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Multi-lab investigation of the effect of debris composition on bridge clogging during floods

Lisa Burghardt[1], Daan W. Poppema[2], Loïc Bénet[3], Davide Wüthrich[2], Sébastien Erpicum[3], Elena-Maria Klopries[1]
[1]Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Aachen, Germany
[2]Department of Hydraulic Engineering, Delft University of Technology, Delft, The Netherlands
[3]Hydraulics in Environmental and Civil Engineering (HECE), Liège University, Liège, Belgium
E-mail: burghardt@iww.rwth-aachen.de

Abstract: *During the European flood of 2021, large debris accumulations were observed at numerous bridges, causing backwater rise, increased upstream flooding, and extended damage. To date, debris accumulation studies mainly focused on debris consisting of logs, at bridge piers or debris racks. However, during the 2021 flood, debris contained a large share of man-made materials in various shapes, often reaching the bridge deck and railing. Therefore, flume experiments on debris accumulation at bridges were conducted at three laboratories in Belgium, Germany and the Netherlands. Hereby, we investigated how backwater rise depends on flow conditions and on debris composition – using debris mixtures of 75% logs with either 25% cubes or 25% plates. Results showed that mixtures with plates caused 1.8 – 2.9 times more backwater rise than those with cubes. This means that previous studies on natural log accumulations may substantially underestimate backwater rise at debris accumulations with e.g. building rubble during flood events. Almost no backwater rise occurred below approximately Fr = 0.2, after which backwater rise increased with the Froude number. Comparison of results between labs agreed relatively well, with backwater rise under the same conditions varying often by 10% to 35%. However, the results of a single series of experiments were higher by up to a factor 2.5. This implies that any multi-flume or multi-lab study should ensure sufficient overlap between test conditions, rather than a pure workload split. Moreover, the observed inter-lab variability implies that multi-lab setups can increase confidence for the generalization of test results to real-world conclusions.*

Keywords: Keywords: *Flood events, Debris accumulation, Bridge designs, Backwater rise, Flume experiments*

1. Introduction

The European river floods of July 2021 caused more than 200 casualties and billions of euros in damage in Belgium, the Netherlands and Germany (Koks et al. 2022; Mohr et al. 2023). Critical infrastructure including roads, bridges and utility networks were severely damaged (Korswagen et al. 2022). At numerous bridges, debris accumulations developed, clogging the bridge and increasing upstream water levels, and thereby inundation depth and area (Burghardt et al. 2022; Landesamt für Umwelt Rheinland-Pfalz 2022). Furthermore, due to increased loads, from both hydraulic conditions and debris accumulations, many bridges were severely damaged and even collapsed, releasing waves of debris and water and leading to a higher damage potential (Tubaldi et al. 2022; Zanke 2013). Since debris accumulations were observed in all three countries, the EU-funded project EMfloodResilience aimed to investigate the effects of debris accumulation at bridges regarding various compositions of debris in transnational cooperation. To date, previous studies mostly focused on accumulations at bridge piers without a deck or at debris racks, with accumulations mainly composed of logs (De Cicco et al. 2018; Schalko 2018; Schmocker and Hager 2013). However, during the 2021 flood event, water levels reached or exceeded the bridge deck at many bridges, and debris accumulations contained a large share of man-made material (e.g. building rubble, vehicles and furniture).

Therefore, new flume experiments were conducted to investigate the hydraulic conditions at bridges during flood conditions in the presence of different shapes of floating debris. Hereto, data on the debris compositions at bridges as well as typical bridge designs was collected (Erpicum et al. 2023). The experiments of the project were split between different labs. This allowed to conduct more experiments in a short time, but also served to study inter-lab variance of the results. From Tullis et al. (2019), relatively simple experiments on the head-discharge relationship of identical weirs in different labs are known to lead to different results (up to 50% difference in the discharge coefficient), due to differences in instrumentation type or calibration, approach flow conditions, measurement location, laboratory measurement methods and human errors. Hence, it is relevant to quantify this uncertainty for backwater rise from floating debris, which involves not only hydraulics but also a chaotic accumulation process.

The aim of this paper is to A) determine the influence of various debris compositions and hydraulic conditions on the backwater rise at bridge structures and B) investigate variance in the effect of debris accumulation at bridges in different labs.

