More than heavy rain turning into fast-flowing water – a landscape perspective on the 2021 Eifel floods

Michael Dietze[1,2], Rainer Bell[3], Ugur Ozturk[4,5], Kristen L. Cook[1,5], Christoff Andermann[1], Alexander R. Beer[6], Bodo Damm[7], Ana Lucia[6], Felix S. Fauer[8], Katrin M. Nissen[8], Tobias Sieg[4], and Annegret H. Thieken[4]

[1]GFZ German Research Centre for Geosciences, Section 4.6 Geomorphology, Telegrafenberg F427, D-14473 Potsdam, Germany
[2]Georg-August-University Göttingen. Faculty of Geosciences and Geography, Goldschmidtstrasse 5, D-37077 Göttingen, Germany
[3]University of Bonn, Department of Geography, Meckenheimer Allee 166, D-53115 Bonn, Germany
[4]University of Potsdam, Institute of Environmental Science and Geography, Karl-Liebknecht-Str. 24-25, D-14476 Potsdam, Germany
[5]GFZ German Research Centre for Geosciences, Section 2.6 Seismic Hazard and Risk Dynamics, Telegrafenberg F427, D-14473 Potsdam, Germany
[6]University of Tübingen, Department of Geosciences, Schnarrenbergstr. 94-96, D-72076 Tübingen
[7]University of Vechta, Department II - Applied Physical Geography, Universitätsstraße 5, D-49377 Vechta
[8]Freie Universität Berlin, Institute of Meteorology, Carl-Heinrich-Becker Weg 6-10, D-12165 Berlin

Correspondence: Michael Dietze (mdietze@gfz-potsdam.de)

Abstract. Rapidly evolving floods are rare but powerful drivers of landscape reorganisation that have severe and long lasting impacts on both the functions of a landscape's subsystems and the affected society. The July 2021 flood that particularly hit several river catchments of the Eifel region in West Germany and Belgium was a drastic example. While media and scientists highlighted the meteorological and hydrological aspects of this flood, it was not just the rising water levels in the main valleys that posed a hazard, caused damage, and drove environmental reorganisation. Instead, the concurrent coupling of landscape elements and the wood, sediment and debris carried by the fast-flowing water made this flood so devastating and difficult to predict. Because more intense floods are able to interact with more landscape components, they at times reveal rare non-linear feedbacks, which may be hidden during smaller events due to their high thresholds of initiation. Here, we briefly review the boundary conditions of the 14–15 July 2021 flood and discuss the emerging features that made this event different from previous floods. We identify hillslope processes, aspects of debris mobilisation, the legacy of sustained human land use, and emerging process connections and feedbacks as critical non-hydrological dimensions of the flood. With this landscape scale perspective, we develop requirements for improved future event anticipation, mitigation and fundamental system understanding.

1 Introduction

The 14–15 July 2021 flood in Western Germany as well as parts of Belgium and the Netherlands revealed the unpreparedness of societies, policy makers, and scientists across many dimensions. The anticipated precipitation amounts had been communicated several days ahead, hydrological models and numerous stream gauges were in place, and information chains and authority

responsibilities were implemented. Yet the flood, which hit several catchments that originate in the Eifel (Fig 1), developed into a massive hazard event that propagated downstream for long distances and persisted for many hours. Meanwhile, and evident from media reports focussing on the preceding rain event and the evolution of the flood, mitigation efforts remained insufficient, the actual flood wave was underpredicted, and emergency activities failed to prevent a disaster that led to 184 fatalities and two missing persons (as of 24 November 2021) in Germany alone (Thieken et al., 2021). This unexpectedly high toll is the highest in Germany since six decades.

The meteorological driver of the crisis was a cyclone named "Bernd" (Schneider and Gebauer, 2021). It travelled from the North Atlantic via France towards central Europe. Over Western Germany, its propagation speed was slowed down by an anticyclone over eastern Europe, causing almost stationary precipitation over the Eifel region from 12 to 15 July, releasing 115 mm rain in 72 h on average in for example the Ahr catchment (Junghänel et al., 2021), with a maximum value of 157 mm on 14 July at the DWD station Köln-Stammheim. The soils in the entire region were already mostly saturated due to frequent previous rain events, which is expressed by an average free storage capacity < 70 mm within the soils' top 60 cm as well as an average soil field capacity of 80–100 % (DWD-Agrowetter, 2022). The meteorological situation was properly forecasted days in advance by several weather prediction models (DWD, 2022; Schneider and Gebauer, 2021). The discrepancy between the accuracy of the meteorological forecasts and the shortcomings of flood hazard forecasting and communication reveals some of the challenges involved in anticipating the impacts of extreme events.

The next element of the evolutionary trajectory of the crisis was the surface runoff of excess rainfall that was not able to infiltrate into the ground, and hence triggered several non-linear processes, positive feedbacks and process connections (Dietze and Ozturk, 2021). Altogether, these dynamics amplified the impact of the flood on the landscape, particularly in the anthropogenic realm. To understand these dynamics, it is necessary to first examine the different landscape elements activated by the event and then to explore their modes of interplay. The flood hit several European countries. In Germany particularly, it impacted two geomorphically distinct regions: the Eifel with the Ahr Valley to the south and the Lower Rhine Bay with the Erft catchment to the north. The Eifel is a typical low mountain range with steep, deeply incised valleys (see Fig. 1 for the slope signature). These valleys cut through numerous Paleozoic lithologies with varying degrees of fracturing, crack orientation, and ground permeability, which impose a pronounced predisposition to gravitational mass movement (Damm et al., 2010). In general, hillslopes are covered by Pleistocene, 1-3 m thick periglacial cover beds that are largely unstable due to the specific grain-size distribution, sensitive to water supply, and frequently incorporated in landslides (Bell, 2007; Damm et al., 2013). Rockfall dominated cliffs are developed on steep slopes. In contrast, the Lower Rhine Bay region including the Erft catchment is an area of subsidence with smooth topography, filled by highly-permeable Cenozoic sediments with a widespread cover of Quaternary loess deposits. There is no susceptibility to gravitational mass movement in this landscape, except for steep landforms that predominantly result from man-made construction (e.g., road escarpments, waste dumps, open pit mining, cf. Fig 1). Both regions hold a long legacy of human land use.

