Bridge Clogging in Belgium and Germany during the 2021 Floods

Daan Willem Poppema[1], Lisa Burghardt[2], Loïc Bénet[3], Davide Wüthrich[1], Elena-Maria Klopries[2], Benjamin Dewals[3], and Sebastien Erpicum[3]

[1]Delft University of Technology
[2]Rheinisch Westfälische Technische Hochschule Aachen
[3]University of Liège

November 01, 2024

Abstract

In the summer of 2021, devastating river floods occurred in Western Europe as a result of extreme rainfall. At numerous bridges, debris accumulations were observed, exacerbating flooding upstream by impeding waterflow and sometimes contributing to bridge failure. Due to widespread building damage and flooding of settlements along the rivers, these accumulations differed markedly from classic logjams, with substantial amounts of man-made objects. A new database of clogged bridges in Belgium and Germany – described in a separate data descriptor – was analysed to characterise bridge clogging and determine the effect of bridge design, bridge location and hydraulic conditions. Nearly half of the debris volume consisted of man-made materials, including building rubble, anthropogenic wood and vehicles. This created remarkably dense accumulations, highlighting the importance of further studying debris accumulations of mixed composition. Examination of the relations between bridge design and accumulation volumes found bridges with narrow pier spacing ([?]10 metres) more susceptible to forming large accumulations. Blocking by the deck and railing also played a prominent role, in conjunction with blocking by the piers, as peak water levels at most bridges (85%) reached or exceeded the deck. These findings can help to better understand bridge clogging effects on flood conditions, to design bridges with lower debris accumulation risks, and to inform future flood hazard assessments, flood risk mapping, and disaster response strategies, especially in urbanised regions.

Hosted file

`Bridge Clogging in Belgium and Germany during the 2021 Floods.docx` available at https://authorea.com/users/849345/articles/1236444-bridge-clogging-in-belgium-and-germany-during-the-2021-floods

Bridge Clogging in Belgium and Germany during the 2021 Floods

Daan Poppema[1]*, Lisa Burghardt[2]*, Loïc Benet[3], Davide Wüthrich[1], Elena-Maria Klopries[2], Benjamin Dewals[3], Sébastien Erpicum[3]

[1] Delft University of Technology, [2] RWTH Aachen, [3] Université de Liège

* Corresponding authors: d.w.poppema@tudelft.nl; burghardt@iww.rwth-aachen.de

Highlights

- Debris accumulations at 71 bridges are analysed, detailing bridge characteristics and debris properties (volume, geometry, composition).
- Debris composition showed a surprisingly large fraction of man-made materials (50%): mainly building rubble, construction wood and vehicles.
- At 85% of the bridges, water reached or exceeded the deck, highlighting the importance of the deck and railing design for bridge clogging.

Abstract

In the summer of 2021, devastating river floods occurred in Western Europe as a result of extreme rainfall. At numerous bridges, debris accumulations were observed, exacerbating flooding upstream by impeding waterflow and sometimes contributing to bridge failure. Due to widespread building damage and flooding of settlements along the rivers, these accumulations differed markedly from classic logjams, with substantial amounts of man-made objects. A new database of clogged bridges in Belgium and Germany – described in a separate data descriptor – was analysed to characterise bridge clogging and determine the effect of bridge design, bridge location and hydraulic conditions. Nearly half of the debris volume consisted of man-made materials, including building rubble, anthropogenic wood and vehicles. This created remarkably dense accumulations, highlighting the importance of further studying debris accumulations of mixed composition. Examination of the relations between bridge design and accumulation volumes found bridges with narrow pier spacing (≤10 metres) more susceptible to forming large accumulations. Blocking by the deck and railing also played a prominent role, in conjunction with blocking by the piers, as peak water levels at most bridges (85%) reached or exceeded the deck. These findings can help to better understand bridge clogging effects on flood conditions, to design bridges with lower debris accumulation risks, and to inform future flood hazard assessments, flood risk mapping, and disaster response strategies, especially in urbanised regions.

Plain language summary

In 2021, devastating river floods hit Western Europe. During these floods, floating debris built up in front of many bridges. This increased flooding by partly blocking rivers and contributed to the failure of bridges. Usually, accumulations mainly include trees, but this time they contained large amounts of building rubble and man-made objects, from flooded and damaged buildings along the river. To study this issue, we documented bridge clogging during the 2021 flood in Belgium and Germany in a database. Analysis showed that about half of the documented debris was from man-made materials, including building rubble, construction wood, cars and caravans. This resulted in remarkably dense accumulations, with more flow resistance and a larger increase in upstream water levels. This highlights that accumulations of mixed debris should be studied more in the future. The largest accumulations happened at bridges with piers placed 10 metres or less apart. Debris blocking by the deck and railing also played a prominent role, as most debris was blocked by flooded bridges, with a submerged deck. These findings can help to design bridges with lower risk of debris blockages, and inform disaster response strategies of where to expect debris accumulation during floods.

1. Introduction

During the summer of 2021, Western Europe experienced a catastrophic flood event, with rainfall of 150 mm to more than 250 mm within 48 hours in parts of Belgium, Germany, and neighbouring countries (Journée et al., 2023; Mohr et al., 2023), which represents three months of averaged precipitations within two days. The flood left a trail of devastation in its wake: destroying buildings, roads, railways, bridges and other infrastructure (Wüthrich et al., 2024), creating more than 30 billion euros of damages (Koks et al., 2021) and leading to at least 221 fatalities (Journée et al., 2023; Thieken et al., 2023). In addition to the immense water discharges, the debris that was transported in the flow caused substantial problems. Debris from destroyed infrastructure (rubbles) alongside with trees, vehicles and other objects were carried away by the floodwaters and subsequently found in the inundated areas. All this floating debris would often be blocked at bridges, creating debris accumulations (see e.g. Figure 1) reducing the conveying capacity of an already overloaded water infrastructure.

These debris accumulations can have devastating consequences on critical infrastructure, as well as on the extent of the flood. They constrict bridge openings and obstruct the flow, leading to backwater rise and increased inundation depths (De Cicco et al., 2018; Schalko et al., 2019; Schalko et al., 2018; Schmocker & Hager, 2013). And crucially, most bridges are built in populated urban areas, so the increased flooding occurs at locations where consequences can be enormous, both in terms of damages as well as disruption to critical services. In addition, debris accumulations can contribute to bridge failure, by increasing the forces acting on a bridge (Kimura et al., 2017; Oudenbroek et al., 2018; Parola et al., 2000) or causing scour that undermines bridge foundations (Diehl, 1997; Lagasse et al., 2010; Pagliara & Carnacina, 2011). As bridges are crucial infrastructure, such failure may have larger consequences. During the 2021 flood, this became painfully clear in the Ahr valley in Germany, where 41 bridges were destroyed by the flood (Burghardt et al., 2024a), severely limiting emergency services and disaster relief for cut-off settlements. These effects underline that debris clogging can play a critical role in exacerbating flood impacts.

These processes highlight the critical need to understand and address the role of debris accumulation during flood events. This subject has received quite some attention in the past, but most available studies focus on accumulations consisting entirely of trees in mountain areas (see e.g. the reviews in Comiti et al., 2016; De Cicco et al., 2018). Multiple studies also showed the critical role of debris during coastal flooding, as large volumes of debris transported by tsunamis and storm surges can propagate inland, causing supplementary forces and impulsive destruction (Chock et al., 2013; Robertson et al., 2007; Saatcioglu et al., 2005; Takahashi et al., 2010; Wüthrich et al., 2020). Specifically for tsunamis, Naito et al. (2014) provided a classification of potential debris, while studying its motion in coastal areas and effects on the built environment. Results pointed out heterogeneous debris mixtures containing shipping containers, vehicles (boats, vessels, cars), utility poles, dislodged buildings and

trees, if present along the coastline. Similarly, during the 2021 flood, the widespread flooding of more urbanised areas brought vehicles, building rubble and many other objects into the debris accumulations (Erpicum et al., 2024b; Korswagen et al., 2022), in contrast to the previously studied accumulations in mountain areas with more natural land use. This is also the reason why the term *'floating debris'* is used throughout this paper. In contrast, for accumulations with only trees, 'large wood accumulation' or 'logjam' are often preferred as more positive terms, in view of the ecological benefits of deadwood in rivers (Ruiz-Villanueva et al., 2016; Wohl et al., 2016).

Figure 1: A debris accumulation in Bad Neuenahr, Germany (bridge 16 in the database by Erpicum et al. (2024)). Trees, vehicles, tanks and other objects are present in front and on top of the bridge, with debris interlocking with the bridge superstructure. Photo by Philipp von Ditfurth (Jannaschk, 2021).

Observations suggest that the different shapes and materials of man-made objects compared to trees change the accumulation process, flow resistance, backwater rise and interlocking with other debris or bridge elements (see Figure 1, and Bayón et al., 2024; Burghardt et al., 2024b). However, quantifying these effects requires systematic knowledge of the composition and characteristics of these heterogeneous mixed debris accumulations, which is currently much more limited than for natural debris accumulations (Table 1). Moreover, such a comprehensive understanding of the mixture composition can support the development of realistic physical models to better reproduce the hydraulic processes occurring during floods. In addition, analysis of the accumulations and the main features of the bridges at which these occurred can help identifying how bridge design can be optimised to decrease the probability of debris accumulation. This would be especially useful for regions affected by the 2021 flood, where some bridges were destroyed and still need to be rebuilt, but equally advantageous for future bridge design in general. Lastly, improved knowledge on the accumulation characteristics and on the effect of bridge design will help to improve flood risk assessments and damage estimations, in the mapping of future flood risks or in evacuation decisions during floods.