2. Methodology

2.1. Laboratories and flumes

The experiments were conducted in the laboratories of the universities TUDelft (The Netherlands), RWTH Aachen (Germany) and ULiege (Belgium), to split the workload and examine inter-lab variance. In all three labs, experiments were conducted in flumes with a width of 1.2 m, at a 1:16 model scale. In Liège, experiments were additionally conducted in a 1 m wide flume, at a 1:19 scale. The flume characteristics are described in detail in Table 1, with flumes codes (B1, B2, G1, N1) named after the country (Belgium, Germany, Netherlands). In all labs, the effect of debris on backwater rise was measured following the same protocol and using the same type of debris. Hydraulic conditions were defined in terms of the initial Froude number and water level, set through the pump discharge and controlled via a weir located on the downstream end of the flume. Debris was dropped into the flume every three minutes from a drop-in device, in small batches of a fixed volume. Any debris that passed the bridge was immediately re-added to the flume with the drop-in device, to ensure the accumulation volume at the bridge equals the known dropped-in volume. Water levels during the test were measured with ultrasonic distance sensors (UDS). To compare hydraulic conditions in detail, flow velocities without debris at the beginning of a test were measured with acoustic doppler velocimeters (ADV) with a sampling rate of 100 Hz at 15 points uniformly distributed over the flow area and for the flow conditions mentioned in Table 1.

Table 1. Flume characteristics in the three laboratories

	Liège (B1)	**Liège (B2)**	**Aachen (G1)**	**Delft (N1)**
Flume width [m]	1.2	1	1.7, narrowed to 1.2	1.5, narrowed to 1.2
Model scale	1:16	1:19	1:16	1:16
Flume length [m]	7.2	10	32	40
Flume height [m]	1.2	0.5	1.7	0.8
Inclination [°]	0	0	0	0
Location of the UDS [m]*	4, 2.5, 1.5, 0.25, -1	4, 3, 2, 1, -0.5	4.5, 3.5, 2.5, 1.5, 0.25, -1	6.5, 3.5, 1.5, 0.25, -1
Maximum discharge [m³/s]	0.25	0.2	1.2	0.1
Flow equalization	Synthetic screen at inflow	Metal grid and synthetic screen at inflow	Cubic flow equalizer at inflow	Ramp with flow guides
Water level control	Weir downstream of the bridge	Weir downstream of the bridge	Weir downstream of the bridge	Weir downstream of the bridge
Location of the downstream mesh [m]*	-2.5	-2.5	-4	-27
Orientation of the downstream mesh	Horizontal	Horizontal	Horizontal	Vertical
Location of the drop-in device [m]*	3.5	5.5	5	5.5
Height of the drop-in device [m]	0.8	0.5	1.2	0.8
Position of cameras	Side- and top-view at bridge	Side-view at bridge	Side- and top-view at bridge	Top-view at bridge
Location of velocity measurements [m]*	3.5	5.5	4.5	4
Conditions for velocity measurements	Fr = 0.27, h = 27 cm	Fr = 0.25, h = 21.1 cm	Fr = 0.27, h = 27 cm	Fr = 0.15, h = 27 cm

*Locations given in meters against the flow direction with regard to the downstream edge of the bridge.

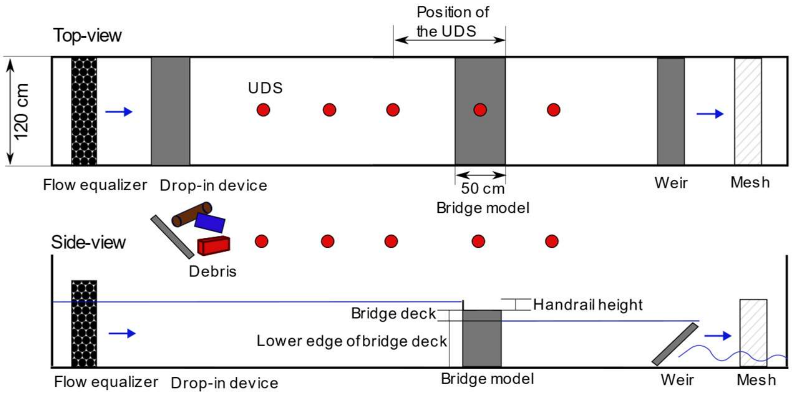

Figure 1. Schematic overview of the set-up used in all three laboratories

2.2. Bridge models

The bridge models were based on the characteristic bridge design data collected in the course of the EMfloodResilience project (Erpicum et al. 2023). A bridge model with two piers, a central opening and two half openings at either side was created (Figure 2). The mean documented opening width of the bridges with large debris accumulations was 8.5 m and the mean pier width 1.1 m. This resulted in a total width of 8.5 m × 2 + 1.1 m × 2 = 19.2 m for the prototype bridge. With a flume width (and therefore bridge width) of 1.2 m, this resulted in a model scale of 1:16 and the bridge dimensions displayed in Figure 2. In Liège and Delft, bridges with a rectangular opening and a freeboard of 27 centimeters between bridge deck and channel bottom were implemented. Due to the large number of arched bridges in the German study area, an arched bridge was tested in Aachen, with the same 27 cm freeboard at the top of the arch. The bridges were later exchanged between Aachen and Liège in order to determine the influence of the opening shape (and therefore of the blockage ratio) on the backwater rise. As shown in Figure 2, up to a water level of 15.3 cm both bridge models with a scale of 1:16 have the same blockage ratio (A_{bridge}/A_{water}) while the blockage ratio of the arched bridge increases with higher water levels compared to the rectangular bridge opening. These bridges had a bridge deck height of 7.5 cm and 6.5 cm high handrails, composed of 2 mm thick bars and a spacing of 5 mm. The bridge in the flume B2 was a rectangular bridge at scale 1:19, 21.1 cm high with a deck of 6.4 cm and no handrail.