Although the official data collection on economic flood impacts in Germany's federal states of North Rhine-Westphalia and Rhineland-Palatinate is ongoing, current estimates point at 33 billion Euro damage to private households, infrastructure, forestry, and agriculture as well as viticulture enterprises (Fekete and Sandholz, 2021). In Germany, the Ahr valley was hit

hardest: 62 out of 75 bridges were destroyed and almost all wineries were heavily affected (BMI, 2021). In Rhineland-Palatinate at least 65000 people were directly affected by the event. 135 people lost their lives, at least 766 people were injured and two are still missing (Schmid-Johannsen et al., 2022). However, societal impacts occurred not only during the event itself. Months later, inner cities remain severely damaged, and commercial and gastronomy businesses are still heavily disrupted. Their reopening depends on the timely and simultaneous restoration of key infrastructure like electricity, telecommunications, water and sewage. Disruption also affects schools and childcare facilities in some places putting another burden on affected families. Physiological illnesses as well as psychological impacts on people who lost their homes, relatives and friends during the flood represent a long-term legacy of the flood event, also beyond the areas actually impacted by the flood. Former floods in Germany revealed that a devastating experience preoccupied affected people for years (Thieken et al., 2016). Therefore, socio-psychological support is a key to recovery.

Based on empirical field studies during, immediately after, and over several weeks after the flood, we propose four critical non-hydraulic dimensions of flood-related processes. We present examples for each of these dimensions and discuss consequences of their interaction. These representative case studies form the basis of our synthesis of requirements to improve mitigation efforts for future events.

2 Method overview

In this text, we decisively pursue a descriptive approach, focusing on generalised implications of systematic findings during field mapping campaigns carried out early after the flood event. There are several reasons for this approach. The amount and quality of data during the flood, such as gauge data, satellite imagery and on-site instrumental data are limited due to abundant could cover. Likewise, post-flood remote sensing data (BBK-DLR, 2022) is only available for the main valley sections but not for headwater systems, where the flood gained its momentum and non-linearity (Dietze and Ozturk, 2021). Finally, model results that are currently produced do not capture the non-hydrodynamic dimension of the flood while high resolution 3D terrain information, essential for quantitative evaluation of erosion and deposition patterns are currently still being produced (Bell et al., 2022; Wenzel et al., 2022).

Nevertheless, we are able to constrain the antecedent conditions, driver mechanisms and, to some extent, the impacts of the flood event based on instrumental data. Spatially resolved precipitation information (Weigl and Winterrath, 2009; CDC, 2022) as 1 km^2 gridded hourly data were stacked as 72 h sums throughout the main event duration (12–15 July 2021). In addition, instrumental station data (CDC, 2022) of representative sites were used to characterise the severity of the rain event. We fitted intensity-duration-frequency (IDF) curves to historical annual maximum precipitation measurements. The IDF model was fitted with the extended consistent quantile estimation method (Fauer et al., 2021) and evaluated for the DWD station Weilerswist-Lommersum (Fig. 2).

Flood affected areas and the surface change due to erosion and deposition of sediment and large woody debris were inspected by analysing aerial RGB imagery. The material was collected one day after the flood and allowed a comparison of emerging
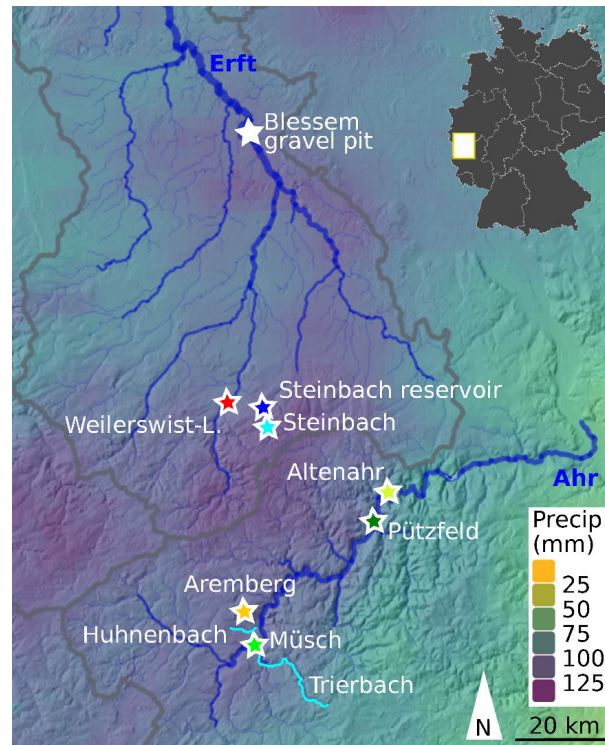
Figure 1. Map of the affected area. 3-day precipitation accumulated for 12–15 July 2021 from RADOLAN data (CDC, 2022). Stars indicate locations of pictures of other figures in this article. Light blue lines depict rivers of special interest mentioned in the text. Background map shows two of the most affected river systems, Erft and Ahr (line width indicating stream order), on top of a hillshade and slope map (red colours). Inset shows the location of the map within Germany.

surface features with imagery from months before the event (BBK-DLR, 2022). However, the availability and format of the
85   data (web service) only allowed non-quantified, descriptive studies.

