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A MATTER OF DEBRIS COMPOSITION: ANALYZING DEBRIS ACCUMULATIONS AT BRIDGES AFTER THE 2021 FLOOD

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ABSTRACT

This study presents an analysis of debris accumulations at bridges and flume experiments, based on field data collected after the extreme flood event which hit Belgium and Germany in 2021. Post-flood photos were analyzed regarding bridge designs, debris accumulation volumes and debris compositions as well as flooding conditions. This showed that the voluminous debris accumulations contained a large share of anthropogenic materials characterized by various shapes. Based on averaged bridge data, prototype bridges were chosen for the experimental modelling, which was conducted in three laboratories in Belgium, Germany and the Netherlands. Thanks to this multi-lab approach, over 250 experiments were conducted, determining the effect of upstream hydraulic conditions, debris shape and bridge design on backwater rise. Compared to debris accumulations with only logs, backwater rise increased with larger shares of plates in the debris compositions, while decreasing with the same shares of cuboid elements. The number of piers and the geometry of the bridge deck showed a strong effect on the clogging behavior, and a closed handrail led to higher backwater rise compared to a porous or no handrail. As a result of various test set-ups and continuous comparisons, inter-lab differences could be determined and reduced, and therefore resulting in a more reliable dataset. On this basis, recommendations for future bridge design and operational flood protection measures were derived.

Keywords: Large wood, Driftwood accumulation, Bridge designs, Backwater rise, Scale experiments

1. Introduction

Heavy rainfall in Western Europe caused catastrophic flooding in 2021, leading to water levels far above the 100-year design flood at several places (Mohr et al., 2023; Ludwig et al., 2023). Large parts of critical infrastructure were severely damaged, including drinking water and energy supply as well as many bridges (Burghardt et al., 2024; Wüthrich et al., 2024). At numerous bridges in Belgium and Germany, large volumes of floating debris were blocked, altering flow conditions and eventually contributing to bridge failure (Burghardt et al., 2024; Szymczak et al., 2022; Erpicum et al., 2024). Heterogenous debris accumulations were observed, with a high share of anthropogenic objects, mainly originating from high water levels in urban areas (Mohr et al., 2023). While recent studies have focused on debris accumulations at bridges or debris racks with mostly heterogenous and natural debris components (Schalko, 2018; Schmocker and Hager, 2011, 2013), this study aims to classify the proportion and shape of voluminous anthropogenic materials within the debris accumulations and quantify their effect on backwater rise at bridges. Therefore, data on debris properties was derived from an in-depth analysis of photos documenting debris accumulations after the 2021 flood event. Based on this data, flume experiments were conducted in three laboratories in Belgium, Germany and the Netherlands. Besides determining the influence of debris shape on backwater rise, the effect of bridge design on backwater rise and accumulation behavior were analyzed. Thereby, a large dataset of experimental data was created and inter-lab differences were evaluated, providing recommendations for the design of new bridges within the affected areas. In addition, major bridge clogging was recently observed during floods in Italy, Switzerland and France, pointing out the widespread relevance of this issue and the broad applicability of these results.

2. Data collection

In total, 71 bridges were analyzed, 38 of them located in Belgium. While most of the bridges in Belgium were located on the river Vesdre, one bridge on the river Hoëgne and two bridges on the river Helle were included in the data collection due to an exceptional documentation of debris accumulation. In Germany, 30 of the 33 bridges were located on the river Ahr, two on the river Vicht and one on the river Inde. With the help of 205 aerial and handheld photos (at least one arial and one handheld photo per bridge), taken promptly after the flood event in 2021, bridges and the accumulated debris were evaluated, focusing on three main aspects:

(1) Bridge properties regarding damage, pier and bridge deck design, location and geometry,

(2) Hydraulic conditions at the bridge and

(3) Debris accumulation properties, including volume and composition regarding type and shape of the debris components.

Additionally, construction drawings, in-situ measurements and publicly available geodata were used to backtrack bridge geometries. Visible debris volumes were measured by length and width as well as height based on the contours of the accumulation and side-view photos. They therefore define the bulk accumulation volume including pore volume. The photo analysis was carried out using the software ImageJ (Version 1.53) by three different researchers and compared afterwards. If all estimates varied by more than 15%, results were discussed with all three scientists, all estimation methods were presented and a final estimation was conducted. If results varied by less than 15%, the mean value was used.

