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Structural damage, clogging, collapsing: Analysis of the bridge damage at the rivers Ahr, Inde and Vicht caused by the flood of 2021

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Abstract

During the flood event in 2021 within Western Europe, many bridges were severely damaged, particularly in North Rhine-Westphalia and Rhineland-Palatinate in Germany. Within this study, a statistical analysis of the damages caused to bridges by the flood event was carried out. First, locations and damages of bridges along the rivers Inde, Vicht and Ahr were mapped. Based on these data, statistical correlations among the damage patterns were analyzed. Approximately 25 bridges along both rivers Inde and Vicht were damaged, while over 80 bridges along the Ahr were damaged. Notably, bridges located near residential areas suffered more severe damage than those in rural areas. In addition, the presence of debris played a significant role in damaging bridges. Although the bridge design did not emerge as the crucial factor, the bridge height could be determined as a contributing factor influencing the extent of damage along all three rivers. Also, the extent of damage increased as soon as overtopping of bridges occurred. Based on these findings, recommendations for the reconstruction of the numerous destroyed bridges could be identified which agree with existing literature. Additionally, recommendations regarding the estimation of 100-year design floods and the implementation of clogging into flood hazard maps were derived.

KEYWORDS

debris flow, extreme events, flood damages

1 | INTRODUCTION

Despite the increases in droughts and heatwaves as a result of the rising global mean temperature, it is predicted that the likelihood of river floods will increase and return periods for specific flood flows will shorten (Kundzewicz et al., 2018; Lange et al., 2020; Lee et al., 2023). The extent of flood events is generally associated with many uncertainties and the effects of the 2021 flood event in Western Europe were not expected. Unleashed by persistent rainfall and intervals of heavy rainfall, the precipitation event evolved from a flash flood to a river flood within the low mountain range in Northwest Europe. This flood led to major damages in Belgium, Germany, Luxembourg, and the Netherlands, especially in the region of the Eifel mountains along the rivers Ahr and Erft. With over 180 casualties it is considered as the second most severe natural disaster in Germany (Schäfer et al., 2021). Direct damage from the 2021 flood for the German regions is estimated to be approximately 33.4 billion euros (Trenczek et al., 2022). Water levels of the 100-year flood were far exceeded and large parts of the gauging infrastructure were destroyed, causing research on the 2021 flood having to rely on estimates of the discharge rather than measurements. Besides the strong influence of the surrounding landscape, clogging at narrow river sections for instance in front of bridges was identified as a major cause for the increase in inundation depth (Ludwig et al., 2023).

Shortly after the flood event, it became especially apparent within the Ahr valley that a large part of the so-called critical and sensitive infrastructure, which ensures the supply of essential goods and services, had been destroyed. This includes the sectors of energy and water supply, as well as the transport sector. For both road and rail transport, bridges are crucial facilities for ensuring infrastructure and services (Pohl, 2015; Tubaldi et al., 2022). The role of bridges for the connection of communities, especially for the Ahr valley and along the river Inde, became evident shortly after the flood. The regions infrastructure along the Ahr is characterized by numerous historic stone bridges, with bridges constructed from the 18th century till 2019 that connect parts of municipalities across the river. After the flood event, rescue and safety measures were hampered or even hindered by destroyed bridges due to the loss of connectivity within the region (Deutsches Komitee Katastrophenvorsorge e.V., 2022; Lemnitzer et al., 2023).

Flood events have been identified as a common cause of bridge failure in the last decades globally (Deng et al., 2016; Diaz et al., 2009; Tan et al., 2020). Bridges represent a direct constriction of the runoff cross-section, also known as hydraulic bottlenecks, due to bridge piers, abutments, and the superstructure (Deutsches Institut für Normung e. V., 1998; Patt et al., 2021). Thus, several hydraulic effects can be observed at bridge structures, which may pose a threat to its structural integrity. The bridge's profile in the river section alters the flow paths and thus local energy losses occur, leading to rising water levels upstream (Deutsches Institut für Normung e. V., 1998; Yarnell, 1934). Under certain flow conditions, this increase of water level, caused solely by the presence of the bridge structure, can already lead to overtopping of the bridge (Picek et al., 2007). In addition, a flow change may occur below the bridge deck, which can result in increased flow velocities as well as increased hydraulic forces on the structure and riverbed. This enhances the risk of scouring due to erosion of the bed and poses a risk for the stability of the bridge structure (Patt & Jüpner, 2020; Tubaldi et al., 2022). For the development of a flow change in the vicinity of the structure, the constriction ratio, that is, the ratio between the cross-sectional area of the bridge and the cross-sectional area of the channel, is decisive (Yarnell, 1934). The greater the cross-sectional area of a bridge structure, which is achieved by lowering the constriction ratio, the lower the risk of a flow change will be (Deutsches Institut für Normung e. V., 1998; Malavasi & Guadagnini, 2003; Patt & Jüpner, 2020). The impact of a bridge increases further once the water level reaches or exceeds the bridge's deck, so that a pressurized or submerged flow regime establishes (Carnacina et al., 2019; Deutsches Institut für Normung e. V., 1998; Picek et al., 2007; Tubaldi et al., 2022). Despite an observed upswell of the water level in front of the bridge, a lowering of the water level or even a hydraulic jump (transition from subcritical to supercritical flow) downstream of the bridge may occur depending on the Froude number (Chu et al., 2016; Picek et al., 2007). The hydraulic load on the bridge, especially its deck, is increased severely during overtopping and uplifting forces can occur, which pose an additional threat to the stability of the bridge structure (Kerenyi et al., 2009; Tubaldi et al., 2022; Zhu et al., 2018). In addition, the extent of the flood plain may be increased, as the water flow is disrupted and the structure has to be bypassed.

Furthermore, in the event of a flood, high water volumes often coincide with transport of debris. At bridge locations, the blocking of a cross-section caused by the accumulation of debris—also known as clogging or blockage—can further raise the water levels and alter flow processes (Bezzola et al., 2002; Gschnitzer et al., 2017; Hartlieb, 2017; Schmocker et al., 2016). The forces due to collisions of large objects transported within the debris with the bridge as well as the accumulation of large amounts of flotsam also increase the loads on the bridge and were identified as a major factor for bridge failure during floods (Diehl, 1997; Drdácký & Sližková, 2007; Gschnitzer et al., 2017). The blockage can cause an overtopping or bypassing of the bridge, even at lower water levels compared with the bridge deck altitude. Depending on the bridge structure, failure of individual components can lead to progressive collapse of the entire structure (Starossek, 2007). This demolition, and thus the abrupt release of the accumulated water masses, can cause the propagation of so-called surge waves, through which both water volumes and flotsam move at high velocities (Zanke, 2013). As a result, the risk of damage to surrounding buildings rises and can lead to an extension of the inundated area. In previous design approaches, these hydraulic loads on bridges due to flotsam accumulation and backwater rise were not considered or their importance underestimated (Tubaldi et al., 2022).

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Documentations of the effect of bridge structures on flood events and their damage also exist in historical records, for example, during the flood events 1804 and 1910 in the Ahr valley. Despite the knowledge of the damage due to flood events, bridges have been rebuilt contemporary in the same locations, underlining the relevance of bridges for mountainous regions. Temporary bridges, some of which are not designed to withstand floods, still form part of the infrastructure today. The aim of this study is to analyze the damages that occurred to bridges on the rivers Inde, Vicht, and Ahr as a result of the 2021 flood. In particular, it is the goal to identify relevant factors that influenced the damage mechanisms of bridges. This is done by a statistical analysis on the after-flood recording of the damage patterns of bridges visible from the outside along three German rivers. As a synthesis, recommendations for the reconstruction of historical bridges and the design of flood-adapted bridges within the investigated flood-prone areas are derived.