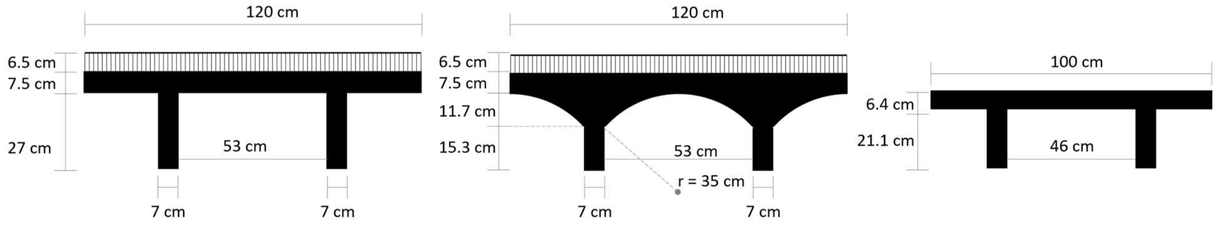

Figure 2. The bridge models with a rectangular (left) and arched (middle) opening shape for flume B1, G1 and N1 and (right) the rectangular bridge for flume B2. All bridges measured 50 cm in the flow direction.

2.3. Debris compositions

Data on debris compositions during the flood event 2021 was collected in the course of the EMfloodResilience project (Erpicum et al. 2023). Debris accumulations contained not only trees, but also large amounts of manmade objects. Debris mixtures with 75% logs (by volume) and 25% plates or cubes were selected as representative of accumulations with a large amount of flat objects (building rubble, compressed caravans, etc.) resp. voluminous objects (vehicles, furniture, tanks, etc.). To study the effect of debris composition on backwater rise, these two debris compositions were used in our experiments (Figure 3). The logs varied in length between 10 cm and 80 cm, with a diameter/length ratio of 1/20. The size distribution of the logs, documented in Table 2, is based on Rickli et al. (2018). The plates, made of plywood, measured 10 × 6 × 0.2 cm. The cubes, made of Douglas fir, measured 9 × 9 × 18 cm. Most tests at 1:16 scale were conducted with 76 L of debris, divided in 12 batches. For some initial tests on the effect of debris composition, under fixed hydraulic conditions, a larger volume of up to 190 L was introduced, using the same batch sizes. For tests at 1:19 scale, the total volume of debris was reduced to 50 L which resulted in five batches with similar compositions as in Table 2, but without the logs of 80 cm.

Table 2. Debris compositions per batch for tests conducted with 76 L debris (12 batches)

Batch composition	Number of cubes	Number of plates	Number of logs per log length							
			80 cm	70 cm	60 cm	50 cm	40 cm	30 cm	20 cm	10 cm
25% plates, 75% logs	$^{14}/_{12}$*	0	¾*	1 ¼*	2	3	5	10	20	50
25% cubes, 75% logs	0	127	¾*	1 ¼*	2	3	5	10	20	50

*Fractions divided over batches, i.e. every sixth batch two cubes, every fourth batch no log of 80 cm length and two of 70 cm.

Figure 3. Debris components

2.4. Test program

To determine the effect of the hydraulic conditions, two factors were varied during the experimental modelling: the initial water level (h_0) and the initial Froude number (Fr_0). The modelling program can be found in Tables 3 and 4. There are more repetitions for the tests conducted with $h_0 = 27$ cm and $Fr_0 = 0.28$, because these conditions were used for the initial tests in flume B1, where purely the effect of debris composition was widely investigated under fixed hydraulic conditions. Later, hydraulic conditions were also varied, and the workload was divided over multiple labs and flumes. To distinguish between both series in Belgium within flume B1, they are referred to as S1 (series 1) and S2 (series 2). In total, 161 experiments were conducted for the debris compositions and bridge designs described in this paper.

Table 3. The hydraulic conditions and number of repetitions for the experiments in flume B1, G1 and N1 (scale 1:16), using a porous handrail. #/# refers to the number of repetitions per debris composition (75% logs, 25% plates/ 25% cubes respectively).

