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Bridge Clogging in Belgium and Germany During the 2021 Floods

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Key Points:

- Analysis of debris accumulations at 71 bridges, 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 deck and railing design for bridge clogging

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Abstract During 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, revealing substantial amounts of man-made objects. A new database of clogged bridges in Belgium and Germany (described in a separate data descriptor) was analyzed to characterize bridge clogging and determine the effect of bridge design, bridge location and hydraulic conditions. Results showed that 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 that bridges with narrow pier spacing ($\leq$10 m) are more susceptible to extreme clogging. Blocking by the deck and railing also played a prominent role, in conjunction with blocking by the piers, as peak water levels at 85% of the analyzed bridges reached or exceeded the deck. Altogether, 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 urbanized 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 approximately 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 occurred at bridges with piers placed 10 m 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 designing bridges with lower risk of debris blockages, and inform disaster response strategies on 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 hr in parts of Belgium, Germany, and neighboring countries (Journée et al., 2023; Mohr et al., 2023), equivalent to three months of average precipitation in just 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 damage (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 later found in the inundated areas. All

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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.

This pointed out that these debris accumulations can have devastating consequences on critical infrastructure, as well as on the extent of the flood. Debris constricts bridge openings and obstructs the flow, leading to backwater rise and increased inundation depths (De Cicco et al., 2018; Schalko et al., 2018, 2019; 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, in terms of both damages and disruption to critical services. In addition, debris accumulations can contribute to bridge failure by increasing the loads (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). Since bridges are crucial infrastructure, such failure may have larger consequences. During the 2021 flood, this became painfully clear in the Ahr valley (Germany), where 41 bridges were destroyed by the flood (Burghardt, Klopries, & Schüttrumpf, 2024), severely limiting emergency services and disaster relief for cut-off settlements. These effects clearly 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 accumulations during flood events. This subject has received 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 (Nistor et al., 2017; Robertson et al., 2007; Takahashi et al., 2010; Wüthrich et al., 2020). For tsunamis, Naito et al. (2014) found heterogeneous debris mixtures containing shipping containers, vehicles (boats, vessels, cars), utility poles, dislodged buildings and trees. Similarly, during the 2021 flood, the widespread flooding in heavily urbanized areas brought vehicles, building rubble and many other objects into the debris accumulations (Erpicum, Poppema, Burghardt, Benet, Wüthrich, et al., 2024; Korswagen et al., 2022), in contrast to the previously studied accumulations in mountain areas, characterized by a more natural land use. This also explains why this paper uses the term "*floating debris*," while for accumulations with only trees, "large wood accumulation" or "logjam" are often preferred, reflecting the positive ecological benefits of deadwood in rivers (Ruiz-Villanueva et al., 2016; Wohl et al., 2016).

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, Poppema, et al., 2024). However, quantifying these effects requires systematic knowledge of the composition and characteristics of these heterogeneous mixed debris accumulations at bridges, which is currently significantly more limited than for natural debris accumulations in rivers (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 where these occurred can help identifying optimal bridge designs that can decrease the probability of debris accumulation. This would be particularly valuable for regions affected by the 2021 flood, where multiple bridges were destroyed and still need to be rebuilt, but it would also provide important insights for future bridge design more broadly. 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.

Therefore, *this study aims* to characterize bridge clogging that occurred 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

This study investigated the clogging of bridges along six rivers in Belgium and Germany during the 2021 flood event. The return period of the flood is estimated to be approximately 9,000 years for the river Ahr (Ludwig et al., 2023; Vorogushyn et al., 2022) and well over 200 years for the Belgian rivers (Journée et al., 2023). The rivers Ahr, Inde and Vicht are situated (largely) in western Germany, the Vesdre, Helle, and Hoëgne (largely) in

Figure 1. A debris accumulation in Bad Neuenahr-Ahrweiler, Germany (bridge 16 in the database by Erpicum, Poppema, Burghardt, Benet, Klopries, 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).

Belgium (Figure 2, Table 2). The Ahr is the only studied river that belongs to the Rhine catchment, while the other five are part of the Meuse catchment.

In Germany, 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). It is characterized 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 toward the source (MKUEM, 2019). The Vicht is a tributary of the Inde, which joins the Rur in Germany. The Inde's discharge is regulated by a drinking water reservoir, the Wehebachtalsperre, at the Wehebach tributary. In Germany, of the 33 clogged German bridges in the database, 30 are at the Ahr, one at the Inde and two at the Vicht. Clogging was especially severe around Altenahr, Kreuzberg and Pützfeld.

