Lehmkuhl *et al.*
Environmental Sciences Europe (2022) 34:107
https://doi.org/10.1186/s12302-022-00685-1

Environmental Sciences Europe

EDITORIAL

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Assessment of the 2021 summer flood in Central Europe

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Abstract

The flood event in July 2021 in the uplands of the Eifel-Ardennes mountains in Germany, Belgium and The Netherlands and their foreland was caused by heavy rainfall and resulted in one of the largest flood disasters in Western Europe for decades. Due to climate change, it can be assumed that such events will become more frequent in future. Even though such extreme flood can happen at any time, the consequences and impacts can be significantly reduced by appropriate technical and non-technical measures. However, such measures always require a comprehensive understanding and knowledge of previous events and comparable processes. Therefore, this special issue aims at collecting the scientific evaluation and its implications of the 2021 extreme summer flood. This editorial serves as an introduction for an article collection published in the journal *Environmental Sciences Europe*, providing an overview of the current state of integrative assessment of the 2021 summer flood in Central Europe.

Keywords: River floods, Water research, Climate change, Fluvial morphodynamics, Integrative assessment

In summer 2021, parts of Germany, Belgium and The Netherlands were hit by an extreme flood event, specifically the uplands of the Eifel-Ardennes mountains. In Germany, effects were focused on the catchments of the rivers Ahr, Erft, Inde and Rur, with the most severe damage in the Ahr valley. Entire villages and small-to-medium cities were several meters inundated, buildings were destroyed and even some entire properties were no longer available (see e.g., Korswagen et al. [1]). More than 180 people lost their lives, more than 750 people were injured and thousands were economically affected. A disproportionate number of people from particularly vulnerable population groups, such as elder or disabled persons, were among the victims of the flood. Many people still suffer the physical, psychological and material consequences of the flood disaster in March 2022 [2, 3].

Even though it is impossible to avoid such extreme flood events, the consequences and impacts can be significantly reduced by appropriate technical and non-technical measures. Generally, the objective of all measures must be to ensure that such extreme events do not lead to a flood disaster on the scale observed. However, such measures always require a comprehensive understanding and knowledge of previous events and comparable processes. Therefore, this special issue aims at collecting the scientific evaluation and its implications of the 2021 extreme summer flood.

The flood disaster was caused by an atmospheric low named Bernd, which brought abundant precipitation of up to 200 mm in the Eifel between 13 and 15 July 2021 ([4, 5]; Fig. 1). A peak discharge of approx. 1000 to 1300 m^3/s was estimated at the Altenahr gauge [6]. Reconstructions of two historical floods, on 21. July 1804 and 13 June 1910 by Roggenkamp and Herget [7, 8], show a comparable discharge at Dernau of 1,208 and 549 m^3/s, respectively. However, these historical events have not