Bridge opening	**Fr_0**	**h_0 [cm]**							
		15	**22**	**24**	**27**	**30**	**33**	**35**	**39**
Arched	**0.13**				2/1				
	0.2								
	0.27-0.28	2/2	2/1		2/2	2/2		4/4	
	0.4	2/2	2/2		2/2	3/4		2/2	
	0.5	2/2	2/2		2/2				
Rectangular	**0.13**		3/1		4/4		1/2		
	0.21		0/1	2/0					
	0.27-0.28		0/1		7/7				2/0
	0.4				2/0				

Table 4. The hydraulic conditions and number of repetitions for the experiments in flume B2 (scale 1:19), using no handrail and rectangular openings. #/# refers to the number of repetitions per debris composition (75% logs, 25% plates/ 25% cubes respectively).

Fr_0	**h_0 [cm]**						
	10	**15**	**20**	**21**	**24**	**31**	**37**
0.13				4/4			
0.2							1/1
0.27	2/4	2/2	2/2	2/2	2/2	2/1	
0.4	2/2	2/2	2/2		2/2		
0.6	2/2	2/2	2/2				

3. Results

3.1. Visual Observations

Visual observation already showed the impact of debris composition on the clogging process and backwater rise. The accumulation of debris with 25% of plates was observed to be denser compared to accumulations with cubes. As shown in Figure 4, most of the cubes floated near the surface of the accumulation, while plates exhibited more interlocking with the logs compared to the cubes, resulting in a more homogenous distribution over the accumulation depth. The presence of plates throughout the accumulation, combined with their larger surface area per debris volume, lead to plates creating more flow resistance and backwater rise, as visible in the side-view images of Figure 4 c, d (and analyzed quantitatively later). The same side-view images show that at Froude number 0.27 debris accumulates along the whole bridge opening, down to the flume bed. Also, the slope of the water surface shows that the water level is lower near the bridge and that backwater rise increases in the upstream direction. Overtopping of the bridge deck was observed earlier during the tests (i.e. for lower debris volumes), when plates were used in the debris composition compared to cubes. With increasing Froude number, the final carpet length decreased for both debris compositions.

For tests with an initial water depth above the handrail elevation, no debris was blocked and no backwater rise due to clogging occurred, since the debris were transported over the bridge deck. For tests conducted at a Froude number of 0.13, the shape of the accumulation changed. The flow was not strong enough to pull debris down towards the bed and a long carpet of floating debris formed. Also, backwater rise was very low at these conditions. In this regime, backwater rise mostly results from a different physical process, as water flows underneath a roughness, rather than through a porous medium. Conversely, more debris was pulled down at higher Froude numbers, resulting in accumulations of shorter length and higher density.