In Belgium, debris accumulation was studied in the Vesdre river 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, that is, 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 the 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 characterized 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). Of the 38 Belgian bridges with clogging in the database, 35 are on the Vesdre, two on the Helle and one on the Hoëgne (tributaries of the Vesdre). Clogging was especially severe in Pepinster and Verviers.

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, Poppema, Burghardt, Benet, Klopries, et al., 2024). A total of 71 bridges affected by debris clogging were studied (38 in Belgium and 33 in Germany, mainly at the Vesdre resp. Ahr river), 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 focusing on debris arrived late, when accumulations had often already been removed and dismantled. The database and analysis focus on three main aspects of debris accumulation, as summarized in Figure 3:

1. *Bridge characteristics*: 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 flow width during the 2021 flood.
3. *Accumulation characteristics*, 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, Poppema, Burghardt, Benet, Wüthrich, et al., 2024).

2.2.1. Bridge Characteristics

For the bridge characteristics, the database documents the bridge location, observed damage and the design of the bridge in general, including bridge deck, piers and railing (Figure 3). Bridge characteristics were collected based on the following sources:

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Table 1
Literature Overview of Debris Composition Measurements in and Around Rivers

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 1,700 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 artifacts was insignificant.
Bayón et al. (2023, 2024)	63 flood events in 46 countries	Urban, worldwide	Of the 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.

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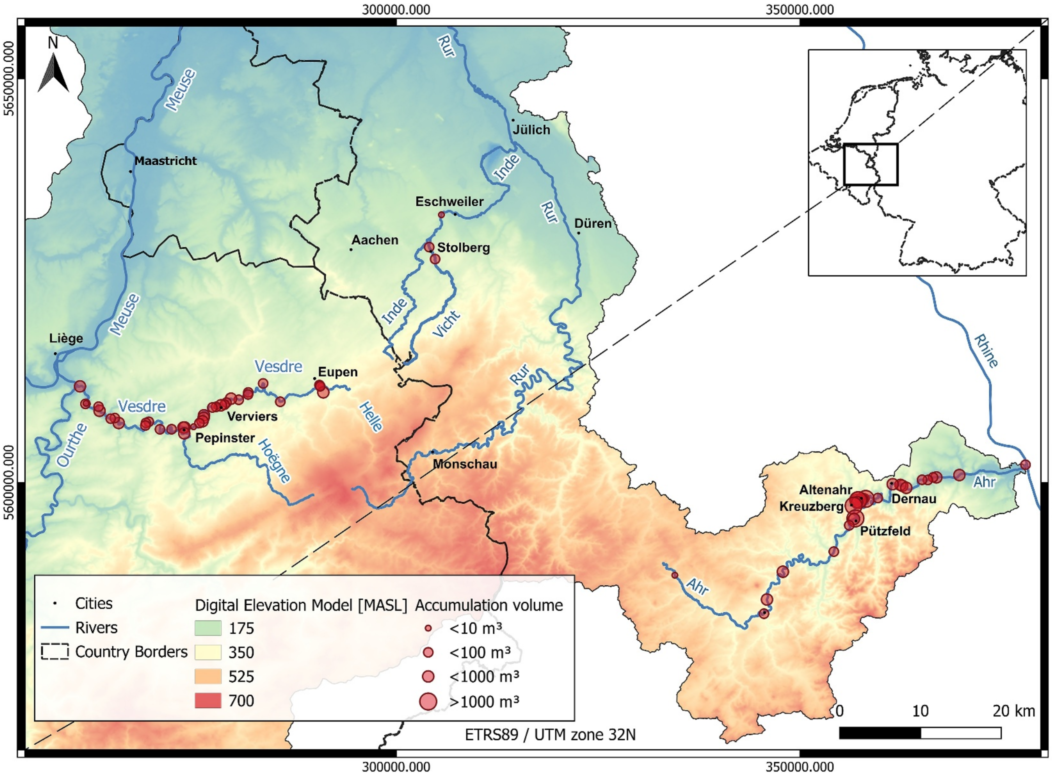

Figure 2. Map of the study area and the studied rivers, with debris accumulation volumes and locations indicated.

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.

Table 2
Characteristics of the Rivers Examined in This Study, Including Physical Characteristics, Average Annual Discharge, and Estimated Peak Discharge During the 2021 Flood

River	Tributary of	Catchment area [km^2]	Length [km]	Average slope [%]	Average discharge [m^3/s]	(Estimated) discharge during 2021 flood [m^3/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

Note. Sources: (Bauwens et al., 2011; Bruwier et al., 2015; Cuvelier et al., 2018; Deroanne & Petit, 1999; LfU, 2023; MKUEM, 2019; NRW, 2023a, 2023b; Wasserverband Eifel-Rur, 2021a, 2021b).