Table 1: Debris composition measurements reported in literature

Study	Flood event	Debris location	Debris contents
Waldner et al. (2007)	Switzerland, 2005	40 driftwood accumulations, in Swiss streams and at lakes	On average 33% of the accumulation volume was deadwood (ranging from 12% to 55%), 58% fresh wood (ranging 15%-80%), 9% construction and firewood (ranging 5%-20%). Of the not yet cleaned-up accumulations, half of the volume consisted of pieces shorter than 7 m. For the full size distribution, see their Fig. 9.8.
Rickli et al. (2018)	None, regular conditions	In-stream large wood in 10 small Swiss mountain streams	By count, 6% of the large wood pieces consisted of entire trees, 20% snags with rootwads, 7% rootwads, 63% parts of logs, 4% parts of crowns. Half of the wood volume consisted of pieces shorter than 7 m. For the full size distribution, see their Fig. 3.
Bänziger (1990)	Switzerland, 1987	Accumulations of 1700 m^3 total around Goms, Switzerland	35% of the accumulation volume was deadwood, 48% fresh wood, 17% construction and firewood. The median log length (by piece count, not volume) was 4 m. For the full size distribution, see their Fig. 7.
Manners et al. (2007)	None: regular conditions	3 bank accumulations at the Indian River (Hudson River watershed, USA)	On average, 69% of the accumulation volume was large wood (diameter>10 cm), 17% medium wood (1 cm<*d*<10 cm), 5% small wood (*d*<1 cm), 7% leaves, 2% soil.
Diehl (1997)	Multiple	144 field investigations of driftwood accumulations at bridges across the USA	Predominantly natural wood: two small accumulations contained 50% trash, three accumulations largely saw logs from storage areas, one contained parts of a boat and dock, for the other accumulations the presence of human artefacts was insignificant.
Bayón et al. (2023, 2023b)	63 flood events in 46 countries	Urban, worldwide	Of 269 photos with debris ('urban flood drifters') present in streets or rivers, 37% of the photos contained vehicles (predominantly cars), 7% furniture, 22% plastic debris, 21% construction debris, 18% woody debris, 10% metal debris and 9 % other debris.

Therefore, *this study aims* to characterise bridge clogging in Belgium and Germany during the 2021 floods and to determine the effect of bridge design, bridge location and hydraulic conditions on the observed clogging.

2. Methodology

2.1. Study area

For this study, the clogging of bridges along six rivers in Belgium and Germany during the 2021 flood event was investigated. The rivers Ahr, Inde and Vicht are situated (largely) in western Germany, the Vesdre, Helle and Hoëgne (largely) in Belgium (Figure 2, Table 2). The Ahr, which originates in Blankenheim at 520 m above sea level and joins the river Rhine near Sinzig, is the largest river in this study (Table 2) and the only one that belongs to the Rhine catchment area. It is characterised by steep hillsides and confined bedrock of sandstone, siltstone and clay slate. The share of urban areas increases in downstream direction, while the catchment area is dominated by forests and grasslands towards the source (MKUEM, 2019). The other five studied rivers are all part of the Meuse catchment.

The *Vicht* is a tributary of the *Inde*, which eventually joins the Rur in Germany. The Inde's discharge is regulated by a drinking water reservoir, the Wehebachtalsperre, at the Wehebach tributary.

In Belgium, debris accumulation was studied at the river Vesdre, and its tributaries Helle and Höegne. The *Vesdre* (Weser in German) originates in the High Fens plateau in north-eastern Wallonia. After 70 km, near Liege, it joins the Ourthe, i.e. the main Belgian tributary of the Meuse. The Vesdre dam (also called Eupen dam) just before the town of Eupen and the La Gileppe dam regulate discharge in the upper part of the catchment, and provide drinking water reservoirs of approximately 25 Mm^3 each. The lower part of the Vesdre region is mostly characterised by urban and industrial areas (Bauwens et al., 2011). The *Helle* (Hill in German) also originates in the High Fens plateau and merges with the Vesdre in Eupen (Vesdre river km 55, measured from its mouth). Upstream of the city of Eupen, a part of the Helle discharge is diverted through a tunnel into the aforementioned Vesdre dam (Bruwier et al., 2015). Lastly, the *Hoëgne* joins the Vesdre at Pepinster. The Hoëgne is not regulated by reservoirs, causing periodic flood events (Bruwier et al., 2015). Both the Helle and Hoëgne have comparatively steep slopes, of 1.6% and 1.7% (Table 2).

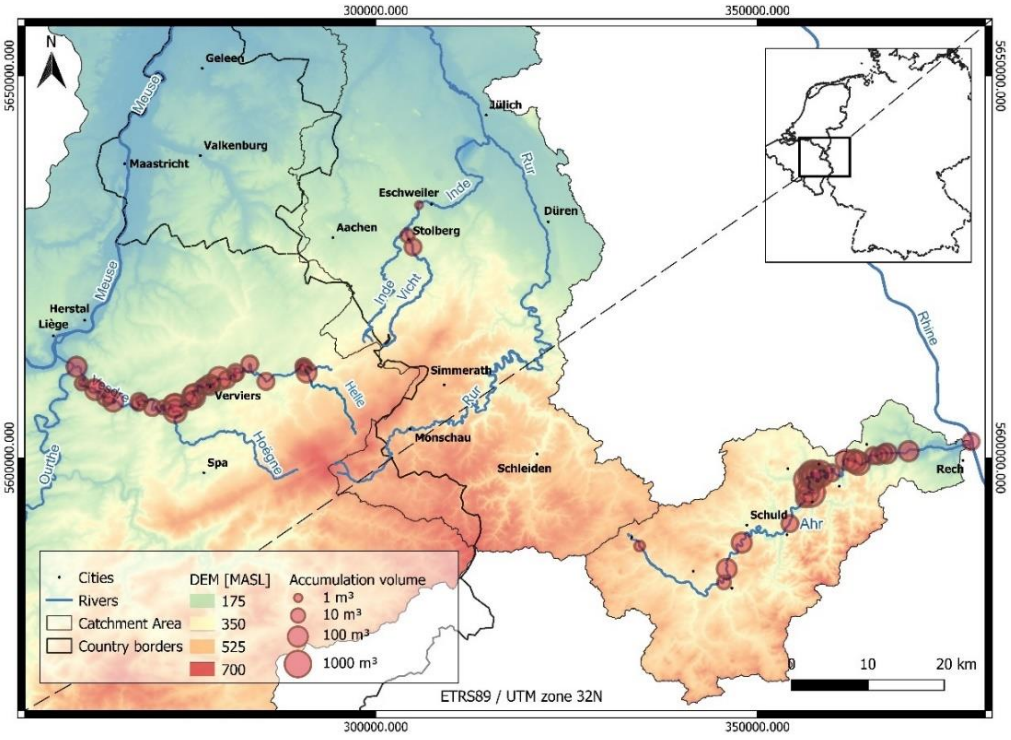

Figure 2: Map of the study area and the studied rivers, with debris accumulations indicated.

Table 2: Characteristics of the rivers examined in this study, including physical characteristics, average annual discharge and estimated peak discharge during the 2021 flood. Sources: (Bauwens et al., 2011; Bruwier et al., 2015; Cuvelier et al., 2018; Deroanne & Petit, 1999; Eifel-Rur, 2021a, 2021b; LfU, 2023; MKUEM, 2019; NRW, 2023a, 2023b)

	Tributary of	Catchment area [km²]	Length [km]	Average slope [%]	Average discharge [m³/s]	(Estimated) Discharge during 2021 flood [m³/s]
Ahr	Rhine	900	86	0.5	7	800-1200
Inde	Rur	344	47	0.7	2.8	>100
Vicht	Inde	104	23	1.1	0.6	>100
Vesdre	Ourthe	683	70	0.8	11	660
Helle	Vesdre	37	25	1.6	1.1	340
Hoëgne	Vesdre	200	30	1.7	3.5	265

2.2. Database construction and analysis

This paper presents an analysis derived from a database on debris accumulation at bridges in Belgium and Germany during the 2021 floods (Erpicum et al. 2024). A total of 71 bridges affected by debris clogging were studied (38 in Belgium and 33 in Germany, mainly at the rivers Vesdre resp. Ahr), mostly based on aerial and handheld photos of the accumulations taken during or just after the flood. This photo analysis was needed to provide reliable information on the nature of the accumulations, since field surveys arrived late to investigate debris, when accumulations had often already been removed and dismantled. The database and analysis focus on three main aspects of debris accumulation, as summarised in Figure 3:

(1) **Bridge properties**: bridge location, damage and geometry, including the general bridge design and properties of the piers, deck and railing.
(2) Local **hydraulic conditions**, including estimated peak water levels, discharge and the flow width during the 2021 flood.
(3) **Accumulation properties**, including estimated accumulation dimensions, its location at the bridge, and the debris composition.

For each of these categories, the main data collection methods for the database and the analysis steps are discussed below. Further details of the database construction as well as the database itself can be found in the companion data descriptor (Erpicum et al., 2024b).

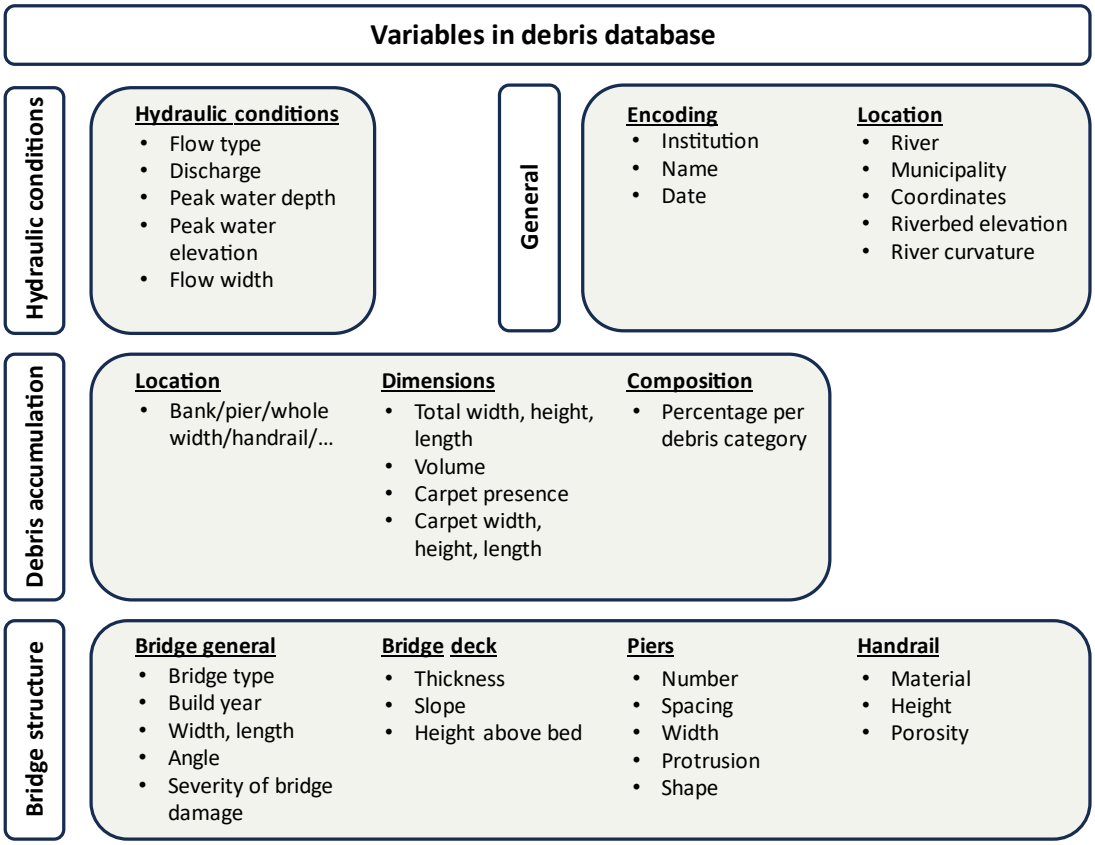

Figure 3: Overview of the main variables documented in the debris database

2.2.1. Bridge properties

For the bridge properties, the database documents the bridge location, observed damage and the design of the bridge in general, bridge deck, piers and handrail (Figure 3). Bridge properties are based on the following sources:

(1) Construction drawings, received from the Landesbetrieb Mobilität Rheinland-Pfalz or Deutsche Bahn in Germany, and Service Public de Wallonie in Belgium.

