Directive 2007; Radice et al. 2016). Despite the Floods Directive was emanated around 15 years ago, shortcomings and weaknesses are still evident in the implementation phases. For example, it is not clear how the impact of hydromorphological alterations, sediments and sediment transport is considered in preparing flood risk management plans (Nones et al. 2017; Nones 2019; Bauer et al. 2019; Sofia and Nikolopoulos 2020; Nardini 2022; Adamson 2018). Generally, flood maps are developed by applying two-dimensional (2-D) hydraulic models. However, such numerical models are usually developed by considering only “clear water” (i.e., no sediment transport and morphological changes) and non-erodible channels, driving potential underestimations of the flood risk (Moel et al. 2009; Alfieri et al. 2014; Hartmann and Spit 2016), as in the case proposed described in Sect. "Examples of interactions between flooding events and geomorphology in rivers".

From the short overview of the legislative background reported in this section, it is evident that a rethinking of how rivers and flood-associated risk are assessed and managed in the light of WFD and FD is needed, considering sediments as an integral part of freshwater systems. For the future, a more holistic and comprehensive approach is advisable, to better understand the interactions between all the elements that contribute to shaping fluvial environments.

It is worth noticing that the current Flood Risk Management approach proposed by the European FD is nowadays also promoted in the United States and Asia, given that it involves a combination of management measures, including structural and non-structural measures (Adnan et al. 2020; Cvetkovic and Martinovic 2021; Knox et al. 2022; Lashford et al. 2022), therefore the theses discussed in this mini-review can be transferred to other regions.

Fluvial floods and river hydromorphology

A river is a dynamic system governed by hydraulic and sediment transport processes (Chang and Ghani 2014). It is largely recognized that fluvial systems show great spatial and temporal interactivity, and this reflects in very complex systems, where multiple stressors interact (Birk et al. 2020; Hamidifar and Nones 2023). Focusing on hydraulic infrastructures developed to address flood-related risks, such as dams and levees, these structural interventions in the upstream river reaches can alter both water discharge and sediment load not only at the local scale, but also downstream, potentially leading to problems for settlements and infrastructures located in the lowland part of the basin, eventually increasing the local water level and consequently the flood risk (Merz et al. June 2013; Liu et al. 2018; Hooke 2015; Merz et al. 2021).

Flood risk assessment and flood hazard mapping are inventible steps to obtain a sustainable integrated flood management concept (Weak Points and in the Flood Risk Modelling Chain 2021). Despite the recent development in theoretical and numerical modelling, the proper engineering understanding of the main processes, such as long-term morphological changes, vegetation-sediments interactions and large wood recruiting at the watershed scale, is still quite limited, also because of difficulties in schematizing and numerically implementing those mechanisms (Hartmann and Spit 2016; Sayers et al. 2002). Typically, flood risk models and maps developed in the past decades do not account for sediment- and wood-related processes, eventually driving to possible underestimations of flooded areas and associated water extents and depths (Nones and Pescaroli 2016). This derives also from a lack of detailed sedimentological data on both bedload and suspended load during high-flow conditions, as such conditions are generally very difficult to monitor. However, high-flow data are paramount in accurately calibrating modelling tools (Liu et al. 2022), specifically the ones that are then applied to simulate flooding conditions.

In the past, reduced attention has been given to evaluating how bed morphology and sediment transport can impact flood risk and modify inundation levels and extent (Radice et al. 2016; Sinnakaudan et al. 2003; Sholtes et al. 2018; Song et al. 2019). Historical data and geomorphic analyses stressed that flood risk can be correlated not only with water discharge, but also with channel conveyance (James 1999; Stover and Montgomery 2001). Indeed, the stage-discharge relationship can be significantly altered by sediments, leading to errors in numerically estimating the magnitude and arrival time of flood waves (Wang et al. 2019; Contreras and Escauriaza 2020). An increase in sediment delivery ratios can directly increase flood risk, as accumulation along banks can reduce riverine cross sections, therefore reducing the room for the river (Korup et al. 2004; Pinter and Heine 2005) or altering the channel conveyance and the river planform (Hamidifar and Nones 2023). To investigate the impact of channel morphology variations on river hydraulics during flooding events, scholars used field observations (Rickenmann et al. 2016; Wyżga et al. 2016) and numerical models (Sinnakaudan et al. 2003; Li et al. 2014; Guan et al. 2015; Staines and Carrivick 2015). These studies have shown that the influence of sediment transport and morphological alterations represent a significant key driver of flood risk. Historical data and geomorphic analyses can inform water managers and engineers about the most adequate modelling tools, providing a better understanding of how the river morphology evolves (James et al. 2012; Arnaud et al. 2015), also in response to flooding events. Those preliminary studies demonstrated the difference between estimating flood risk by considering only clear water and by accounting for the presence of sediments and channel/floodplain geomorphic processes (Brierley and Hooke 2015; Warner et al. 2018).

Alluvial watercourses are generally considered dynamic systems characterized by erodible boundaries and self-adjusting beds, which react to varying liquid and solid discharges supplied from upstream (Sinnakaudan et al. 2003; Rickenmann et al. 2016). Considering that water can flood the river surroundings when the in-channel levels are sufficient to exceed the bank height, local flood risk can be seen as driven by changes in the river channel stage, which may be eventually impacted by variations in both flow magnitude and channel conveyance (Leopold and Maddock 1953; Yalin 1992; Schumm and Lichty 1965). As introduced above, variations in sediment processes (yield and transport) and channel morphology can change river morphodynamics at multiple spatiotemporal scales (Slater et al. 2015; Nones et al. 2014; Singh 2004), ultimately leading to an impact on flood risk by, for example, reducing channel capacity (Slater et al. 2015), adjusting the fluvial morphology following variations in the upstream sediment supply from upstream (Thorne et al. 2007), varying the cross-section via bed aggradation and degradation caused by damming and backwater effects (Brierley and Hooke 2015; Warner et al. 2018; Leopold and Maddock 1953; Yalin 1992; Neuhold et al. 2009; Guan et al. 2016; Costabile and Macchione 2015; Bohorquez and Moral-Erencia 2017). Moreover, management practices can change the flow regime of a catchment, determining its geomorphological behaviour and how it responds to floods (O'Connell et al. 2004; Wheater and Evans 2009; European Commission, Integrated sediment management 2022; Díez-Herrero and Garrote 2050; Shah et al. 2020; Yildirim and Demir 2021; Bronstert et al. 2018), especially along floodplains, generally, more dynamic systems subjected to cyclical erosion and sedimentation phenomena.

Rationale and limitations of this mini-review

In the present research, six European case studies were reviewed, aiming to provide evidence on the potential impact of sediments and morphological changes during flooding events. This mini-review is limited to significant and well-documented events that happened in mountainous and lowland river basins in Europe during the last twenty years, selected as representative of the situation generally observed in the continent. It is worth noticing that this work does not aim to be exhaustive, but rather to provide clear examples of the importance of considering sediments and other materials such as wood in planning flood risk management strategies. For additional insights on flood risk analysis and assessment, the readers can refer e.g., to the recent review provided by Díez-Herrero and Garrote (Díez-Herrero and Garrote 2050),

Despite these limitations, the present study aims to generate additional discussion on the importance of including sediments in all the European water-related directives, following a path started by SedNet (sednet.org) just after the publication of the WFD (Brils 2008) and resulted, after more than 20 years of work, in the integrated sediment management guidelines and good practices in the context of the WFD (European Commission 2022).

Even if based only on European case studies, the conclusions presented here can be transferred to other regions, as the approach proposed by the FD is currently being proposed, for example, in Asia and the United States (Shah et al. 2020; Yildirim and Demir 2021).

Examples of interactions between flooding events and geomorphology in rivers

More than 2000 flood events happened in Europe from 2000 to 2015, as can be seen in the flood distribution reported in Fig. 1. It can be noticed that France, Spain, Poland, Norway and Germany are the countries where most flooding events occurred in this period (Hamidifar and Nones 2023).

In the following subsections, a few significant events that happened in the last twenty years in different European countries, including the countries mentioned above, are reviewed in detail. These examples of how sediments and other materials like wood can impact flood risk in both lowland and mountainous watersheds aim to point out the importance of considering all the fluvial components (water, sediments, biota, humans) in flood risk mapping.

Flash flood in Braunsbach (Germany), 2016

Bronstert et al. (2018) noted that an extreme event occurred in May 2016. The accumulated 131 mm rainfall and a maximum 5-min intensity of 157 mm/h happened in just two hours (16:00–18:00), causing a flash flood that significantly impacted the cities of Grimmbach and Orlacher Bach in southwestern Germany (Fig. 2). The cycling path of the Grimmbach's outlet was clogged and damaged by large amounts of wood. Besides, the Braunsbach town was devastated by discharges transported along the Orlacher Bach. Fortunately, no casualties