Debris components were classified using eight categories: (1) natural wood, (2) anthropogenic wood, (3) plastic tanks/containers, (4) metal tanks/containers, (5) vehicles, (6) household items, (7) industry items, (8) building rubble. For each debris category, their volume fraction within each accumulation was estimated. Furthermore, it was noted that these categories were characterized by specific shares of three characteristic shapes: logs, flat shapes and cuboid shapes. These shapes were determined to be most representative in documented debris accumulations. Natural wood, mainly consisting of trees, was therefore classified with a log fraction of 100% and no cube or plate fraction whereas vehicles and tanks were characterized by a cube fraction of 100%. Household and industry items as well as building rubble showed a large share of up to 40% flat and 40% cuboid objects.

The photo analysis showed that the debris accumulations ranged from 0.5 cubic meters to over 4000 m^3 for the largest debris accumulations in Germany. In Belgium and Germany, 40% of large accumulations occurred at bridges with a pier spacing of less than 10 meters. On 83% of all bridges, the water level at least reached the bridge deck, and often overtopped the structure. This highlights the influence of the bridge deck itself on clogging probability and backwater rise. The debris compositions were characterized by at least 50% of anthropogenic materials in both Germany and Belgium, since more than half of the analyzed bridges were located in urban areas. As displayed in Figure 1, over 90% of the analyzed accumulations were composed of logs while at 24 bridges shares of plates or cubes made up at least ten percent. Based on this dataset, seven characteristic debris compositions (blue squares in Figure 1), which represent the range of observed debris compositions, were used in the subsequent experimental modelling.

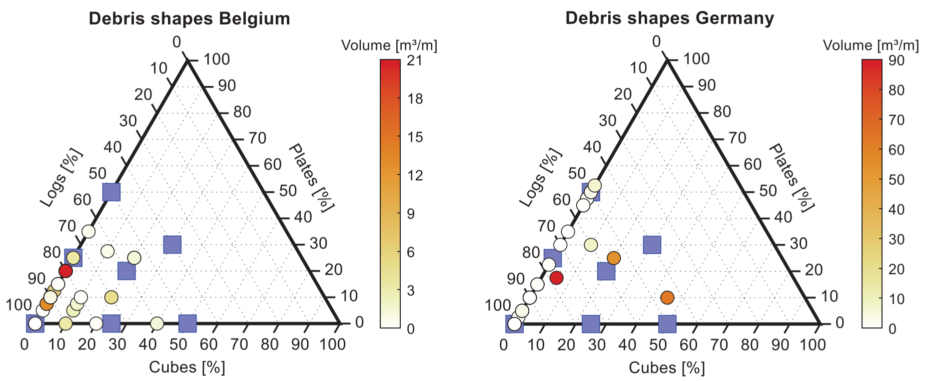

Fig. 1. Debris compositions regarding volume and shape distribution observed in Belgium and Germany. Blue squares indicate the debris mixtures studied in the experimental modelling.

3. Experimental modelling

The goal of the experimental modelling was to examine the effect of hydraulic conditions, debris shape and bridge design on upstream backwater rise. Tests were conducted in three laboratories in Aachen (referred to as flume G1), Liège (flume B1) and Delft (flume N1). Based on averaged data of the bridge characteristics obtained in Section 2, a prototype bridge with two 1.1 m wide piers, a central opening span of 8.5 m and an opening height of 4.3 m was chosen. With a 1.2 m wide flume available in all three laboratories, this resulted in a Froude scaling ratio of 1:16 and the model dimensions shown in Figure 2. Additionally, to investigate the effect of bridge design, tests in a one-meter-wide flume with a Froude scaling of 1:19 were conducted in a second flume in Liège (flume B2). Here, the number of piers was varied and tests were conducted with two piers, one centrally positioned or no pier. Backwater rise was measured using four ultrasonic water level sensors positioned upstream of the bridge, distancing one meter apart. Debris was added to the flume at least four meters upstream of the bridge and 0.5 meters upstream of the first water level sensor. Hydraulic conditions were set in terms of the upstream water level h and Froude number $\mathrm{Fr} = v/(gh)^{0.5}$ of the approach flow.

Seven characteristic debris compositions, obtained from Figure 1, were modelled in the experiments. A volume of up to 190 L of debris, derived from the averaged data of photo analysis by applying the Froude scaling ratio of 1:16, was added to each flume per experiment. Debris volumes were divided into equal batches, ranging from 3.6 to 11 L, depending on debris composition and model scale, and added to the flume every three minutes. Debris that passed the bridge, was readded to the flume, to ensure similar debris accumulation volumes during every experiment. As displayed in Figure 3, debris shapes were mimicked using logs in varying lengths with a diameter/length ratio of 1/20 based on a study by Steeb et al. (2019) who recorded mean length and mean diameter values for natural logs after riverine flood events. Flat objects were represented by blue plywood plates, measuring 10 × 6 × 0.2 cm based on mean values derived from the photo analysis. For voluminous objects, e.g. tanks, red cuboids made of Douglas fir with 9 × 9 × 18 cm in size were used. Debris was dried between the tests to ensure floating behavior. Handrails were varied in porosity, using a steel bar handrail (porosity of 83%, visible in Figure 2), a closed handrail (no porosity) or no handrail based on the bridge characteristics observed during the photo analysis. Hydraulic conditions were varied regarding the Froude number of the approach flow and the water level at the bridge at the beginning of debris transport.