(2) An online cartographic portal of the 2021 flood event with georeferenced maps and aerial photos for Germany (https://arcgis.bbk.itzbund.de/arcgis/apps/sites/#/hochwasser2021) and pre-event georeferenced maps and aerial views for Belgium (www.geoportail.wallonie.be/walonmap).

(3) In situ measurements (if access to the structure or part of it was possible).

(4) Post-event pictures.

When multiple information sources were available, the first available source on the list was used, ensuring maximum data accuracy with a reasonable measurement effort.

2.2.2. Local hydraulic conditions

Local hydraulic conditions in the database include estimates per bridge of the peak water level, discharge and, for the Ahr valley, the flow width (maximum horizontal extent of the flooded area at the bridge location). Peak water levels and discharges at the Arh are based on reconstructed gauge data from the State Office Landesamt für Umwelt Rheinland-Pfalz in Germany; the flow widths are

based on field surveying and estimated coverage of the inundation areas conducted by the same state office (personal communication, 2022). Data for the Inde and Vicht is provided by the WVER Wasserverband Eiful-Rur (personal communication, 2022). In Belgium, water levels are based on a post-event field survey performed by the Walloon Administration. Discharges are based on hydrological modelling of the flood event from distributed rain data performed by Dessers et al. (2023).

2.2.3. Accumulation properties

Accumulation properties are based on the analysis of handheld and aerial photos taken during or directly after the flood. For the 71 bridges investigated, a total 205 photos with visible debris were used, sourced from local governments, news agencies, inhabitants of the area and social media. The accumulation properties include:

- The total length, width and height of the accumulation, measured from accumulation edge to edge (e.g. from the most upstream to the most downstream point, measured parallel to the river axis).
- The accumulation volume, measured by compartmentalizing accumulations into sections (blocks) and estimating the visible width *W*, length *L*, height *H* and hence volume *V* of each section (for an example, see Figure 3 in Erpicum et al. (2024b)). These volumes are based on the contours of accumulations, so they describe the bulk accumulation volume (including pores), not the solid volume.
- The debris composition, i.e. the estimated volume fraction of the debris categories listed in Table 3.

The software ImageJ (version 1.53) was used to measure lengths and surfaces from pictures, using data from the bridge's geometry or surrounding structures for scale. Information from photos from different perspectives, including aerial and handheld photos, was combined to obtain both horizontal and vertical dimensions. To maximise the accuracy of the estimations, three cases were initially analysed by three different researchers. This resulted in a refined procedure and more stringent definition of parameters, after which remaining variations between researchers were limited, e.g. up to 15% for accumulation volumes. For all following bridges, each evaluation was performed independently by two different researchers. If both estimations differed less than 15%, the average value was encoded in the database. If they differed by 15% or more, results were discussed to get a value approved by both researchers.

Based on the debris categories in the database (type A to H in Table 3), debris composition was additionally analysed in terms of debris shape, based on the premise that object shape likely governs the blocking probability, the degree of interlocking between debris pieces and the permeability of both individual debris and the full accumulation. Hereto, the debris volume is categorised as elongated

shapes (referred to as 'logs'), flat shapes ('plates') and bulky objects ('cubes'), in line with previous studies in coastal engineering, including Wüthrich et al. (2020) and Stolle et al. (2018). The volume of debris in each of the debris categories is assigned to these three shape classes, following the ratios in Table 3. This results in an estimate of the fraction of log-shaped, plate-shaped and cuboid debris in every accumulation, pivotal for the realistic reproduction of accumulations in physical models.

Table 3: The debris categories distinguished in the database, and the ratios used to translate this into volumes of log-shaped, plate-shaped and cuboid debris.

Debris type	Log fraction	Plate fraction	Cube Fraction
A - Natural wood (trees)	1	-	-
B - Anthropogenic wood (construction wood and woody debris)	0.5	0.5	-
C - Plastic tanks and containers	-	-	1
D - Metal tanks and containers			
E - Vehicles (cars and caravans)	-		1
F - Household items (furniture, appliances)	0.2	0.4	0.4
G - Industry items (large installations)	0.2	0.4	0.4
H - Building rubble (not fully wooden. E.g. roof parts, insulation)	0.5	0.5	-

This characterization of the debris accumulations relies on the analysis of photos, and hence on information visible on photos which were mostly taken after the flood event. This inherently means that the hidden part of any accumulation is assumed to be of similar composition as the visible outside surface. Also, the submerged part of accumulations is not visible, leading to an underestimation of debris volumes, especially for photos taken during the actual flood. Given the difficulty of detailed field observations in an area where immediate disaster relief and cleaning operations obviously take precedence, these limitations are deemed acceptable, especially because they allow for systematic characterization and analysis of bridge clogging in a larger area, rather than at a single bridge. Nonetheless, these caveats imply that data is more suitable for the overall characterization of bridge clogging and general trends, than for detailed quantitative conclusions on individual accumulations.

3. Results

3.1. Characterization of clogging

To characterise the clogging, it is important to examine the clogging locations, severity and differences between Belgium and Germany. The locations of the clogged bridges are indicated in Figure 2 and Figure 4A, B. In Belgium, 35 of the 38 bridges with clogging in the database are at the Vesdre, two at the Helle and one at the Hoëgne (tributaries of the Vesdre). Clogging was especially severe in Pepinster and Verviers (river km 33 to 24). In Germany, 30 of the 33 clogged bridges in the database are at the Ahr, one at the Inde and two at the Vicht. Clogging was especially severe around Altenahr, Kreuzberg and Pützfield (river km 37 to 28), with the only observed accumulations of a volume of more than 3,000 m^3 occurring within this area. Overall, these numbers mean that any comparison of database results between Belgium and Germany for the 2021 flood is very much dominated by the rivers Vesdre resp. Ahr. In both countries, bridge damage was substantial, with overall 18% of the considered bridges structurally compromised and a further 27% too damaged to be used (Figure 4C, 4D). On average, damage was more severe at the bridges with larger accumulations.

Comparing the accumulations in both countries, accumulations in Germany were generally larger, with a mean debris volume of 118 m^3 in Belgium vs 518 m^3 in Germany. Part of this is related to the Ahr being wider than the Vesdre. Consequently, normalised volumes of debris per meter of bridge length (i.e. m^3/m) decreases the disparity between countries somewhat (Figure 4E, 4F), but normalised debris volumes in Germany still remain larger. Both countries show many relatively small accumulations and a few very large accumulations, overall resulting in a spread of more than three orders of magnitude in the observed debris volumes.

