# Backwater rise due to driftwood accumulation

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## ABSTRACT

Transported driftwood during flood events can lead to accumulation at river infrastructures or intentionally be retained at driftwood retention structures. In both cases, the driftwood accumulation results in backwater rise upstream of the cross section and may consequently overtop the adjacent river embankments. During previous investigations various governing parameters for the estimation of the backwater rise were detected, but some findings are still contradictory. Within this study a series of hydraulic flume experiments were conducted to identify the decisive parameters on the backwater rise testing predefined driftwood accumulations. The effects of the approach flow condition (inflow flow depth and Froude number) as well as the driftwood accumulation characteristics (accumulation length, bulk factor and driftwood characteristics) were considered to enable the prediction of the expected backwater rise. The results of the experiments show that the backwater rise depends mainly on the Froude number and the driftwood accumulation characteristics (e.g. log diameter and driftwood accumulation compactness).



## KEYWORDS

Backwater rise; bridge clogging; driftwood retention; flooding; large woody debris


## INTRODUCTION

During the 2005 flood event in Switzerland approximately 30'000 t of driftwood were transported (Bezzola and Hegg 2007; VAW 2008; Waldner et al. 2010). The transported driftwood led to numerous accumulations and clogging of the flow cross section at river infrastructures such as bridges or weirs. This resulted in severe problems due to the backwater rise upstream of the blocked cross section and consequently flooding of the surrounding area.

Engineering measures are necessary to reduce the destructive power of the interaction between transported driftwood and river infrastructures during flood events. They can be divided in (1) maintenance of the catchment area (e.g. removal of deadwood, erosion or landslide prevention and forest maintenance), (2) safe downstream conveyance of driftwood and (3) retention structures (e.g. racks or nets). The construction of retention structures is an essential measure to retain large driftwood volumes during flood events (Perham 1987; Wallerstein et al. 1996; Bradley et al. 2005; Hartlieb and Bezzola 2000). These retention structures also lead to a backwater rise and hence to decreasing flow velocity and increased sediment deposition (Bradley et al. 2005; Lange and Bezzola 2006), thereby intensifying the backwater rise.

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When planning a driftwood retention structure, the backwater rise is a relevant design parameter for the rack height and the adjacent river embankments. The backwater rise directly determines the required rack height to prevent the retained driftwood from getting flushed over the rack. Furthermore, the resulting backwater rise at a bridge or weir due to driftwood blocking is an important parameter to conduct flood hazard assessments.

## STATE OF THE ART

In order to investigate the backwater rise due to driftwood accumulation various studies were conducted. Knauss (1995) tested four different driftwood rack configurations (diagonal, V-shaped in and against flow direction and straight rack) and investigated the impact of coarse and fine driftwood material on the backwater rise. He defined the backwater rise due to driftwood accumulation at a rack with the backwater parameter $\alpha$:

$$\alpha = \frac{h_2 - h_1}{\frac{v_1^2}{2g}}$$

Equation 1: Backwater parameter $\alpha$ (Knauss 1995).

With $h_2$ = flow depth with driftwood accumulation [m], $h_1$ = initial flow depth without driftwood accumulation [m], $v_1$ = initial flow velocity without driftwood accumulation [m/s], and $g$ = gravitational acceleration [m/s$^2$].

The backwater parameter $\alpha$ depends mainly on the flow velocity and consequently on the specific discharge $q$, the driftwood characteristics as well as the rack configuration. For coarse driftwood $\alpha$ equals 1.5 and can increase up to $\alpha \approx 2.3$ for finer material. Compared to a straight rack, the V-shaped rack (V pointing in flow direction) results in a smaller backwater rise due to its larger rack length. The driftwood pile up at a V-shaped rack is reduced which favors the development of a driftwood carpet. Thus the driftwood placement is rather loose with a smaller backwater rise. In addition Knauss (1995) observed an increase of the backwater rise with increasing approach flow Froude number for the V-shaped rack.

Rimböck (2003) studied the design of rope net constructions for driftwood retention. His experiments showed that the governing parameters affecting the backwater rise are the driftwood characteristics (mixture and wood type), discharge $Q$, bed slope $J$, as well as the channel roughness $k_{st}$. The flow velocity at the upper end of the driftwood carpet should not exceed 0.8-1 m/s. Hence the driftwood is less compact and the risk of overtopping the retention structure can be reduced.