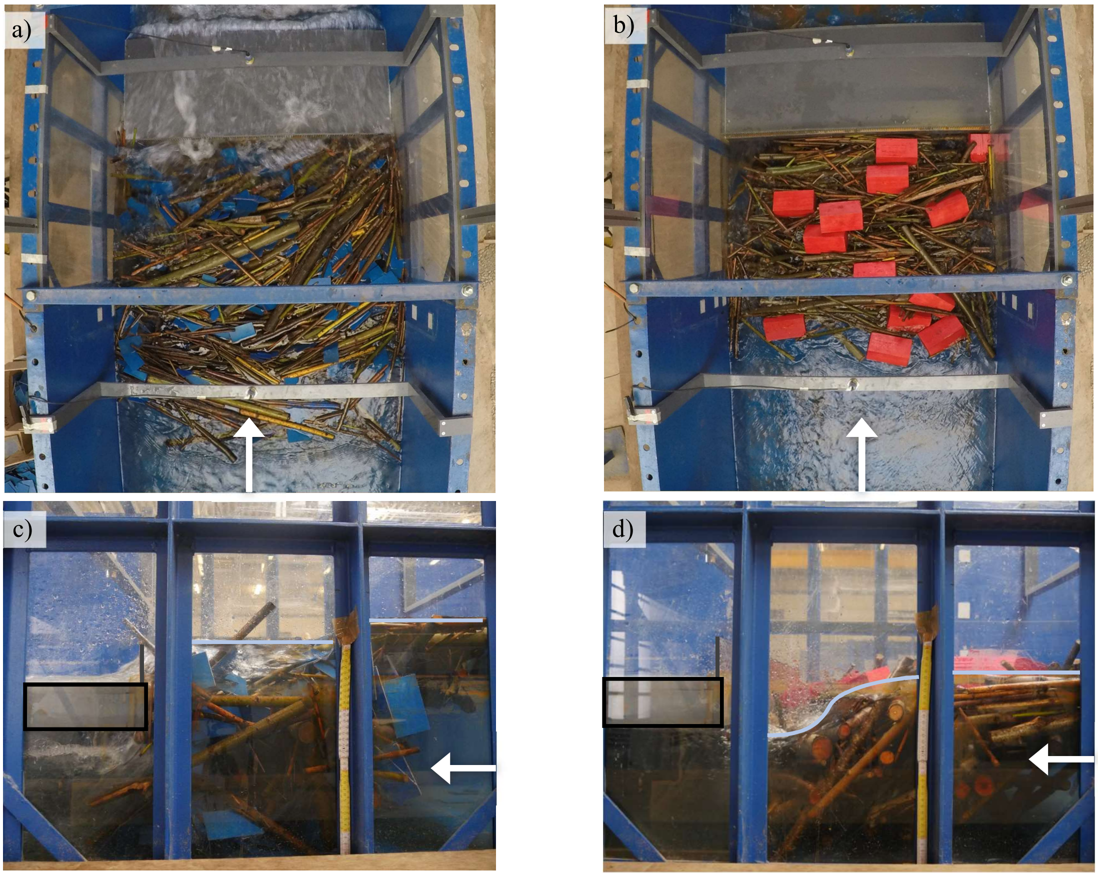

Figure 4. Documentation of the carpet length and shape for the two debris compositions in top view with a) 25% of plates and 75% of logs and b) 25% of cubes and 75% of logs and in side view (c and d respectively) at same hydraulic conditions. h_0 = 27 cm, Fr_0 = 0.28, flume B1, after adding 76 L of debris. White arrows indicate the flow direction, black lines the bridge deck, gray lines the handrail and light blue lines the water level in front of the bridge.

3.2. Backwater rise

Comparing the effect of the debris composition, showed that the relative backwater rise was higher for debris compositions with 25% of plates in comparison to experiments conducted with 25% of cubes. This was observed consistently in all laboratories. Figure 5 shows the development of the relative backwater rise in relation to the volume of debris added into flume B1, where a relative backwater rise of one signifies a doubling of the original water depth. The backwater rise increases with each batch of debris added to the flume and blocked in front of the bridge.

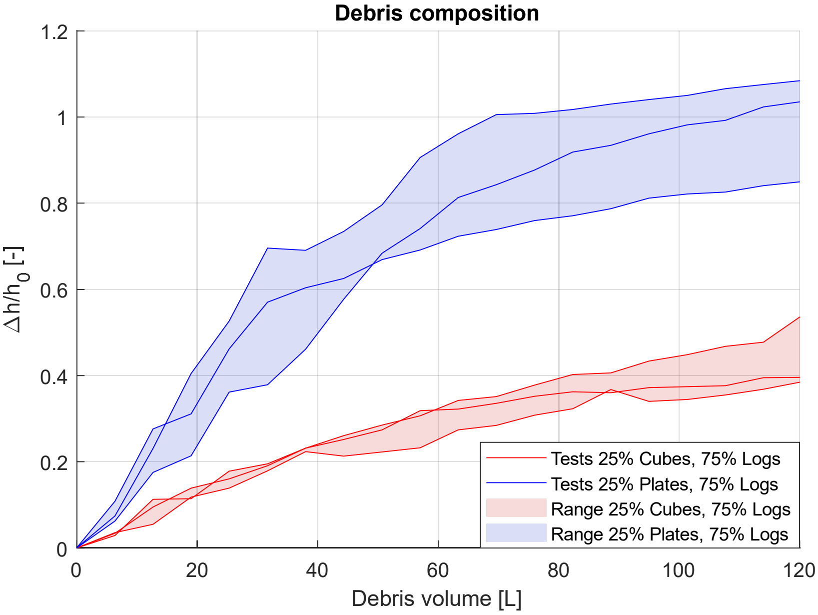

Figure 5. Relative backwater rise for tests conducted with different debris compositions in flume B1 (Liège). Range indicates the interval between the mininum and maximum values. The initial water depth is 27 cm at an initial Froude number of 0.28.

Results between labs are compared in Figure 6, all under the same hydraulic conditions ($Fr_0 = 0.28$, initial water level at the underside of the bridge deck). Hereto the backwater rise at a fixed volume is compared, rather than the full development over time, since this was observed to be similar between all tests and all labs. For the 1:16 model scale, a debris volume of 76 L is used. For the 1:19 model scale of flume B2, an equivalent volume of 38.6 L is used, based on the scaling of $\Delta h/h_0$ with V/Bh_0^2 reported by Schalko (2018), and the considered water depths (just below the bridge deck: 27 cm and 21.1 cm at the two scales). Comparing results between labs, the debris composition with plates again leads consistently to a higher relative backwater rise than debris with cubes. On average, a factor of 2.4, ranging from 1.8 to 2.9 was determined. The initial tests series in flume B1 (Flume B1, S1) resulted in a factor 2.5 higher absolute backwater rise than the other test series for both debris compositions. The backwater rise at rectangular and arched bridges under same hydraulic conditions with the initial water level at the bottom of the bridge deck resulted in similar relative backwater rise for both flumes G1 and B1 S2. Overall, excluding test series S1 of flume B1, results compared quite well between labs: the average backwater rise under the same test conditions (same debris composition, same Fr_0 and same h_0) varied between 10% and 35% between the different labs and flumes.