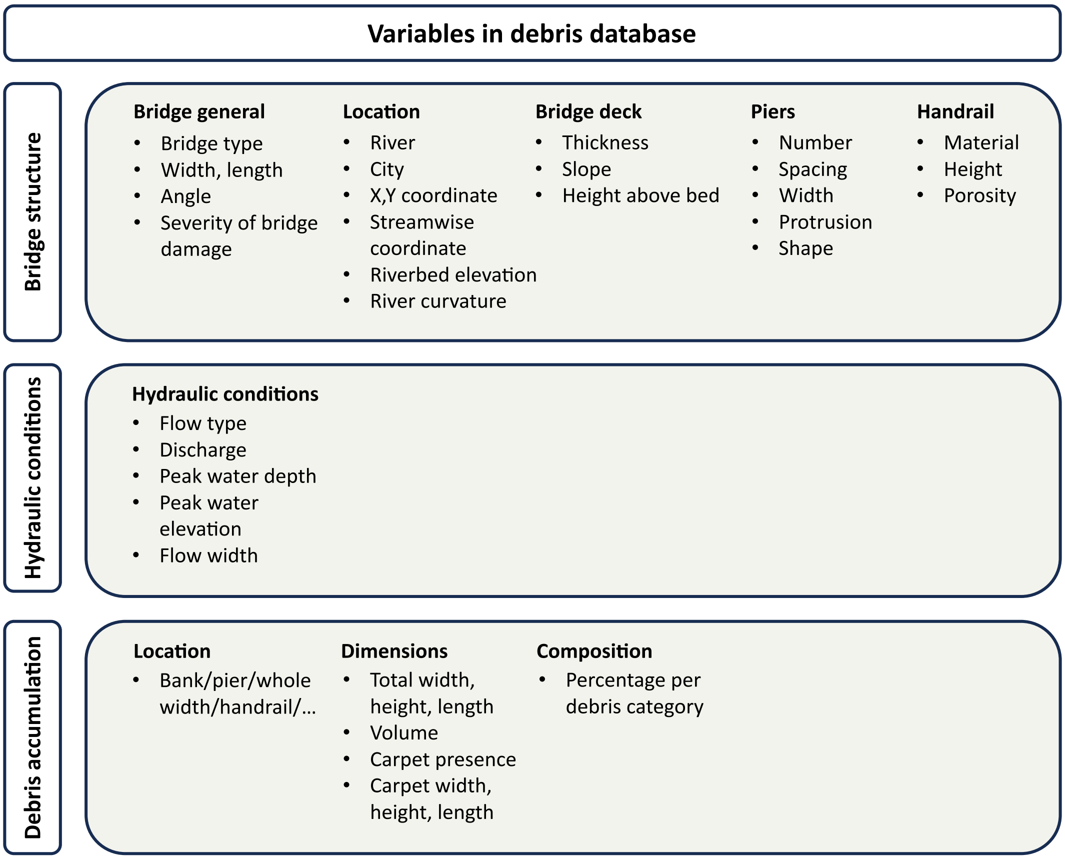

Figure 3. Overview of the main variables documented in the debris database.

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 Ahr are based on reconstructed gauge data from the State Office Landesamt für Umwelt Rheinland-Pfalz in Germany; the flow widths are based on field surveys and estimated coverage of the inundation areas conducted by the same state office. Data for the Inde and Vicht is provided by the Wasserverband Eifel-Rur. In Belgium, water levels are based on a post-event field survey performed by the Walloon Administration. Discharges are based on hydrological modeling of the flood event from distributed rainfall data performed by Dessers et al. (2023).

2.2.3. Accumulation Characteristics

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

- The total length, width and height of the accumulation, measured from edge to edge (e.g., from the most upstream to the most downstream point of the accumulation, measured parallel to the river axis).
- The accumulation volume, measured by subdividing 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, Poppema, Burghardt, Benet, Wüthrich, et al. (2024)). It is important to mention that 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, that is, the estimated volume fraction of the debris categories listed in Table 3.

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 from buildings)	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	–

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 to define the scale. Information from photos from different perspectives, including aerial and handheld photos, was combined to obtain both horizontal and vertical dimensions. To maximize the accuracy of the estimations, three cases were initially analyzed by three different researchers. This resulted in a refined procedure and more stringent definition of parameters, after which remaining variations between researchers were limited, for example, 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 analyzed 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. Three different shapes were distinguished: elongated shapes (referred to as "logs"), flat shapes ("plates") and bulky objects ("cubes"), in line with previous studies in coastal engineering (Stolle et al., 2018; Wüthrich et al., 2020). Per debris category in the database, the average volume fraction of each of the three debris shapes was estimated, resulting in the ratios in Table 3. For every accumulation, the volume in each of the debris categories is assigned to the three shape classes following these ratios. 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.