A different rack configuration with the objective to reduce the backwater rise was introduced by Schmocker and Weitbrecht (2013). They presented the so-called bypass retention where the driftwood is retained parallel to the main stream in a bypass channel. The bypass channel is located at the outer bend of a river and the rack is placed parallel to the river axis. Due to the secondary currents in the river bend the driftwood is transported at the outer bend and into the bypass channel. The approach flow is parallel to the driftwood rack, which leads to a smaller backwater rise. Since the bed load remains in the main channel, the bypass retention has only a reduced influence on the sediment transport capacity.

Further experiments on the backwater rise were conducted by Schmocker and Hager (2013). To simplify small scale model tests, they identified $F_o$ and the loosely placed driftwood volume $V_L$ as the key parameters for the accumulation process.

Hartlieb (2014) conducted a dimensional analysis to parameterize the backwater rise due to driftwood accumulation. He also identified $F_o$ and the bulk factor $a$ as the relevant parameters. The bulk factor $a = V_L/V_S$ can be described by the loosely placed driftwood volume $V_L$ and the solid driftwood volume $V_S$. Therefore, it defines whether a driftwood accumulation is compact (low bulk factor) or loose (high bulk factor). He evaluated several test results of driftwood accumulation at hydraulic structures and concluded that an increase of $F_o$ and a decrease of $a$ lead to a higher backwater rise.

## OBJECTIVE

Despite recent research, the knowledge on the backwater rise due to driftwood accumulation is still limited and some results are contradictory. Tab. 1 summarizes the relevant parameters for the backwater rise due to driftwood accumulation identified in previous studies.

Tab. 1: Summary of relevant parameters for the backwater rise due to driftwood accumulation.

| *Literature* | Approach Froude number $F_o$ | Rack configuration | Bulk factor $a$ | Discharge $Q$ | Driftwood characteristics | Bed Slope $J$ | Channel Roughness $k_{st}$ | Driftwood volume $V_D$ |
|---|---|---|---|---|---|---|---|---|
| Knauss, 1995 | x | x | | x | x | | | |
| Rimböck, 2003 | | | | x | x | x | x | |
| Schmocker & Weitbrecht, 2013 | x | x | x | | | | | |
| Schmocker & Hager, 2013 | x | | | | x | | | x |
| Hartlieb, 2014 | x | x | x | | | | | |

The few available formulae for the backwater rise were established for a limited number of tests and apply mostly to a specific rack placement. Hence, the objective of the present study was to systematically investigate the resulting backwater rise due to a driftwood accumulation and to expand the existing parameter range. The effects of the approach flow condition (inflow flow depth and Froude number) as well as the driftwood accumulation characteristics (accumulation length and bulk factor, driftwood characteristics) were considered. The findings of this study should enable the estimation of the expected backwater at a driftwood rack. This would allow for a more precise design of driftwood retention structures and consequently an improvement of flood hazard assessments.

## SCALE MODEL

### Hydraulic Flume

The experiments were conducted in a glass-sided flume at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). The flume is 8 m long, 0.4 m wide, 0.7 m high and its slope can be manually adjusted. A flow straightener at the inlet generated undisturbed inflow. The inflow discharge can be automatically regulated with a valve. The approach flow hydraulics (subscript $o$) are characterized by the flow depth $h_o$ and the flow velocity $v_o = Q_o/(Bh_o)$, or the Froude number $F_o = v_o/(gh_o)^{1/2}$, with $Q_o$ = discharge, $B$ = channel width and $g$ = gravitational acceleration. Fig. 1 shows the test setup and notation.