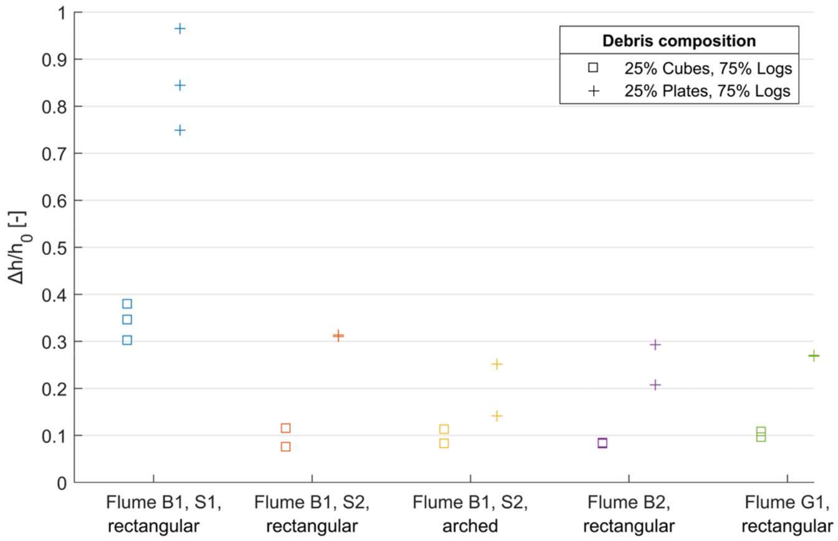

Figure 6. Relative backwater rise with regard to opening shape and the debris composition of the bridge model for tests conducted in all three laboratories at an initial water depth at the lower edge of the bridge deck and for $Fr_0 = 0.28$; for 1:19 model scale (flume B1, G1) $V = 76$ L and $h_0 = 27$ cm; for 1:16 model scale (flume B2) $V = 38.6$ L and h_0=20 cm - 21.1 cm. S1 and S2 refer to the series 1 and 2 of the experiments in flume B1.

Lastly, the effect of the Froude number on the backwater rise was considered, using results from all labs, still with an initial water level just below the deck. The results are plotted in Figure 7, corroborating once again the difference between the two debris compositions, with higher backwater rise when plates are present. Moreover, these result highlight that all test series conducted in the different labs agree well, with the exception of the initial test series conducted in flume B1. In all flumes, it was observed that the backwater rise increased with increasing Froude number. For the initial Froude number of 0.13 almost no backwater rise could be documented. The threshold for the development of a backwater rise due to clogging was identified between Froude number 0.13 and 0.27. Recent theoretical developments on the flow resistance of accumulations (Follett et al. 2020; Poppema and Wüthrich (in press)) already indicate that for a given accumulation geometry, the backwater rise increases more slowly at low Froude numbers. In addition, the accumulation geometry changes markedly at low Froude numbers, with little debris pulled down to block the bridge openings and the accumulation growing horizontally. Altogether, this results in backwater rise being almost absent at these low Froude numbers.