2.2.4. Database Quality and Limitations

This characterization of the debris accumulations relies on image analysis, and hence on information visible on photos, which were mostly taken after the flood event. This inherently means that any hidden part of any accumulation is assumed to be of similar composition as the visible outside surface. Since no data of dismantled debris compositions after the flood event is available and due to missing validation possibilities, no estimation of possible underwater accumulations was carried out. This might lead to underestimation of debris volumes, especially for photos taken during the flood. Conversely, the estimation of bulk accumulation volumes, including pores, rather than the solid volume leads to an overestimation of debris volumes. Given the difficulty of detailed field observations in an area with ongoing disaster relief and cleaning operations, these limitations are deemed acceptable, especially because they allow for systematic characterization and analysis of bridge clogging over a larger area, rather than at a single bridge. Nonetheless, these practical limitations imply that the data are more suitable for the overall characterization of bridge clogging and general trends, than for detailed quantitative conclusions on individual accumulations. This especially applies to data on debris categories and shapes, as these depend on the consecutive estimation of accumulation volume, debris composition and volume fraction per debris shape, leading to compound uncertainties.

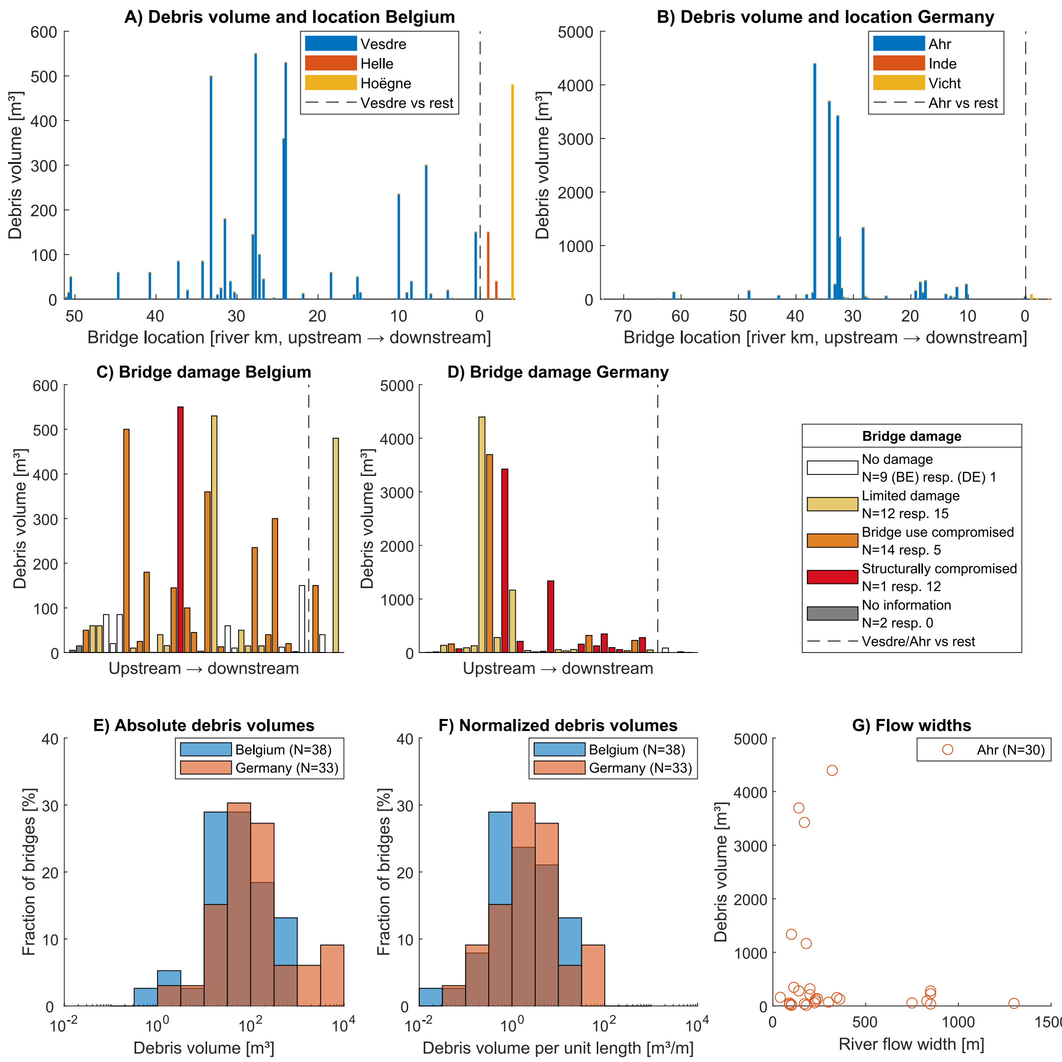

Figure 4. (a) Plot of the debris volumes and the location of the blocked bridges in Belgium, measured along the path of the river Vesdre. Negative values indicate bridges on the Helle and Hoëgne (tributaries). (b) Idem for Germany, with river km measured along the Ahr, negative values for the Inde and Vicht (different catchments). Note the different *y*-axis between (a) and (b). (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. Note: bar colors are semi-transparent, to show histogram overlap. (f) Idem, with volumes normalized by bridge length. (g) The width of the flooded area (river width) versus debris volumes for the river Ahr.

3. Results

3.1. Characterization of Clogging

To characterize 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 Figures 2, 4a, and b. In Belgium, 35 of the 38 clogged bridges in the database are on the Vesdre, with clogging especially severe in Pepinster and Verviers (river km 33 to 24, Figure 4a). In Germany, 30 of the 33 clogged bridges in the database are at the Ahr, with the largest accumulations clustered around Altenahr, Kreuzberg and Pützfeld (river km 37 to 28, Figure 4b). Overall, these numbers mean that the comparison of database results between Belgium and Germany for the 2021 flood is very much dominated by the Vesdre and Ahr rivers. Also, the clustering of bridge clogging around specific towns implies that most extreme accumulations occurred just a small distance from preceding accumulations (Figures 4a and 4b). In both countries, bridge damage was substantial, with overall 18% of the considered bridges structurally compromised and a further 27% substantially damaged. On average, observations showed that damage was more severe at the bridges with larger accumulations (Figures 4c and 4d).