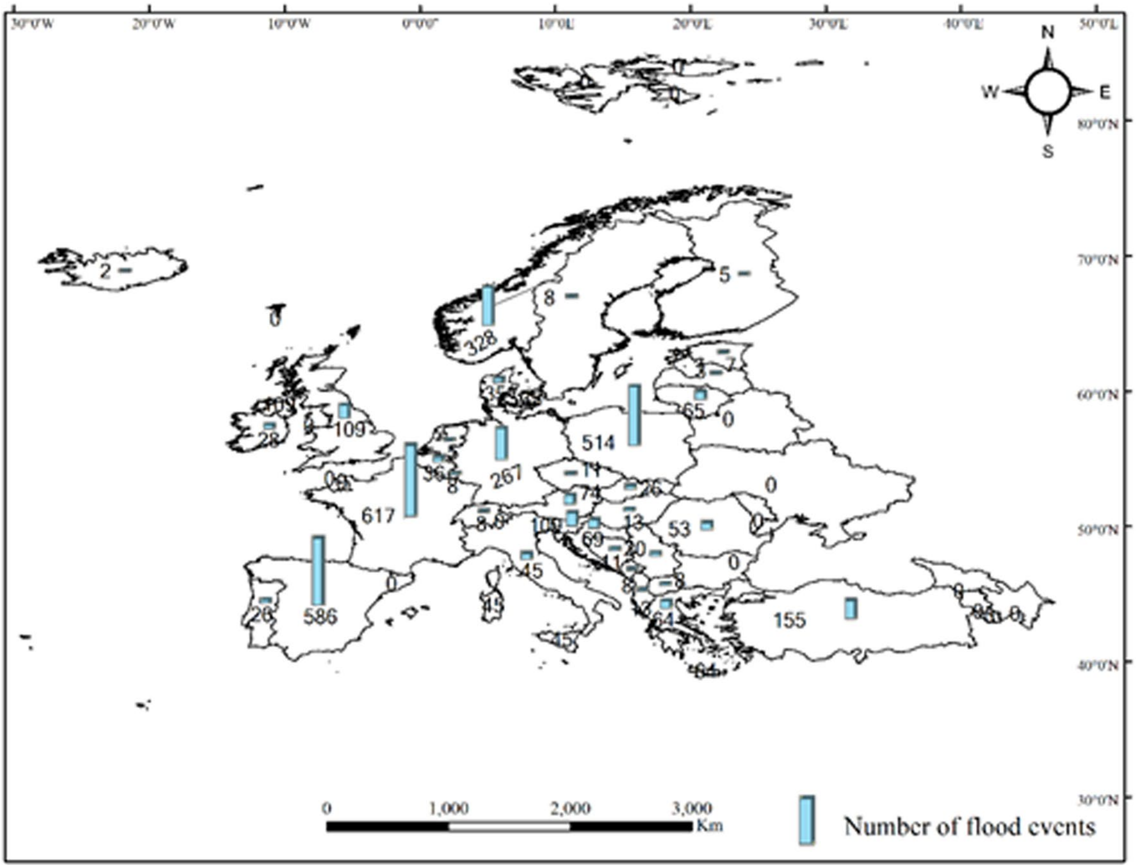

Fig. 1 The number of flood events that happened in European countries (except Russia) from 1992 to 2015 (Data available at https://www.eea.europa.eu/data-and-maps/data/european-past-floods)

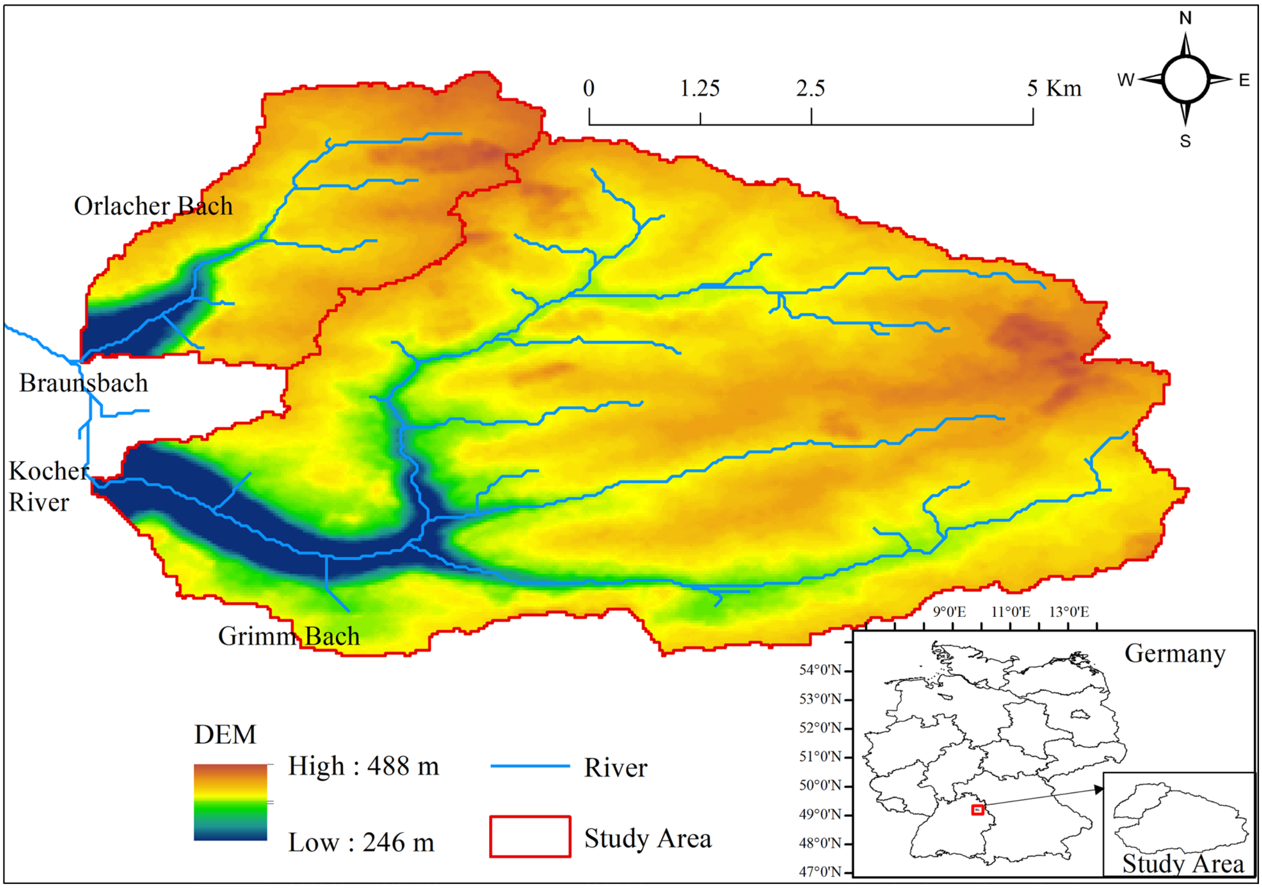

Fig. 2 The location and the Digital Elevation Model (DEM) of the Kocher River, the Grimm Bach and the Orlacher Bach, in Germany

caused by the event were recorded. However, damages were estimated to be more than 100 million euros, and this impacted the local municipality, as more than two years were needed before recovering from the event.

Due to the severe damages caused by this flood hazard, one of the most urgent points was to figure out the driving forces of the event, and to further develop integrated management policies. Lucía et al. (2018) applied a combined approach, including peak discharge estimation, comparing available aerial photographs before and after the flood, and field observations were used to analyse changes in channel width. Besides, a mapping of landslides and landslide connectivity with the channel network and the amount of large wood recruited and deposited in the channel was performed, showing the strict correlations between the hydrological and geomorphological events.

The post-event survey aimed at understanding the morphological changes and large wood dynamics caused by the flash flood, and it was conducted by an integrated methodology combining geomorphological, sedimentological, and hydraulic data and evidence. Field survey information was combined with remote sensing to analyze channel changes and the sources and dynamics of wood at the sub-reach scale.

Gaume and Borga (2008) proposed to estimate the peak discharge to further understand the hydrological response and its potential correlation with the morphological response. The morphological characteristics before the flash flood were obtained using ArcGIS to process orthophotos and a digital elevation model. These data were derived from uncrewed aerial vehicles, allowing for describing the topography with high resolution, and for evaluating channel variations caused by the flooding event in detail. At last, to analyze the large wood dynamics, a large wood budget was made by employing the approach proposed by Benda and Sias (2003) and improved by Comiti et al. (2016) to account for flood conditions. A series of metrics (e.g., average channel slope, drainage area at the upper limit of the reach, unit stream power, stream power index, confinement index) was derived to correlate morphological changes to the flood hydrograph.

Looking at the studies made after this flooding event, it can be concluded that the channel and hydraulic parameters' response to extreme events can be explained by the morphology of the catchment and the local channels. Besides sediment, it should be noted that also large wood, which mostly comes from the fluvial corridor, can represent a significant component during a flash flood in mountain watersheds, therefore demonstrating the morphological changes and the recruitment and deposit rates of large wood should be considered in mapping and mitigating flash flood hazards.

Flood in Central Europe, 2021

The July 2021 flood in Central Europe (Fig. 3) has been known as one of the most severe disasters in Europe during the last half century, which the cause being extreme precipitations with up to 150 mm within only 4 h (15:00–18:00). This disaster claimed many lives of central Europe, especially leading at least 180 deaths in Germany. Moreover, according to Munich Re (2021), such a flood caused a total cost of EUR 46 billion and Germany alone has lost around EUR 33 billion. The German Landers of North Rhine-Westphalia and Rhineland-Palatinate, Belgium, Netherlands and Luxembourg were all catastrophically affected by this disaster, with the two German regions being the two most affected. The northeast of the low mountain range Eifel in Germany, namely the villages along the rivers Ahr and Erft, both left tributaries of the Rhine River, were devastatingly affected, with buildings, household goods, industries, and critical infrastructure such as railways, roads and bridges severely damaged.

Due to the devastating impact of this flood and to better assess, predict, prevent, and manage future hazards, scientists and practitioners, including Karlsruhe Institute of Technology (KIT), the World Weather Attribution (WWA), Roggenkamp and Hergert (2022), and Korswagen et al. (2022), collaborated actively to find solutions across discipline boundaries. The KIT Center for Disaster Management and Risk Reduction Technology (CEDIM, www.cedim.kit.edu, last access: 9 May 2022) in Germany applied the so-called Forensic Disaster Analyses (FDA) cooperated to deeply investigate the root causes of disasters and managed to have a better understanding of how natural hazards become socio-economic disasters, also thanks to the ability to investigate the disaster timely, within a few hours. After examining the dynamics and interrelations of disasters, identifying major risk drivers, estimating the impact (damage, fatalities, and displaced people) and inferring possible implications for disaster mitigation, CEDIM's FDA demonstrated that the flood risk in those affected regions was seriously underestimated since the historical data was not considered into