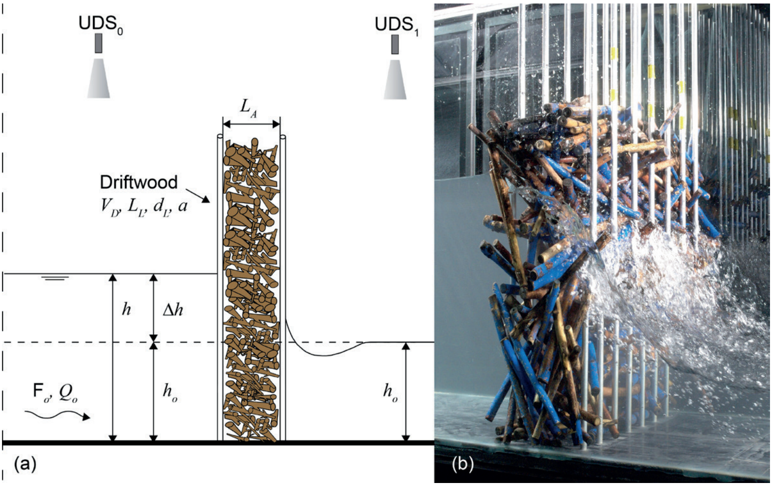


Figure 1: (a) Test setup and notation. Initial approach flow conditions ($F_o$, $h_o$) without driftwood accumulation. UDS = Ultrasonic Distance Sensor. (b) Picture from the model test.

The backwater rise is mainly governed by the initial driftwood accumulation, whereas the subsequently developing driftwood carpet has only a minor effect (Schmocker and Hager 2013). The accumulation was therefore simplified as a pre-installed driftwood volume $V_D$ placed in between two racks. These racks, placed 3 m downstream of the intake, consisted of seven steel poles with a diameter of $d$ = 0.008 m and therefore had a negligible effect on the overall backwater rise. The driftwood contained logs of length $L_L$ and diameter $d_L$. The driftwood accumulation had a width of $L_A$, a constant height of 0.4 m and a bulk factor of $a = V_L / V_S$. The range of $a$ = 2 - 5 was selected based on recent observations from WSL on driftwood accumulations in nature (Waldner et al. 2010). The approach flow depth $h_o$ and the resulting flow depth $h = h_o + \Delta h$ (with $\Delta h$ = backwater rise) were measured using two ultrasonic distance sensors, $UDS_0$ placed 1 m upstream and $UDS_1$ 1 m downstream of the driftwood accumulation. Additional flow depths were measured using a manual point gauge.

**Model driftwood**

During the experiments the model driftwood without branches was divided in seven wood classes to represent a broad range of $L_L$ and $d_L$ (Fig. 2). The smallest class A consisted of matchsticks. While $d_L$ is rather constant for the classes A-D, it shows a wide range for classes E-G. Class G is a mixture of the smallest class A and class E. The model driftwood dimensions were scaled according to natural driftwood observed during the flood event 2005 (Waldner et al. 2010). Furthermore, the effect of fine material as small branches and leaves on the backwater rise was neglected.

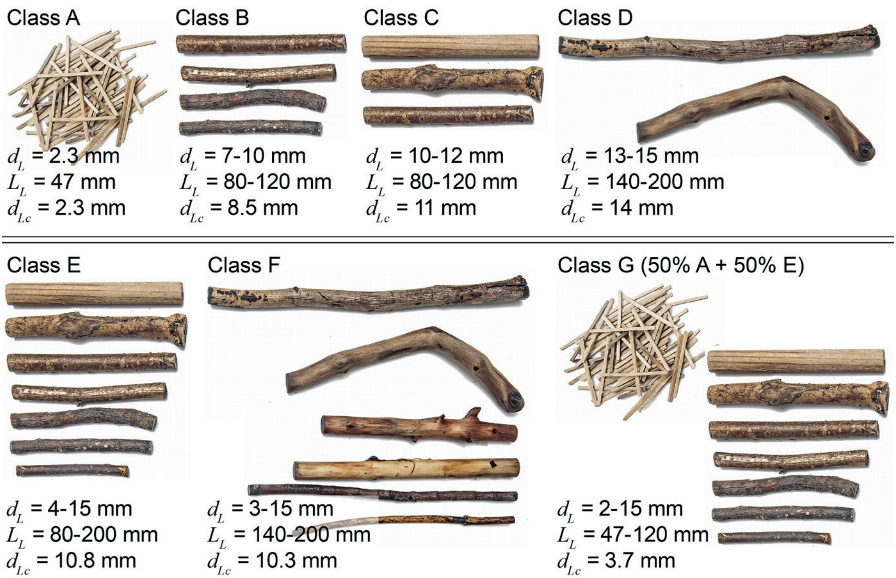


Figure 2: Wood classes used in the experiments with $d_L$ = log diameter, $L_L$ = log length and $d_{Lc}$ = characteristic log diameter.