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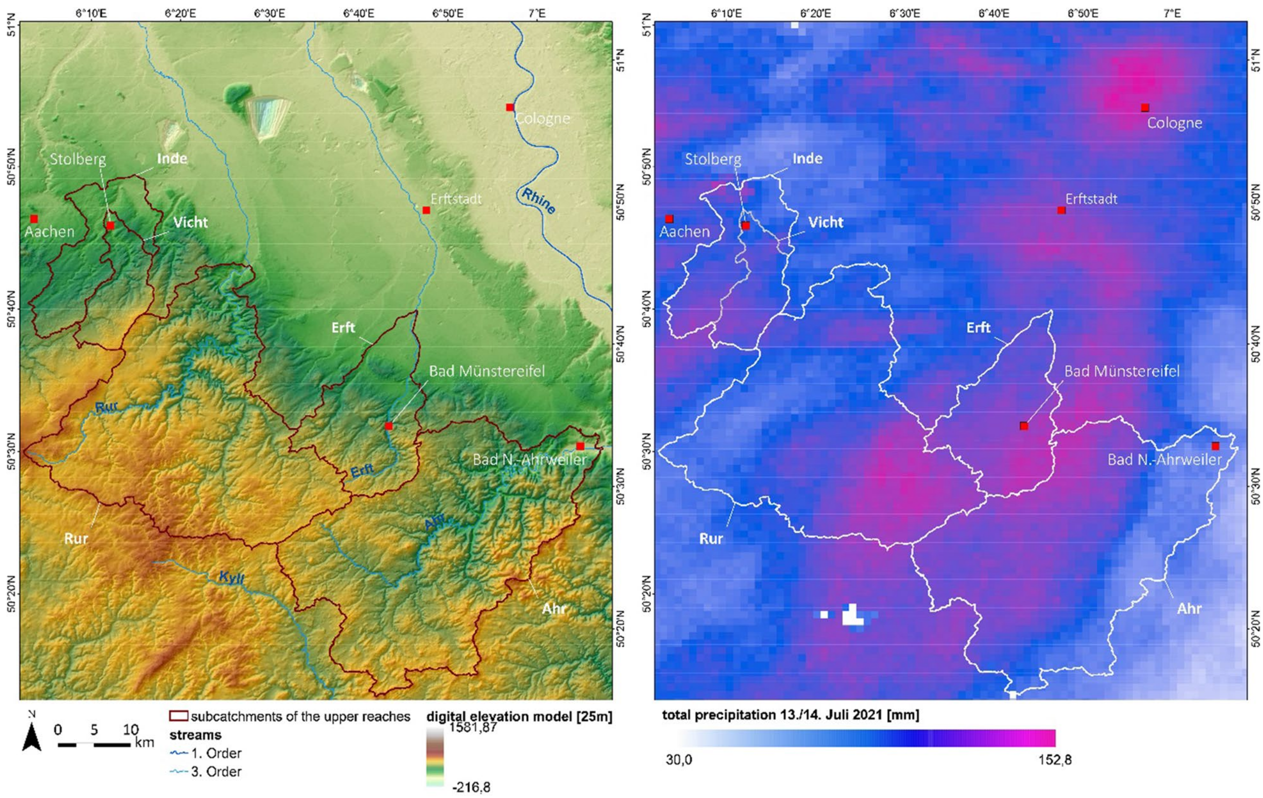

Fig. 1 Relief and precipitation for selected catchments of rivers affected by the flood in summer 2021 based on Radar data (adapted from Döscher et al. [5]) at the northern margin of the Eifel mountains

been considered in the flood hazard maps of Rhineland-Palatinate, as they occurred outside the gauge measurement periods, resulting in a misinterpretation of the design water levels for a given return period of such large floods. Despite the overall indicative role of reconstructed historical floods, frequent arguments for neglecting them are *inter alia* uncertainties in water levels, and unconstrained changes in land use and runoff characteristics. The economic consequences are also systematically underestimated. In the light of post-event evidence estimations should use such historical information as well as mounting evidence that climate change further increases the risk of extreme flood events, both allowing to assessed future flood hazard and flood risks more thoroughly.

Due to their flash flood characteristics, the geomorphological effects of pluvially triggered floods in the Central European uplands differ clearly from the effects of lowland river floods. Narrow and often steep valleys in combination with thin and saturated cover beds and thus reduced retention potential promote rapid surface runoff on slopes and hence a fast-rising flood hydrograph, further enhanced by mostly narrow floodplains. This phenomenon has been known in the literature for some time and was first described as the "partial drainage area effect" by Dune and Leopold [9]. Figure 2 provides an example of enormous erosion in a natural bend of the Ahr River.

Arguably, the 14–15 July 2021 event activated more than just a fluvial process domain, with the most important impacts on the affected landscape being caused by other than just hydrological dynamics. Dietze et al. [10] reviewed the boundary conditions of the flood and discuss the emerging features that made this event different from previous ones. They address rain-triggered gravitational and hyper-concentrated hillslope processes interacting with the river systems, aspects of large woody and anthropogenic debris mobilization, the legacy of sustained human land use amplifying the swiftness and magnitude of the flood, and previously not anticipated though emerging process connections and feedbacks as critical non-hydrological dimensions of the flood. Accounting for those and perhaps further non-hydrological dimensions of rain-triggered extreme events would be a further laudable step to take for increasing the preparedness for future events, also in other regions.