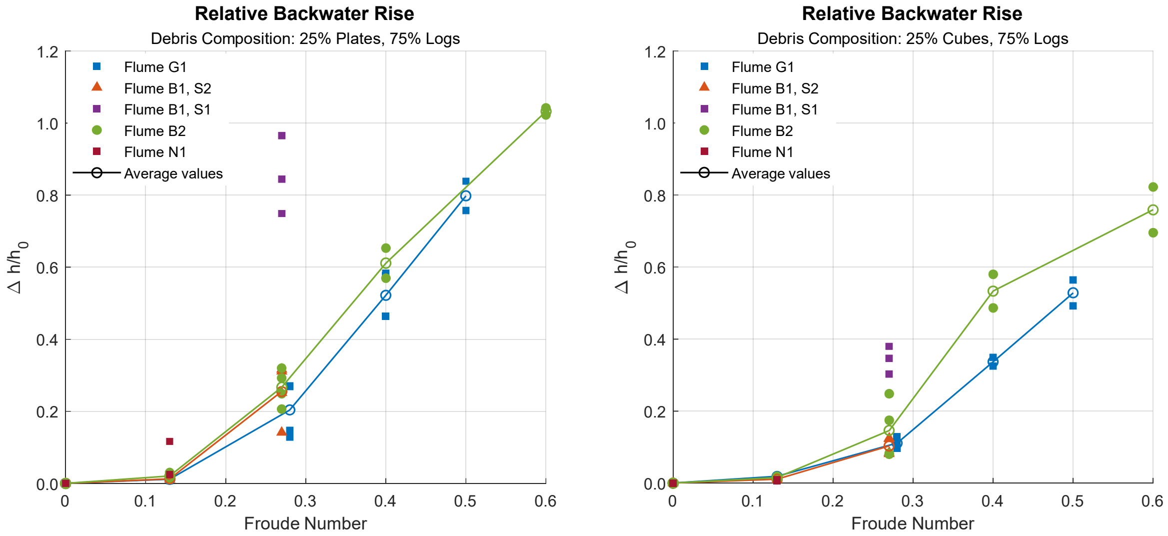

Figure 7. Relative backwater rise with regard to the Froude number and the debris composition for tests conducted in all three laboratories with both bridge designs, with initial water levels at the bottom of the bridge deck. Reported backwater rise results for a debris volume of 76 L for model scale 1:16 and 38.6 L for model scale 1:19.

Regarding the effect of the initial water depth at constant Froude number, it could be observed that the relative backwater rise slightly decreases with increasing initial water depth. Still the effect of the Froude number on backwater rise is more dominant and the same relation as shown in Figure 7 can be drawn.

3.3. Velocity measurements

The measurements of flow velocities at the hydraulic conditions stated in Table 1 indicated differences in the velocity field between flume G1 and B1 (see Figure 8), even though the average velocity is the same. While the flow velocities ranged between 0.4 and 0.7 m/s in flume G1, with stronger velocity at the center bottom of the flume than on the sides and near the surface, a less symmetric and less homogenous flow field with larger amplitude variation was measured for flume B1 series 2.

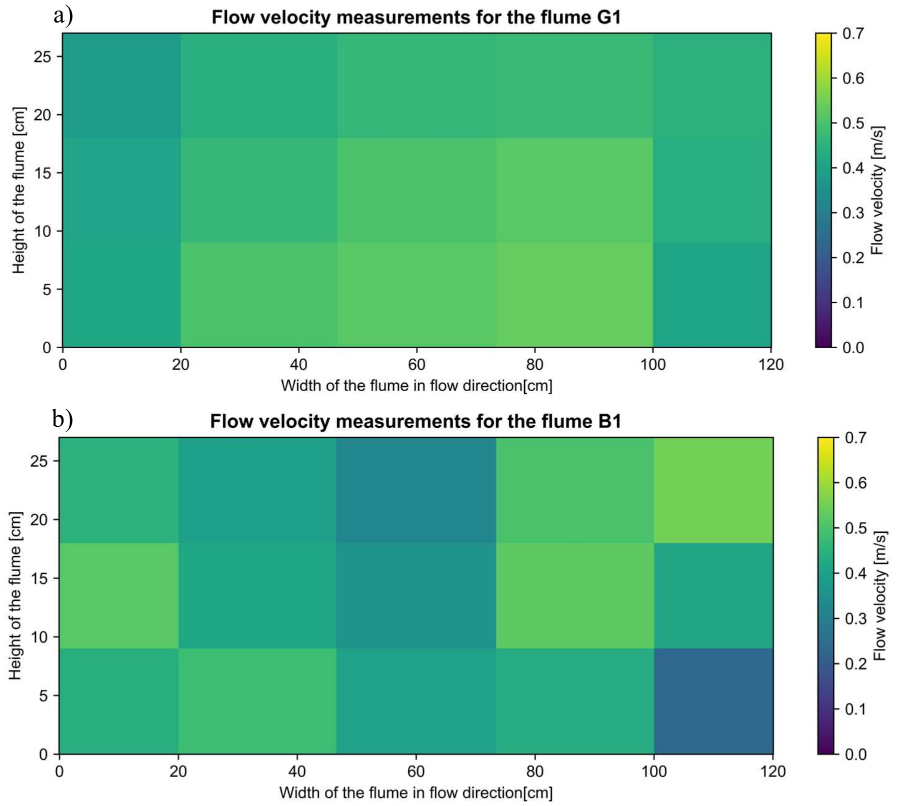

Figure 8. Measurements of the flow velocities for the flumes a) G1 in Aachen and b) B1 S2 in Liège, for the same discharge and flow depth for each measurement point ($Fr_0 = 0.27$, $h_0 = 27$ cm, $Q = 148$ L/s).

4. Discussion

In line with studies conducted by Schmocker and Hager (2013) and Schalko (2018), relative backwater rise was observed to increase with increasing Froude number in all three laboratories. Even though the absolute value of backwater rise differed slightly between all flumes, the Froude number was confirmed to be a major influencing factor on the backwater rise upstream of a blocked bridge for all flumes. The backwater rise observed at the lowest Froude number tested was similarly low in all flumes, supporting findings on the general process of the development of debris accumulation (Follett et al. 2020; Poppema and Wüthrich (in press)). Also, an effect of the Froude number on the carpet length and therefore the density of debris accumulations could be detected: with increasing Froude number, the carpet length decreased which indicated a denser debris accumulation.