Another relevant aspect of the wood classes is the characteristic log diameter $d_{Lc}$. It was calculated as a function of the mean circumference $U_m$. In case of driftwood accumulation at a rack, water has to pass around the logs. Therefore the characteristic log diameter $d_{Lc}$ of the wood class can be calculated with Equation 2.

$$d_{Lc} = \frac{U_m}{\pi} = \frac{\sum \pi \cdot d_L \cdot N(d_L)}{N \cdot \pi} = \frac{\sum d_L \cdot N(d_L)}{N}$$

Equation 2: Characteristic log diameter $d_{Lc}$.

With $d_L$ = log diameter [m], $N(d_L)$ = number of logs with $d_L$ in wood class and $N$ = total number of logs.

**Test program and procedure**

The experiments were conducted within four test series to identify the impact of various parameters on the backwater rise. In series I the effect of $F_o$ was tested for three different $h_o$ with all other parameters kept constant. Series II to IV investigated the effect of the parameters a, $L_A$ and $d_{Lc}$ for different $F_o$ with all other parameters kept constant. The test program with the investigated parameters is listed in Tab. 2.

Tab. 2: Test program

| Test series | Test | Tested effect | Wood class | $h_o$ [mm] | $F_o$ | $a$ | $d_{Lc}$ [mm] | $L_A$ [mm] |
|---|---|---|---|---|---|---|---|---|
| I | 1 | $h_o$, $F_o$ | G | **50, 100, 150** | **0.2-1.4** | 3.6 | 3.7 | 100 |
| | 2 | | F | | | 3.8 | 10.3 | |
| II | 3 | $a$ | C | 100 | 0.2-1.4 | **2.4** | 11 | 100 |
| | 4 | | | | | **3.2** | | |
| | 5 | | | | | **3.6** | | |
| III | 6 | $L_A$ | F | 100 | 0.2-1.4 | 3.8 | 10.3 | **50** |
| | 7 | | | | | | | **100** |
| | 8 | | | | | | | **200** |
| IV | 9 | $d_{Lc}$ | A | 100 | 0.2-1.4 | 3.6 | **2.3** | 100 |
| | 10 | | B | | | | **8.5** | |
| | 11 | | D | | | | **14** | |

Previous studies at VAW investigated the effect of driftwood mixture on the backwater rise and showed that the driftwood mixture could be represented by the mean diameter of the mixture (Schmocker and Hager 2013). Therefore, the effect of a mixture of various driftwood classes was not tested herein. Furthermore, the log length and shape were not investigated as separate parameters, as this is accounted for with the bulk factor.

The experimental procedure can be described by the following steps:

1. Measurement of $h_o$ and $F_o$ without driftwood accumulation.
2. Inserting the two bar racks in the flume and adding the respective driftwood class and volume for the driftwood accumulation.
3. Measurement of $\Delta h$ in front of the driftwood accumulation for the respective ho and $F_o$.

## RESULTS

The Test series I has been conducted to identify the effect of $F_o$ on the backwater rise for various $\boldsymbol{h_o}$. Fig. 3a shows $\boldsymbol{\Delta h}$ for $\boldsymbol{h_o}$ = 50, 100 and 150 mm, wood class G, $\boldsymbol{a}$ = 3.6 and $\boldsymbol{L_A}$ = 100 mm. $F_o$ was varied from 0.2 to 1.4. For $\boldsymbol{h_o}$ = 150 mm only $F_o$ from 0.2 to 0.6 were tested, since the resulting backwater rise for $F_o \geq 0.8$ overtopped the maximum driftwood accumulation height of 0.4 m. The results show that the backwater rise $\boldsymbol{\Delta h}$ increases linearly with increasing $F_o$ (Fig. 3a). The backwater rise $\boldsymbol{\Delta h}$ for $\boldsymbol{h_o}$ = 100 mm and $F_o$ = 1.2 is 6.5-times higher than for $F_o$ = 0.2. In order to identify the effect of the approach flow depth on the backwater rise, the relative backwater rise $\boldsymbol{\Delta h/h_o}$ was plotted on the ordinate (Fig. 3b). The data for all three approach flow depths $\boldsymbol{h_o}$ collapse, hence the relative backwater rise is independent from $\boldsymbol{h_o}$.