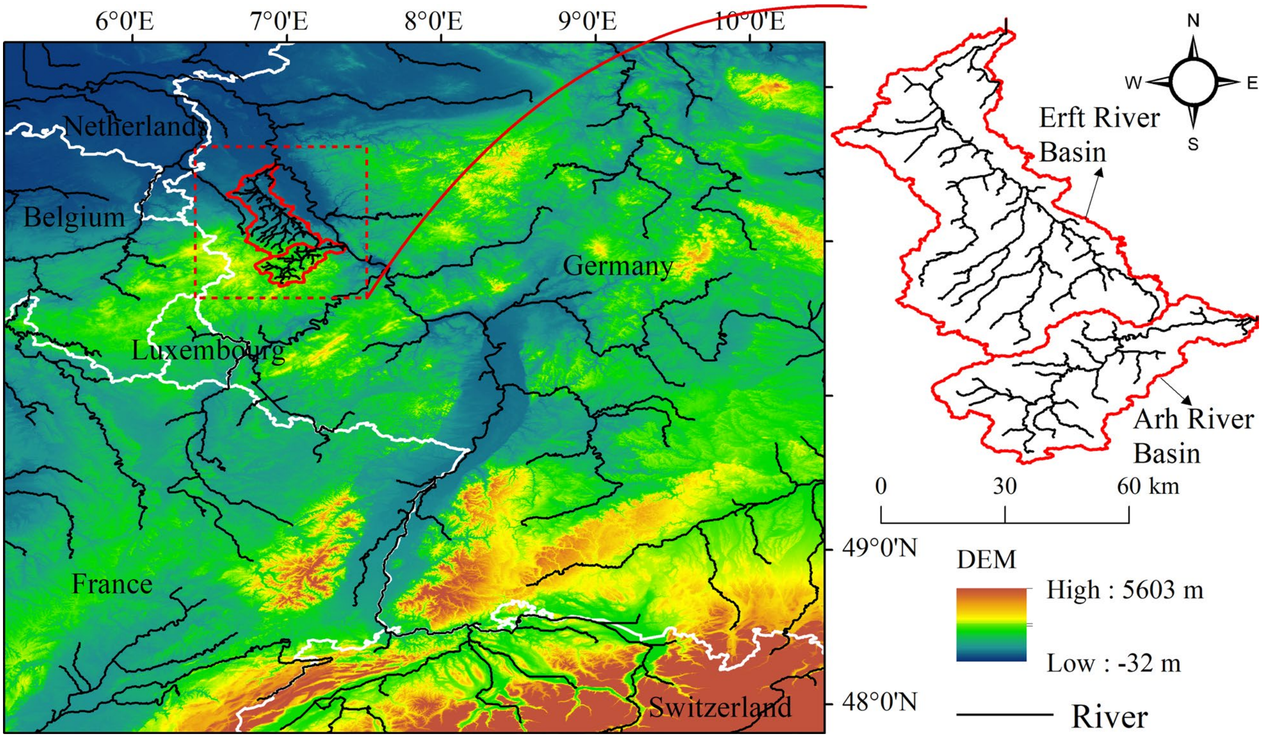

Fig. 3 The location and the Digital Elevation Model (DEM) of the Erft River Basin and the Arh River Basin

flood hazard maps, which were developed only based on information retrieved from gauge measurements taken during the few last decades.

It is suggested by a recent report of the World Weather Attribution (WWA) that an increase in precipitation, which has similar meteorological characteristics to the rivers Ahr, Erft, and the Meuse, may lead to climate change (Kreienkamp et al. 2021). Except for the extremer rainfall, humid weather conditions led to antecedent precipitations index higher than that of the average wet period, which ultimately caused a greater susceptibility to floods. In addition, the steep slopes of the Ahr and the other river valleys contributed to triggering the process of rapid rainfall-runoff transformation.

Faranda et al. (2022) investigated the atmospheric drivers and dynamics of the event, applying an attribution approach based on atmospheric circulation analogues. This study has shown that the recent cut-off lows in Western Europe tend to hold more stability, resulting in longer-lasting precipitation events and an increased risk of flooding.

Korswagen et al. (2022) took a field trip to the Ahr Valley to discuss structural failures of buildings and, according to their outcomes, the structural failures were mainly caused by erosion and damming of debris and flood water flow. Hillslope denudation and widespread landslides lead to excessive sedimentation in the river network, in turn contributing to morphological changes that interact nonlinearly with flood propagation. Besides, the post-event image presented in their work illustrated that large amounts of debris were transported in crowded and overcrowded systems, with severe consequences for the transmission and impact of flooding. Moreover, construction sediment and woody debris brought from upstream valleys were trapped in the channel, potentially damming bridges and blocking the river channel, resulting in a further enhancement of water levels.

Apel et al. (2022) applied a simplified hydrodynamic flood model to retroactively incorporate spatially explicit information, shedding light on the expected extent of flooding and its influences. Though the German government and the Global Flood Awareness System (GloFAS) which was developed by the European Commission and the European Centre for Medium-Range Weather Forecasts (ECMWF) have their river flood forecast system, it only provided expected discharges or water levels at specific river gauges. And flood forecasts released by the German government and the GloFAS suffered from problems such as low spatial resolution, non-inclusion of flood protection facilities, and forecasting floods based on previously prepared hazard maps rather than on actual events. The hydrodynamic flood models were thus introduced to derive critical locations of life-threatening flow conditions, vehicle instability, and structural failures of buildings and infrastructure from inundation and flow velocity maps. Due to the ability of the hydrodynamic model to simulate the building collapse, persons drowning, or floating and toppling cars, these prediction results can greatly improve current disaster management and early warning response. However, no information on morphological changes and the impact of sediment transport can be derived from such a modelling approach, decreasing its overall impact.

Looking at the event from a socio-economic point of view, Fekete and Sandholz (2021) summarized the failure of (early) warning chains and the inadequacy of prevention and protection measures in Germany, while stressing the importance of identifying communication problems in warning chains in the case of a flash flood. On this line, Thiebes and Schrott (2021) used the data of July 2021 to propose a relevant analysis and a thorough discussion over how early warning systems work or fail and what they can achieve, as well as where possible weaknesses might lie.

In short, to avoid and better prepare for extreme events that are likely to occur in the future, it is of great significance to predict both physical characteristics and potential impacts on society given the fact that the preservation of our natural environment is essential (Taylor et al. 2018; Merz et al. 2020; WMO WMO Guidelines 2015), but should co-exist with the societal development.

Flood in the lower Orba River (Italy), 2019

On 21–22 October 2019, an extreme flood event happened in northwest Italy (Fig. 4), causing significant damage along the lower Orba River. During the period from 18–24 October 2019, the majority of northwest Italy was affected by prolonged and intense precipitation. This extreme precipitation event also brought a severe flood to the Orba River and the Lemme, with Albedosa, Piota and Stura valleys being the severest affected areas in the catchment. This event caused only one fatality, but agricultural activities, structures and infrastructures were damaged severely, with significant consequences on the local economy (Liguria 2019).

To evaluate the flood-water dynamics and derive hydro-geomorphic hazard maps, Mandarino et al. (2021a) conducted an extensive field survey campaign by laying more emphasis on flood-induced erosion and sedimentary landforms, damage to anthropogenic structures, areas of flood, maximum water levels and major flood directions. Thanks to such field investigations, the authors were able to point out that floods were a major trigger of erosional and depositional processes, affecting the riverbed and the floodplain (Mandarino et al. 2021a). During these processes, a generalized intense

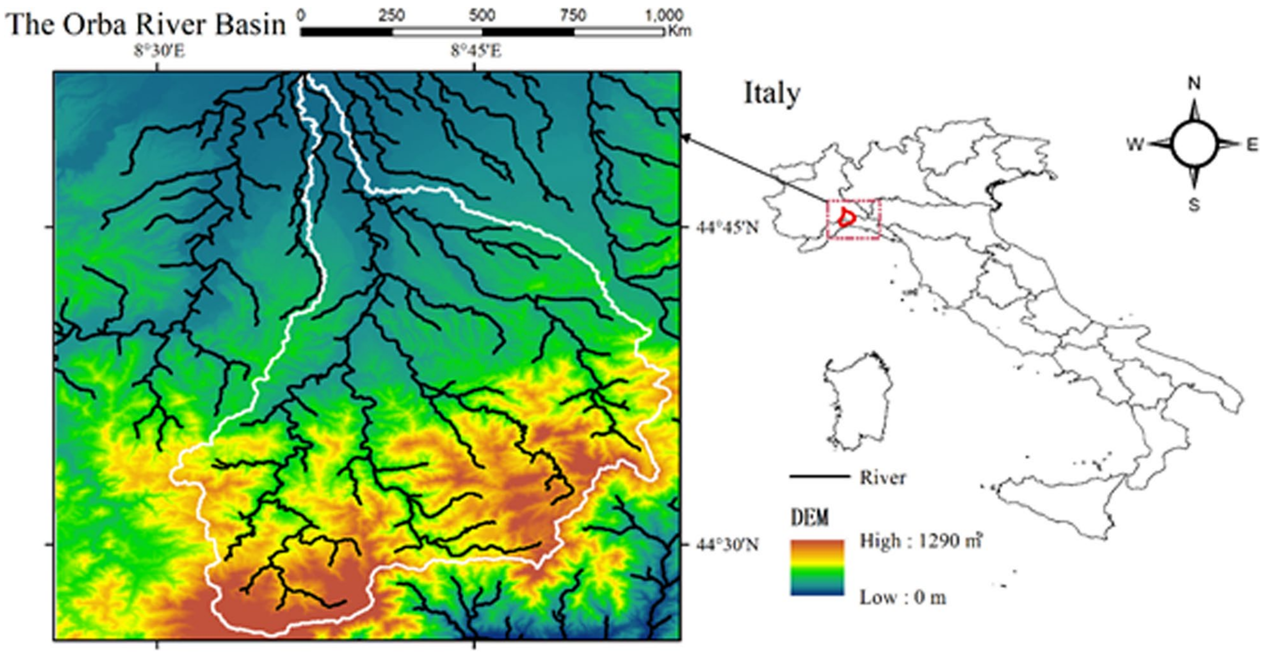

Fig. 4 The location and the Digital Elevation Model (DEM) of the Italian Orba River

sediment mobilization affected the active channel, while no significant variations were observed in the planform. Moreover, in the inner part of some of the observed river bends, especially in Pasaracqua and Grava, downstream of Retorto and on the inner side of Casalchemeli, a clear record of riverbank deposits was present, which usually originates from the damage or collapse of the embankments of the main and dirty roads, as in the case of Capriata, near the bridges on both sides of the confluence of Panatiani, Garzaia and Bormeida. Silt deposits were recognized mainly in depressed areas or upstream of road embankments. Severe surface erosion has also been formed on road embankments, together with their destruction and partial collapse downstream of these infrastructures, probably because of the clogging of drainage pipes because of the sediments transported during the flood. Concerning the upstream of Garzaia, flood waters reactivated the scour holes in the dusty road embankments, triggering severe erosion and sedimentation processes downstream, with risks of collapse. Moreover, a large amount of floating large woody debris was trapped by single obstacles like riparian vegetation and scaffolding, resulting in backwater effects. Overall, this event resulted in banks' instability and remobilization of sediments in the river channel, reactivation of extensive riparian protection scour, and locally associated channel widening. Large lowland areas have been flooded, contributing to erosion and deposition processes that extensively shaped newly formed and existing landforms.