Core information about the flood event is based on extensive and multi temporal field mapping campaigns throughout the wider Eifel region, decisively including headwater regions and their coupling with tributaries of the Ahr river. Surveys of flood water marks, erosional features along channels and hillslopes, deposited sediment bodies caused by ponding and hydrodynamic ejection of bed material, and large woody debris accumulations were carried out one day after the flood, and repeatedly within
90   2–3 weeks, and 2–4 months. Surveys included the documentation of the type of feature as denoted above, information on the location and size and a description of the geomorphic process regime responsible for its creation. The material presented in this text is limited to representative examples, because a quantitative regionalisation needs to be based on post-event high resolution terrain information (see above).
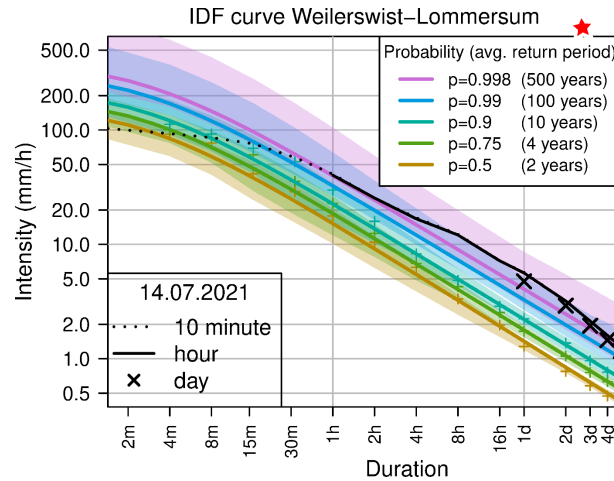
Figure 2. IDF curve for the weather station Weilerswist-Lommersum. Observations of 14 July precipitation are added in black based on different measurement intervals. Coloured lines depict different non-exceedance probabilities, respective shadings indicate 90 % confidence intervals.

3   Flood dimensions and emerging aspects

3.1   Hydrometeorological dimension

According to Fig. 1 based on radar and station observations (RADOLAN data set; (Weigl and Winterrath, 2009)) the precipitation amount for the 72 h period 12–15 July at Weilerswist-Lommersum is similar to the amount observed in Blessem (Fig. 1). Moreover, the time series at the selected station is sufficiently long for the calculation of robust IDF curves (daily precipitation is available since 1905 and hourly precipitation since 2004). The analysis confirms the unusual extreme character of the precipitation amounts during the July event (black lines and crosses in Fig 2). Sub-daily as well as daily and multi-day amounts exceeded the values corresponding to a 500-year return period determined under the assumption of stationary climate conditions.

3.2   Hillslope dimension

In typical scenarios, hillslope runoff delivers unconcentrated Hortonian or saturation overland flow to the streams, where discharge can accumulate and build up deeper and faster hydrographs. For the July 2021 flood, during post-event mapping campaigns we have witnessed several occasions where ephemeral headwater drainages had turned into streams, conveying overland flow some decimetres deep (Fig. 3a). These local phenomena allowed overland flow velocity to increase by one to two orders of magnitude (Dietze and Ozturk, 2021), which was further amplified by the effects of infrastructure (see section 2.3), such as forest tracks with rain ditches running alongside. While the tracks perpendicular to slope aspect were extensive runoff collectors (evidenced by systematic high water marks throughout mapped regions), the ditches efficiently conveyed
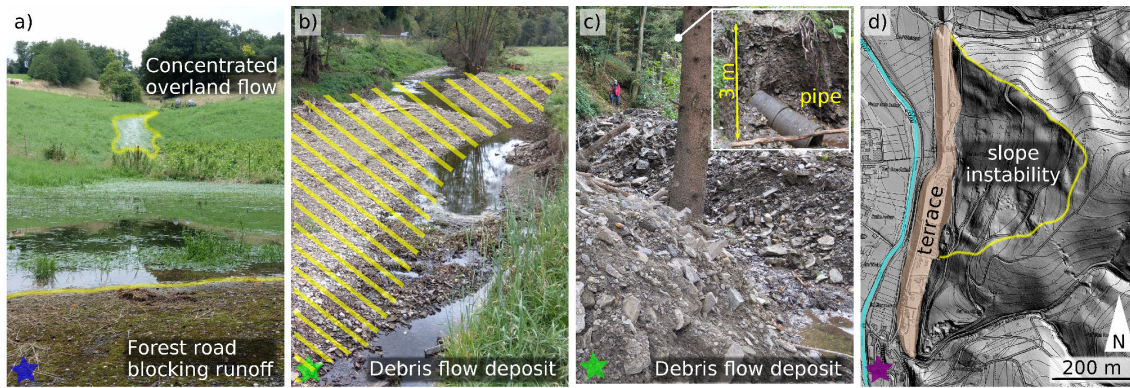
Figure 3. Landscape features emerging from the flood. For locations of these pictures see star signatures in Fig. 1. a) Focussed discharge along the hillslope causing deep and fast flow and thus efficient drainage in the background. However, the provided water is not routed downslope in the foreground but ponded by infrastructure, and released at selected spots with increased erosive stream power. b) Deposition area of the debris flow shown in (c), injecting massive debris into the main channel (Trierbach), temporally blocking the stream and causing severe reorganisation of the hydraulic geometry. c) Lateral deposits of the debris flow at the end of the valley confined section. Inset shows upstream knickpoint formed by overspill and erosion of clogged drainage pipe (50 cm diameter). d) Old slope instability (yellow line) above a 20 m high engineered terrace with industrial infrastructure on it. The terrace just east of the town of Antweiler had been undercut by the Ahr river during the flood.