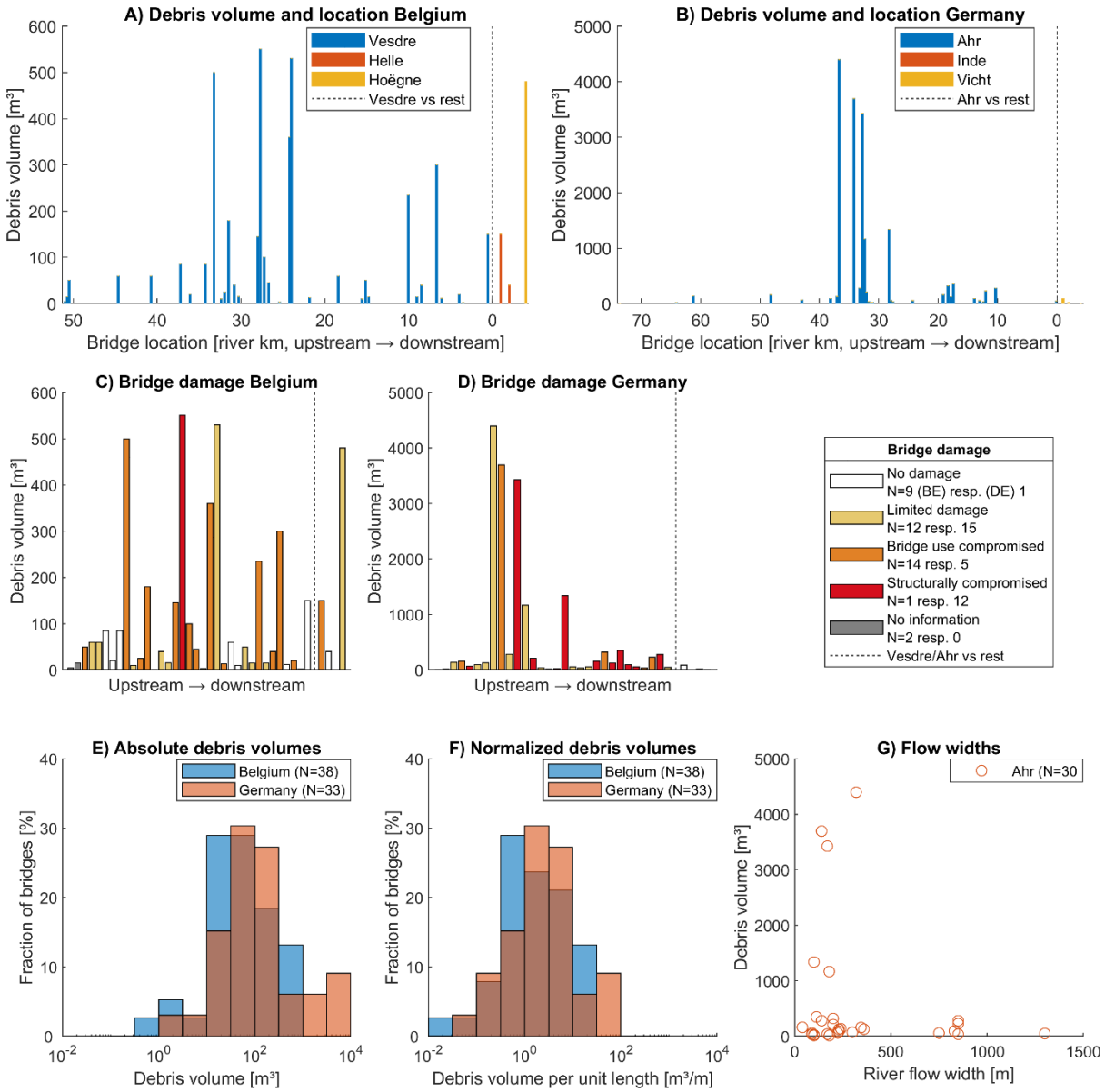

Figure 4: A) Plot of the debris volumes and the location of the blocked bridges in Belgium, measured along the path of the river Vesdre. Negative values indicate bridges on the Helle and Hoëgne (tributaries). B) Idem for Germany, with river km measured along the Ahr, negative values for the Inde and Vicht (different catchments). Note the different y-axis. C) and D) Bridge damage in both countries, plotted in the same order as subplot A and B, but evenly spread over the x-axis. Note the different y-axes. E) Comparison of absolute debris volumes at Belgian and German bridges. NB: logarithmic x-axis. F) Idem, with volumes normalised by bridge length. G) The width of the flooded area (river width) vs debris volumes for the river Ahr.

The actual flow width (width of the inundated area) during the flood was generally much wider than the river channel or bridge under "normal" conditions. The analysed data only contains flow widths for the Ahr bridges, showing a mean flow width of 330 m, compared to a mean bridge length of 55 m. This implies that substantial overbank flow and flooding occurred. Notably, the large accumulations occurred at relatively narrow flow widths (Figure 4G). Likely, this is explained by locations with the widest flow having had large flooded areas where debris could deposit, aided by trees, buildings and other obstacles in the floodplains that were able to catch floating debris. Contrarily, at places with a more constricted river, debris likely tended to follow the river channel, thus decreasing the chances of being stuck along the way and increasing those of reaching the bridge.

3.2. Case studies: extreme accumulations

A closer examination of the largest accumulations, presented in Table 4, shows substantial variation between cases. The largest accumulation, approximately 4,400 m³ consisting primarily of trees, occurred at the riverbank right next to a bridge in Pützfeld, Germany (Figure 5A). The debris' location against the railway track (built as a raised embankment) means the debris accumulation likely generated relatively limited flow resistance and backwater rise. However, it shows the large amount of debris transported during the flood, which could under different circumstances (e.g. different river curvature or bridge angle) accumulate in the river channel. The second largest accumulation (Figure 5B, ~3,700 m³) is completely different, with a very dense accumulation in the channel in front of a railway bridge. This debris was mainly of anthropogenic (i.e. man-made) origin, including caravans, building rubble and tanks from heating systems. A similar accumulation (slightly less dense, with several cars and slightly more trees) occurred at two parallel bridges in Altenahr, visible on Figure 5C. Accumulations in Belgium were slightly smaller and generally without vehicles, but otherwise comparable in composition. For instance, the two accumulations visible in Figure 5D (in Pepinster, Belgium) both contained a mixture of trees and building rubble. This photo taken during the flood also shows the extent of the flooding and, from the water flowing down into the river in the middle of the photo, the backwater rise caused by the debris accumulation. In addition, the background shows a second clogged bridge, shortly after the first one.

Figure 5 Examples of clogged bridges in the database. A) Pützfeld, Germany (bridge id 63 in the database, taken after the flood). Photo based on an aerial survey by GeoFly GmbH and provided by Virtual City Systems. B) Kreuzberg, Germany (bridge id 62, after the flood). Source: Baumert (2024). C) Altenahr, Germany (bridge id 55 and 56, after the flood). Photo by Polizei Thüringen (2021). D) Pepinster, Belgium (foreground: bridge id 59; background: bridge id 60. During the flood) Credit: Vedia. The flow direction is from left to right and foreground to background.

Table 4: A characterization of the five largest accumulations of both countries in the database. Bridge id refers to the id's used in the database by Erpicum et al. (2024). River km gives the distance from the mouth of the respective river. Estimated debris volumes are given in m³ (V) and in m³ per meter of bridge length (V'). Deck height above bed refers to the underside of the deck. For bridges with multiple spans, the minimum span width (minimum distance between piers, or between pier and abutment) is given.

Country	Bridge ID	River	Municipality	River km	*V* [m³]	*V'* [m³/m]	Water depth [m]	Deck height above bed [m]	Deck thickness [m]	Number of piers	Span width [m]
Belgium	53	Vesdre	Verviers	27.7	550	14	7.2	6.0	1.0	3	6.4
	60	Vesdre	Pepinster	24.1	530	19	7.6	3.7	1.5	2	8.2
	112	Hoëgne	Pepinster	1.2*	460	21	4.6	3.4	1.4	1	9.3
	36	Vesdre	Verviers	33.2	400	12	7.1	4.2	1.5	2	10.5
	59	Vesdre	Pepinster	24.2	360	13	6.3	3.1	1.0	2	7.8
Germany	63†	Ahr	Pützfeld	36.7	4396	88	4.0	3.3	1.0	3	10.0
	62	Ahr	Kreuzberg	34.2	3695	62	9.0	4.5	0.8	3	5.5
	56‡	Ahr	Altenahr	32.4	3424	53	6.8	4.9	1.5	2	9.0
	47	Ahr	Altenahr	32.4	1337	27	9.0	5.8	1.3	1	20.0
	55‡	Ahr	Altenahr	28.1	1165	19	6.8	5.0	1.2	4	10.0

*1.2 km from the confluence with the Vesdre, which is at Vesdre river km 24.0.

†Debris accumulation located at the riverbank directly next to bridge.

‡Bridge 55 and 56 form a twin bridge, i.e. a road and railroad bridge about 15 m apart.

3.3. Debris contents

A multitude of different objects and materials was present in the debris accumulations, as visible in photos of accumulations (e.g. Figure 1, Figure 5). Detailed analysis of the type and volume of objects in the accumulations showed that on average about half of the material was natural wood (trees), in both Belgium and Germany (Figure 6A, 6B). The other half of the debris mixture was of anthropogenic origin, often in the form of anthropogenic wood (construction wood, cut and without bark) or building rubble (parts of roofs, insulation material, etc.) from upstream buildings destroyed by the flood. In Germany, a substantial fraction of the debris also consisted of vehicles: cars and caravans. These were not present on the photos of Belgian accumulations, probably because campsites or parking areas were not located directly along the river or not flooded as severely. Other debris types present are tanks and containers (shipping containers, water tanks, petroleum tanks of heating systems, etc), household items (furniture, electrical appliances) and industrial items (large equipment from factories along the river).

The composition of individual accumulations is shown in Figure 6C and 6D for all clogging events investigated in the present study (Figure 2). Overall, data showed different compositions at various bridges, showing a clear dependence on the geographical location as well as on the land use of the riverbanks. As an example, data shows that the overall vehicle volume in Germany is largely caused by the accumulation at river kilometre 34 that contained a large number of caravans (see the photo in Figure 5B). It shows the dependence of the debris composition on the local presence of transportable objects or materials, such as caravans at a campsite along the river. Similarly, the large accumulation volumes and high building rubble content around Ahr river kilometre 35 – i.e. the heavily

damaged towns of Altenahr and Kreuzberg – show that the debris volume and composition at bridges are directly linked to the local flooding severity and damage in an area.

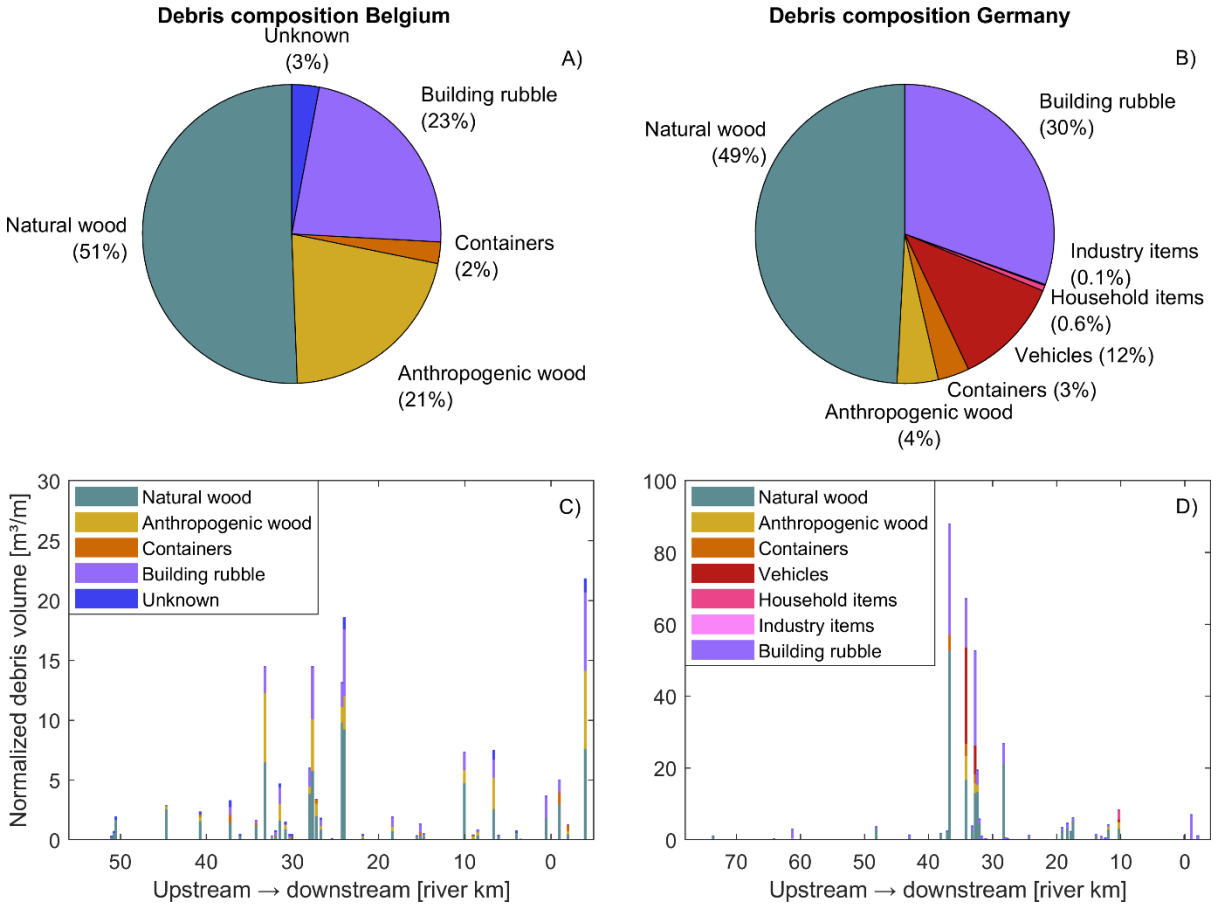

Figure 6: The composition of the accumulations in Belgium (subplot A and C) and Germany (B and D). The top row shows the volume fractions of the total debris volume per country, the bottom row the composition per accumulation.