Comparing the accumulations in both countries, those at German bridges were generally larger, with a mean debris volume of 518 m^3 in Germany versus 118 m^3 in Belgium. This is partially related to the Ahr being wider than the Vesdre. Consequently, normalized volumes of debris per meter of bridge length (i.e., m^3/m) somewhat decrease the disparity between countries (Figures 4e and 4f), but normalized 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.

The actual flow width (of the inundated area) during the flood was generally much wider than the river channel or bridge under "normal" conditions. The analyzed 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, pointing out the bidimensional nature of this process. Notably, the large accumulations occurred at relatively narrow flow widths (Figure 4g).

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 m^3 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 may instead accumulate at the bridge in the river channel under different circumstances (e.g., without the river bend). The second largest accumulation (Figure 5b, 3,700 m^3) is completely different, with a very dense accumulation in the channel in front of a railway bridge. This debris was mainly of anthropogenic 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 in 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.

3.3. Debris Composition

A multitude of different objects and materials was present in the debris accumulations, as visible in photos of accumulations (e.g., Figures 1 and 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 (Figures 6a and 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 damaged 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 Figures 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 kilometer 34 that contained a large number of caravans (see the photo of Figure 5b). Similarly, the large accumulation volumes and high building rubble content around Ahr river kilometer 35—that is, 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.

Table 4

A Characterization of the Five Largest Accumulations of Both Countries in the Database

Country	Bridge ID	River	Municipality	River km	V [m^3]	V' [m^3/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[a]	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[b]	Ahr	Pützfeld	36.7	4,396	88	4.0	3.3	1.0	3	10.0
	62	Ahr	Kreuzberg	34.2	3,695	62	9.0	4.5	0.8	3	5.5
	56[c]	Ahr	Altenahr	32.4	3,424	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[c]	Ahr	Altenahr	28.1	1165	19	6.8	5.0	1.2	4	10.0

Note. Bridge ID refers to the id's used in the database by Erpicum, Poppema, Burghardt, Benet, Klopries, et al. (2024). River km gives the distance from the mouth of the respective river. Estimated debris volumes are given in m^3 (V) and in m^3 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. [a]1.2 km from the confluence with the Vesdre, which is at Vesdre river km 24.0. [b]Debris accumulation located at the riverbank directly next to bridge. [c]Bridge 55 and 56 form a twin bridge, that is, a road and railroad bridge about 15 m apart.

The shape of the objects in the accumulations was analyzed by examining the debris categories (Figure 6). Visual observations showed the presence of three main features: (a) elongated one-dimensional objects (here called "logs"); (b) flat two-dimensional objects ("plates") and (c) voluminous three-dimensional objects ("cubes" or

Figure 5. Examples of clogged bridges in the database. (a) Pützfeld, Germany (bridge ID 63 in the database by Erpicum, Poppema, Burghardt, Benet, Klopries, et al. (2024)). Photo based on an aerial survey after the flood event 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.