collected water to release spots that acted as new gully heads (based on freshly developed erosional features). Once such gullies had formed, it is physically plausible that a positive feedback loop was implemented (Molina et al., 2009; Anderson and Anderson, 2010), leading to increasingly faster and more erosive discharge towards the valley bottoms. Hence, during the flood, concurrent landscape reorganisation, namely gullying by a concentration of overland flow amplified by infrastructure, 115 most likely played a key role in changing the drainage efficiency. This spatial feedback is not accounted for in commonly applied hydraulic models.

Hillslopes not only contributed material through unconcentrated overland flow and focussed fluvial processes but also via gravitational mass wasting, most importantly in the form of debris flows, shallow and deep-seated landslides. During field mapping campaigns immediately after the event, we documented numerous debris flows emerging from hillslopes. These 120 debris flows altered the hillslopes by erosion of soil and vegetation, and severely impacted the channels that drain the valleys. They injected coarse particles and woody debris to the channels, which had a series of consequences. In many cases, the channel thalweg was displaced or the entire trunk river was relocated within the flood plain, the local gradient was changed, and in some cases the entire flow was blocked at least temporarily (Fig. 3b). These abrupt changes have follow-on effects on channel morphology, for example bed-armouring due to sediment sizes exceeding transport capacity, and the excavation of 125 the bed including bedrock downstream, with enhanced capacity of future bedload transport and potential knickpoint migration upstream (Berger et al., 2011; Hu et al., 2021). Most of the mapped debris flow source points were locations where excess water

was able to enter a debris flow channel, ultimately triggering this mass wasting process. In most cases there were ditch-lined roads that collected and delivered the water. In addition to excess water, the investigated debris flows had at least one location in their contributing area that served as a massive source of mobile material. For example, the debris flow in Fig. 3c mobilised large amounts of material downstream of a 4–5 m high knickpoint, which formed by the overflow of a manufactured forest track crossing the channel. This artificial dam had a 50 cm drainage tube that quickly got clogged, causing backfilling and finally overtopping by the flood water. The high energy release at the resulting waterfall base caused erosion of the surrounding slope sections and the channel bed, sourcing rock material and trees into the debris channel and then into the main channel, the Trierbach, downstream (Fig. 1). Evidently, there were several previous debris flow deposits visible in the eroded bank of the Trierbach, indicating that the entering debris channel had been active several times in the past.

The landsliding component of hillslope material contribution had a series of triggers, mechanisms and time lags to the precipitation phase. Post flood mapping revealed numerous shallow landslides that were not related to fluvial undercutting as a trigger, but were located on steep concave slope sections, hence at preferentially wetter slope positions (Giuseppe et al., 2021). This suggests that their activity was triggered by excess precipitation before and during the rainfall event. These features typically had a spatial extent of a few to a few tens of metres and were in most cases not connected to a channel. In contrast, there were also numerous river banks on the outer side of river bends that showed significant undercutting and, consequently slope failures (Ozturk et al., 2018). These well-connected landscape elements were able to deliver sediment and woody debris directly to the channel (Fig. 4a). Such slope instabilities ranged in length from a few metres to features that have affected significant parts of valley hillslopes. In some cases, entire hillslopes with older instabilities were undercut (Fig. 3d) and might become reactivated subsequently. One such example of a river meander bend is depicted in Fig. 4b, where a 100 m long and 16 m high rock face was stripped of its debris apron as the Ahr river level rose by about 5 m above the current water level (cf. the flood impact scar in Fig. 4b). Subsequent visits to the site revealed traces of slope movement, such as extending cracks in a paved road crossing just above the rock slope. It is unclear how increased soil moisture during the winter period (Dietze et al., 2020) will affect the transient activity of this rock slide. Hence, further close monitoring of the slope instability is required to anticipate its failure and the potential for subsequent blockage effects on the Ahr River.