The flooding event caused major damage to the surrounding arable land, transportation infrastructure and buildings. In addition, the spatial distribution of flood-induced ground effects and the dominant flood flow direction on the floodplain highlighted the interference of roads and levees with flood propagation, thus accelerating the initiation of erosion and sedimentation processes (Horacio et al. 2019; Mandarino et al. 2021b). Areas outside the lowland pile suffered great destruction not only by unrepaired damages, but also by levee overtopping, indicating that it is vital to include the transport of vegetation, woods, and sediments in the development of flood management policies.

Flood in Switzerland, 2005

A flood that happened in Switzerland (Fig. 5) in August 2005 has been regarded as the costliest disaster in Switzerland ever since the historic flood of 1972, causing six fatalities and a total loss of more than CHF 3000 million (around EUR 3080 million) (Hilker et al. 2009; Hegg et al. 2000). Continuous rainfall occurred over most of Switzerland between Lake Geneva and Lake Constance from August 18 to 23, with most of the rainfall concentrated in the 48 h from August 21 to 23 and exceeding 100 mm. In some areas of northern Switzerland, the rainfall reached 260 mm in 3 days. Extensive and continuous heavy rainfall caused severe flooding in many steep mountain streams in the Prealps region and large lowland rivers on the Swiss plateau north of the Alpine arch (such as the

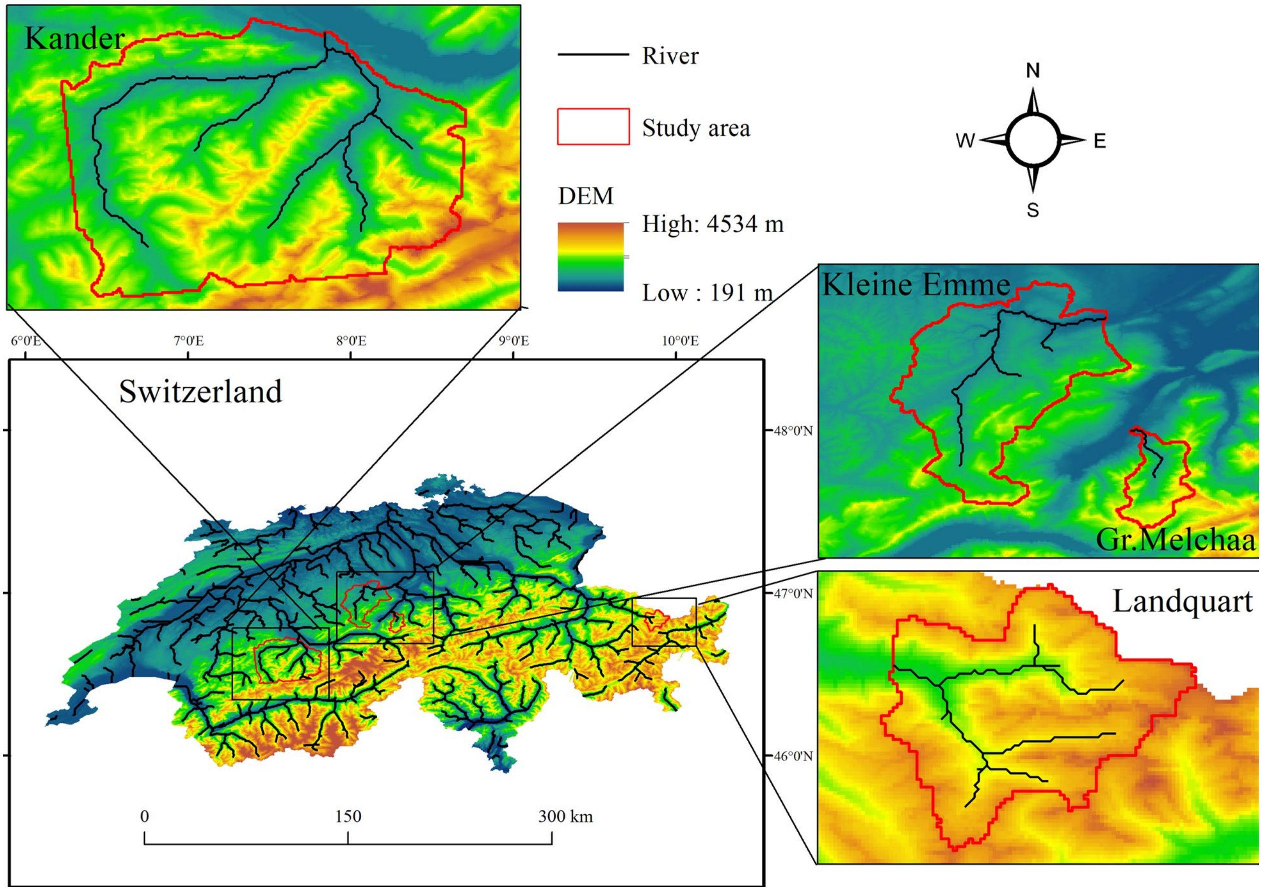

Fig. 5 The location and the Digital Elevation Model (DEM) of the Swiss basins of the Kander River, the Kleine Emme River, the Gr. Melchaa River, and the Landquart River

Aare and Reuss basins), leading to very significant landslide activity within and outside forests (Raetzo et al. 2005). This study demonstrated that the sediment-related geomorphic processes were the main reasons causing this flood hazard (Rickenmann et al. 2016). Sustained and partially intense precipitation from August 20 to 22 resulted in many mountain rivers discharging well above the threshold for bedload motion.

Generally, the main source of sediment in flash floods is the lateral and vertical erosion of the riverbed (Bezzola et al. 2005). During this flood event, lateral erosion occurred at several locations with a frequency and extent never observed in Switzerland. Moreover, lateral erosion damaged about 60% of the bank protection along the shoreline (Sinnakaudan et al. 2003). As a consequence, some sections of the impacted rivers experienced in-channel aggradation resulting in overbank flow, flooding, and overbank sedimentation. Even the cutting of some channels was recorded, resulting in damage to river protection, hydraulic engineering structures, roads, bridges, buildings, and agricultural land. In the Chirel, the Engelberger Aa and the Schächen River together over 350,000 m^3 of bed sediments were deposited in and outside the channel on account, blocking the passage of water under bridges and causing major backwaters. Eventually, they led to, for example, a missed loss of CHF 85 million in the village Oey on the fan of the Chirel River (Badoux et al. 2014). In addition, a large amount of large wood was mobilized in the Tor River and along mountain rivers by landslides, mudslides or lateral erosion of the entire river network (Bezzola et al. 2005). As the riverbed conditions have already deteriorated previously, large wood led to blockage of bridge interfaces or weirs at many critical locations, which not only accelerated riverbed destruction, but also caused backwater and accelerated coarser sediment deposition. The relative importance of sediment transport during the 2005 Swiss floods can also be illustrated by comparing estimates of migrated bedload with estimates of annual mean bedload transport: in the case of the Chirel, the Engelberger Aa and the Schächen rivers, event-based bedload was 4–26 times greater than annual bedload transport.

This example shows that erosion or aggradation triggered by flooding events and high-concentrated currents are likely to lead to increased flood hazards and are probably as critical as changes in streamflow hydrology (Stover and Montgomery 2001; Pinter and Heine 2005). Moreover, intense sediment transport, bedload in particular, during flood events can lead to increased costs of damages (Badoux et al. 2014). Therefore, both sediments and large wood transportation should be considered in flood risk management (Slater et al. 2015), to plan adequate policies and reduction strategies.

Flood in Eastern Europe, 2020

The flood that occurred from June 17 to 23, 2020 in the Siret and Prut River basins in the central and eastern parts of Romania (Fig. 6) is regarded as one of the largest floods ever recorded in this area over the last 80 years (Ionita and Nagavciuc 2021). During the flood event, the eastern part of Romania, the Republic of Moldova, and Ukraine experienced extreme precipitations six times higher than the monthly average (SHS Raport Hidrologic Privind Viitura Pluvială Din Luna 2020).

The flood in the Siret and Prut River basins exhibited unique characteristics due to its different runoff values, water volume, and duration. The flood event in the Siret basin began with a high streamflow upstream on June 15, and remained at a high level until June 21. The water level rose rapidly after June 21, until it peaked on June 24, with the flow reaching 640 m^3/s (Ionita and Nagavciuc 2021). When it comes to the Prut River, the first flood was observed between June 14 and 21, with streamflow twice as high as that between June 13–14. The second largest flood of the Prut River Basin happened on June 22, and this large-scale flood was caused by the high precipitation in the upper stream of the Prut River Basin (SHS Raport Hidrologic Privind Viitura Pluvială Din Luna 2020). The abnormally high daily streamflow remained until June 27, after which the river flow rate began to drop rapidly, returning to its normal values on June 30.