The shape of the objects in the accumulations was analysed by examining the debris categories (Figure 6). Visual observations showed the presence of three main features: (1) elongated one-dimensional objects (here called 'logs'); (2) flat two-dimensional objects ('plates') and (3) voluminous three-dimensional objects ('cubes' or 'cuboids') in each of the categories, as previously discussed in Table 3. Due to the large fraction of natural wood present, all accumulations predominantly consisted of 1D log-shaped objects, as shown in Figure 7, where the percentage of all shapes is visualised in a triangular distribution. Accumulations consisting almost entirely of trees are plotted in the lower left corner of the triangles, including the largest accumulation of Germany (also shown in Figure 5A). Accumulations with logs and plates are plotted along the left edge of the triangle, including the largest accumulation of Belgium. Plate material reaches up to 35% in Belgium, 50% in Germany, often stemming from a high fraction of building rubble – where roof parts or insulation material are examples of flat objects – sometimes also from anthropogenic wood and household items. The accumulations belonging to the rightmost circles in both triangles are characterised by their high cube content (up to 45%), from tanks and containers in Belgium, mostly from vehicles in Germany. Lastly, there are a few accumulations with a substantial content of all three debris shapes, in the middle of

the triangles: e.g. three in Germany with 15%-25% cuboid objects, 20%-30% plate and 50%-65% logs. Overall, the large accumulations – which are most interesting from a water safety perspective – show especially in Germany quite mixed debris shapes.

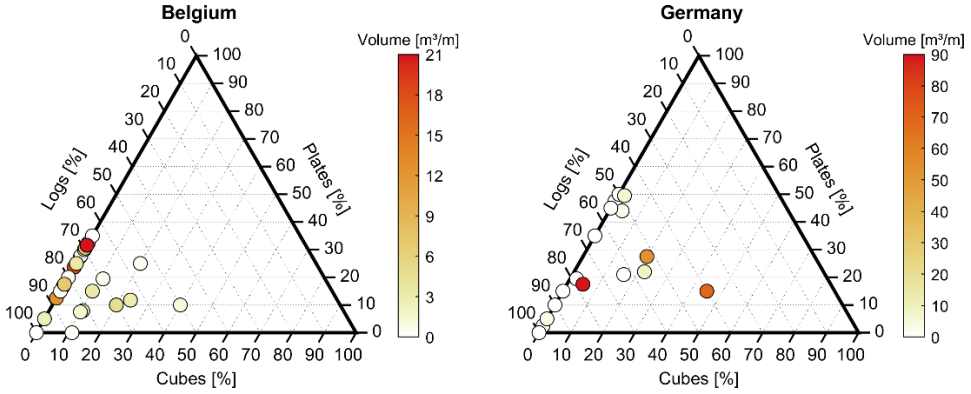

Figure 7: The estimated fraction of log-, plate- and cube-shaped objects in the debris accumulations. Each circle represents an accumulation in the database, colour-coded by volume, with its location along the three axes indicating the volume fraction of log-, plate- and cube-shaped objects in the debris mixture.

3.4. Effects of bridge design and hydraulic conditions

Accumulation volumes were linked to bridge designs and hydraulic conditions. Bridges can block debris and affect debris accumulation at their piers and deck. While the piers can block passing debris during regular conditions, effects from the deck and railing are only possible if the water level reaches the deck (or if the emerged part of floating debris is sufficiently high to collide with the deck). During the flood, most bridges in the database had (peak) water levels above the top of the bridge deck (Figure 8), meaning both the piers and deck generally contributed to a debris blocking.

Span width, i.e. the horizontal distance between piers or abutments, is known from literature to be a major influence on the *probability* of debris blockage (Diehl, 1997). A similar effect on accumulation *volume* is visible in our database (Figure 8). Most large accumulations occurred at span widths of approximately 10 metres or less, where trees longer than the distance between piers initiated clogging. Nonetheless, clogging also occurred at bridges without piers, where the abutments were too far apart to be bridged by trees (e.g. the upper right point in Figure 8C, with a span width of 40 m). The shape of bridge openings had little effect (Figure 8A, 8B) as data shows little difference between bridges with arched or rectangular openings. However, it is noticeable that the three largest accumulations in Germany were all railway bridges. Lastly, one can note that accumulations with more than 10 m^3/m are relatively rare in both countries; they make up 14% of the number of clogged bridges.

A limited freeboard (the distance between deck and water level) is also known to increase the *probability* of blocking (Schmocker & Hager, 2011). For the 2021 flood event, flooding was so extreme that peak water levels reached or exceeded the bridge deck for 85% of the studied bridges (circles above the dashed line in Figure 8C, 8D), frequently exceeding it by several meters. Almost all

substantial accumulations occurred when the water level reached or exceeded the bridge deck, supporting the importance of the bridge deck and railing for the occurrence of large accumulations.

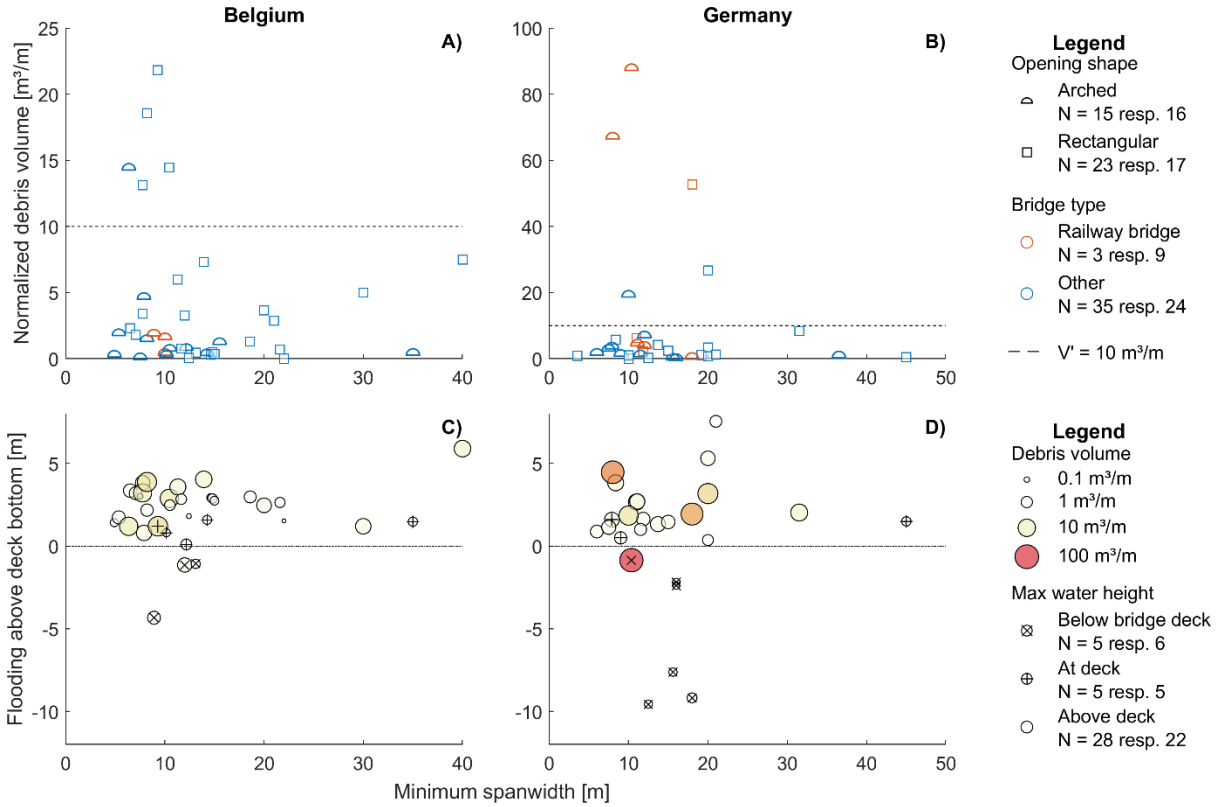

Figure 8: The effect of span width and (subplot A, B) bridge design or (C, D) maximum water levels on accumulation volumes in (A, C) Belgium and (B, D) Germany. Note: maximum water levels are indicated relative to the bottom of the bridge deck. Straight crosses in symbols indicate a flood height between the bottom and top of the deck. Generally, the largest debris volumes occurred at bridges where the span width was limited (≤10 m) and the water level reached or exceeded the deck.

Regarding railings, most bridges in the database have permeable metal structures, but in some cases solid stone walls are used. Figure 9 shows handrail porosities, debris volumes and water heights relative to the edge between the bridge deck and railing. For both countries, the largest accumulations occurred for highly permeable handrails, suggesting that the flow through the handrail might play a role in the accumulation process. In Belgium, no impermeable walls were present in the database, but in Germany, these impermeable railings (stone walls, indicated by blue circles) had considerably lower debris volumes. Interlocking of debris with permeable handrails likely played a role here in maintaining accumulations and preventing debris flowing over the bridge. Conversely, impervious handrails cause more flow resistance and backwater rise, leading to earlier overflow, and possibly earlier release of debris. Also, handrail damage may have enabled easier transport of debris over the bridge. However, firm statistically significant conclusions are difficult to draw since only at three impermeable railings water is actually estimated to have reached the railing. For the other impermeable railings, interaction between handrail and debris would only be possible for large objects floating on the water or for inaccurate height estimations. This means that the sample size in the current database is rather limited and further examination of the effect of low, medium and high handrail porosities (squares, diamonds and triangles in Figure 9) on accumulated debris volumes shows no clear trend.