3.3 Debris mobilisation

Large woody debris played a critical role in rendering the flood non-linear and difficult to predict, from small headwater channels down to the main streams. Tree logs could have been recruited from forest-covered hillslopes with abundant dead wood due to the drought years of 2018 to 2020 (van der Wiel et al., 2021). However, apart from the linear erosive features described in section 2.2, there was limited field evidence of systematic unconcentrated overland flow on hillslopes, and in no occasion pointing at potential flow depths necessary to entrain logs (Baudrick and Grant, 2000) and route them through a maze of standing trees. The recruitment of large woody debris from riparian zones, where lateral erosion impacted former tree habitats (green line signature in Fig. 3a) is thus much more likely. Aerial imagery collected along main rivers a day after the flood (BBK-DLR, 2022) shows substantial removal of trees along the Ahr River and other floodplains. Nevertheless, a quantitative survey of the dead wood delivery capability of the forested hillslopes and riparian zones still needs to be conducted.
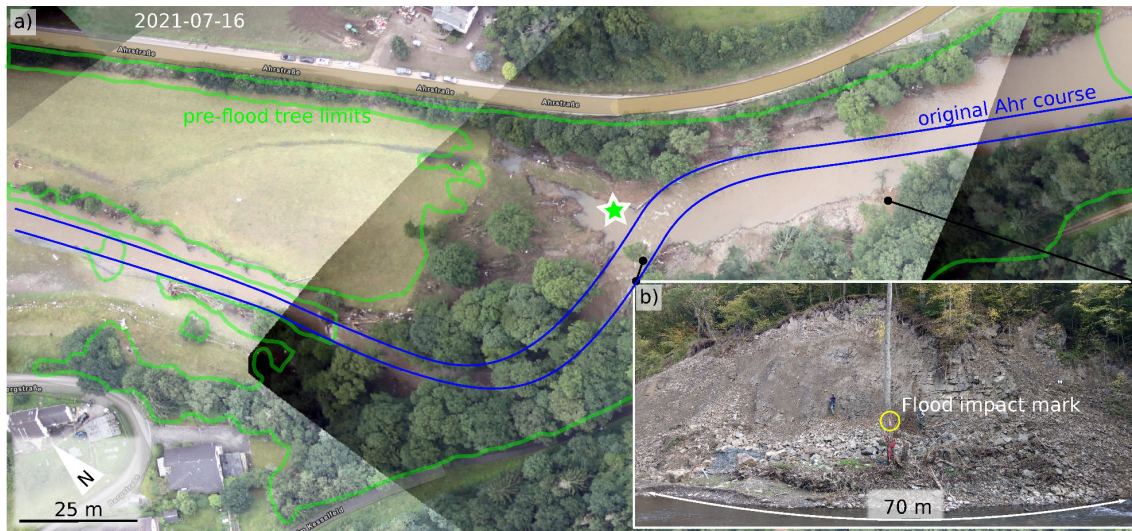
Figure 4. Debris mobilisation features, Ahr valley near Müsch (cf. Fig. 1) Aerial image (BBK-DLR, 2022) taken one day after the flood. The light green outline depicts the tree limit before the flood. Blues lines illustrate the pre-flood course of the Ahr river. b) View from the green star in (a) towards the eroded right bank, which had activated a 16 m high rockslide (persons for scale). Note flood impact mark on a remaining tree at 5 m above current water level.

Ideally, such a survey would be based on high resolution point cloud data, for example from dedicated airborne laser scan missions. Understanding the relative importance and pattern of different large woody debris sources is important not only for restoration efforts in the flood-affected areas, but also for mitigating future flood hazards (Lucia et al., 2018). In a preventive manner, especially given the likely increase in extreme events (IPCC, 2021), the general impact of large woody debris on
165 central European landscape dynamics and the susceptibility of different tree species should be investigated.

The subsequent transport of large woody debris through the river channels had a series of effects (Jochner et al., 2015; Okamoto et al., 2020). In the main streams, clogging of obstacles, mostly bridges, resulted in temporary ponding and backwater effects (Fig. 5a). As a consequence, upstream water levels rose and the inundated areas grew until the obstacle was either bypassed, overtopped or destroyed. In the former case, the bypass location experienced increased flow velocity and thus bed
170 shear stress, resulting in focussed erosion. The latter effect has the potential to generate a pulse of water travelling downstream like an outburst flood. Given the presence of many such obstacles along the course of the Ahr valley (62 out of 75 bridges destroyed) and most likely other streams draining the Eifel, the failure of obstacles most likely contributed to non-linear, pulsed hydrograph behaviour, as partly confirmed by affected people (REFTOBEADDED) and experienced during earlier floods (Roggenkamp and Herget, 2022). However, the large spacing, insufficient time resolution (15 min sampling interval)
175 and eventual failure of existing stream gauges prevent us from resolving this conceptualised hydrograph behaviour and its resulting inundation and shear stress pulses. The traces of these clogs are visible both in the main valleys (BBK-DLR, 2022) and in headwater regions, where we were able to map numerous blockages of first order streams, either at anthropogenic

Figure 5. Effects of large woody debris. For locations on wider map see stars in Fig. 1) Pair of clogged bridges near Altenahr, bypassed along the left and right bank. Note the bipartition of the collected debris with woody material caught by the downstream road bridge and anthropogenic debris collected later by the upstream railway bridge. Note two remaining standing trees in the river depicting the width of the Ahr river before the flood. Aerial image by (BBK-DLR, 2022). b) Huhnenbach near Aremberg about 2 km from its source (see Fig. 1). Note clogging by woody debris at riparian trees and the resulting ejection of coarse bed material out of the channel. c) Another clogging of the Huhnenbach some 20 m upstream of (b), with both ejected coarse debris and deposition of fine sediments in front of the obstacle.

structures (bridges, water passages, fences) or at narrows formed by riparian trees (Fig. 5b). In many reaches, these blockages were formed at a few tens of metres spacing, ponding backwater due to accumulation of organic fine material (Schalko et al., 2018), and implying significant effects already at very small contributing areas. The propagation of non-linear flow effects from small creeks to and throughout the trunk river of a catchment is a crucial step to take for successful future flood impact anticipation.

A further important effect of large woody debris, especially in headwater regions, was the role in ejected coarse inorganic debris from the stream bed (Fig. 4b) onto the floodplain. Also fine material was deposited in front of woody debris obstacles (Fig. 5c) and clogged anthropogenic structures, such as bridges. This readily available fine material is now a temporary source for increased fluvial sediment flux. Hence, even low intensity floods will be able to carry comparably high concentrations of sediment particles. In contrast, the ejected coarse bed particles are currently removed from the fluvial domain until future bank erosion (or human land-use practice) re-incorporates them to the channel. Debris also resulted in permanent alterations to stream courses, due to lateral and vertical erosion, and in some steep channel reaches even led to incision into the underlying weathered bedrock as mapped out systematically in headwater reaches. This again resulted in undercutting of the banks and local landslides. The spatial reorganisation of sediment in the fluvial domain as well as overall changes in river geometry and bed properties – from small creeks a few kilometres past the watershed to major rivers like the Ahr – inevitably caused a transient in the catchment reaction to future floods.