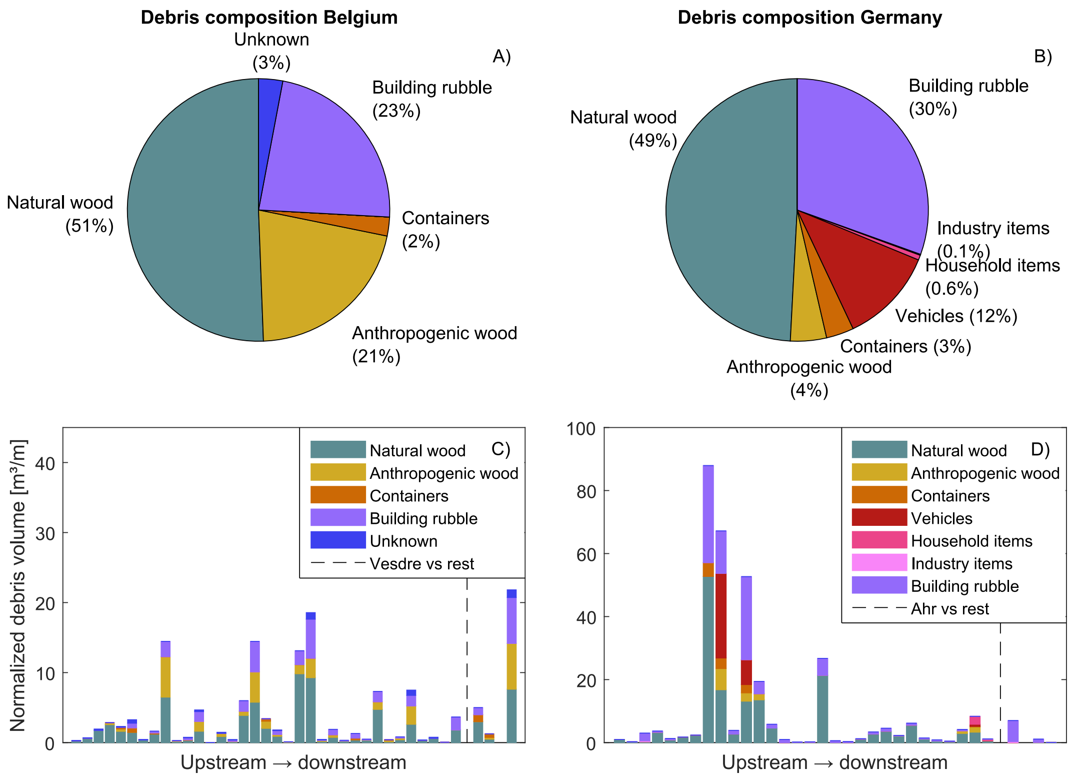

Figure 6. The composition of the accumulations in Belgium (subplot a and c) and Germany (b and d). The top row shows the volume fractions of the total debris volume per country, the bottom row the composition per accumulation.

"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 visualized 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

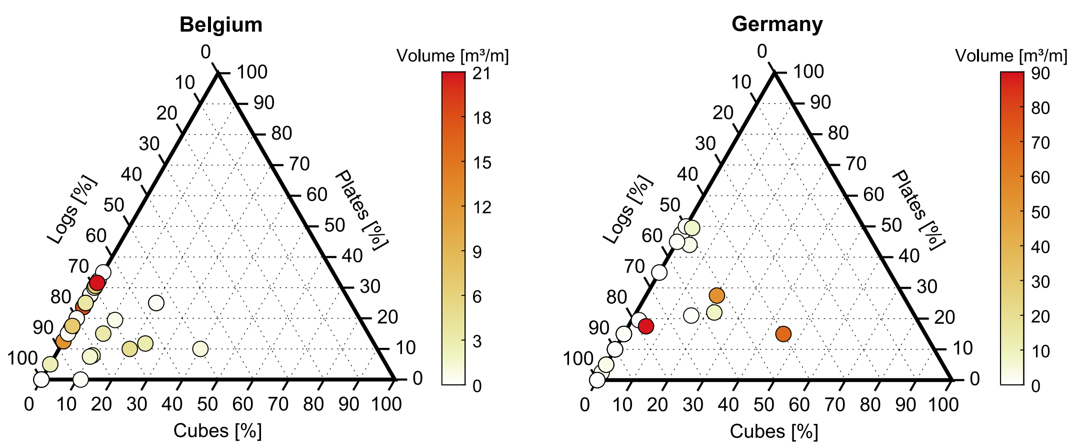

Figure 7. The estimated fraction of log-, plate-, and cube-shaped objects in the debris accumulations. Each circle represents an accumulation in the database, color-coded by volume, with its location along the three axes indicating the volume fraction of log-, plate-, and cube-shaped objects in the debris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