2 | MATERIALS AND METHODS

2.1 | Study area

For this study, the damages on bridges located along the three rivers Ahr, Inde, and Vicht situated in Rhineland-Palatinate (RLP) and North Rhine-Westphalia (NRW) in Western Germany are investigated (see Table 1 and Figure 1). The rivers Inde, Vicht, as well as the source of the river Ahr are located in North-Rhine Westphalia. The river Vicht is the second largest tributary of the river Inde with a catchment area of about 104 km^2 and a mean discharge of 0.57 m^3/s (International Commission on Large Dams, 2013; Land NRW, 2023; Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen, 2023; Wasserverband Eifel-Rur, 2021). In total, the catchment area of the river Inde includes 344 km^2 of cropland, grassland, forest, and urban areas. The headwaters of the Inde lay in Belgium at about 395 m above sea level (masl) and it reaches the Belgian–German border after about 2.5 km downstream. After a total length of 47 km near Jülich, the Inde reaches the Rur in NRW at 81 meters above sea level (Land NRW, 2023; Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen, 2023; Ministerium für Umwelt, Naturschutz und Verkehr des Landes Nordrhein-Westfalen, 2021b; Wasserverband Eifel-Rur, 2023). The estimated discharge of the flood event 2021 exceeds the mean high water values and estimates for a 100-year flood event at Inde and Vicht by far (Goedeking & Landvogt, 2022; Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen, 2023; Wasserverband Eifel-Ruhr, 2024).

TABLE 1 Overview of characteristic data on the rivers Vicht, Inde, and Ahr.

	Vicht (discharge data for gauge Mulartshütte)	Inde (discharge data for gauge Eschweiler)	Ahr (discharge data for gauge Altenahr)
Catchment area (km^2)	104	344	900
River length (km)	23	47	86
Mean slope (‰)	11	5.8	4
Reservoirs (storage volume; m^3)	Dreilägerbachtalsperre (3.67 million)	Wehebachtalsperre (25.1 million)	–
Land use characteristics	67% forests and grasslands, strong anthropogenic changes in Mulartshütte, Zweifall, and Vicht	90° left bend due to lignite mining in Jülich, about one fifth is heavily modified due to settlements and industrial areas	Mainly forests and grasslands, toward confluence the share of urban area increases
Mean discharge (m^3/s)[a]	0.57	2.77	6.86
Mean high water (m^3/s)[a]	16.94	46.57	90.3
Discharge estimates for a 100-year flood (m^3/s)[a]	66.23	113.6	236
Estimated maximum discharge during the flood in 2021 (m^3/s)	>100	n. a.	854
Estimated maximum water levels during the flood in 2021 (m)	>2.5	>3	>10

[a]Prior to 2021.

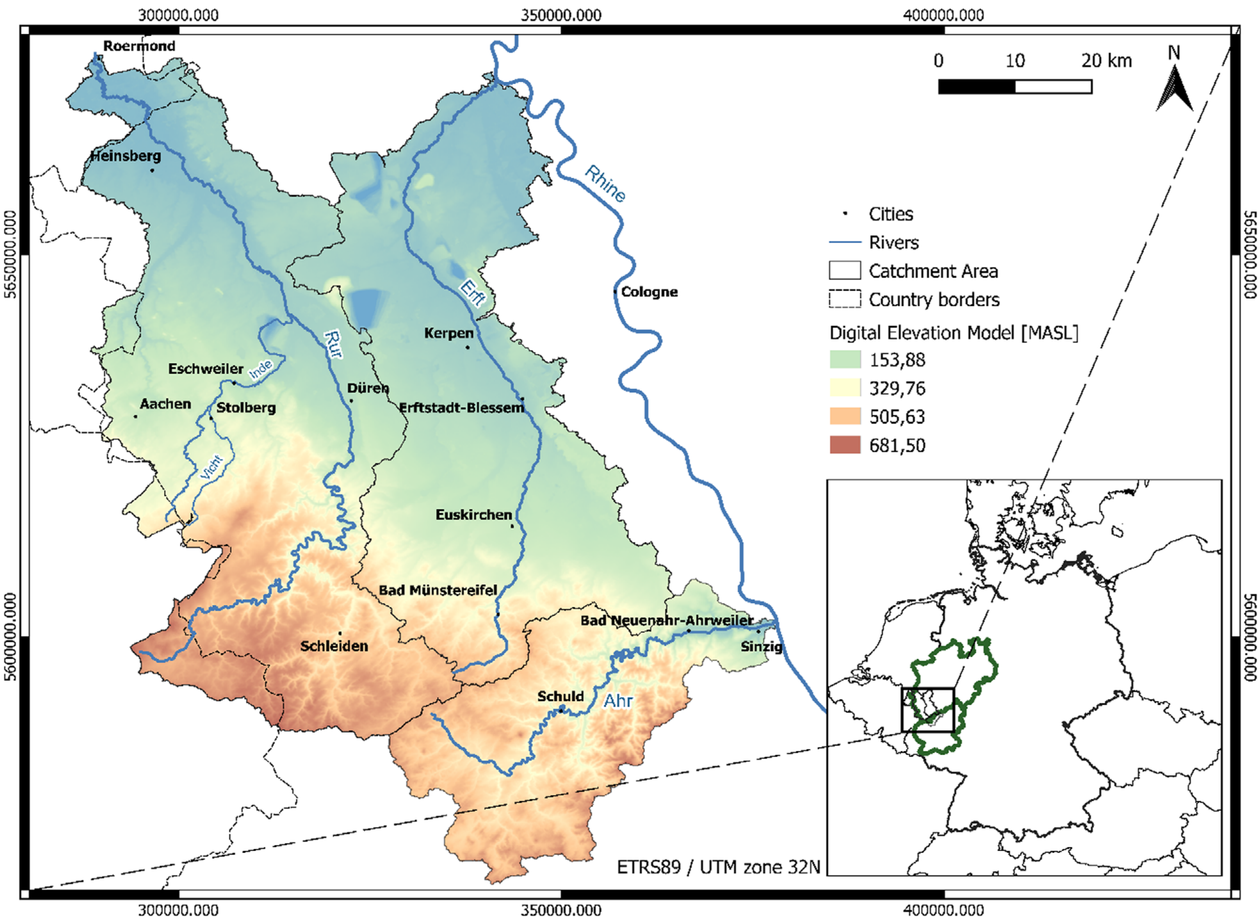

FIGURE 1 Study area of the rivers Vicht, Inde, and Ahr.

The catchment area of the river Ahr has a size of 900 km^2 and is situated in the low mountain range in both NRW (24%) and RLP (76%). The Ahr has a mean discharge of 9.05 m^3/s in winter and 3.28 m^3/s in summer (Ministerium für Klimaschutz, Umwelt, Energie und Mobilität, 2019). The source of the Ahr is located in Blankenheim in NRW at an altitude of 520 masl. After a total length of around 86 km, the Ahr reaches the river Rhine at 53 masl in RLP in the vicinity of Sinzig. The Ahr valley is characterized by steep hillsides and a narrow valley consisting of sandstone, siltstone, and clay slate. Compared with the rivers Inde and Vicht, the course of the Ahr is characterized by large meanders in the river course (Landesamt für Umwelt Rheinland-Pfalz, 2023; Ministerium für Klimaschutz, Umwelt, Energie und Mobilität Rheinland-Pfalz, 2023; Ministerium für Umwelt, Naturschutz und Verkehr des Landes Nordrhein-Westfalen, 2021a). Estimates for discharges of a 100-year flood of the river Ahr were exceeded by more than three times in the flood event 2021 (Landesamt für Umwelt Rheinland-Pfalz, 2022). Reconstruction of two historic flood events in 1804 and 1910 along the river Ahr showed, that similar peak discharges were reached in 1804 even though the water levels were lower compared to 2021. The flood in 1910 is estimated to reach a lower peak discharge with 630 m^3/s but a similar altitude of water levels in Walporzheim (Roggenkamp & Herget, 2021; Vorogushyn et al., 2022). The calculations for the 100-year flood were adjusted in retrospect to 2021 and the discharge for a 100-year design flood was nearly doubled to 434 m^3/s (Landesamt für Umwelt Rheinland-Pfalz, 2023).