3.4 Anthropogenic dimension

The flood happened in a cultural landscape with a long legacy of human land-use. Accordingly, there were typical primary effects of land-use, particularly surface features on flood dynamics such as an increased and accelerated surface runoff on cultivated hillslopes (Bronstert et al., 2020), some of which are already mentioned above (e.g., Fig. 2a, Fig. 4a, clogged structures, shallow landslides due to undercut or oversteepened slopes). During our mapping campaign, we observed systematic changes in fluvial erosion features along small headwater channels. Forest-covered floodplains with strong erosional features were connected to virtually unaffected grassland sections, and intact slopes suddenly showed linearly incised sections without a plausible contributing area. In most of these cases, however, we were able to identify artificial subsurface drainage systems, often visible as fragments of drainage pipes. Not surprisingly, according to interviews with residents, systematic tile drainage is a common practice in the area to improve grassland quality or simply to manage the waste water of dispersed houses. The consequences during the July flood were either an increased discharge contribution where tile drainage remained intact or injection of excess water into the ground where drainage pipes eventually filled up with debris and were clogged. In the former case, the hydrological flashiness of the landscape increased, while in the latter case the result was an elevated susceptibility of hillslopes to failures and incision. Such failures may be local effects, but the increased flashiness had an external effect by increasing the rapid build-up of flood waves in subsequent channels. Since many of the tile drainage and waste water systems are several decades old and not necessarily documented, including their effects in runoff models will be a challenging though necessary future task.

Both regions, Ahr valley and Lower Rhine Bay, hold a long legacy of human land use that influence the susceptibility to gravitational mass movements. According to the German landslide database (Damm and Klose, 2015) the pronounced susceptibility to mass movements in the Ahr valley is exemplified by 49 database records from the middle and lower valley sections over the last about 70 years. The records document a preference for fall processes (73 % of the events), in general consisting of rock- and boulder falls of low magnitude. Sliding processes amount to 27 %. Inadequate land management as a mass wasting driver or trigger is conservatively estimated to explain almost 20 % of all cases (Damm and Klose, 2015). In contrast, the Lower Rhine Bay is virtually not susceptible to gravitational mass wasting, except for artificially oversteepened landforms. Over the last 130 years, only 26 events were documented (Damm and Klose, 2015), all of them exclusively located in engineered landscape parts such as slope cuts, hillside fillings, road embankments, waste dumps, open pit mining and river management activities. Triggers of the few large-magnitude processes (collectively linked to open pit mining sites) were predominantly the direct intervention related to mining and the intrusion of external water into the pits, caused by heavy rainfall or flooding. Hence, direct links of flood magnitude to mass wasting activity are convoluted with land use practice and thus hard to disentangle, at least for past events.

The unprecedented economic damage of more than EUR 30 billion was most likely caused not only by the extent of the affected area (see section 2.1), but also by the velocity of the water flow and the combined impact of water, wood and debris on buildings and infrastructure. Field inspection revealed inundation depths at buildings of several meters affecting not only cellars and ground floors, but also the first floor of many houses (e.g., Roggenkamp and Herget (2022) and own mapping

efforts). Previous major floods in the Ahr valley, Germany, namely 2006 and 2013, also caused inundation damage. However, those previous water levels rose on average to 0.83 and 0.46 m above the ground level, respectively (Thieken et al., 2022). The Ahr valley experienced larger events in the more distant past, such as 1804 Roggenkamp and Herget (2022). However, the settlement and landuse structure was significantly different from 2021, which makes comparisons of comparably large but temporally more distant events challenging. In addition to inundation dpeths, high flow velocities and resulting damage due to impacting debris, undermining of paved surfaces and souring of foundations were reported frequently for these valley confined flood events (Laudan et al., 2017), processes specifically harmful to critical road infrastructure (Kreibich et al., 2002). At downstream reaches, water levels became elevated by deposited debris that reduced accommodation space. None of these processes and damage mechanisms are included in common damage models (Laudan et al., 2017). Likewise, without their inclusion, identification of affected buildings by automatic flood mapping routines (e.g., CEMS, 2022) remains incomplete and requires tedious and time consuming manual data collection to derive a proper damage estimate. In the Ahr valley, CEMS identified around 5000 affected residential buildings while an overlay of the reconstructed water mask and an openstreetmap data set identifed about 7000 buildings. These 7000 buildings are likely to be a too low estimate as the water masks usually do not map the rapid surface runoff, which could also lead to structural damage of buildings. Hence, the development of concepts and readily applicable tools to reliably estimate the damage particularly to infrastructure is an important emerging goal.

The high death toll along the river Ahr could however not just be related to the shortcomings of damage estimates discussed above. A further effect was the general underestimation of the flood magnitude by locals due to an anticipation legacy. During the 2016 flood in the Ahr valley, discharge was estimated to resemble a 100-year event (Demuth et al., 2022). In 2021, residents tended to recall that past event and the way they coped with it. Since the 2021 event was considerably higher and accompanied by geomorphic processes, this ultimately led to an underestimation of its impact. An online survey that was conducted from August to October 2021 in the affected areas (Thieken et al., in prep.) revealed that based on the warnings just 14.8 % of 856 warned residents anticipated massive damage and life-threatening situations (assessed on a Likert-scale from 1 to 6). In addition, public authorities, particularly in the district of Ahrweiler, evacuated very late in the evening when the water had already flooded houses. Hence, many residents endured this threatening flood situation on the roofs of their buildings (or drowned).