The fast discharge and transport of coarser debris of high gradient valley confined floods produces greater

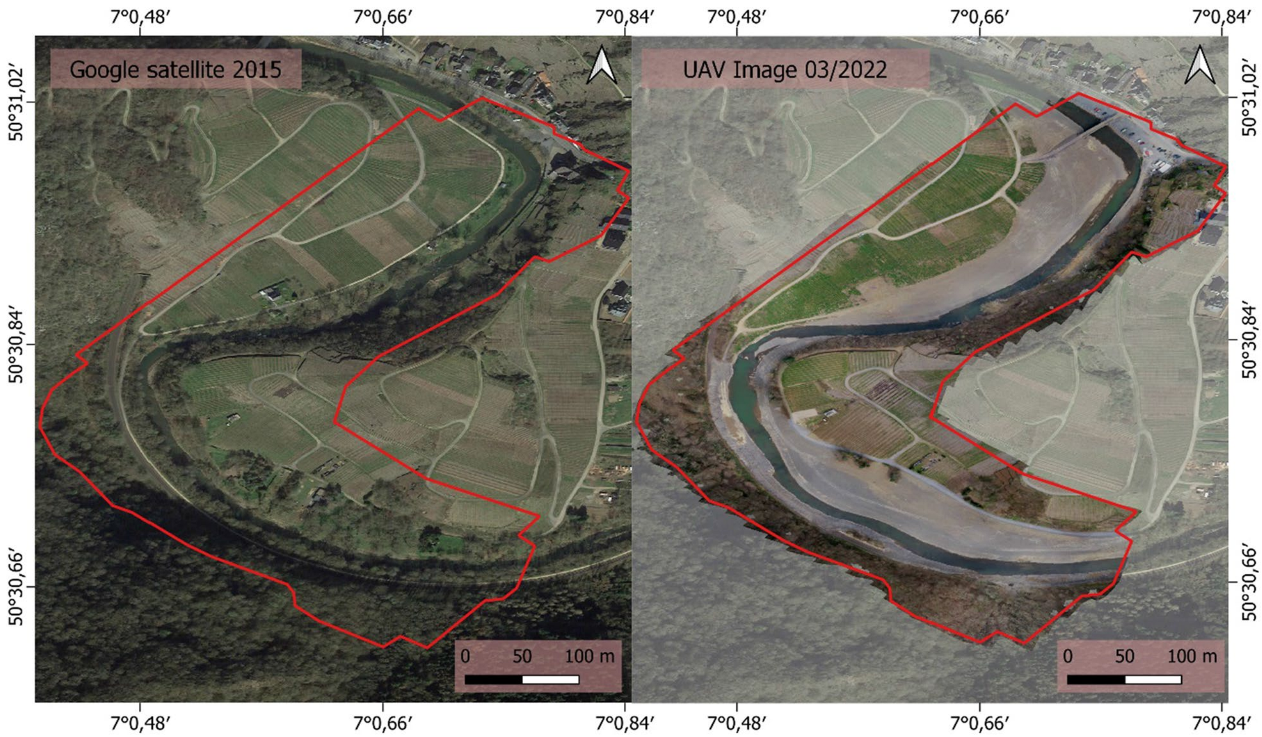

Fig. 2 Bend of the Ahr River close to Laach before (left, Google satellite 2015) and after (right, unoccupied aerial vehicle, UAV. Picture by Physical Geography and Geoecology). The red line indicates the area of UAV coverage. Notice the trees on the left picture and the broad gravel floor on the right

effects on lateral erosion and damages of infrastructure, such as bridges, and houses as well as on incision and backward erosion. In contrast, lowland river floods and flooding often spread over a wide area and can thus inundate large areas, but the damage to infrastructure and buildings is usually less due to the lower flow velocities. Instead, portions of the suspension loads are accumulated as fine sediment and silt on the floodplains.