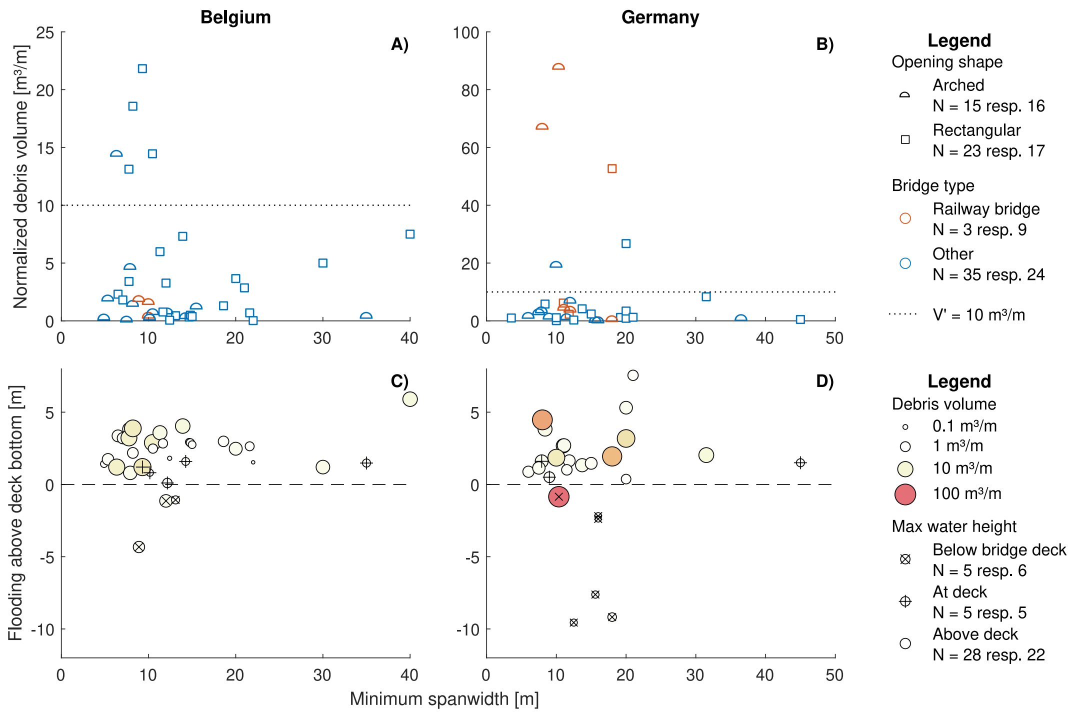

Figure 8. The effect of span width and (subplot a, b) bridge design or (c, d) maximum water levels on accumulation volumes in (a, c) Belgium and (b, d) Germany. Note: maximum water levels are indicated relative to the bottom of the bridge deck. Straight crosses in symbols indicate a flood height between 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.

rightmost circles in both triangular graphs are characterized by their high cube content (up to 45%), from storage 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: for example, 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 quite mixed debris shapes, especially in Germany.

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 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 debris blocking.

Span width, that is, 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 m 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). In these cases, debris was usually blocked by the bridge deck and railing, occasionally by the abutments. The shape of bridge openings had little effect (Figures 8a and 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 exceeding 10 m^3/m are relatively rare in both countries, making up 14% of the number of clogged bridges.

An insufficient 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

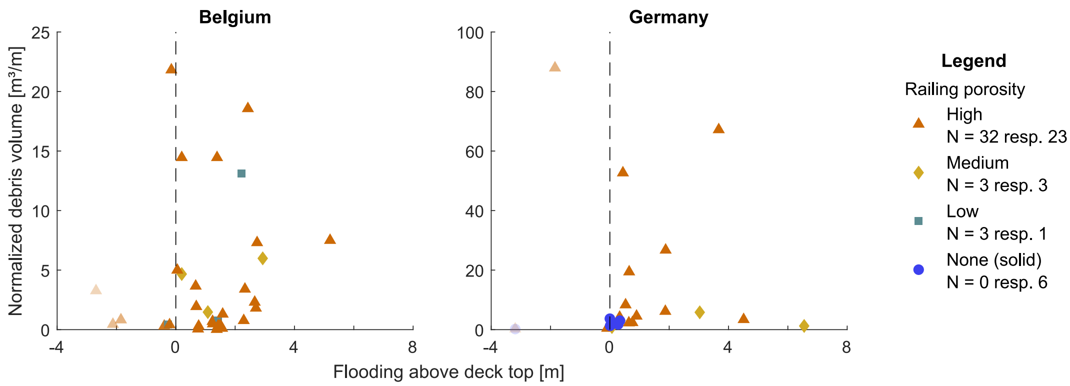

Figure 9. The effect of railing porosity and flooding height on debris volumes in Belgium and Germany. The vertical dashed line indicates where peak water levels reached the edge between deck and railing. Markers with lower water levels than this have increasing transparency to indicate the decreasing chance of debris interacting with the railing. 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.