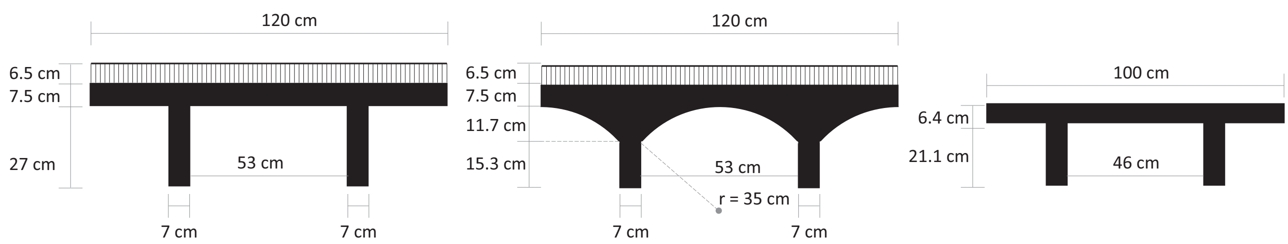

Fig. 2. Bridge model dimensions for bridges with rectangular opening (left) and arched opening (middle) for model scale 1:16 as well as for the model bridge at scale 1:19 (right). All bridges measured 50 cm in flow direction.

Fig. 3. Three debris components: logs, cubes and plates (not to scale)

Generally, backwater rise increased with increasing share of plates in the debris compositions, leading to higher backwater rise and a quicker overtopping of the bridge deck than at accumulations with only logs. On the contrary, debris compositions containing cubes led to lower backwater rise than with solely logs. Nevertheless, logs were required to create an initial blockage at the bridge. With increasing Froude number, the backwater rise for the same debris volume increased as well (see Figure 4). Below Froude number 0.13, almost no backwater rise could be observed, independent of the debris composition. The number of piers showed a significant effect on the clogging behavior, but not on the extent of backwater rise. With reducing number of piers, the initialization of clogging became less likely and more debris passed the bridge at the beginning of the experiment. Nevertheless, as soon as one log was blocked at the bridge piers, the same level of backwater rise could be achieved. At bridges with no pier, no blockage was created and no backwater rise was observed. Bridges with porous or no handrail showed less backwater rise compared to bridges with a closed handrail. Still, the presence of a porous handrail facilitated interlocking between debris and the bridge, whereas at bridges without handrail, debris was transported earlier over the bridge deck, leading to lower backwater rise. At bridges with an arched opening shape a slightly lower backwater rise was observed compared to bridges with rectangular openings. For initial water levels above the bridge deck and handrail height, no debris accumulation was formed and no debris-induced backwater rise was observed. Overall, test results between all three laboratories agreed well and the same dependency of backwater rise on Froude number and debris shape was observed.