In general, an often-neglected aspect of flood events is the emission, remobilization, dispersion and accumulation of pollutants and contaminants transported as or adhering to suspension load (see Fig. 3). Different flood-induced emission sources and pathways can be distinguished especially from urban areas, comprising waste water from destroyed sewage treatment plants, oil, fuel and other pollutants from industrial areas, waste disposal sites, houses and (former) mining areas including their tailings. The corresponding contaminated sediments and compounds are transported and accumulated in sediments downstream or the floodplains of the middle and lower reaches. Wherever the transport energy of the water decreases sufficiently, the contaminants are deposited: in floodplains, gardens, playgrounds, streets and other flooded areas (e.g., basements). Ultimately, this can lead to a significant accumulation of contaminants in the various sedimentation areas provoking environmental and health risks, especially as the July flood affected larger areas than previous floods in the region. The review of Crawford et al. [11] addresses the general problem of remobilization of pollutants during extreme flood events which poses severe risks to human and environmental health. The role of sediment re-suspension, e.g., during flood events, and possible ecotoxicological effects of re-mobilized particle-bound contaminants to aquatic organisms have scarcely been investigated. Effect-based methods are very well suited for investigating the ecotoxicological impact of sediments and suspended matter in floods with regard to their adverse effects on humans and ecosystems [12]. Within the last years several studies were published addressing the ecotoxicological impact of flood events [13–15] or using combined approaches for evaluating flood events and the risk of erosion [12]. Both inorganic and organic pollutants, as potentially remobilized during flood events, can result in various adverse health effects. A range of toxic effects are known after exposure, including neuro-, immune-, haemato- and hepatotoxicity, reproductive toxicity, genotoxicity as well as carcinogenicity. Endocrine effects, e.g., effects on the human thyroid hormone system, are also receiving increasing attention, as recent studies have shown.

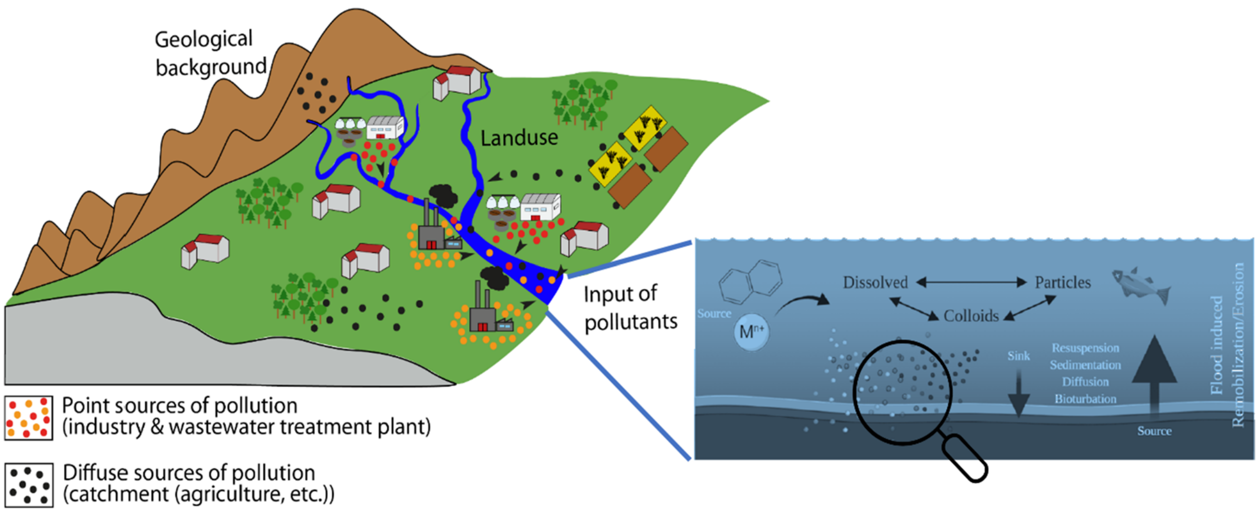

Fig. 3 Pathways of pollutant in river catchments

Bioanalytical methods can be used to create a comprehensive toxicological profile of flood samples, which can be narrowed down to individual substance groups with chemical-analytical information or even partially explained with the detection of toxic individual substances in effect-directed analysis or mass balance calculations. The here presented paper series will also give insights into the ecotoxicological effects of the extreme flood in summer 2021.