2.2 | Data collection

In a first step, all bridge structures along the rivers Ahr, the Inde, and the Vicht were mapped uniformly before and after the flood event. For this purpose, satellite and aerial images were evaluated and both the bridge's locations and their conditions after the flood were documented. For a detailed damage analysis, on-site inspections were carried out in 2021, and more detailed inspections in March and April of 2022. Additionally, aerial photographs were taken with a drone. If available, the construction files of the bridges including inspection reports before and after the flood were evaluated. From this, information on bridge

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characteristics was determined, which include the bridge type, the number of spans of a bridge, the year of construction, and the bridge dimensions. The construction types of the bridges were specifically subdivided with a focus on the clear opening width of the bridges. Bridges with round or oval openings were classified as arch bridges, while bridges with approximately rectangular openings were mostly represented as slab and beam bridges. Truss, cable-stayed, and plate-beam bridges were also grouped into bridges with rectangular opening shapes.

In addition, the runoff patterns and hydraulic conditions at the bridge locations during the July 2021 flood event were observed, if possible. Therefore, water levels, and thus the water level right in front of the bridge, were estimated using flood marks and the extent of the floodplain provided by the state offices for environment RLP and NRW. With the help of aerial photographs and flotsam residue on the bridges and surrounding area, it was estimated whether clogging at the bridge occurred, as well as the degree of clogging (see Figure 2). Thus, flotsam residue on the bridge railing and on trees at the level of or above the bridge deck directly adjacent to the bridge were considered to be indicators of clogging.

As the clogging of bridges and the impact of debris are major causes for damage to bridge structures, aerial photographs, social media data and damage reports of the bridges by the operators were examined and an estimate on the degree of clogging was documented during on-site inspections. With the help of the photo documentation and flotsam deposits, it was also possible to draw conclusions about the overtopping of bridges.

2.3 | Damage mapping and analysis

Damage to the bridge structures was assessed using damage classes (see Table 2). This assessment was limited to damage supposedly induced by the flood 2021. Based on Maiwald and Schwarz (2023), which conducted damage modeling of houses for extreme floods, five damage classes were developed for bridge structures in this study. Bridges that had suffered no damage, slight decorative or weathering-like damage were assigned to damage class D0. Bridges, that had limitations to their trafficability, such as the loss of railings, but had not lost their structural stability, were grouped in damage class D1 (see Figure 3). If the use of the bridge had to be restricted, for example, by the loss of access ramps, the bridge was assigned to damage class D2. If, in addition to restrictions, immediate action was required and the bridge had to be repaired, such as the restoration of the superstructure, and to ensure stability after ground settlement or displacement of the piers, the bridge was assigned to damage class D3. Bridges that were destroyed by the flood event or demolished after the flood event were assigned to damage class D4. For simplification, bridges in damage classes D1 to D3 were grouped and described as damaged, bridges in class D0 as intact, and bridges in class D4 as destroyed.

With the help of the collected damage data, an analysis regarding the occurrence and influencing parameters of bridge damage and demolition was conducted. In this context, it was investigated whether certain damage degrees occurred more frequently depending on the bridge design parameters and the occurrence of the clogging or overtopping processes. A correlation analysis was performed using the software IBM SPSS Statistics (version 29.0.1.0) for a two-tailed correlation analysis with the model Kendall-Tau-b. This correlation analysis was applied since small datasets which are not normally distributed and are additionally ranked were used, e.g. the damage classes or the number of spans. Furthermore, same ranks were often repeated, so that the correlation model Kendall-Tau-b was more applicable. Additional

FIGURE 2 Exemplary photo of a bridge in the upper reaches that showed indication of clogging during the flood event (own figure).

TABLE 2 Damage classes for the bridges affected by the flood 2021 (modified by Maiwald & Schwarz, 2023).

		Damage type				
		Intact	Damaged			Destroyed
Damage criteria	**Damage description**	**D0**	**D1**	**D2**	**D3**	**D4**
Surface damage	Weathering	x				
	Dampness of components	x				
	Loss of handrail, guardrail, and decorations		x			
	Small-scale (<1 m^2) detachment of pavement		x			
	Clogging of road drainage		x			
	Minor to moderate cracks in concrete (<50 cm)			x		
	Light exposure of reinforcement			x		
	Large cracks in concrete (>50 cm)				x	
	Pervasive cracks in concrete (>1 m)				x	
Structural damage	Demolition of access ramps			x		
	Settlement, displacement, tilting, and demolition of piers				x	
	Demolition of the superstructure and individual abutments				x	
	Scouring of the piers				x	
	Large scale removal of building fabric (>1 m^3)				x	
	Complete collapse					x
	Demolition (afterwards)					x

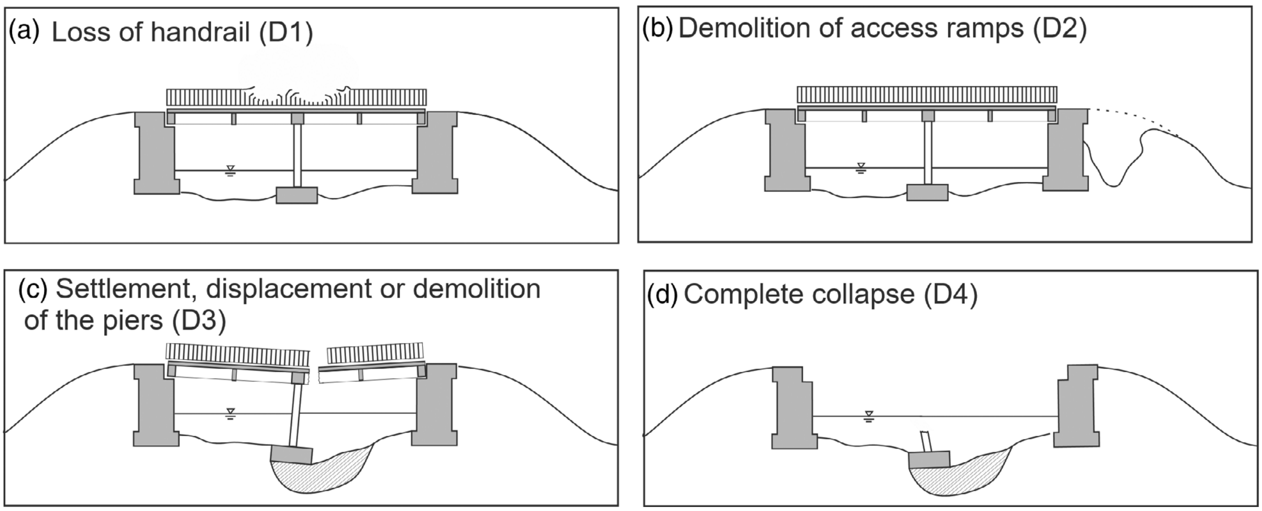

FIGURE 3 Exemplary schemes for the different bridge damages observed after the flood event 2021 (own figure).

bridge design data, for example, the length and height of the bridge, were entered as metric data. The Kendall-Tau-b (τ) ranges from −1 to 1. While a value of 0 indicates no correlation, a value of 1 indicates a strong positive correlation and a value of −1 a strong negative correlation. Correlations between 0 and 0.1 as well as 0 and −0.1 are often interpreted as weak or even negligible. The degree of correlation increases the closer Kendall-Tau-b (τ) is to 1. Within this study, only correlations above the weak level are mentioned. Two significance levels will be distinguished, whereas results with a $\rho > 0.05$ are considered not to be significant. Correlations at the significance level of 0.01 are interpreted as strongly significant. (Akoglu, 2018; Schaeffer & Levitt, 1956).