The extreme flood event that happened on June 2020 has caused significant socio-economic losses not only in the Siret and Prut River basins, but also in other watersheds in East and Central Europe. It is reported that damages worth around EUR 382–412 million were caused by this flood event, including EUR 290 million in Romania, EUR 2 million in the Republic of Moldova, and EUR 90–120 million in Ukraine (RFE/RL 2022; DIGI24 2022; NewsMarker Digurile 2023; DSE Indici Statistici Despre 2022). Infrastructure such as bridges, sidewalks, national roads, railroads, and streets in the affected areas was damaged, and landslides occurred in the mountainous regions of Ukraine. In addition, more than 10,000

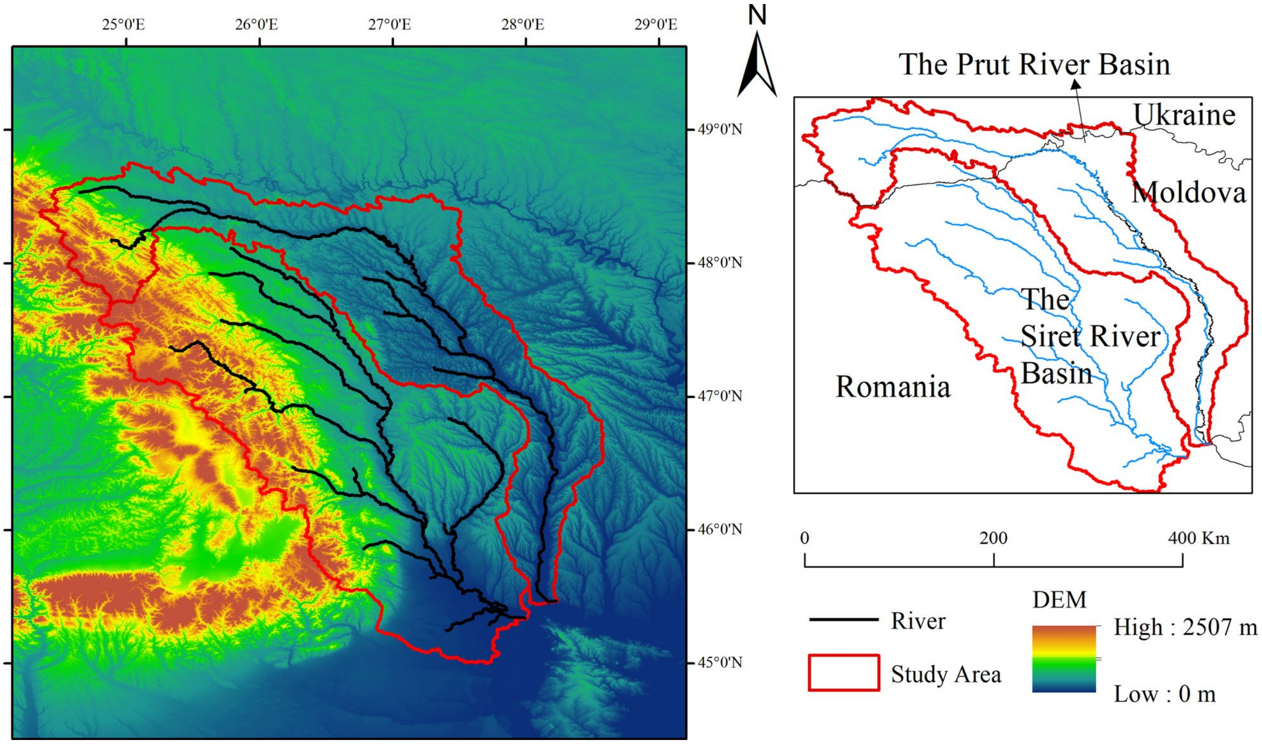

Fig. 6 The location and the Digital Elevation Model (DEM) of the Siret River and Prut River Basins, in Romania, Moldova, and Ukraine

households were ruined by the floods and six people were tragically killed, three each in Romania and Ukraine (RFE/RL 2022; CAPITAL S–Au 2023; Bilanțul and Inundațiilor: Trei Persoane Luate de Viitură 2022). The poor management of the rivers impacted by this flood and the lack of adequate flood risk maps aggravated the overall balance, as many settlements were impacted not only by water, but also by debris flows and landslides.

This event represents another example of the fact that proper water and flood management plans are critical to prevent and reducing flood damage. The Romanian government started implementing the European Flood Management Directive in 2009, while Ukraine and the Republic of Moldova started to do so only in 2022 (Apele Române Național 2017; Dniester Commission Flooding in Western Ukraine 2022), with expected delays connected with the political situation.

Mountain flood in Western Norway, 2017

On 24 July 2017, a flash flood occurred in a small and steep watercourse called Storeiva River Watershed (SRW) in Western Norway (Fig. 7). Despite the small size of this basin (24.75 km^2), the flooding caused more than EUR 7 million in property damage and more than EUR 5 million in post-disaster reconstruction costs (Moraru et al. 2021). In addition, the flood destroyed a small 100-year-old hydroelectric power plant, but, fortunately, no casualties were registered (Moraru et al. 2021). The flash flood was mainly caused by the intense rainfall accompanied by warm weather, typical of a summer morning. Four hours of precipitation caused a recorded peak flow of around 130–280 m^3/s (Leine 2017; Bruland 2020).

To deeply understand the causes and effects of the flood event and apply the research findings to similar watersheds to reduce damages, a hydrologic model was developed as well as the estimation of hydraulic forces (Bruland 2020). The visual documentation during the flood event was also used to help improve the accuracy of the hydrologic model and hydraulic estimations, to eventually address the modelling uncertainties caused by the lack of the gauging station and long-term hydrologic and hydraulic data (Moraru et al. 2021). However, being a mountainous basin, sediments and woods were also intensively mobilized during the event. The modelling result showed that the intense erosion of the left bank led to the water overflow, generating a new water flow path. Moreover, because of the gentler slope, the sediment produced during the generation of the new flow path was deposited into the original river channel, causing water levels to rise due to sedimentation, and subsequent flooding of houses nearby (Moraru et al. 2020).

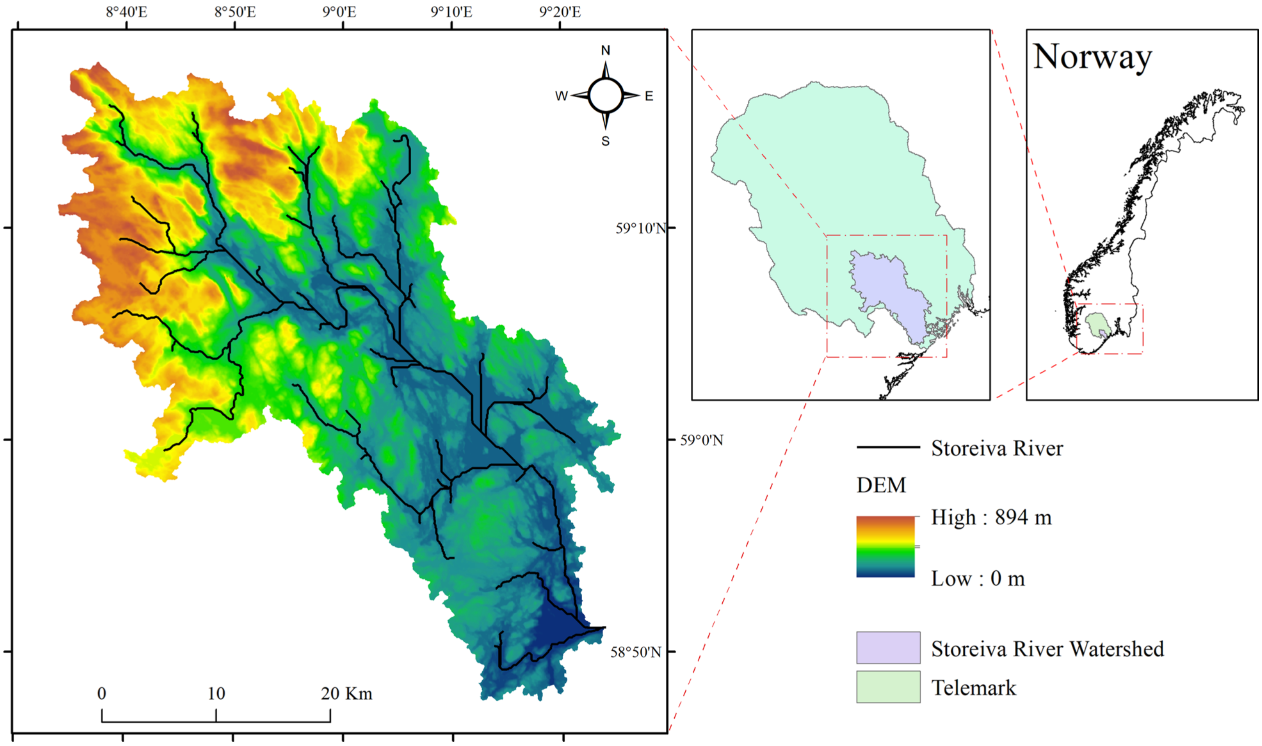

Fig. 7 The location and the Digital Elevation Model (DEM) of the Storeiva River Basin, in Norway

As demonstrated in this example, erosion and sedimentation processes can have a significant impact on the development of mountainous watersheds during flash floods, such as by creating new water flow paths or fostering the aggradation of the main channels. Thus, it is necessary to take sediment transport into flood management considerations, especially in mountain rivers like the SRW watershed. Moreover, this case can also provide a reference for studying flood events in small, steep mountain rivers, by considering hydro-morphological alterations.

Summary and future perspectives

Floods represent the third primary reason causing economic loss worldwide among all natural hazards, causing total damage of USD 51 billion (EUR 48 billion) in Europe between 2006 and 2015. According to the report of the Intergovernmental Panel on Climate Change (IPCC) of 2021, flood damages in the past decade were ten times more severe than in the period 1960–1970 (Masson-Delmotte et al. 2021). With the release of the European Union Floods Directive (2007/60/EC), flood risk assessment and management gained more attention, as additional resources and efforts were dedicated and allocated to the assessment, mitigation and management of flood risk under the background of climate change, population growth and economic changes (Nones 2015; Kreibich et al. 2022; Priest et al. 2016; Skoulikaris 2022).

The present mini-review provides a few examples of flooding events that happened around Europe in the last twenty years, in both mountainous and lowland river basins (Table 1).

These examples report clear evidence that claims for a rethinking of flood risk mapping, moving from a "clear water" perspective to a more holistic approach in modelling flood risk, where the interactions between all the fluvial components are adequately considered.

Focusing on mountain streams, one can notice that a significant relationship often exists between flooding events and the erosion, transport, and deposition of coarse material mainly as bedload. In addition, large wood or woody debris mobilized during the flow can represent another important factor increasing the hazard of floods. Indeed, the mobilization of large wood often increases and aggravates the damage caused by water and sediments, mainly due to the impact that wood can have on human infrastructures like bridges and levees. Lowland watercourses, on the other part, are generally affected by an increase in suspended load during flooding events, with consequent overaggradation of floodplains and an increase in water levels, ultimately leading to an increment in local flood risk.