3.5 Interactions and process connections

Landscape elements and process domains are typically linked by the river network that drains them. Hence, changes in equilibrium processes such as sediment fluxes into a river, ponding, or advancing flood waves can be seen as input signals that are transmitted downstream while becoming modulated in their response. The magnitude and filter function of this modulation can be so strong that the initial input signal is no longer discernible; it gets shredded (Jerolmack and Paola, 2010). One example of this concept, namely the change of the flood's hydrograph by cascades of clogged bridges, has been described in section 2.3. Nevertheless, the modulated response (here the modulated flood wave) still severely impacts downstream reaches – and sometimes even upstream reaches. We follow this concept of signal shredding during landscape interaction through connection mechanisms in the Erft catchment (Fig. 1).

At a comparably small scale, the town of Blessem on the Erft river was subject to such an emerging landscape connectivity case. The excess rain water of Blessem was collected and channelized in pipes below the main road (Frauenthaler Straße, then passed to Radmacherstraße). These pipes ended in a drainage ditch at the western town limit that routed the water towards the Erft river (Fig. 6b), passing by a gravel pit that was protected by a few meter high rampart. During the flood, overbank discharge of the Erft river moved water across the main streets of Blessem (light blue arrows in Fig. 6) and injected excess discharge into the drainage pipes but also ran as overland flow along the streets. In addition, Erft overbank discharge was routed over a field west of the town, towards the drainage ditch already carrying the town's excess water. Whether that excess water caused overspilling of the 2 m deep drainage ditch or if the additional water inflow from the field caused the overspill cannot be resolved here. Regardless, the ditch overtopped and discharge followed the line of steepest descent into the gravel pit, whose protection rampart was not fully closed but had a gap through which the water could enter the pit. As the flow path gradient changed from less than 1 to about 20 degrees down the pit slope, the shear stress increased by two orders of magnitude (Anderson and Anderson, 2010). This high shear stress, combined with the high erodibility of the underlying material (a thin loess cover on tertiary Rhine gravel), resulted in extremely rapid erosion and the development of an erosional margin (yellow line in Fig. 5) that cut backwards by about 250 m within a few hours. The final shape of the erosional margin shows four discrete tongues of enhanced slope retreat (cf. numbered triangles in Fig. 6), which correspond to the main sources of excess water: the road and drainage pipes running through the town of Blessem (triangle 1), two overflow spots of the river Erft across the field at the edge of the town (triangles 2 and 3), and ultimately, the river Erft itself (triangle 4), which routed its whole discharge into the eroded gravel pit. This led to rapid inundation of the pit, massive deposition of > 450,000 m^3 of material, enhanced lateral erosion along the (new) outer bank of the diverted river, as well as significant depth erosion not only of the new course of the river Erft but also in its old bed, forming a knickzone and resulting in a bed elevation lowering of 1.4–1.8 m.

Despite initial media reports of a landslide (i.e., a gravitational mass wasting process) happening near Blessem, all evidence rather imply that it actually was a process driven by flowing water. That process in turn was the result of a local process connection mechanism: backward erosion of the gravel pit margin. At the same time, the mechanism was also controlled by emerging feedbacks, i.e., the reduction of backward erosion by cessation of overbank discharge through base level lowering of the river Erft as it flowed into the gravel pit. Hence, what happened in Blessem is an example of how geomorphic processes first amplified and later counteracted the impact of a hydrological extreme event.

At a larger scale, the Blessem site was almost subject to another process connection case, which would have delivered a further significant wave of water. Through the rivers Erft, Swist and Schießbach, the town is connected to the Steinbach reservoir some 30 km upstream (Fig. 1). The 12 m high earth dam of that reservoir was severely dissected by sustained crown overspill for several hours during the flood event. Gullies of 10 m width and up to 4 m depth formed over a length of about 100 m (quantified by UAV based structure from motion topographic data). If the Steinbach reservoir dam had failed, another 1.2 Mio. m^3 of water would have moved downstream, most likely refuelling the erosion processes in Blessem with another new flood wave all along the river's course from the reservoir.
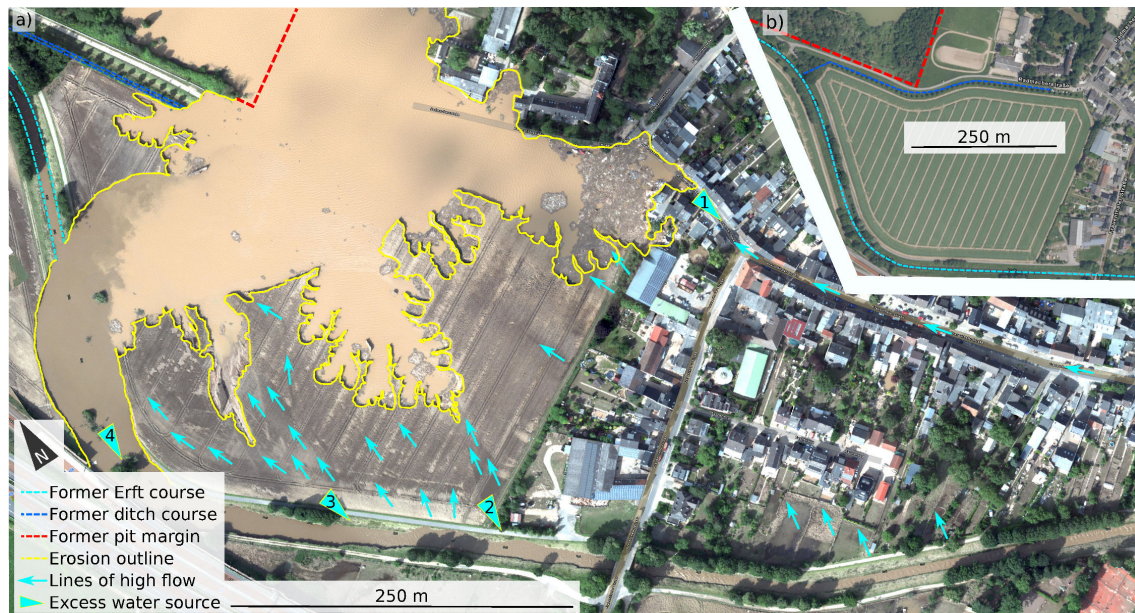
Figure 6. Aerial image (BBK-DLR, 2022) of the town of Blessem. a) Situation shortly after the flood event, with annotated features. The top right inset (b) shows conditions before the flood. The break in slope along the margin of a gravel pit (red dashed line) had started to erode towards the town by fluvial erosion (yellow line) that formed three individual clusters. The erosion was fuelled by overbank discharge of the Erft river, evading the town of Blessem and moving down the main street as well water flowing over the field west of the town margin, following the line of steepest descent. Water flow directions are indicated by blue arrows where visible from aerial imagery. The four numbered blue triangles depict sites of increased water input towards the pit.