Lehmkuhl et al. [16] summarize the geomorphological aspects comparing uplands and lowlands for this July flood event and the resulting sediment pollution by examples from the Inde catchment in North Rhine Westphalia.

Furthermore, large-scale anthropogenic relief changes due to mining in floodplain areas have resulted in an increase of susceptibility to amplified flood effects and such landscapes are prone to catastrophic erosion events during flooding. There are two examples of major backward erosion during this flood event in western German in July 2021: the Inde River flooded the lignite mine of Inden close to the settlement of Lamersdorf and the Erft River flooded an open gravel pit near the town of Erftstadt-Blessem. Both events resulted in massive erosional processes, including the catastrophic destruction of parts of Erftstadt-Blessem. Flooded open cast mining areas and large base-level change on short distance result in a steep local gradient, which in turn promotes increased stream power that could drive intense and rapid headwall erosion eating away terrace landforms for several hundred meters. Boundary conditions are relief (base-level change) and material (flood loam and gravel). In both areas, large gully erosion occurred, resulting in the re-deposition of more than 500,000m^3 of sediments [16, 17].

The consequences of climate change are increasingly being discussed in the public discourse as a cause of severe floods. Therefore, in addition to the natural science perspective, flood impact research should also consider social and socio-ecological issues. The added value of the interdisciplinary approach is generated by linking the natural and social science perspectives, as for example in the question of the social perception and discourse of pollutants due to extreme flooding. The overarching approach enables a systemic view of risks and the consideration of complex societal problems that cannot be captured by a single discipline. Ultimately, however, this overarching approach will only lead to appropriate action if the risks and their consequences are adequately considered in individual and policy decisions. Since many actors are economically driven, the consequences must be translated into appropriate cost estimates for remobilized pollutants during flood events. These cost estimates should include direct economic impacts such as the direct damage to soil and buildings, but also the indirect damage to human health and the provision of ecosystem services. Ideally, wise decision patterns can significantly reduce the risks of future extreme flood events as well as the economic consequences.

Future flood protection and settlement development in the catchments of upland rivers, such as the Ahr, should consider the lessons learned from the flood disaster in July 2021. That event has readjusted the bar for flood protection and shifted it to previously unknown heights. Previous approaches and methods should be questioned and revised. The emergence of an event similar to that one is possible at any time, as historical flood data have already shown. However, according to studies on the influence of climate change the return period of extreme events will rather decrease. Blöschl et al. [18] already showed that in north-western Europe, a typical 100-year event in 1960 has already become a 50- to 80-year event. Hence, due to climate change, we have to expect both, more frequent extreme events like the one in 2021 but occasionally also even larger events. Therefore, measures to improve flood protection and more adapted settlement structures and building methods are already important climate adaptation measures.

Call for papers

This article collection in Environmental Sciences Europe (ESEU) will be the place for articles from different disciplines, such as Geoecology, Geomorphology, Hydraulic engineering, Environmental chemistry, Ecotoxicology, Social ecology, Sociology and Economics. The article collection is intended to provide an overview of the current state of integrative assessment of the 2021 summer flood in Central Europe. We cordially invite all colleagues who feel they can contribute to the topic to submit a manuscript to ESEU with reference to this series.

Acknowledgements
We thank Philipp Schulte and Wolfgang Römer for valuable comments, help during field work and discussions. L. Dörwald carried out drone flights and processed the UAV image. We would like to thank M. Formen and J. Keßels for their help with the figures. FL and HS acknowledge funding from DFG (projectnumber 496274914) and BMBF (01LR2102H, 13N16226). H.H. and C.V. have been supported by the RobustNature Cluster of Excellence Initiative (internal prefunding of Goethe University Frankfurt). HH and CB acknowledge funding from DFG (projectnumber 497800446)

Author contributions
FL and HS conceptualized the manuscript. JS, CB, MD, PL, CV, HH contributed specific aspects to the manuscript and improved the manuscript content. All authors read and approved the final manuscript.

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests. HH is Editor-in-Chief of this Journal.

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Received: 22 September 2022 Accepted: 25 September 2022
Published online: 29 October 2022

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