3 | RESULTS

3.1 | Bridge designs

In the course of mapping the damage, 88 bridges were recorded along the river Inde and 67 bridges along the river Vicht prior to the 2021 flood (see Table 3). This results in bridge densities of 1.7 bridges per kilometer on the Inde and 2.9 bridges per kilometer on the Vicht. The highest bridge densities were observed in the cities of Eschweiler and Stolberg along the river Inde with up to seven bridges per kilometer. It was possible to inspect 77 bridges after the flood, while the detailed analysis for 11 bridges was not possible due to private property restricting access. The detailed analysis of the bridge designs is documented in Annex 1–3 (see the Data S1). Similarly, along the river Vicht, the highest bridge density of 12 bridges per kilometer could be observed in Stolberg. Especially within the city center of Stolberg, small pedestrian bridges were recorded along the Vicht. Due to restricted access and the destruction of bridges, 15 bridges could not be observed in detail during the survey.

With 114 bridges along the Ahr at the time of the flood, a bridge density of 1.3 bridges per kilometer was determined. The local communities of Dümpelfeld and Altenahr as well as the town of Bad Neuenahr-Ahrweiler were characterized by the highest density of bridges along the Ahr. While the average distance between bridges in Dümpelfeld was about 300 m and in Altenahr around 400 m, the distance between the 24 bridges in Bad Neuenahr-Ahrweiler was around 500 m.

Along all three rivers, road bridges accounted for the largest proportion of bridges, followed by pedestrian and bicycle bridges. In total, eight railway bridges were documented along the river Inde and 18 along the river Ahr. Furthermore, a pipe bridge and two coal conveyor bridges were documented at the river Inde as well as two pipe bridges along the river Vicht. Regarding the opening shape, bridges with a rectangular opening shape such as truss, plate, frame, and beam bridges were combined in the analysis. Along the rivers Inde and Vicht, bridges with a rectangular opening shape predominated. Only five bridges along the river Vicht and 11 bridges along the river Inde were arch bridges. The proportion of arch bridges along the river Ahr reached 36% while slab bridges were mostly recorded along the upper reaches. Furthermore, bridges along the river Ahr showed more diverse characteristics. While single-span bridges made up the largest proportion of bridges along the rivers Inde and Vicht, bridges with up to two piers had approximately similar proportions along the river Ahr. Bridges along the river Vicht were the smallest in size compared with the rivers Ahr and Inde. They did not exceed a length of 40 m and therefore had no more than two spans. The largest proportion of bridges along the river Ahr was documented to have a length between 40 and 80 m. The characteristic bridge height measured between 1 and 2 m along the river Inde as well as between 2 and 3 m along the river Vicht. The mean bridge height along the river Ahr reached up to 11 m with smaller bridges along the upper river course and most bridges being three to 5 m long between the middle and lower reaches.

3.2 | Frequency of damage

In total, 32% of the 77 analyzed bridges along the river Inde were damaged or destroyed due to the flood event in 2021, meaning that those bridges were classified between the damage classes D1 and D4 (see Figure 4). Damages in the category D1 made up the largest proportion of bridge damages while the bridges were distributed similarly across the other classes. Most damaged bridges were located in the urban areas of Eschweiler and Stolberg, where the bridge density is highest. It was possible to document the damage classes for 52 of the bridges

TABLE 3 Bridge design before the flood along the rivers Vicht, Inde, and Ahr.

	Vicht	Inde	Ahr
Number of bridges before the flood (–)	67	88	114
Bridge density (bridges/km)	2.9	1.7	1.3
Maximum bridge density (bridge/km)	12	7	5
Proportion of arched bridges (%)	9	13	41
Mean bridge length (m)	14.0	30.2	77.3
Mean bridge height (m)	3.1	3.2	11.0
Mean bridge width (m)	6.5	7.5	7.0
Mean clear opening width (m)	2.4	17.5	11.0
Mean number of spans (–)	1.1	1.6	2.9

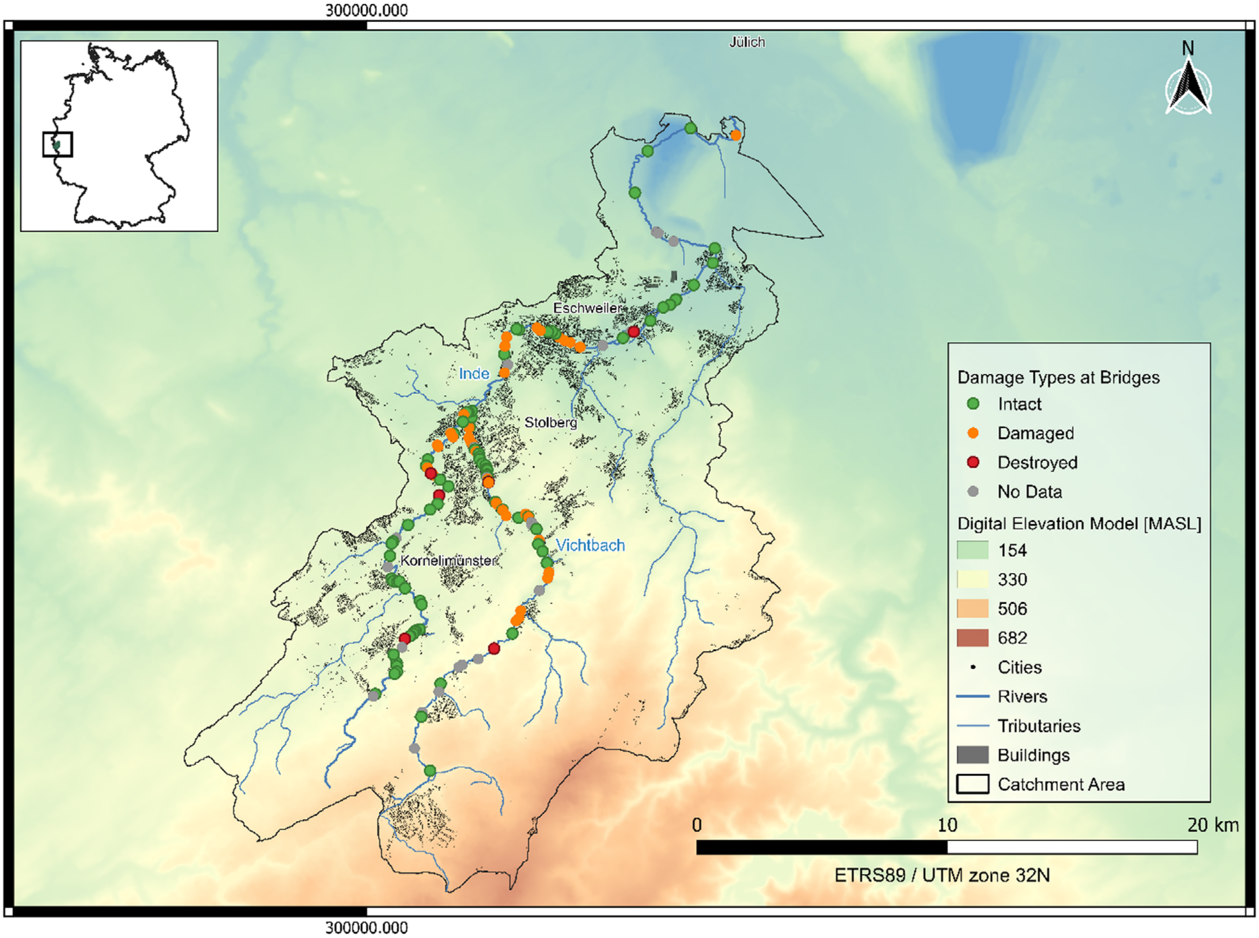

FIGURE 4 Damage mapping of the bridges at the rivers Inde and Vicht affected by the flood 2021 (own figure).

along the river Vicht. Half of the bridges were categorized as damage class D0. This is followed by 23 bridges with damage class D1. One bridge was assigned to damage class D2, no bridge to damage class D3 and two bridges to damage class D4. Most damaged bridges were located in the urban areas of Stolberg and Zweifall along the river Vicht. The proportion of bridges damaged in urban areas is more than three times higher than the proportion of bridges damaged in rural areas.