4 Challenges and future needs

A particular phenomenon of the July 2021 flood was the widespread activity of mostly small features that ultimately added up to unexpectedly large effects in the main valleys of the Ahr and Erft rivers. There was not one dominating factor that can explain the event magnitude, but rather the interaction of many seemingly unrelated effects, a situation that needs to be considered jointly, and conceptualised and implemented in predictive models as well as upcoming mitigation strategies. Some of these isolated effects were straightforward to detect and can be implemented in future strategies, such as insufficiently designed bridges or protective dams. Other effects are inherently difficult to identify and even harder to conceptualise and ultimately implement into models and risk management strategies. Examples for the latter category are tile drainage systems of unknown extent and capacity or injected versus ejected volumes of sediment. These latter effects could, however, be incorporated to the models via Monte Carlo simulations, e.g., considering the full range of potential sediment budget, to at least quantify within the uncertainties bounds of the model estimates.

These emerging effects rendered the flood an extreme beyond the hydrological scope. Hence, this underlines the need for a cross-topic consideration of its internal and external drivers, its effects, and its internal feedbacks. This touches especially

the non-hydrological processes and their representation in posterior models, future predictions and concepts as well as hazard zone definitions, in addition to the fruitful efforts already emerging from the hydrological realm. For example, while it is evidently important to provide close range forecasting of potentially inundated areas, it is as important to develop and implement methods to forecast potential effects driven by overland flow and stream discharge. These include outlining potentially unstable hillslopes, riverbed changes, cascading effects and landscape connectivity effects. Connectivity effects do not necessarily need to be restricted to gravel pits and upstream water reservoirs, as revealed here. More likely are far-reaching effects, for example triggered by blocked tunnels, undermined bridges, valley damming mass wasting deposits and channel straightening that swiftly initiate long lasting effects.

Upcoming fundamental research needs to quantify the severity and modes of landscape reorganisation as well as constraining the duration of the transient that is now dominating the functional relationships of the affected regions. Key elements of these functional relationships are the reorganisation of the hydraulic geometry, the fluvial and sediment coupling between channels and adjacent hillslopes, and landuse and settlement planning. Approaching all these questions crucially depends on dedicated, high resolution and continuous empirical data from distributed field instrumentation (also properly operating during future extreme events) in close junction with metrics of societal activities. The 2021 flood clearly demonstrated a flaw in classic flood sensing approaches: collection of just a single metric, water level, by gauges at a few spots along the main stream, that overall got destroyed significantly before peak discharge had arrived. To overcome this systematic shortcoming, other systems need to be implemented, systems that are able to collect distributed multivariate data at high temporal resolution and that are not endangered by hostile flood conditions. For example, at scales from global to small catchments Ekström and Stark (2013), Cook et al. (2021), Walter et al. (2017) seismic networks have proven to deliver near real time information that allow the detection, location and description of catastrophic mass wasting events. Instead of just the main channel, such high quality flood related process information should also be available for headwater regions, where the 2021 flood gained its momentum and non-linearity.

Headwater regions are also the areas where proper flood risk reduction actions can be implemented. The German Federal Water Act allows the federal states to identify flood generating areas, which are areas that tend to quickly produce surface runoff. Land management can be regulated in such statutory areas to prevent further deterioration of the infiltration capacities of soils. Currently, only the Freestate of Saxony makes use of this option. Besides land management planning and engineering solutions, flood risk reduction decisively needs to consider sensibilisation of citizens to overcome the anticipation bias due to the legacy of experienced events of lower magnitude of less non-linear effects.

Data availability. All data used in this article are freely available under the references denoted in the text.

Author contributions. MD and UO conceptualised the article, and collected field data. MD, RB, KCL, CA, AB AL, AT contributed to the field survey and mapping efforts. BD contributed landslide data base analysis. FF, KN, TS and AT performed and evaluated climatic and hydraulic risk and damage analysis. All authors contributed equally to the preparation and writing of the manuscript.

340 *Competing interests.* The authors declare there are no competing interests.

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