Debris composition was shown to be a second factor of significant influence on backwater rise. With the presence of plates within the logs, the amount of backwater rise increased along all labs compared to the same debris volume with cubes and logs. This is also in line with findings by Schalko (2018), showing that finer material was responsible for higher backwater rise. In comparison to the effect of the debris composition and the Froude number, the differences due to the bridge opening shape are negligible.

While most studies across the three flumes had comparable results, the first test series (flume B1, S1) shows the greatest difference compared to the other test series with a relative backwater rise of factor up to one. Since the initial Froude number and the initial water level were set up similarly to the latter test series in the same flume, the differences in absolute backwater rise are unexplained and seem to occur due to an unnoticed difference in the test setup or procedure. Nonetheless, the relative difference between the two debris compositions is 2.2 and therefore comparable to the plate mixture generating 2.4 times as much backwater rise as cubes in the other test series.

Nevertheless, it was observed that the flume characteristics can have at least as much influence on the backwater rise as the debris composition. In order to further document the differences between the three experimental set-ups, more repetitions under same conditions would be needed. The differences can be classified as: (1) differences in model, (2) in scale and (3) in measurement (Tullis et al. 2019). Variances in the velocity profile could be responsible for the observed variations in backwater altitudes. Velocity distribution in natural river is rarely known, in particular during flood events. During the experiments, local velocities over the cross section differed between labs (Figure 8), even though the cross-sectional averaged flow velocity was the same. Possibly, hydraulic conditions were affected by the different flow equalizers and inflow facilities used. Also, in Aachen, a narrowing of the flume was necessary, and the drop-in device was located at a higher altitude than in Liège and Delft, which could have further influence on the flow conditions, e.g. generation of waves and turbulence. Furthermore, the flumes were composed of different materials, which implicated different roughness values. At last, the density of the debris can be identified as a further influence on the formation of the debris accumulation. Since the debris was made of wood, the saturation of debris could differ between the labs depending on the schedule and on the drying process between tests. In conclusion, despite the slight differences in backwater rise between the labs, it is useful to conduct experiments in multiple labs in order to capture the variances between different model set-ups as a source of uncertainty and therefore to collect more representative and trustable data.

As Bocchiola et al. (2008) and Schalko (2018) further state, each clogging process underlays a certain factor of randomness which also occurs in nature during real flood events. In order to determine a possible range of relative backwater rise, further tests with a sufficient number of repetitions would be needed. Also, the exact composition of debris during an extreme flood event is difficult to predict, but guiding values could be determined. Firstly, mean values of possible backwater rise used for e.g. the design of bridges or the determination of flood hazard around clogged structures, based on Froude numbers resulting from two-dimensional modelling. Secondly, maximum values that might be considered in catastrophe management plans, evacuation plans or when critical or vulnerable infrastructures such as hospitals or nursery schools are affected. Therefore, knowing the whole span of possible backwater rise at structures at risk of clogging is crucial.

5. Conclusions and Outlook

This study provides a comprehensive analysis of clogging processes at bridges and presents an extension of former studies by investigating an addition of lower Froude numbers, multiple debris shapes and having scale models of *complete* bridges, including the bridge deck and railing. These results are based on physical model tests conducted in three laboratories in Belgium, Germany and the Netherlands. Results showed negligible backwater rise for Froude numbers below 0.2. For higher values an increase of backwater rise at clogged bridges could be observed and the Froude number was confirmed as a major influencing factor. The shape of the debris was determined to be another key parameter affecting the backwater rise, with debris compositions containing plates leading to values up to 3 times higher than the debris compositions with cubes. Besides slight variations in backwater rise between the three labs and between repetitions at each lab, the same effects of Froude number and debris shape could be identified. To reveal these variances resulting from different experimental set-ups, a careful comparison of the results conducted under similar conditions is needed. A substantial number of tests conducted under the same conditions is necessary in order to determine potential sources for differences in the results. The multi-lab approach applied in this study, facilitated the identification of uncertainties and the collection of representative data.

Overall, the debris content was shown to be another important factor influencing the backwater rise upstream of a blocked bridge. This can be included in disaster management plans and help to assess potential hazards at bridges during flood events. The input of man-made debris could be reduced with the help of technical debris retention measures, e.g. racks. Furthermore, early warning and evacuation plans especially for campsites would be recommended. The clogging of bridges during extreme flood events has a major influence on the inundation areas and should also be included in flood risk and flood hazard maps. Altogether, these results provide relevant information for a more precise estimation of the consequences associated with debris clogging, in support of more effective flood protection measures and debris management strategies.

6. ACKNOWLEDGMENTS

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