In comparison to the rivers Inde and Vicht, bridges along the river Ahr suffered more damage, with larger proportions of bridges within the categories D1 till D4. About three quarters of the 114 bridges along the Ahr were categorized as damaged (see Figure 5). Of these, about 41 of the bridges were destroyed and the rest damaged. In the upper reaches of the Ahr between Blankenheim and Dorsel in NRW, only two of the 20 bridges suffered damage in the course of the flood (see Figure 6). In the middle reaches of the Ahr, ~90% of the bridges were damaged, in the lower reaches ~85%. Along the rivers Ahr and Inde, the proportion of damaged bridges within populated areas is more than twice as high as in rural areas. Overall, it can be summarized for all three rivers, that damage to bridges was found especially in the densely populated areas in the middle and lower reaches.

3.3 | Statistical analysis of causes of damage

In order to determine possible causes of damage during the flood event and to derive flood adapted bridge designs, statistical correlations of the bridge designs and extent of damage at the bridges were analyzed. Along all three rivers, different statistical correlation patterns could be observed, but mostly no significant statistical correlations between the bridge design and the extent of damage was determined (see Figure 7 and Annex 4–6 in the Data S1). Therefore, none of the design aspects mentioned below could be identified as the major cause of damage to the bridges in this case study. Still, indications for damage prone bridge designs can be derived.

While the correlation between the length of the bridge and the damage class was slightly negative for

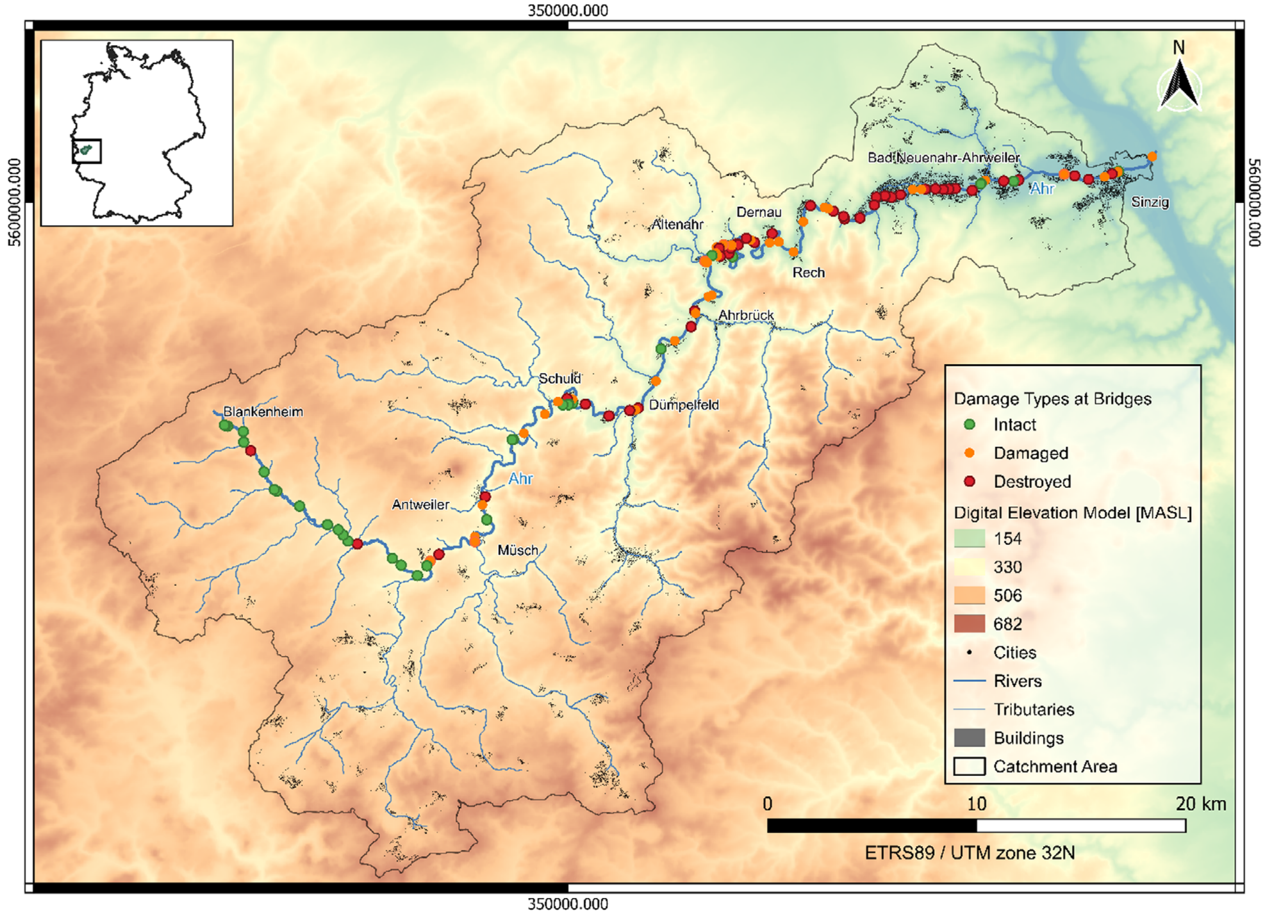

FIGURE 5 Damage mapping of the bridges at the river Ahr affected by the flood (own figure).

the rivers Vicht and Ahr, a slightly lower positive correlation was determined for the river Inde. The negative correlation would indicate, that longer bridges would be less prone to bridge damage during floods. Between the width of a bridge and the occurred damage, a significant negative correlation of −0.27 at the 0.01 level was determined for bridges along the Ahr. Here, the results for the rivers Inde and Vicht are opposed with a slight positive correlation of 0.03 along the Vicht and a slight negative correlation of −0.16 for the river Inde. Along all three rivers, a slightly negative correlation of up to −0.19 was determined for the bridges regarding the height of the bridge and the extent of damage. This is the only correlation that matches along all three rivers and reaches a level higher than 0.1. While the level of correlation is still week, it indicates that a lower extent of damage on a bridge could result with a higher bridge deck.

Regarding the clear opening width, bridges along the rivers Inde and Ahr showed slightly positive correlations of around 0.06 with the extent of damage. The result for the river Vicht differed strongly with a negative correlation of −0.60, indicating that the extent of damage decreased with an increasing opening width. While the correlation coefficient for the rivers Inde and Vicht showed a positive trend up to 0.04 regarding the number of spans and the damage classes, a stronger negative correlation of −0.23 was derived for the bridges along the river Ahr. This suggests on the contrary, that the extent of damage would have decreased with an increasing number of bridge piers. For the shape of the opening no statistical correlation could be observed along the three rivers since bridges with a rectangular opening were more dominant along the rivers Inde and Vicht and therefore no representative distribution was derived. Regarding the year of construction and the degree of bridge damage, no significant correlation could be determined. Along the rivers Inde and Ahr, it was observed that pedestrian bridges and lightweight constructions for hiking and bicycle bridges suffered damage to a larger extent.