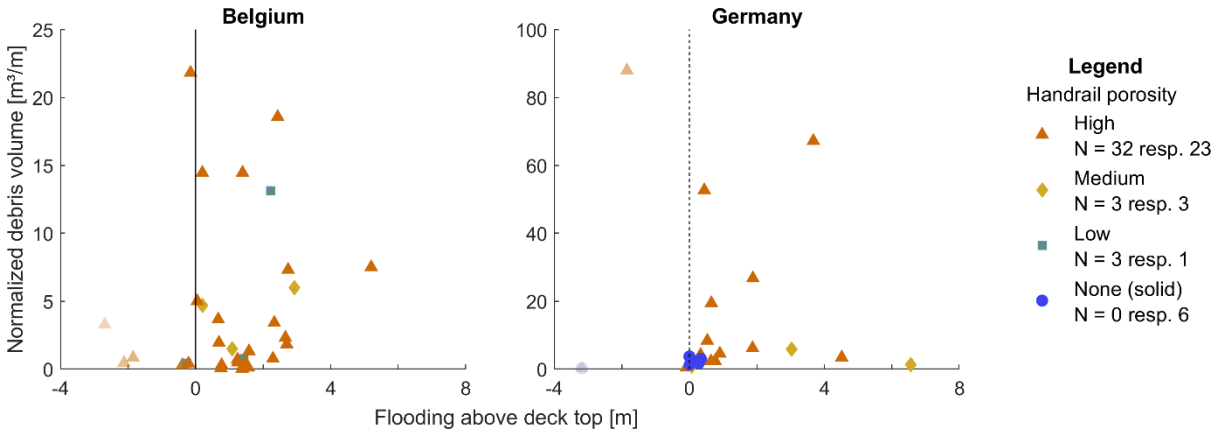

Figure 9: The effect of handrail porosity and flooding height on debris volumes in Belgium and Germany. The vertical dashed line indicates where peak water levels reached the edge between deck and handrail. Markers with lower water levels than this have increasing transparency to indicate the decreasing likelihood of debris interacting with the handrail. High porosity refers to handrail with thin elements and large spacing, medium to thin elements with low spacing, low to broad elements with low spacing and no porosity to solid walls.

4. Discussion

4.1. Debris content

Highly heterogeneous debris contents appeared as one of the typical features of the July 2021 flood in Belgium and Germany, with approximately half of the total debris volume of man-made origin, containing large amounts of building rubble (parts of roofs, walls, insulation, etc) and construction wood, smaller amounts of tanks, containers and household items (furniture, appliances) and occasionally vehicles (cars, caravans) in addition to trees. Typically, previous investigations reported accumulations that consisted almost entirely of trees, also referred to as 'log jam' or 'large wood accumulation'. As an example, in field investigations of 144 floating debris accumulations at bridges throughout the United States (Diehl, 1997), two small accumulations appeared to have a 50/50 split between trash and woody debris, one contained parts of a boat and dock; in all others the role of man-made objects was insignificant. This is the consequence of floods mostly occurring in natural areas, where bank erosion and flooding of forests along the river can bring large amounts of trees into the river (Diehl, 1997; Lucía et al., 2015; Rickenmann, 1997; Steeb et al., 2017). Nonetheless, large amounts of man-made objects have been reported before at floods in more urbanised areas. For instance, in a photo analysis of debris in rivers and streets after 63 floods in urbanised areas (Bayón et al., 2023, 2024), woody debris, plastic and building rubble were each visible on approximately 50%-60% of the *photos*, and affected vehicles on 35% of the photos. This is likely due to their focus on urbanised areas compared to the mix or urban and natural areas hit by the 2021 flood. Indeed, in our analysis, trees were visible on the large majority of photos, and made up approximately 50% of the *debris volume*. Similar observations were made during coastal flooding, where tsunamis and storm surges transported a large number of heterogeneous debris that accumulated as coastal structures, forming heavily packed '*debris-dams*' (Chock et al., 2013).

For natural woody debris, previous experiments repeatedly showed the importance of debris size, shape and type. Logs are less easily transported when they are longer, thicker or have rootstock

(Braudrick & Grant, 2000; Diehl, 1997). Once in transport, the probability of wood pieces to be blocked at bridges increases with increasing log length (Bezzola et al., 2002; Diehl, 1997; Gschnitzer et al., 2017; Schalko et al., 2020; Schmocker & Hager, 2011); with increasing stiffness (Hartlieb, 2015); or with increasing branching or rootstock presence (Bezzola et al., 2002; Gschnitzer et al., 2017). Once blocked, backwater rise increases with increasing specific density (Hartlieb, 2015) and decreasing log thickness (Follett et al., 2020; Schalko et al., 2019) – similar to how the flow rate of groundwater is lower in finer soils. Accordingly, mixtures with a higher organic fine material content (leaves, twigs) between logs also create more backwater rise (Schalko, 2018; Schalko et al., 2019). Hence, for debris mixtures with both man-made materials and natural wood, which inherently have an even larger spread in size, shape and density, debris properties must affect the accumulation process and backwater rise even more. Honingh et al. (2020) demonstrated that debris mixtures with plastic bags and bottles create denser accumulations and can more than double the backwater rise compared to pure logjams. Studies on more diverse mixtures or larger objects are scarce, but it stands to reason that observed impermeable flat objects, such as plastic sheet, sheet wood or wall panels from collapsed caravans (Figure 5B, 5C), lead to denser and less permeable accumulations and therefore to more backwater rise. This is supported by pictures of some accumulations (e.g. Figure 5B), which seem to form dams with low porosity and permeability. On the other hand, cuboid objects (containers) have been shown to exhibit a lesser interlocking nature and be washed away more easily by wave events (Wüthrich et al., 2020), so the same likely applies to cuboid objects in river accumulations. Apart from shape effects, man-made objects also exhibit more variation in material and hence density. Denser objects in the mixture, which are more easily pulled down (or even sink instead of floating), facilitate the generation of an accumulation that extends deeper into the water column instead of forming a floating carpet, thereby increasing backwater rise. Overall, these effects point towards mixed debris causing denser accumulations and more backwater rise. However, more research is needed to confirm and especially quantify these effects.

4.2. Bridge design

Analysis of the bridge designs and accumulations showed that bridges with large accumulations tend to have some common features. First and foremost, almost all large accumulations in both countries occurred at bridges with limited span widths. It was already well-known that the accumulation risk increases greatly at limited span widths, where a single tree can bridge the distance between two piers (or the abutments) and initiate clogging (Bocchiola et al., 2008; Diehl, 1997; Lange & Bezzola, 2006; Schmocker & Hager, 2011). However, the exact span widths at risk depend directly on the length of waterborne trees, and thus on the trees found in an upstream area. Hence, this study provides valuable quantification, that in this area a pier spacing of 10 metres or less substantially increases the debris accumulation risk. This is something that should be taken into account in the reconstruction of damaged bridges.

Furthermore, at almost all bridges with large accumulations, peak water levels reached or exceeded the deck. A few clogged bridges reported water levels below the deck – five in Belgium and six in Germany. Any causality between water levels and debris accumulation is likely bi-directional, with high water levels at the deck allowing for blockage by the deck and hence larger accumulations, while larger accumulations simultaneously cause more backwater rise. The importance of blockage at the deck and railing is further supported by clear cases of blocking by the deck, such as in Figure 1, where debris interlocks with the bridge deck and arch, at a bridge without piers. Moreover, the severity of the flood, with sometimes the bridge deck being flooded by 5 metres of water, means that debris could also pass *over* bridges (cf. Piton et al., 2020 on debris release at dams). Here, the design of the bridge superstructure plays a role in the degree of interlocking that occurs between debris and bridge. For instance, porous handrails are known to cause more debris to be stuck in the handrail (Schmocker & Hager, 2011), potentially fixing debris in place when water levels rise until (well) above the bridge deck.

Although the role of the deck and railing have received some attention in the past (Bezzola et al., 2002; Gschnitzer et al., 2017; Schmocker & Hager, 2011), most research has focused on the interaction between bridge piers and debris (e.g. De Cicco et al., 2020; Lagasse et al., 2010; Lyn et al., 2007; Panici & de Almeida, 2020; Panici & de Almeida, 2018; Schalko et al., 2020). The fact that 85% of the clogged bridges in the database experienced water levels at or above the deck calls for more specific research on the impact of deck and handrail design on bridge clogging. And as a more immediate implication for practice, the widespread bridge flooding and large water depths over the bridge (Figure 8) imply that building higher bridges could have large safety benefits, decreasing flow resistance and backwater rise by the deck itself, debris blockage by the deck, damage to the bridge and the likelihood of the bridge being unusable during or after a flood.

Regarding bridge types, the three largest accumulations in Germany were remarkably all railway bridges. It is possible that the raised construction of the connecting railway on embankments blocked debris (e.g. Figure 5A) or funnelled it toward the bridge, whereas roads would normally be constructed at lower elevations and therefore allow for more overland passage of debris. However, this hypothesis cannot be substantiated by data, given the low number of railway bridges within the dataset, as well as the absence of a similar trend in Belgium. Since the number of entries in the database was limited by the availability of bridges with both debris accumulation photos and corresponding structural data, this also calls for future research on bridge clogging during floods.

Lastly, we want to stress that debris clogging at bridges not only depends on the bridge design and hydraulic conditions, but also on the debris that reaches that location. This means that for blockage at a given bridge, debris must A) be ‘picked-up’ by the flow at some point upstream, B) not be blocked at any bridge in between, C) not be deposited anywhere else before reaching the bridge and D) not

simply flow *around* the bridge. Throughout this paper, all these aspects are present. The role of debris generation is visible in the debris composition, where a few bridges blocked a large number of caravans, made possible by the presence of flooded campsites upstream. Blockage at intermediate bridges is inherently present in the many closely spaced bridges in the area, and exemplified by the two clogged bridges in Figure 5D. The same photo illustrates how flooding well outside the actual river channel would allow debris to easily flow around a bridge. The observed trend that the sections of the Ahr with the largest flooded river width have smaller debris accumulations, is probably due to the same principle, and due to debris being trapped by trees, buildings or other obstacles in the flooded area. Overall, the importance of these codependent and chaotic processes means that any correlation between bridge design and debris clogging can easily be hidden. This also points out the need for further research to forecast the volumes of debris that might become available during future floods.