It is worth mentioning that, from the examples provided here, one cannot conclude that considering river sediments in flood risk maps will automatically reduce the costs associated with flood damages. However, as shown here, there is evidence that not considering sediments can lead to primary and secondary impacts and damages. Taking sediment transport and morphological changes into account in flood management and optimizing relevant regulations to highlight its importance is essential, also to eventually reduce costs due to sediment-related damages. This is especially needed when floods, lateral and vertical erosion can lead to the destruction of man-made facilities and hydraulic infrastructures such as bridges, and this debris is then deposited in the river, further expanding backwater, and intensifying the destructive force of floods.

Moreover, it is vital to take into consideration climate change in the development and implementation of

Table 1 Summary of the case studies

Country	Type of flood	River basin	Key elements to be considered	References
Germany	Flash flood	Mountainous	Sediments, wood material	Bronstert et al. (2018), Lucía et al. (2018), Gaume and Borga (2008), Benda and Sias (2003), Comiti et al. (2016)
Central Europe	River flood	Lowland	Sediments, society	)
Italy	River flood	Lowland	Sediments, vegetation	Liguria (2019), Mandarino et al. (2021a), Horacio et al. (2019), Mandarino et al. (2021b)
Switzerland	Flash flood	Mountainous	Sediments, wood material	Slater et al. (2015), Hilker et al. (2009), Hegg et al. (2000), Raetzo et al. (2005), Bezzola et al. (2005), Badoux et al. (2014)
Eastern Europe	River flood	Lowland	Sediments, legislation	Ionita and Nagavciuc (2021), SHS Raport Hidrologic Privind Viitura Pluvială Din Luna (2020), RFE/RL (2022), DIGI24 (2022), NewsMarker Digurile (2023), DSE Indici Statistici Despre (2022), CAPITAL S–Au (2023), Bilan-ul and Inundaiilor (2022), National and de Management (2017), Dniester Commission Flooding (2022)
Norway	Flash flood	Mountainous	Sediments, wood material	Moraru et al. (2021), Leine (2017), Bruland (2020), Moraru et al. (2020)

The elements to be considered are derived from post-event analyses

European flood risk management plans to mitigate the impact of floods and reduce their negative effects from a long-term perspective.

Author contributions

Conceptualization, M.N. and Y.G.; methodology, M.N. and Y.G.; writing-original draft preparation, Y.G and M.N.; writing-review, Y.G and M.N. All the authors have read and agreed to the submitted version of the manuscript.

Funding
This research was funded by NCN National Science Centre Poland–call PRELUDIUM BIS-3, Grant Number 2021/43/O/ST10/00539.

Data availability

Not applicable.

Declarations

Competing interests

The authors declare no competing interests.

Received: 30 June 2023 Accepted: 25 September 2023

References

Adamson M (2018) Flood risk management in Europe: the EU 'Floods' directive and a case study of Ireland. Int J River Basin Manag 16(3):261–272. https://doi.org/10.1080/15715124.2018.1437744

Adnan MSG, Abdullah AYM, Dewan A, Hall JW (2020) The effects of changing land use and flood hazard on poverty in coastal Bangladesh. Land Use Policy 99:104868. https://doi.org/10.1016/j.landusepol.2020.104868

Albano R, Mancusi L, Abbate A (2017) Improving flood risk analysis for effectively supporting the implementation of flood risk management plans: the case study of "Serio" Valley. Environ Sci Policy 75:158–172. https://doi.org/10.1016/j.envsci.2017.05.017

Alfieri L, Salamon P, Bianchi A, Neal J, Bates P, Feyen L (2014) Advances in Pan-European flood hazard mapping. Hydrol Process 28:4067–4077. https://doi.org/10.1002/HYP.9947

Apel H, Vorogushyn S, Merz B (2022) Brief communication: impact forecasting could substantially improve the emergency management of deadly floods: case study July 2021 floods in Germany. Nat Hazards Earth Syst Sci 22:3005–3014. https://doi.org/10.5194/nhess-22-3005-2022

Apele Române Planul Național de Management Actualizat Aferent Porțiunii Din Bazinul Hidrografic Internațional Al Fluviului Dunăreacare Este Cuprinsă În Teritoriul României 2016–2021; 2017 (**in Romanian**)

Arnaud F, Piégay H, Schmitt L, Rollet AJ, Ferrier V, Béal D (2015) Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: the Old Rhine Downstream of the Kembs Diversion Dam (France, Germany). Geomorphology 236:163–177. https://doi.org/10.1016/j.geomorph.2015.02.009

ARPA Liguria (2019) Rapporto Speditivo Dell'evento Meteo-Idrologico Del 19–22/10/2019. Agenzia Reg. per la Prot. dell'Ambiente Ligure 2019. In Italian

Badoux A, Andres N, Turowski JM (2014) Damage costs due to bedload transport processes in Switzerland. Nat Hazards Earth Syst Sci 14:279–294. https://doi.org/10.5194/nhess-14-279-2014

Bauer M, Dostal T, Krasa J, Jachymova B, David V, Devaty J, Strouhal L, Rosendorf P (2019) Risk to residents, infrastructure, and water bodies from flash floods and sediment transport. Environ Monit Assess 191:1–19. https://doi.org/10.1007/S10661-019-7216-7

Benda LE, Sias JC (2003) A quantitative framework for evaluating the mass balance of in-stream organic debris. For Ecol Manag 172:1–16. https://doi.org/10.1016/S0378-1127(01)00576-X

Bezzola GR, Hegg C (2008) Ereignisanalyse Hochwasser 2005, Teil 2—Analyse von Prozessen, Massnahmen Und Gefahrengrundlagen; 2008 (**in German**)

Birk S, Chapman D, Carvalho L, Spears BM, Andersen HE, Argillier C, Auer S, Baattrup-Pedersen A, Banin L, Beklioğlu M et al (2020) Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. Nat Ecol Evol 4:1060–1068. https://doi.org/10.1038/s41559-020-1216-4

Bohorquez P, del Moral-Erencia JD (2017) 100 years of competition between reduction in channel capacity and streamflow during floods in the Guadalquivir River (Southern Spain). Remote Sens 9:727. https://doi.org/10.3390/rs9070727

Brierley G, Hooke J (2015) Emerging geomorphic approaches to guide river management practices. Geomorphology 251:1–5. https://doi.org/10.1016/J.GEOMORPH.2015.08.019

Brils J (2008) Sediment monitoring and the European water framework directive. Ann Ist Super Sanita 44:218–223

Bronstert A, Agarwal A, Boessenkool B, Crisologo I, Fischer M, Heistermann M, Köhn-Reich L, López-Tarazón JA, Moran T, Ozturk U et al (2018) Forensic hydro-meteorological analysis of an extreme flash flood: the 2016-05-29 event in Braunsbach, SW Germany. Sci Total Environ 630:977–991. https://doi.org/10.1016/j.scitotenv.2018.02.241

Bruland O (2020) How extreme can unit discharge become in steep Norwegian Catchments? Hydrol Res 51:290–307. https://doi.org/10.2166/nh.2020.055

CAPITAL S-Au Dat Banii Pentru Localitățile Afectate de Inundații Available online: https://zaxid.net/poveni_tag52230/newsfrom748/ (accessed on 21 March 2023)

Chang CK, Ab Ghani A (2015) Quantifying the effects of sediment transport on river channel geometry and flood level—a case study of the December 2014 flood. Int J River Basin Manag. https://doi.org/10.1080/15715124.2022.2138408

Comiti F, Lucía A, Rickenmann D (2016) Large wood recruitment and transport during large floods: a review. Geomorphology 269:23–39

Contreras MT, Escauriaza C (2020) Modeling the effects of sediment concentration on the propagation of flash floods in an Andean Watershed. Nat Hazards Earth Syst Sci 20:221–241. https://doi.org/10.5194/nhess-20-221-2020

Costabile P, Macchione F (2015) Enhancing river model set-up for 2-D dynamic flood modelling. Environ Model Softw 67:89–107. https://doi.org/10.1016/J.ENVSOFT.2015.01.009

Cvetkovic V, Martinovic J (2021) Innovative solutions for flood risk management. Int J Disaster Risk Manag 2(2):71–100. https://doi.org/10.18485/ijdrm.2020.2.2.5

De Moel H, Van Alphen J, Aerts JCJH (2009) Flood maps in Europe—methods, availability and use. Nat Hazards Earth Syst Sci 9:289–301. https://doi.org/10.5194/nhess-9-289-2009

Díez-Herrero A, Garrote J (2020) Flood risk analysis and assessment, applications and uncertainties: a bibliometric review. Water, 12(7):2050. https://doi.org/10.3390/w12072050

DIGI24 Inundații Devastatoare În Cea Mai Ploioasă Lună Iunie Din Ultimii 60 de Ani. Available online: https://www.digi24.ro/stiri/actualitate/inundatii-devastatoare-in-cea-mai-ploioasa-luna-iunie-din-ultimii-60-de-ani-patru-oameni-au-murit-o-fetita-a-fost-luata-de-viitura-1327761 (accessed on 21 November 2022)

Directive 2000/60/EC—Directive 2000/60/EC of the European Parliament and of the Council of 23 (2000) Establishing a Framework for Community Action in the Field of Water Policy (Water Framework Directive). Off J Eur Parliam 2000(L327):1–82

Dniester Commission Flooding in Western Ukraine: Causes, Lessons Learned and Potential to Avoid Harmful Future Effects Available online: https://www.efas.eu/en/news/flooding-western-ukraine-june-2020 (accessed on 21 November 2022)

DSE Indici Statistici Despre Numărul Situațiilor Excepționale Ce S-Au Produs În Republica Moldova Pe Parcursul 01.06.2020–30.06.2020 Available online: https://dse.md/ro/date_statistice (accessed on 21 November 2022)

El Hourani M, Härtling J, Broll G (2022) Hydromorphological assessment as a tool for river basin management: problems with the german field survey method at the transition of two ecoregions. Hydrology 9:120. https://doi.org/10.3390/HYDROLOGY9070120.