Furthermore, the correlation between bridge design and the overtopping and clogging of bridges during the flood event was analyzed. Overtopping of bridges (whether induced by clogging or not) resulted in major bridge damages but also damages to the surrounding area. Again, the statistical correlations between all three

FIGURE 6 Documentation of different damage classes along the river Ahr: (a) loss of handrail, (b) large scale removal of building fabric, (c) loss of the superstructure, and (d) complete collapse (own figures).

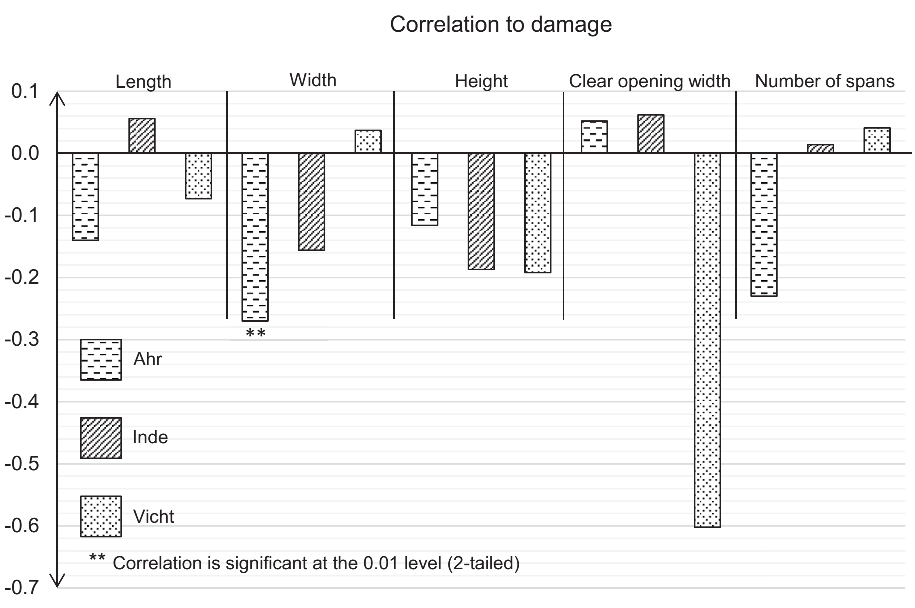

FIGURE 7 Summarizing correlation analysis regarding the bridge design characteristics and damage (own figure).

rivers differed strongly, showing the large variations of the flood event and damage mechanisms between all three regions. It has to be considered that the statistical analysis has been performed without considering structural design, hydraulic conditions and geotechnical aspects. Along the river Inde at 41 out of the 77 bridges indications of clogging were found and 51 bridges were categorized as overtopped. Nearly half of these bridges documented as blocked showed signs of overtopping. About 60% of all bridges along the river Vicht were categorized as clogged and 67% as overtopped. For about 45% of all bridges along the river Ahr, it was possible to make definite statements with regard to clogging and overtopping. About 60 of the bridges analyzed for this purpose were clogged, of which 45 were severely clogged. The overtopping of bridges was mainly documented in the middle and lower reaches of the Ahr. Only half of the 50 bridges categorized as overtopped showed definite signs of clogging.

In the course of the statistical correlation, a τ of about -0.60 was determined for the number of spans and the proportion of bridges along the river Inde that were clogged per span class. On the contrary, the correlation analysis delivered positive correlation coefficients of 1 for the river Vicht and 0.14 for the river Ahr, but also no significant correlation. Similar results were calculated for the analysis regarding the increasing number of piers and the proportion of bridges that were overtopped (see Figure 8). While for the rivers Ahr and Vicht, positive correlation coefficients of 0.33 and 1 were determined, a negative significant correlation of -0.75 was determined for the river Inde. For the clear opening width, no clear significant correlation could be found regarding the proportion of bridges that were overtopped and clogged. The results between the rivers Inde and Ahr differ strongly, while a significant correlation coefficient of -1 was determined, assuming that bridges with a longer clear opening width were also more likely to be overtopped along the river Inde. Except for the river Vicht, a positive correlation of up to 0.84 was determined for the proportion of bridges that were overtopped and the damage class. This indicates that the extent of damage on a bridge increased as soon as overtopping occurred. A similar correlation was also seen regarding the proportion of bridges with indication of clogging, but with a lower correlation coefficient of up to 0.32 at the rivers Inde and Vicht.

From the on-site visits several further damage patterns could be observed. While the highest degree of clogging mostly occurred on the cut bank of the meander loop, the higher degree of damage occurred on the slip-off slope. At heavily damaged bridges, a high degree of morphological changes such as bank erosion was mostly visible in the surrounding area. Railway embankments have also suffered severe damage as they were not designed for the impoundment of water masses. As observed in the city of Bad Neuenahr-Ahrweiler, bridges with shallow foundations were very likely to be destroyed.

4 | DISCUSSION

A comparison of the results among all three rivers reveals that the damage patterns varied strongly. Still, the extent of damage at bridges was documented to increase strongly within urban areas along all three rivers. This matches the results of Patt et al. (2021) whereas greater damage to the structure and higher water levels were observed in most cases in urban areas. Further differences in the damage patterns can also be attributed to varying regional conditions along the catchment areas of the three rivers. While the Ahr valley, as a notch valley, has steep slopes which confine the river course, lower water levels could be found along the rivers Inde and Vicht with a higher share of flatland. Factors such as soil conditions and runoff formation may also have influenced water levels and thus the runoff patterns on the rivers differently. This results in varying hydraulic loads

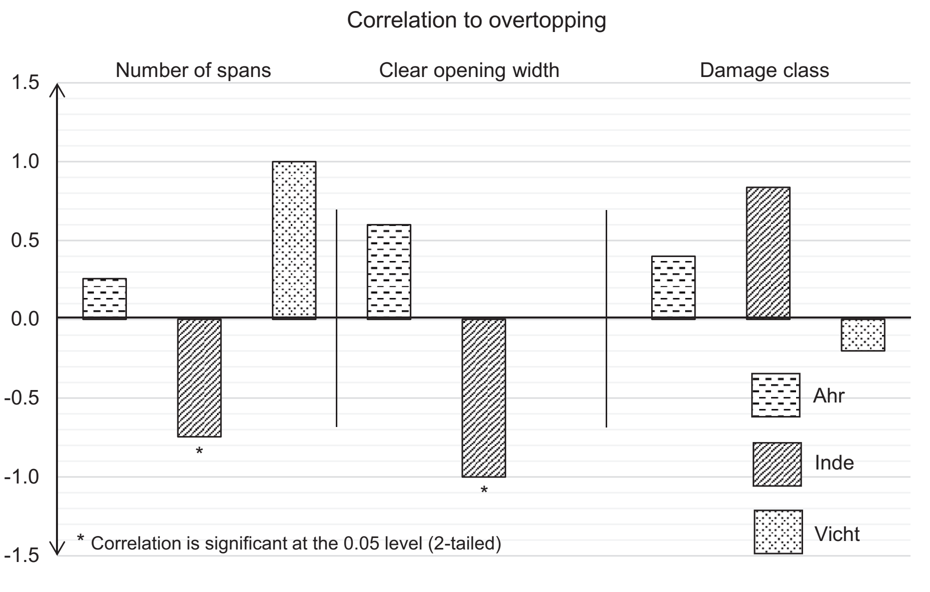

FIGURE 8 Summarizing correlation analysis regarding the bridge design characteristics and overtopping (own figure).

on bridge structures and therefore different damage patterns along all three catchment areas. Thus, the hydraulic conditions can be identified as an important factor for the damage pattern (Brandimarte & Woldeyes, 2013; Kerenyi et al., 2009).