5. Conclusions

A database of debris clogging at Belgian and German bridges during the 2021 summer floods was developed. The observed debris accumulations at the bridges ranged in volume from a few m^3 to more than 4,000 m^3, i.e. up to 88 m^3 per meter of bridge length. Especially larger accumulations were able to disrupt the flow of the river and cause substantial backwater rise. During the 2021 floods, this intensified the flood consequences, increasing damage in an area already heavily afflicted by this extreme event. To better understand the potential danger that such accumulations can pose and where they are most likely to occur, the characteristics of the accumulations and related bridge features were studied in more detail.

About half of the debris volume was identified as man-made materials – building rubble, construction wood, vehicles, furniture, etc – due to flooding occurring in an area with narrow river valleys and towns built in the river floodplains. While most previous research focused on accumulations purely consisting of trees, this study shows that in 2021 trees only accounted for 50% of the average accumulation. This has major implications for the resulting backwater rise, as building rubble, (crushed) caravans and other man-made objects differ in shape, permeability and density from trees. Heterogeneous mixtures can form accumulations with a lower permeability and porosity than pure logjams, causing markedly more backwater rise. As a result, existing relations to estimate the backwater rise of natural accumulations can lead to a dangerous underestimation of the risks when making flood hazard maps or evacuation decisions in more urban environments. Hence, more research on the effect of debris shape and type on backwater rise is urgently needed.

Furthermore, the bridge design and damage status at all debris accumulations were studied. The debris accumulations and severity of the flood itself caused 45% of the clogged bridges to be structurally damaged, or otherwise too damaged to be used afterwards. In both countries, the largest accumulations occurred at bridges where the distance between piers was small (≤10 m), allowing logs

to bridge the distance between piers, thereby initiating further clogging. Simultaneously, at most of the bridges, peak water levels reached at least the bridge deck, and frequently exceeded it by several meters. This has major implications: first, having water reaching the deck means that the deck itself will be responsible for backwater rise, irrespective of the presence of debris. Secondly, it means that the deck and railing can block debris, in addition to the piers. Thirdly, having water well above the deck means debris might flow over the bridge and continue downstream, depending on the degree of debris interlocking. Consequently, the deck and handrail height and design are decisive factors in debris accumulation and backwater rise, and future studies on debris accumulation should explicitly take their role into account.

In summary, drawing on data gathered during the 2021 floods in Belgium and Germany, this research offers valuable insights into characterizing debris accumulations and main bridge features that triggered substantial clogging. It is believed that this information will be helpful in better understanding the processes associated with debris accumulation at bridges, as well as supporting the development of targeted debris management strategies to reduce flood risk during future events.

Acknowledgements

This research was carried out within the context of Interreg project EMfloodReselience, project no. 228, co-funded by the European Regional Development Fund. The authors thank Florence Dütz, Gianni Massin, Mariana Vélez Pérez, Lino Schröter, and Mariia Gimelbrant for their assistance in the photo analysis.

Data availability

The dataset used in this paper is described in the data descriptor by Erpicum et al. (2024b), under DOI 10.1038/s41597-024-03907-8 and can be found in (Erpicum et al., 2024a)Erpicum et al. (2024), under DOI 10.5281/zenodo.11551195.

References

Bänziger, R. (1990). Schwemmholz im Unwettersommer1987. *Schweizer Ingenieur und Architekt*, *108*(47), 1354. doi: 10.5169/seals-77563.

Baumert, J. (2024). Flut im Ahrtal: Klagt Staatsanwaltschaft den ehemaligen Landrat an? *Südwestrundfunk*. https://www.swr.de/swraktuell/rheinland-pfalz/koblenz/entscheidung-wird-ex-landrat-pfoehler-nach-flutkatastrophe-ahrtal-angeklagt-100.html

Bauwens, A., Sohier, C., & Degré, A. (2011). Hydrological response to climate change in the Lesse and the Vesdre catchments: contribution of a physically based model (Wallonia, Belgium). *Hydrol. Earth Syst. Sci.*, *15*(6), 1745-1756. doi: 10.5194/hess-15-1745-2011.

Bayón, A., Valero, D., & Franca, M. J. (2023). *Electronic supplementary material of 'Urban Flood Drifters (UFDs): identification, classification and characterization*. Retrieved 10-01-2024 from https://github.com/arnaubayon/UFD

Bayón, A., Valero, D., & Franca, M. J. (2024). Urban Flood Drifters (UFDs): identification, classification and characterisation. *Journal of Flood Risk Management*, *17*(3), e13002. doi: 10.1111/jfr3.13002.

Bezzola, G. R., Gantenbein, S., Hollenstein, R., & Minor, H. E. (2002). Verklausung von Brückenquerschnitten (Blocking of bridge cross-sections). *Proc. Intl. Symposium 'Methoden und Konzepte im Wasserbau'.* VAW-Titteilung 175: 87-97, ETH Zurich (in German).

Bocchiola, D., Rulli, M. C., & Rosso, R. (2008). A flume experiment on the formation of wood jams in rivers. *Water Resources Research*, *44*(2). doi: 10.1029/2006WR005846.

Braudrick, C. A., & Grant, G. E. (2000). When do logs move in rivers? *Water Resources Research*, *36*(2), 571-583. doi: 10.1029/1999WR900290.

Bruwier, M., Erpicum, S., Pirotton, M., Archambeau, P., & Dewals, B. J. (2015). Assessing the operation rules of a reservoir system based on a detailed modelling chain. *Nat. Hazards Earth Syst. Sci.*, *15*(3), 365-379. doi: 10.5194/nhess-15-365-2015.

Burghardt, L., Klopries, E.-M., & Schüttrumpf, H. (2024a). Structural damage, clogging, collapsing: Analysis of the bridge damage at the rivers Ahr, Inde and Vicht caused by the flood of 2021. *Journal of Flood Risk Management*, e13001. doi: 10.1111/jfr3.13001.

Burghardt, L., Poppema, D. W., Bénet, L., Wüthrich, D., Erpicum, S., & Klopries, E.-M. (2024b). Multi-lab investigation of the effect of debris composition on bridge clogging during floods. In R. M. Boes, I. Albayrak, S. Felder, B. Crookston, & V. Heller, 10th International Symposium on Hydraulic Structures (10th ISHS), ETH Zurich, Zurich, Switzerland.

Chock, G., Robertson, I., Kriebel, D., Francis, M., & Nistor, I. (2013). Tohoku, Japan, earthquake and tsunami of 2011: Performance of structures under tsunami loads.

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

Cuvelier, T., Archambeau, P., Dewals, B., & Louveaux, Q. (2018). Comparison Between Robust and Stochastic Optimisation for Long-term Reservoir Management Under Uncertainty. *Water Resources Management*, *32*(5), 1599-1614. doi: 10.1007/s11269-017-1893-1.

De Cicco, P. N., Paris, E., Ruiz-Villanueva, V., Solari, L., & Stoffel, M. (2018). In-channel wood-related hazards at bridges: A review. *River Research and Applications*, *34*(7), 617-628. doi: 10.1002/rra.3300.

De Cicco, P. N., Paris, E., Solari, L., & Ruiz-Villanueva, V. (2020). Bridge pier shape influence on wood accumulation: Outcomes from flume experiments and numerical modelling. *Journal of Flood Risk Management*, *13*(2), e12599.

Deroanne, C., & Petit, F. (1999). Longitudinal evaluation of the bed load size and of its mobilisation in a gravel bed river. In *Floods and Landslides: Integrated Risk Assessment* (pp. 335-342). Springer.

Dessers, C., Archambeau, P., Dewals, B., Erpicum, S., & Pirotton, M. (2023). Hydrological modelling of July 2021 floods in Vesdre and Amblève catchments. EGU General Assembly, Vienna, Austria.

Diehl, T. H. (1997). *Potential drift accumulation at bridges* (Report nr FHWA-RD-97-028). US Department of Transportation: Federal Highway Administration.

Eifel-Rur, W. (2021a). *Die Inde*. https://wver.de/fluss/die-inde/

Eifel-Rur, W. (2021b). *Die Vicht*. https://wver.de/fluss/die-vicht/

Erpicum, S., Poppema, D. W., Burghardt, L., Benet, L., Klopries, E.-M., Wüthrich, D., & Dewals, B. (2024a). *Database - Bridge clogging and debris - July 2021 flood* Version 1.0). doi: 10.5281/zenodo.11551195

Erpicum, S., Poppema, D. W., Burghardt, L., Benet, L., Wüthrich, D., Klopries, E.-M., & Dewals, B. (2024b). A dataset of floating debris accumulation at bridges after July 2021 flood in Germany and Belgium. *Scientific Data*, *11*(1), 1092. doi: 10.1038/s41597-024-03907-8.

Follett, E., Schalko, I., & Nepf, H. (2020). Momentum and Energy Predict the Backwater Rise Generated by a Large Wood Jam. *Geophysical Research Letters*, *47*(17). doi: 10.1029/2020GL089346.

Gschnitzer, T., Gems, B., Mazzorana, B., & Aufleger, M. (2017). Towards a robust assessment of bridge clogging processes in flood risk management. *Geomorphology*, *279*, 128-140. doi: 10.1016/j.geomorph.2016.11.002.

Hartlieb, A. (2015). *Schwemmholz in Fließgewässern--Gefahren und Lösungsmöglichkeiten. Habilitationsschrift*. Technische Universitat Munchen.

Honingh, D., van Emmerik, T., Uijttewaal, W., Kardhana, H., Hoes, O., & van de Giesen, N. (2020). Urban River Water Level Increase Through Plastic Waste Accumulation at a Rack Structure [Brief Research Report]. *Frontiers in Earth Science*, *8*. doi: 10.3389/feart.2020.00028.

Jannaschk, J. (2021). *"Haben so etwas wie dieses Hochwasser in der Form und Intensität noch nie erlebt": Feuerwehrmann berichtet von der Lage vor Ort im Katastrophengebiet Ahrweiler*.

Watson. https://www.watson.de/leben/nah-dran/611491321-flut-katastrophe-feuerwehrmann-berichtet-vor-ort-von-der-lage-in-ahrweiler

Journée, M., Goudenhoofdt, E., Vannitsem, S., & Delobbe, L. (2023). Quantitative rainfall analysis of the 2021 mid-July flood event in Belgium. *Hydrol. Earth Syst. Sci.*, *27*(17), 3169-3189. doi: 10.5194/hess-27-3169-2023.

Kimura, N., Tai, A., & Hashimoto, A. (2017). Flood caused by driftwood accumulation at a bridge. *International Journal of Disaster Resilience in the Built Environment*, *8*(5), 466-477.