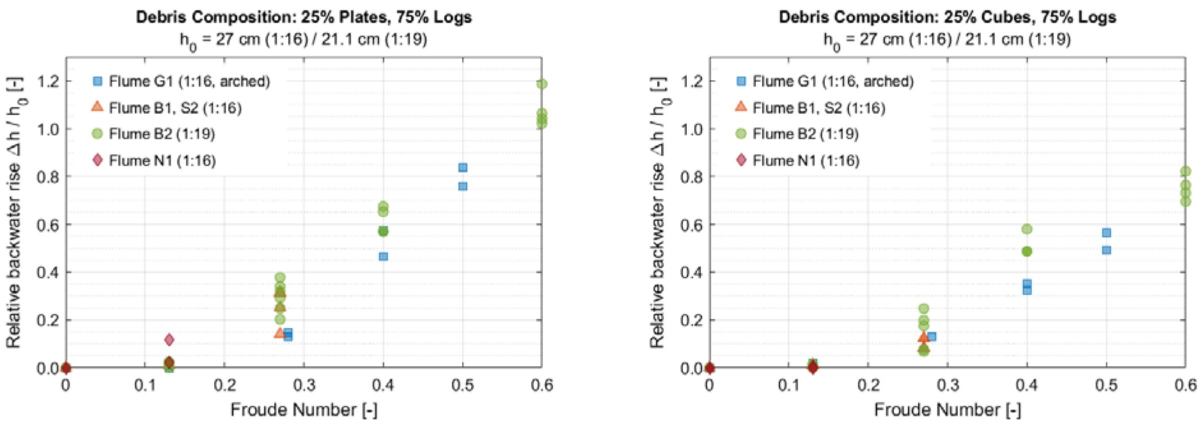

Fig. 4. Relative backwater rise as a function of the Froude number and debris composition conducted in all three laboratories at two model scales. Displayed backwater rise results after adding 76 L (model scale 1:16) and 38.6 L (model scale 1:19) to the flume measured four meters upstream of the bridge.

4. Discussion

The dataset collected after the 2021 European flood is based on post-flood photos which solely show visible debris accumulations. Up to 50% of the visible, floating debris accumulations consisted of anthropogenic materials. In general, objects of higher density are transported underwater, closer to the channel bottom, and therefore not visible in the photos, which may result in them not being included in the collected data. These materials might lead to large debris accumulations underwater and a higher flow resistance which would cause even higher backwater rise. In this study, floating behavior of debris was ensured but further studies on different debris densities in combination with debris shape are required. Furthermore, the estimation is based on bulk volumes, which might have led to an overestimation of debris volumes. Since debris accumulations are removed promptly after a flood event to enable reconstruction, data collection on debris components is impeded and must be carried out quickly. Yet, the estimated volumes of these accumulations highlight the importance of debris and their various compositions for hydraulic conditions during flood events. The flume experiments showed that debris-induced backwater rise can double the initial water depth for high Froude numbers. A similar effect of the Froude number on backwater rise compared to studies on debris racks could be identified (Schalko, 2018). The actual effects on backwater rise strongly depend on the natural occurrence of debris in the catchment area, the elevation and shape of the surrounding areas of the bridge and the flood discharge. As is evident from the data collection, river and valley width will have a strong influence on accumulation characteristics at a bridge. At the middle reaches of the Ahr river, which are characterized by narrow and steep hillslopes, larger debris volumes were observed compared to the river Vesdre, where a wider flood plain allowed the bypassing of many blocked bridges. Furthermore, in line with studies conducted by Schmocker and Hager (2011), the bridge deck design including handrail noticeably affected backwater rise but also clogging behavior.

Overall, this study underlines the effects of debris accumulations at bridges during flood events in urban areas, focusing on inundation depth and pointing out their relevance in flood management strategies. While bridges are often not yet included in flood risk and flood hazard maps and therefore backwater rise due to a bridge itself might be underestimated, water levels at blocked bridges might be considerably underestimated. Already at water levels far below the bridge deck, considerable backwater rise was observed in this study and overtopping of the bridge is facilitated due to blocked debris. Hence, bridge clogging can pose a significant safety risk to residents as well as emergency personnel and should be included in early warning measures. Furthermore, the static impacts on bridges for flood events with water levels as high as the bridge deck as well as the forces occurring due to debris accumulation and impounding should be considered during the reconstruction of affected bridges. With the help of new design approaches for flooded bridges, the risk of bridge failure and therefore damage potential due to flood waves can be reduced. In line with Bezzola et al. (2002) and Gschnitzer et al. (2017), an effect of the number of bridge piers on debris behavior was visible during the experiments. Accordingly, larger bridge spans and a lower number of bridge piers would be beneficial, in order to reduce the clogging probability. In addition, the implementation of debris retention measures especially upstream of densely populated areas is recommendable in order to reduce the risk of bridge clogging.

5. Conclusions and outlook

With the help of extensive data collection of bridge clogging after the 2021 flood event, debris volumes and debris compositions at 71 bridges were quantified. Large debris volumes of over 500 m^3 were determined, especially at bridges with flood water levels at or above the bridge deck. It was observed that up to half of the debris accumulations consisted of anthropogenic materials with various shapes. The results of the experimental modelling indicate, that backwater rise increased for increasing shares of flat elements within the debris compositions and with increasing Froude numbers. These results highlight the significant effect that debris accumulations can have on flood events and inundation depth at bridges especially in the vicinity of urban areas. This underlines the importance of precise early warning measures for residents and emergency measures in order to reduce flood risk and flood damages. Therefore, the inclusion of bridge clogging in flood risk and flood hazard maps is recommended. Based on the data derived from both photo analysis and flume experiments, recommendations for flood adapted bridge designs and design approaches for the construction of bridges were derived. Further research on the effect of debris densities is needed to determine more precise estimations of backwater rise at bridges during flood events.

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