The differences within the statistical analysis between all three rivers indicate that, in general, many factors determine the damage pattern and the destruction of a bridge structure. Similar to Tubaldi et al. (2022) it can be concluded, that the bridge type was not a decisive factor in the damage to a bridge during a flood. For the design parameters of bridge length, width, clear opening width and number of spans no significant statistical correlation could be found for the degree of damage at a bridge. A slight negative correlation was derived for the extent of damage and the increasing height of the bridge, which indicates, that higher bridges were less prone to damage during the flood 2021. This corresponds to the legal requirements found in DIN 19661–1 in Germany as well as the findings of Zevenbergen et al. (2012) and Gschnitzer et al. (2017), which recommend the consideration of a minimum freeboard of 0.5 m above the estimated water level of a flood with a 100-year return interval during the design of bridge structures. Still, the implementation of a larger freeboard is recommendable. Along the rivers Inde and Ahr, it was furthermore noticed that lightweight constructions such as pedestrian bridges were more likely to be damaged during floods.

Within the correlation analysis, a high degree of clogging and overtopping of the bridges could be observed along all three rivers in different extents. Similar to previous studies, as conducted by Diehl (1997) and Jempson (2000), clogging of the bridge opening can be identified as another factor on the damage mechanisms. The processes of clogging and damage to the bridges are very complex and could only be roughly estimated in this study. The presence of clogging could facilitate further damage mechanisms, e.g. due to scouring, which could not be assessed in detail in the course of this study. Even though, overtopping and clogging were more often documented at bridges with higher damage classes, those processes cannot solely be identified as the cause for damage or demolition. Still, early conclusions of this statistical analysis match data from previous studies. Similar to Bezzola et al. (2002), a correlation between the number of piers and the possibility of clogging could be found at both rivers Vicht and Inde. The opposite result for the river Ahr could be explained by the extent of the flood and the surroundings of the bridges as water levels reached far above the bridge deck for many bridges. Even though many of the clogged bridges were also classified as overtopped, this does not prove a causality and the process of overtopping depends on more factors. The water level as well as the conditions of the surrounding area are also very decisive for the overtopping of a bridge. Furthermore, the debris volume and composition can further alter flow patterns at a clogged bridge. During the flood event 2021, a high proportion of man-made material (e.g., building rubble and vehicles) could be observed within the debris accumulations and the effect on flow conditions still has to be studied. Nevertheless, the presence of a clogged bridge can be mentioned as a contributing factor to increased water levels in front of the bridge and thus to larger flooding areas (Birkmann et al., 2023; Landesamt für Umwelt Rheinland-Pfalz, 2022; Schalko, 2018; Schmocker & Hager, 2011).

Overall, it must be said that many other factors, which could not be investigated in this study, have a decisive effect on the extent of damage to a bridge during a flood: for example, the statics of the bridge and the components (Drdácký & Sližková, 2007). The type of foundation and the type of erosion protection can play a significant role in the resistance of a bridge against high runoff volumes. The presence of clogging can lead to increased flow velocities at the bridge components and enhance erosion leading to scour (Beltaos et al., 2007; Zevenbergen et al., 2006). The foundation in turn depends decisively on the soil conditions and floods with a low return interval can have a decisive impact on the scouring processes. Furthermore, the loads on the structure are increased during clogging and overtopping, due to the increased hydrostatic and hydrodynamic pressures as well as the occurrence of buoyancy forces during submerged flow conditions. The flexibility of the bridge structure, especially of integral bridges, has also already been identified by Tubaldi et al. (2022) as a factor in the vulnerability to scour and scour-induced settlements. Additionally, the bridge deck was identified as the most vulnerable component of an integral bridge. The shape of the abutments and the flow conditions on them can also be critical to the extent of damage to the bridge (Pohl, 2015). Another crucial factor for damage at a bridge is the condition of the structure which should be kept as good as possible with the help of maintenance. The status of bridges prior to the flood event in 2021 could not be assessed in this study.

At the outset, it must be stated, that this evaluation could not be carried out in detail where bridges were demolished during the flood or if clearance work had already taken place. In addition, not all construction data for the bridges could be obtained due to the various responsibilities. This resulted in compromised data for the statistical analysis with data that was not normally distributed and not checked for autocorrelation. Along the river Vicht only bridges with up to two spans with a comparably lower bridge length could be observed which

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then may lead to the contrary results for the correlation analysis regarding the clear opening width. Also bridge design characteristics as the bridge length and its height differed strongly along all three rivers. As estimates on the extent of clogging are only based on aerial photographs and flotsam residues and no data about the exact composition and volume of debris was available, statements on the extent of clogging should be treated with caution. Furthermore, only little data were available for collapsed bridges, thus an extension to the data collection would be advisable. For future studies, the collection of data and structural assessments of the bridge structure right after the flood event are recommended. The flood event 2021 reached a scale that was not anticipated and exceeded hitherto existing dimensioning concepts of a 100-year design flood. A comparison with further flood events in different catchment areas and with historic flood induced damage could also complement the data collection and allow more definite conclusions on the correlation between bridge design parameters and damage patterns for each catchment area. Even though correlations do not imply causality, first recommendations can be derived from the conducted analysis and based on previous studies.

4.1 | Reconstruction

For the reconstruction of the bridges, four main areas for recommendations for action can be identified from this study as well as previous studies (see Figure 9). These include adaptations in the cross section, the superstructure, the piers, and the dimensioning processes. With the help of these changes, the probability of clogging as well as the hydraulic backwater rise can be reduced, overall increasing the resistance of the structure against hydraulic stresses (Jempson, 2000; Patt & Jüpner, 2020).

The size of the cross section was determined to be an important factor for the extent of damage, clogging, and overtopping of a bridge during this analysis. In order to increase the clear bridge opening, the superstructure of the bridges should be raised and more flow cross-section as well as a higher freeboard should be guaranteed (Gschnitzer et al., 2017; Zevenbergen et al., 2012). Additionally, larger span widths should be achieved in the design of new bridges, thus reducing the number of bridge spans and piers (Gschnitzer et al., 2017; Rutschmann, 2017). Abutments should be located outside the flow cross-section with appropriate protection from erosion (Deutsches Institut für Normung e. V., 1998; Pohl, 2015). At the same time, as far as technically possible, small bar arch construction methods should be dispensed with. Although these can increase the span widths, they have an increased raking effect for flotsam due to the superstructure. In the event of flooding with water levels at the bridge deck and the accumulation of flotsam, this increases the loads on the bridge structure and carries the risk of the structure being torn down. In addition, the bridge superstructures should be designed as narrow as possible, making its geometry favorable for