Koks, E. E., Van Ginkel, K. C. H., Van Marle, M. J. E., & Lemnitzer, A. (2021). Brief communication: Critical infrastructure impacts of the 2021 mid-July western European flood event. *Natural Hazards and Earth System Sciences*, *22*(12), 3831-3838. doi: 10.5194/nhess-22-3831-2022.

Korswagen, P. A., Harish, S., Oetjen, J., & Wüthrich, D. (2022). *Post-flood field survey of the Ahr Valley (Germany): building damages and hydraulic aspects*. D. U. o. Technology. doi: 10.4233/uuid:3cafd772-facd-4e3a-8b1a-cee978562ff1.

Lagasse, P. F., Clopper, P. E., Zevenbergen, L. W., Spitz, W. J., & Girard, L. G. (2010). *Effects of debris on bridge pier scour,* (NCHRP Rep. 653). Transportation Research Board. doi: 10.17226/22955.

Lange, D., & Bezzola, G. R. (2006). Schwemmholz: Probleme und Lösungsansätze. *VAW-Mitteilungen*, *188*.

LfU. (2023). *Pegel Altenahr / Ahr (Gauge Altenahr / Ahr)*. Landesamt für Umwelt (LfU) Rheinland-Pfalz - Hochwasservorhersagezentrale (Environmental Agency of Rhineland-Palatinate - Flood Forecasting Center). https://www.hochwasser.rlp.de/flussgebiet/ahr/bad-bodendorf#abfluesse

Lucía, A., Comiti, F., Borga, M., Cavalli, M., & Marchi, L. (2015). Dynamics of large wood during a flash flood in two mountain catchments. *Nat. Hazards Earth Syst. Sci.*, *15*(8), 1741-1755. doi: 10.5194/nhess-15-1741-2015.

Lyn, D. A., Cooper, T. J., Condon, C. A., & Gan, L. (2007). *Factors in debris accumulation at bridge piers*. Purdue University & U.S. Dept. of Transportation.

Manners, R. B., Doyle, M., & Small, M. (2007). Structure and hydraulics of natural woody debris jams. *Water Resources Research*, *43*(6). doi: 10.1029/2006WR004910.

MKUEM. (2019). *Die Ahr*. Ministerium für Klimaschutz, Umwelt, Energie und Mobilität Rheinland-Pfalz (MKUEM). https://wasser.rlp-umwelt.de/servlet/is/1210/

Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J. E., Ehmele, F., Feldmann, H., Franca, M. J., Gattke, C., Hundhausen, M., Knippertz, P., Küpfer, K., Mühr, B., Pinto, J. G., Quinting, J., Schäfer, A. M., Scheibel, M., Seidel, F., & Wisotzky, C. (2023). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe – Part 1: Event description and analysis. *Nat. Hazards Earth Syst. Sci.*, *23*(2), 525-551. doi: 10.5194/nhess-23-525-2023.

Naito, C., Cercone, C., Riggs, H. R., & Cox, D. (2014). Procedure for Site Assessment of the Potential for Tsunami Debris Impact. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *140*(2), 223-232. doi: 10.1061/(ASCE)WW.1943-5460.0000222.

NRW, U. (2023a). *Daten Pegel: Eschweiler* Elektronisches Wasserwirtschaftliches Verbundystem (ELWAS). https://www.elwasweb.nrw.de/elwas-web/index.xhtml#

NRW, U. (2023b). *Daten Pegel: Mulartshütte* Elektronisches Wasserwirtschaftliches Verbundystem (ELWAS). https://www.elwasweb.nrw.de/elwas-web/index.xhtml#

Oudenbroek, K., Naderi, N., Bricker, J. D., Yang, Y., Van der Veen, C., Uijttewaal, W., Moriguchi, S., & Jonkman, S. N. (2018). Hydrodynamic and debris-damming failure of bridge decks and piers in steady flow. *Geosciences*, *8*(11), 409.

Pagliara, S., & Carnacina, I. (2011). Influence of large woody debris on sediment scour at bridge piers. *International Journal of Sediment Research*, *26*(2), 121-136. doi: 10.1016/S1001-6279(11)60081-4.

Panici, D., & de Almeida, G. A. (2020). Influence of pier geometry and debris characteristics on wood debris accumulations at bridge piers. *Journal of Hydraulic Engineering*, *146*(6), 04020041.

Panici, D., & de Almeida, G. A. M. (2018). Formation, Growth, and Failure of Debris Jams at Bridge Piers. *Water Resources Research*, *54*(9), 6226-6241. doi: 10.1029/2017WR022177.

Parola, A. C., Apelt, C. J., & Jempson, M. A. (2000). *Debris forces on highway bridges*. Transportation Research Board.

Piton, G., Horiguchi, T., Marchal, L., & Lambert, S. (2020). Open check dams and large wood: head losses and release conditions. *Natural Hazards and Earth System Sciences*, *20*(12), 3293-3314.

Polizei Thüringen. (2021). *Flut hinterlässt Bilder der Zerstörung im Landkreis Ahrweiler*. General-Anzeiger. Retrieved 10-01-2024 from https://ga.de/fotos/region/flutkatastrophe-im-kreis-ahrweiler-bilder_bid-61312581#41

Rickenmann, D. (1997). Schwemmholz und Wasserkraft. *Wasser Energie Luft*, *89*(5-6), 115. doi: 10.5169/seals-940182.

Rickli, C., Badoux, A., Rickenmann, D., Steeb, N., & Waldner, P. (2018). Large wood potential, piece characteristics, and flood effects in Swiss mountain streams. *Physical Geography*, *39*(6), 542-564. doi: 0.1080/02723646.2018.1456310.

Robertson, I. N., Riggs, H. R., Yim, S. C., & Young, Y. L. (2007). Lessons from Hurricane Katrina Storm Surge on Bridges and Buildings. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *133*(6), 463-483. doi: 10.1061/(ASCE)0733-950X(2007)133:6(463).

Ruiz-Villanueva, V., Piégay, H., Gurnell, A. M., Marston, R. A., & Stoffel, M. (2016). Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges. *Reviews of Geophysics*, *54*(3), 611-652.

Saatcioglu, M., Ghobarah, A., & Nistor, I. (2005). Effects of the December 26, 2004 Sumatra earthquake and tsunami on physical infrastructure. *ISET Journal of earthquake technology*, *42*(4), 79-94.

Schalko, I. (2018). *Modeling hazards related to large wood in rivers* ETH Zurich]. doi: 10.3929/ethz-b-000293084.

Schalko, I., Lageder, C., Schmocker, L., Weitbrecht, V., & Boes, R. M. (2019). Laboratory flume experiments on the formation of spanwise large wood accumulations: I. Effect on backwater rise. *Water Resources Research*, *55*(6), 4854-4870. doi: 10.1029/2018WR024649.

Schalko, I., Schmocker, L., Weitbrecht, V., & Boes, R. M. (2018). Backwater rise due to large wood accumulations. *Journal of Hydraulic Engineering*, *144*(9), 04018056. doi: 10.1061/(ASCE)HY.1943-7900.0001501.

Schalko, I., Schmocker, L., Weitbrecht, V., & Boes, R. M. (2020). Laboratory study on wood accumulation probability at bridge piers. *Journal of Hydraulic Research*, *58*(4), 566-581. doi: 10.1080/00221686.2019.1625820.

Schmocker, L., & Hager, W. H. (2011). Probability of Drift Blockage at Bridge Decks. *Journal of Hydraulic Engineering*, *137*(4), 470-479. doi: 10.1061/(ASCE)HY.1943-7900.0000319.

Schmocker, L., & Hager, W. H. (2013). Scale Modeling of Wooden Debris Accumulation at a Debris Rack. *Journal of Hydraulic Engineering*, *139*(8), 827-836. doi: 10.1061/(ASCE)HY.1943-7900.0000714.

Steeb, N., Rickenmann, D., Badoux, A., Rickli, C., & Waldner, P. (2017). Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. *Geomorphology*, *279*, 112-127. doi: 10.1016/j.geomorph.2016.10.011.

Stolle, J., Takabatake, T., Nistor, I., Mikami, T., Nishizaki, S., Hamano, G., Ishii, H., Shibayama, T., Goseberg, N., & Petriu, E. (2018). Experimental investigation of debris damming loads under transient supercritical flow conditions. *Coastal engineering*, *139*, 16-31. doi: 10.1016/j.coastaleng.2018.04.026.

Takahashi, S., Sugano, T., Tomita, T., Arikawa, T., Tatsumi, D., Kashima, H., Murata, S., Matsuoka, Y., & Nakamura, T. (2010). *Joint Survey for 2010 Chilean Earthquake and Tsunami Disaster in Ports and Coasts* (PARI Technical Note 1224). Kuriyama, Japan: Port and Airport Research Institute.

Thieken, A. H., Bubeck, P., Heidenreich, A., von Keyserlingk, J., Dillenardt, L., & Otto, A. (2023). Performance of the flood warning system in Germany in July 2021 – insights from affected residents. *Nat. Hazards Earth Syst. Sci.*, *23*(2), 973-990. doi: 10.5194/nhess-23-973-2023.

Waldner, P., Rickli, C., Köchli, D., Usbeck, T., Schmocker, L., & Sutter, F. (2007). Schwemholz. In G. R. Bezzola & C. Hegg (Eds.), *Ereignisanalyse Hochwasser 2005, Teil 1 - Prozesse, Schäden und erste Einordnung* (pp. 181-193). Bundesamt für Umwelt (BAFU),.

735 Wohl, E., Bledsoe, B. P., Fausch, K. D., Kramer, N., Bestgen, K. R., & Gooseff, M. N. (2016). Management
736 of large wood in streams: an overview and proposed framework for hazard evaluation. *JAWRA*
737 *Journal of the American Water Resources Association*, *52*(2), 315-335.
738 Wüthrich, D., Arbós, C. Y., Pfister, M., & Schleiss, A. J. (2020). Effect of Debris Damming on Wave-
739 Induced Hydrodynamic Loads against Free-Standing Buildings with Openings. *Journal of*
740 *Waterway, Port, Coastal, and Ocean Engineering*, *146*(1), 04019036. doi:
741 doi:10.1061/(ASCE)WW.1943-5460.0000541.
742 Wüthrich, D., Korswagen, P. A., Selvam, H., Oetjen, J., Bricker, J., & Schüttrumpf, H. (2024). Field survey
743 assessment of flood loads and related building damage from the July 2021 event in the Ahr
744 Valley (Germany). *Journal of Flood Risk Management*, e13024. doi: 10.1111/jfr3.13024.