reached or exceeded the bridge deck in 85% of the studied bridges (circles above the dashed line in Figures 8c and 8d), frequently exceeding it by several meters. Almost all substantial accumulations occurred where the water level reached or exceeded the bridge deck, supporting the importance of the bridge deck and railing for the occurrence of large accumulations.

Regarding railings, most bridges in the database have permeable metal structures, but in some cases solid stone walls are used. Figure 9 shows railing 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 railings, 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. Further examination of the effect of low, medium and high railing porosities (squares, diamonds and triangles in Figure 9) on accumulated debris volumes shows no clear trend.

4. Discussion

4.1. Debris Volume and Composition

Highly heterogeneous debris contents appeared as one of the typical features of the July 2021 flood in Belgium and Germany, whose analysis is the objective of this study. While acknowledging the limitations of the photo analysis approach in exactly determining the volume and composition of (partially submerged) accumulations, the general picture shows a stark contrast to typical large wood accumulations. Approximately half of the total debris volume was estimated to be of man-made origin, with 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 consisted of equal parts trash and woody debris, one contained parts of a boat and dock; but in all others the role of man-made objects was insignificant. This is the consequence of floods mostly occurring downstream of 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 during floods in more urbanized areas. For instance, in a photo analysis of debris in rivers and streets after 63 floods in urbanized 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 urbanized areas compared to the mix or urban and natural areas hit by the 2021 flood. 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 at 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); increasing stiffness (Hartlieb, 2015); and 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). 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 sheets, sheet wood or wall panels from collapsed caravans (Figures 5b and 5c), lead to denser and less permeable accumulations and therefore to higher 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 toward mixed debris causing denser accumulations and more backwater rise. However, more research is needed to confirm and especially quantify these effects, since non-floating debris were possibly not captured by this image-based analysis. This also points out the need for further studies on the effect of debris density on clogging processes.

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 critical span width depends 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 m 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 triggered 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 m 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 railings are known to cause more debris to remain at the railing itself (Schmocker & Hager, 2011), potentially maintaining debris in place when water levels rise until (well) above the bridge deck.

The largest accumulations occurred at bridges with highly permeable railings, while at bridges with impermeable railings (only present in Germany), accumulations were limited. Interlocking of debris with permeable handrails likely played a role here in maintaining accumulations and preventing debris from flowing over the bridge. Conversely, impervious railings cause more flow resistance and backwater rise, leading to earlier overflow, and possibly earlier release of debris. Also, railing damage may have enabled easier transport of debris over the bridge. While this conceptually matches the debris blockage probabilities observed in the lab by Schmocker and Hager (2011), statistically significant conclusions are difficult to draw since our database contains only three bridges with impermeable railings where water is estimated to have actually reached the railing. For the other impermeable railings, interaction between railing and debris would only be possible for large objects floating on the water or for inaccurate water level estimations.

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 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, 2018; Panici & de Almeida, 2020; 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 railing 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 at 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 funneled it toward the bridge, whereas roads would normally be constructed at lower elevations and therefore allow for more debris to flow around the bridge. In addition, these bridges were likely able to withstand the flood event due to their stable construction and therefore collected debris that might have been trapped at smaller bridges further upstream which collapsed during the flood event. However, these hypotheses cannot be substantiated by data, given the low number of railway bridges within the data set, 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 latter 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 complex 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, that is, 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 entirely 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 compared to 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 afterward. 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 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. Second, it means that the deck and railing can block debris, in addition to the piers. Third, 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 as well as railing 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 characterizes the observed debris accumulations and main bridge features that triggered substantial clogging. This information helps in better understanding the processes associated with debris accumulation at bridges, and can support the development of targeted debris management strategies to reduce flood risk during future events.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data set used in this paper is described in the data descriptor by Erpicum, Poppema, Burghardt, Benet, Wüthrich, et al. (2024), under DOI 10.1038/s41597-024-03907-8 and can be found in Erpicum, Poppema, Burghardt, Benet, Klopries, et al. (2024), under DOI 10.5281/zenodo.11551195. Images were analyzed with ImageJ version 1.53, available under https://imagej.net/ij/download.html.

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