European Commission Common Implementation Strategy for the Water Framework Directive (2000/60/EC); 2014; Vol. 428

European Commission, Integrated sediment management—Guidelines and good practices in the context of the Water Framework Directive, 2022. Available at https://environment.ec.europa.eu/system/files/2022-09/CISdocumentsedimentfinalTO_BE_PUBLISHED_1430554724.pdf (accessed on 10 December 2022)

European Community Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks. Off. J. Eur. Union 2007, L288/27, 27–34

Faranda D, Bourdin S, Ginesta M, Krouma M, Messori G, Noyelle R, Pons F, Yiou P (2022) Attribution of extreme weather events in the context of climate change; National Academies Press

Fekete A, Sandholz S (2021) Here comes the flood, but not failure? Lessons to learn after the heavy rain and pluvial floods in Germany 2021. Water 13:3016. https://doi.org/10.3390/W13213016

Fryirs KA, Brierley GJ (2012) Geomorphic analysis of river systems: an approach to reading the landscape. John Wiley and Sons. ISBN 9781405192750

Gaume E, Borga M (2008) Post-flood field investigations in upland catchments after major flash floods: proposal of a methodology and illustrations. J Flood Risk Manag 1:175–189. https://doi.org/10.1111/j.1753-318x.2008.00023.x

Guan M, Wright NG, Sleigh PA, Carrivick JL (2015) Assessment of hydro-morphodynamic modelling and geomorphological impacts of a sediment-charged Jökulhlaup, at Sólheimajökull, Iceland. J Hydrol 530:336–349. https://doi.org/10.1016/J.JHYDROL.2015.09.062

Guan M, Carrivick JL, Wright NG, Sleigh PA, Staines KEH (2016) Quantifying the combined effects of multiple extreme floods on river channel geometry and on flood hazards. J Hydrol 538:256–268. https://doi.org/10.1016/j.jhydrol.2016.04.004

Gurnell AM, Rinaldi M, Belletti B, Bizzi S, Blamauer B, Braca G, Buijse AD, Bussettini M, Camenen B, Comiti F et al (2016) A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquat Sci 78:1–16. https://doi.org/10.1007/s00027-015-0424-5

Habersack H, Hein T, Stanica A, Liska I, Mair R, Jäger E, Hauer C, Bradley C (2016) Challenges of river basin management: current status of, and prospects for, the river Danube from a river engineering perspective. Sci Total Environ 543:828–845. https://doi.org/10.1016/j.scitotenv.2015.10.123

Hamidifar H, Nones M (2023) Spatiotemporal variations of riverine flood fatalities: 70 years global to regional perspective. River 2(2):222–238. https://doi.org/10.1002/rvr2.45

Hartmann T, Spit T (2016) Implementing the European flood risk management plan. J Environ Planning Manag 59(2):360–377. https://doi.org/10.1080/09640568.2015.1012581

Heckmann T, Cavalli M, Cerdan O, Foerster S, Javaux M, Lode E, Smetanová A, Vericat D, Brardinoni F (2018) Indices of sediment connectivity: opportunities, challenges and limitations. Earth-Sci Rev 187:77–108. https://doi.org/10.1016/J.EARSCIREV.2018.08.004

Hegg C, Badoux A, Bassi A, Schmid F (2001) Unwetterschäden in Der Schweiz Im Jahre 2000. Wasser Energie Luft—eau énergie air 93:117–130 (**in German**)

Hilker N, Badoux A, Hegg C (2009) The Swiss flood and landslide damage database 1972–2007. Nat Hazards Earth Syst Sci 9:913–925. https://doi.org/10.5194/NHESS-9-913-2009

Hooke JM (2015) Variations in flood magnitude–effect relations and the implications for flood risk assessment and river management. Geomorphology 251:91–107. https://doi.org/10.1016/j.geomorph.2015.05.014

Horacio J, Ollero A, Noguera I, Fernández-Pasquier V (2019) Flooding, channel dynamics and transverse infrastructure: a challenge for middle Ebro River Management. J Maps 15:310–319. https://doi.org/10.1080/17445647.2019.1592719

HotNews Bilanțul Inundațiilor: Trei Persoane Luate de Viitură, 71 Evacuate, Aproape 400 de Case Inundate Available online: https://www.hotnews.ro/stiri-esential-24133784-inundatii-romania-bilant-igsu-trei-persoane-luate-viitura-71-evacuate-aproape-400-case-inundate.htm (accessed on 2 December 2022)

Ionita M, Nagavciuc V (2021) Extreme floods in the eastern part of Europe: large-scale drivers and associated impacts. Water (switzerland) 13:1122. https://doi.org/10.3390/W13081122/S1

Jager NW, Challies E, Kochskämper E, Newig J, Benson D, Blackstock K, Collins K, Ernst A, Evers M, Feichtinger J et al (2016) Transforming European Water Governance? Participation and river basin management under the EU Water Framework Directive in 13 Member States. Water 8:156. https://doi.org/10.3390/w8040156

James A (1999) Time and the persistence of alluvium: river engineering, fluvial geomorphology, and mining sediment in California. Geomorphology 31:265–290. https://doi.org/10.1016/S0169-555X(99)00084-7

James LA, Hodgson ME, Ghoshal S, Latiolais MM (2012) Geomorphic change detection using historic maps and DEM differencing: the temporal dimension of geospatial analysis. Geomorphology 137:181–198. https://doi.org/10.1016/j.geomorph.2010.10.039

Knox RL, Wohl EE, Morrison RR (2022) Levees don't protect, they disconnect: a critical review of how artificial levees impact floodplain functions. Sci Total Environ 837:155773. https://doi.org/10.1016/j.scitotenv.2022.155773

Korswagen PA, Harish S, Oetjen J, Wüthrich D (2022) Post-flood field survey of the Ahr Valley (Germany): building damages and hydraulic aspects. Delft Univ Technol, Delft

Korup O, McSaveney MJ, Davies TRH (2004) Sediment generation and delivery from large historic landslides in the Southern Alps, New Zealand. Geomorphology 61:189–207. https://doi.org/10.1016/J.GEOMORPH.2004.01.001

Kreibich H, Van Loon AF, Schröter K, Ward PJ, Mazzoleni M, Sairam N, Abeshu GW, Agafonova S, AghaKouchak A, Aksoy H et al (2022) The challenge of unprecedented floods and droughts in risk management. Nature 608:80–86. https://doi.org/10.1038/s41586-022-04917-5

Kreienkamp F, Philip SY, Tradowsky JS, Kew SF, Lorenz P, Arrighi J, Belleflamme A, Bettmann T, Caluwaerts S, Chan SC et al (2021) Bert Van Schaeybroeck 13, Robert Vautard 5, Demi Vonk 8, Niko Wanders 12 1-Deutscher Wetterdienst (DWD). R Netherlands Meteorol Inst 13:18

Lashford C, Lavers T, Reaney S, Charlesworth S, Burgess-Gamble L, Dale J (2022) Sustainable catchment-wide flood management: a review of the terminology and application of sustainable catchment flood management techniques in the UK. Water 14(8):1204. https://doi.org/10.3390/w14081204

Leine A-LØ (2017) Flomberegning for Storelva i Utvik (087.4Z) (Flood Estimates for Storelva in Utvik (087.4Z), Report No. 94/2017)

Leopold LB, Maddock TJ (1953) The hydraulic geometry of stream channels and some physiographic implications

Li W, van Maren DS, Wang ZB, de Vriend HJ, Wu B (2014) Peak discharge increase in hyperconcentrated floods. Adv Water Resour 67:65–77. https://doi.org/10.1016/J.ADVWATRES.2014.02.007

Liu C, Walling DE, He Y (2018) Review: the international sediment initiative case studies of sediment problems in river basins and their management. Int J Sediment Res 33:216–219. https://doi.org/10.1016/J.IJSRC.2017.05.005

Liu H, Du J, Yi Y (2022) Reconceptualising flood risk assessment by incorporating sediment supply. CATENA 217:106503. https://doi.org/10.1016/J.CATENA.2022.106503

Lucía A, Schwientek M, Eberle J, Zarfl C (2018) Planform changes and large wood dynamics in two torrents during a severe flash flood in Braunsbach, Germany 2016. Sci Total Environ 640–641:315–326. https://doi.org/10.1016/j.scitotenv.2018.05.186

Mandarino A, Luino F, Faccini F (2021a) Flood-induced ground effects and flood-water dynamics for hydro-geomorphic hazard assessment: the 21–22 October 2019 extreme flood along the Lower Orba River (Alessandria, NW Italy). J Maps 17:136–151. https://doi.org/10.1080/17445647.2020.1866702

Mandarino A, Luino F, Turconi L, Faccini F (2021b) Urban geomorphology of a historical city straddling the Tanaro River (Alessandria, NW Italy). J Maps 17:29–41. https://doi.org/10.1080/17445647.2020.1746420/SUPPL_FILE/TJOM_A_1746420_SM3246.PDF

Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, et al (2021) Climate Change 2021: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A, Connors

SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Eds. Cambridge University Press 2021

Merz B, Elmer F, Kunz M, Mühr B, Schröter K, Uhlemann-Elmer S (2013) The extreme flood in June 2013 in Germany. La Houille Blanche 1:5–10. https://doi.org/10.1051/LHB/2014001

Merz B, Kuhlicke C, Kunz M, Pittore M, Babeyko A, Bresch DN, Domeisen DIV, Feser F, Koszalka I, Kreibich H et al (2020) Impact forecasting to support emergency management of natural hazards. Rev Geophys 58:e2020RG000704

Merz B, Blöschl G, Vorogushyn S, Dottori F, Aerts JCJH, Bates P, Bertola M, Kemter M, Kreibich H, Lall U et al (2021) Causes, impacts and patterns of disastrous river floods. Nat Rev Earth Environ 2:592–609. https://doi.org/10.1038/s43017-021-00195-3

Moraru A, Pavlíček M, Bruland O, Rüther N (2021) The story of a steep river: causes and effects of the flash flood on 24 July 2017 in western Norway. Water 13:1688. https://doi.org/10.3390/w13121688

Moraru A, Rüther N, Bruland O (2020) Current trends in the optimization of hydraulic flood simulations in ungauged steep rivers. River Flow 2020. In: Proceedings of 10th conference on fluvial hydraulics 1231–1238. https://doi.org/10.1201/b22619-170

Munich Re Hurricanes, Cold Waves, Tornadoes: Weather Disasters in USA Dominate Natural Disaster Losses in 2021. Nat. disaster losses 2021 2022