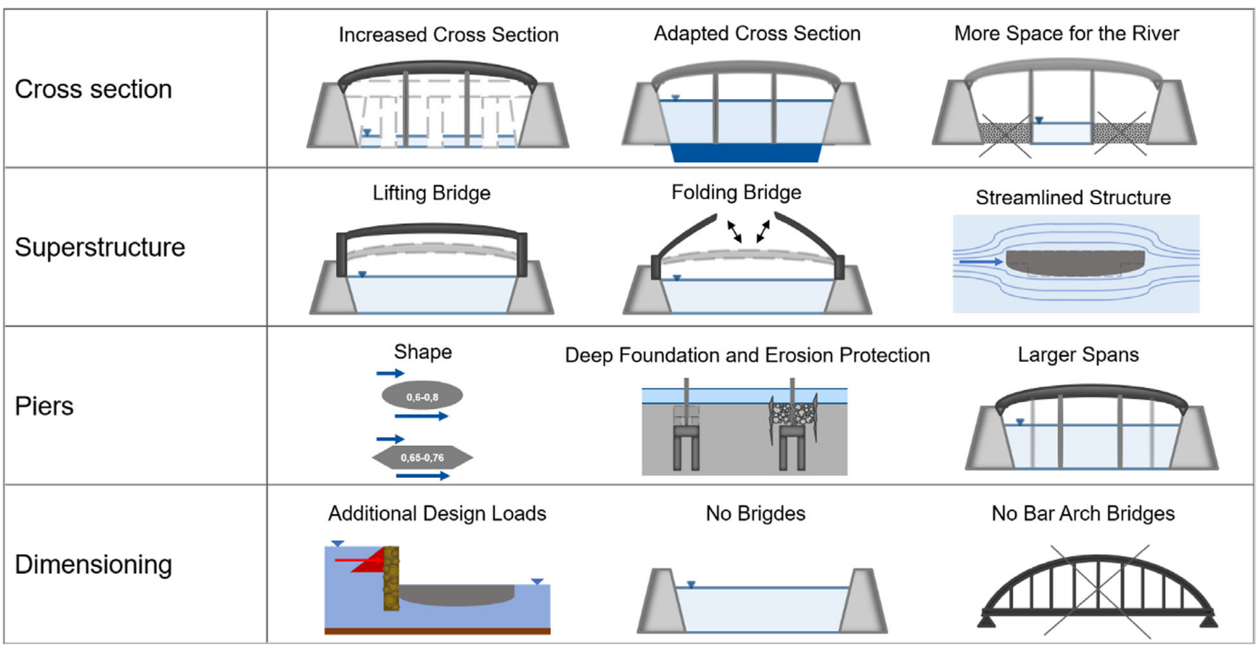

FIGURE 9 Recommendations for flood-adapted bridges (own figure).

flowing water in order to reduce the backwater in front of the bridges and the potential for clogging. (Ahmari et al., 2021; Goedeking & Landvogt, 2022; Greco et al., 2021) Obstructed bridge spans should be kept clear during reconstruction to provide more space for the river to flow and to reduce runoff obstructions. The demolition of approach ramps to bridges is a common damage pattern during the 2021 flood, so the German Committee for Disaster Reduction recommends that approach ramps should be designed to withstand overtopping (Deutsches Komitee Katastrophenvorsorge e.V., 2022). This should prevent the damage caused by erosion and maintain the operational capability of the bridges. Further, the implementation of streamlined pier designs and deep foundations as well as erosion control for new bridge structures is recommended (Lamb et al., 2017; Pohl, 2015; Zevenbergen et al., 2012). Loads due to impact of clogging, damming and overtopping, for example, lifting forces and increased debris impact on the slip-off slope, should also be regarded in the new design processes (Jempson, 2000).

Along all three rivers high bridge densities in comparison to other low mountain range rivers especially within urban areas were observed. Other low mountain range rivers in this region have comparatively lower bridge densities with less than one bridge per kilometer. On the Rur, for example, there is an average of 0.7 bridges per kilometer, and on the Olef, 0.9 bridges per kilometer. This also correlates with areas where high damages were registered. The non-reconstruction of certain bridges or, for example, the merging of road and pedestrian bridges to reduce the number of drainage obstacles should also be considered. This can help to reduce the effects of backwater rise and therefore the extent of the inundated area. Regarding the alteration of flow due to clogging, an implementation of very low fords for dispensable usages, for example, hiking or bicycle bridges, could be considered. Due to the low bridge deck altitude, the bridges would be overtopped early enough, that debris would pass the deck and the risk of clogging would be reduced. Furthermore, the position of a bridge in relation to its surroundings can be crucial for the effects on river discharge. Bridges constructed after 1804 and repeatedly demolished after the flood events in 1910 and 2021 could therefore be located further upstream or downstream in the vicinity of floodplain areas, where the bridge can be bypassed by debris and water without increasing the risk for settlements.

Within this study, the dominant role of the clogging process in relation to the extent of damage of the bridge could be observed. A professional exchange between communities and bridge designers is recommended in order to interchange knowledge and ensure an effective reconstruction (Birkmann et al., 2023). Regarding the return period of historic flood events especially in the Ahr valley and a comparably short record of gauge data, an underestimation of the 100-year design flood should be further examined. With increasing record time spans, the reassessment of outliers and therefore adaption of design values becomes crucial. Furthermore, the maintenance of bridges and the assurance of a good structural status of the bridge are crucial in order to prevent future damages. Structural adaptations of the bridge, such as raising the bridge deck, will be limited to certain locations and traffic payloads. Therefore, in addition to structural and design adaptation options, the topics of debris management and retention are crucial as stated in DIN 19661–1. A variety of flotsam traps or even bypass solutions have already been developed. However, morphological changes as well as the geomorphological conditions must be considered. With the help of hydraulic models, the effect of a bridge on the flood discharge and impacts of bridge designs, clogging, overtopping as well as influence of the bridge position can be determined in detail. Furthermore, the transport process of debris and the risk of clogging can be assessed. These results should also be implemented in flood hazard and flood risk maps in order to be able to predict changes in the inundation area due to bridges and their potential collapse. (Mohr et al., 2023; Schmocker & Hager, 2011; Tubaldi et al., 2022).

5 | CONCLUSION AND OUTLOOK

Bridges proved to be a crucial drainage obstacle during the July 2021 flood, while the loss of bridges once again highlighted their supporting role for the infrastructure especially in the Ahr valley. As with other structures and infrastructures, rebuilding according to the old status quo is not very sustainable or resilient for the bridges. Due to the great importance as critical infrastructure and the potentially high damage potential of bridges, a coordinated, knowledge-based and adapted reconstruction of the bridge infrastructure is necessary. With the help of the findings of this study, a unique dataset of damages, clogging and overtopping resulting at bridges along all three rivers Ahr, Inde, and Vicht after the flood event 2021 was conducted. These data can further serve more in-depth analysis of damage mechanisms, for example, regarding morphological changes at bridge structures and the loads on bridges for an assessment of the statics. Furthermore, crucial factors for the new design of flood-adapted bridges were determined and confirmed with the help of former studies and existing design recommendations. Additionally, the role of clogging, the influence of the number of bridge piers on the clogging probability as well as the importance of the surroundings and the positioning of the bridge can be highlighted. Reducing the number of piers and their position within the riverbed, increasing the bridge height as well as the adaption of design procedures accounting for debris impact and overtopping could be elaborated as proposals for the adapted bridge construction methods. Furthermore, the mechanism of clogging during a flood event still must be investigated in more detail, especially regarding the various debris compositions that were present in 2021 along the three rivers investigated in this study. These clogging processes are often not incorporated within flood risk maps; thus, the sizes of inundation areas are underestimated and rescue measures hindered. Therefore, the ongoing reassessment of return periods for design values with regard to increasing record time spans as well as the evaluation of clogging risk and effects within hazard communication are recommended.

However, these results will not solely serve as part of the new assessment bases. Static aspects and the condition of the structure prior to the flood could not be considered in this study and can also be decisive for the failure of a bridge structure. Further aspects as watercourse maintenance, disaster management, spatial planning and the expansion of retention facilities will also have to be considered. With regard to climate change, the aim is to achieve a sustainable structure that can withstand potentially stronger and more frequent future flood events.

Due to the uncertainties in the statistical evaluations, two-dimensional hydro-numerical simulations and flume experiments of the runoff events at selected sites will also be carried out to more accurately represent the processes of clogging and their influence to the runoff event. Thereby, the extent of clogging and the effect of debris composition will be examined in more detail. These findings will also serve to improve the new design procedures and decision-making processes of the reconstruction of essential bridges and the construction new bridges within Western Europe.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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