Mysiak J, Testella F, Bonaiuto M, Carrus G, De Dominicis S, Cancellieri UG, Firus K, Grifoni P (2013) Flood risk management in Italy: challenges and opportunities for the implementation of the EU floods directive (2007/60/EC). Nat Hazards Earth Syst Sci 13:2883–2890. https://doi.org/10.5194/nhess-13-2883-2013

Nardini AGC (2022) Making room for our forthcoming rivers. Water (switzerland) 14:1220. https://doi.org/10.3390/w14081220

Nardini A, Sansoni G, Schipani I, Conte G, Goltara A, Boz B, Polazzo A (2008) The Water Framework Directive: A Soap Bubble? An Integrative Proposal: FLEA (Fluvial Ecosystem Assessment). CIRF—Discussion Paper 1–25

Neuhold C, Stanzel P, Nachtnebel HP (2009) Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application. Nat Hazards Earth Syst Sci 9:789–799. https://doi.org/10.5194/nhess-9-789-2009

NewsMarker Digurile de Protecție de Pe Râurile Prut Și Nistru Available online: https://newsmaker.md/ro/digurile-de-protectie-de-pe-raurile-prut-si-nistru-urmeaza-sa-fie-restabilite/ (accessed on 12 April 2023)

Newson MD, Large ARG, Newson MD, Large ARG (2006) 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. Earth Surf Process Landforms 31:1606–1624. https://doi.org/10.1002/ESP.1430

Nones M (2015) Implementation of the floods directive in selected EU member states. Water Environ J 29:412–418. https://doi.org/10.1111/WEJ.12129

Nones M (2019) Dealing with sediment transport in flood risk management. Acta Geophys 67:677–685. https://doi.org/10.1007/s11600-019-00273-7

Nones M, Gerstgraser C (2016) Morphological changes of a restored reach: the case of the Spree River, Cottbus, Germany. GeoPlanet Earth Planet Sci. https://doi.org/10.1007/978-3-319-27750-9_14

Nones M, Pescaroli G (2016) Implications of cascading effects for the EU floods directive. Int J River Basin Manag 14:195–204. https://doi.org/10.1080/15715124.2016.1149074

Nones M, Guerrero M, Ronco P (2014) Opportunities from low-resolution modelling of river morphology in remote parts of the world. Earth Surf Dyn 2:9–19. https://doi.org/10.5194/esurf-2-9-2014

Nones M, Gerstgraser C, Wharton G (2017) Consideration of hydromorphology and sediment in the implementation of the EU water framework and floods directives: a comparative analysis of selected EU Member States. Water Environ J 31:324–329. https://doi.org/10.1111/WEJ.12247

O'Connell P, Beven K, Carney J, Clements R, Ewen J, Fowler H, Harris G, Hollis J, Morris J, O'Donnell G, et al (2004) Review of impacts of rural land use and management on flood generation. Res Plan. ISBN 0855211415

Pinter N, Heine RA (2005) Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, lower Missouri River, USA. J Hydrol 302:70–91. https://doi.org/10.1016/J.JHYDROL.2004.06.039

Priest SJ, Suykens C, Van Rijswick HF, Homewood S (2016) The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries. Ecol Soc. https://doi.org/10.5751/ES-08913-2104-50

Radice A, Longoni L, Papini M, Brambilla D, Ivanov VI (2016) Generation of a design flood-event scenario for a mountain river with intense sediment transport. Water (switzerland) 8:597. https://doi.org/10.3390/w8120597

Raetzo H, Ereignisanalyse Hochwasser RC (2005) Teil 1—Prozessse, Schäden Und Erste Einordnung. Bundesamt Für Umwelt BAFU, Eidg. Forschungsanstalt WSL, Bern Birmensdorf, Switz 2007:195–210 (**In German**)

RFE/RL Inundații În România: Viitura de Pe Râul Prut a Ajuns La Intrarea În Țară Available online: https://romania.europalibera.org/a/inundatii-in-romania-viitura-de-pe-raul-prut-a-ajuns-la-intrarea-in-tara/30689642.html (accessed on 30 December 2022) (**in Romanian**)

Rickenmann D, Badoux A, Hunzinger L (2016) Significance of sediment transport processes during piedmont floods: the 2005 flood events in Switzerland. Earth Surf Process Landf 41:224–230. https://doi.org/10.1002/esp.3835

Roggenkamp T, Hergert J (2022) Hochwasser Der Ahr Im Juli 2021—Abflusseinschätzung Und Einordnung. Hydrol. und Wasserbewirtschaftung 66:40–49

Sayers PB, Hall JW, Meadowcroft IC (2002) Towards risk-based flood hazard management in the UK. Proc Inst Civ Eng Civ Eng 150:36–42. https://doi.org/10.1680/cien.2002.150.5.36

Schumm SA, Lichty RW (1965) Time, space, and causality in geomorphology. Am J Sci 263:110–119. https://doi.org/10.2475/ajs.263.2.110

Segovia C (2021) An approach to assess the integration of the water framework directive and floods directive

Shah SMH, Mustaffa Z, Teo FY, Imam MAH, Yusof KW, Al-Qadami EHH (2020) A review of the flood hazard and risk management in the South Asian Region, particularly Pakistan. Sci Afr 10:e00651. https://doi.org/10.1016/j.sciaf.2020.e00651

Sholtes JS, Yochum SE, Scott JA, Bledsoe BP (2018) Longitudinal variability of geomorphic response to floods. Earth Surf Process Landf 43:3099–3113. https://doi.org/10.1002/ESP.4472

SHS Raport Hidrologic Privind Viitura Pluvială Din Luna, June 2020. (**in Romanian**)

Simonelli T, Zoppi L, Molinari D, Ballio F (2022) Invited perspectives: when research meets practice: challenges, opportunities, and suggestions from the implementation of the floods directive in the largest Italian River Basin. Nat Hazards Earth Syst Sci 22:1819–1823. https://doi.org/10.5194/NHESS-22-1819-2022

Singh VP (2004) On the theories of hydraulic geometry. Int J 18:196–218

Sinnakaudan SK, Ab Ghani A, Ahmad MSS, Zakaria NA (2003) Flood risk mapping for pari river incorporating sediment transport. Environ Model Softw 18:119–130. https://doi.org/10.1016/S1364-8152(02)00068-3

Skoulikaris C (2022) Toponyms: a neglected asset within the water framework and flood directives implementation process; the case study of Greece. Acta Geophys. https://doi.org/10.1007/s11600-022-00962-w

Slater LJ, Singer MB, Kirchner JW (2015) Hydrologic versus geomorphic drivers of trends in flood hazard. Geophys Res Lett 42:370–376. https://doi.org/10.1002/2014GL062482

Sofia G, Nikolopoulos EI (2020) Floods and rivers: a circular causality perspective. Sci Rep 10:1–17. https://doi.org/10.1038/s41598-020-61533-x

Song Y, Zeng X, Zhang Y, An C, Ma M, Fu X (2019) Effect of sediment transport on the temporal and spatial characteristics of flash floods: a case study of "721" flood in Beijing. J Tsinghua Univ 59:990–998. https://doi.org/10.16511/j.cnki.qhdxxb.2019.26.023

Staines KEH, Carrivick JL (2015) Geomorphological impact and morphodynamic effects on flow conveyance of the 1999 Jökulhlaup at Sólheimajökull, Iceland. Earth Surf Process Landf 40:1401–1416. https://doi.org/10.1002/ESP.3750

Stefanidis K, Kouvarda T, Latsiou A, Papaioannou G, Gritzalis K, Dimitriou E (2022) A comparative evaluation of hydromorphological assessment methods applied in rivers of Greece. Hydrology 9:43. https://doi.org/10.3390/HYDROLOGY9030043

Stover SC, Montgomery DR (2001) Channel change and flooding, Skokomish river, Washington. J Hydrol 243:272–286. https://doi.org/10.1016/S0022-1694(00)00421-2

Taylor AL, Kox T, Johnston D (2018) Communicating high impact weather: improving warnings and decision making processes. Int J Disaster Risk Reduct 30:1–4

Thiebes B, Schrott L (2021) Hochwasserkatastrophe 2021—Was in Der Frühwarnung Verbessert Werden Muss. Neue Gesellschaft-Frank-Furter Hefte 11:31–36

Thomas A (2022) Sectoral versus environmental scales: implementing river continuity restoration and river basin approach in areas of production. Environ Sci Policy 128:94–101. https://doi.org/10.1016/j.envsci.2021.11.009

Thorne CR, Evans EP, Penning-Rowsell EC (2007) Future flooding and coastal erosion risks. Futur Flood Coast Eros Risks. https://doi.org/10.1680/ffacer.34495

Wang X, Yan X, Duan H, Liu X, Huang E (2019) Experimental study on the influence of river flow confluences on the open channel stage-discharge relationship. Hydrol Sci J 64:2025–2039. https://doi.org/10.1080/02626667.2019.1661415

Warner BP, Gartner JD, Hatch CE (2018) Fluvial geomorphic assessment and river corridor mapping as flood risk management tools in Massachusetts, USA. J Flood Risk Manag 11:S1100–S1104. https://doi.org/10.1111/jfr3.12328

Weak Points in the Flood Risk Modelling Chain—an Initiative by the IAHR Committee on Flood Risk Management 2021 2021

Wheater H, Evans E (2009) Land use, water management and future flood risk. Land Use Policy 26:S251–S264. https://doi.org/10.1016/J.LANDUSEPOL.2009.08.019

WMO WMO Guidelines on Multi-Hazard Impact-Based Forecast and Warning Services; 2015; ISBN 9781457706691

Wohl E, Bledsoe BP, Jacobson RB, Poff NL, Rathburn SL, Walters DM, Wilcox AC (2015) The natural sediment regime in rivers: broadening the foundation for ecosystem management. Bioscience 65:358–371. https://doi.org/10.1093/biosci/biv002

Wyżga B, Zawiejska J, Radecki-Pawlik A (2016) Impact of channel incision on the hydraulics of flood flows: examples from Polish Carpathian Rivers. Geomorphology 272:10–20. https://doi.org/10.1016/j.geomorph.2015.05.017

Yalin MS (1992) River mechanics. River Mech

Yildirim E, Demir I (2021) An integrated flood risk assessment and mitigation framework: a case study for middle Cedar River Basin, Iowa, US. Int J Disaster Risk Reduct 56:102113. https://doi.org/10.1016/j.ijdrr.2021.102113

Publisher's Note