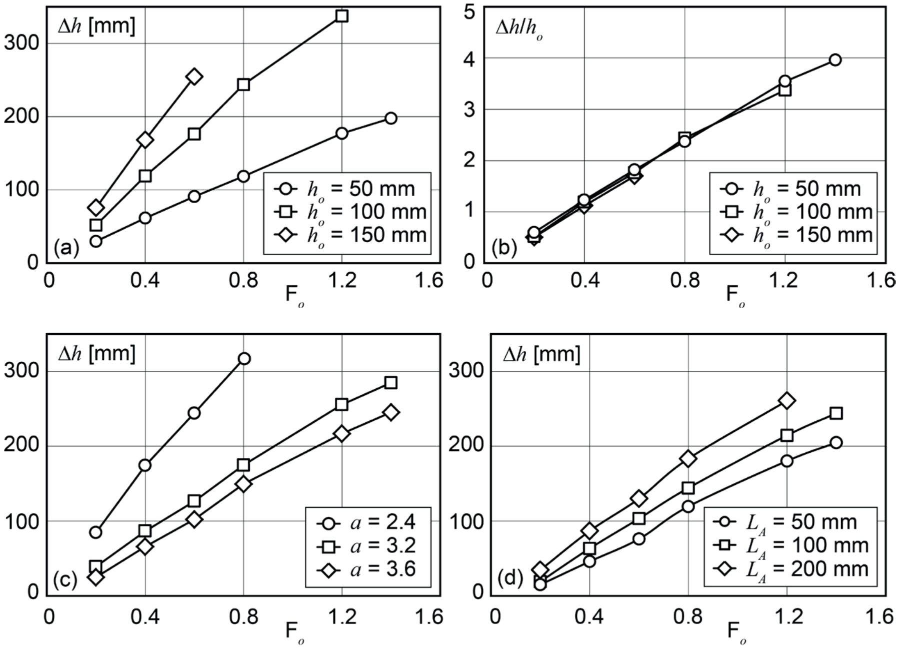


Figure 3: (a) $\boldsymbol{\Delta h}$ and (b) $\boldsymbol{\Delta h/h_o}$ for three different $\boldsymbol{h_o}$ various $F_o$, wood class G, $\boldsymbol{L_A}$ = 100 mm and $\boldsymbol{a}$ = 3.6. (c) $\boldsymbol{\Delta h}$ for $\boldsymbol{h_o}$ = 100 mm, various $F_o$, three different $\boldsymbol{a}$, $\boldsymbol{L_A}$ = 100 mm and wood class C. (d) $\boldsymbol{\Delta h}$ for $\boldsymbol{h_o}$ = 100 mm, various $F_o$, three different $\boldsymbol{L_A}$, wood class F and $\boldsymbol{a}$ = 3.8.

The bulk factor $\boldsymbol{a}$ describes the compactness of the driftwood accumulation. During the experiments a certain bulk factor was established by placing the respective driftwood volume $\boldsymbol{V_D}$ between the two racks. Fig. 3c shows the backwater rise for test series II with $\boldsymbol{a}$ = 2.4, 3.2, 3.6, $F_o$ = 0.2-1.4, $\boldsymbol{L_A}$ = 100 mm, $\boldsymbol{h_o}$ = 100 mm and the wood class C. The experiments for $\boldsymbol{a}$ = 2.4 were limited to $F_o$ = 0.2-0.8 to avoid an overtopping of the maximum driftwood accumulation height. The backwater rise $\boldsymbol{\Delta h}$ for $F_o$ = 0.8 equals 317 mm for $\boldsymbol{a}$ = 2.4 compared to

$\Delta h$ = 150 mm for $a$ = 3.6. Therefore, the backwater rise is decreasing with increasing bulk factor (i.e. loose driftwood accumulation). A compact driftwood accumulation represents a higher flow resistance compared to a loose driftwood accumulation, leading to a higher backwater rise. These findings were observed for all wood classes. As expected the bulk factor acts like the porosity factor in groundwater flows.

The impact of the driftwood accumulation length on the backwater rise (Test series III) is plotted in Fig. 3d. The experiments were conducted for $F_o$ = 0.2-1.4, $h_o$ = 100 mm, $a$ = 3.8 and wood class F. The driftwood accumulation length was varied between $L_A$ = 50, 100 and 200 mm. As plotted in Fig. 3d, the backwater rise increases with increasing $L_A$. A higher accumulation length represents a greater flow resistance and consequently leads to an increased backwater rise.

The geometric driftwood characteristics can be described by the characteristic log diameter $d_{Lc}$ of the respective wood class. A small $d_{Lc}$ allows for a more dense driftwood accumulation.

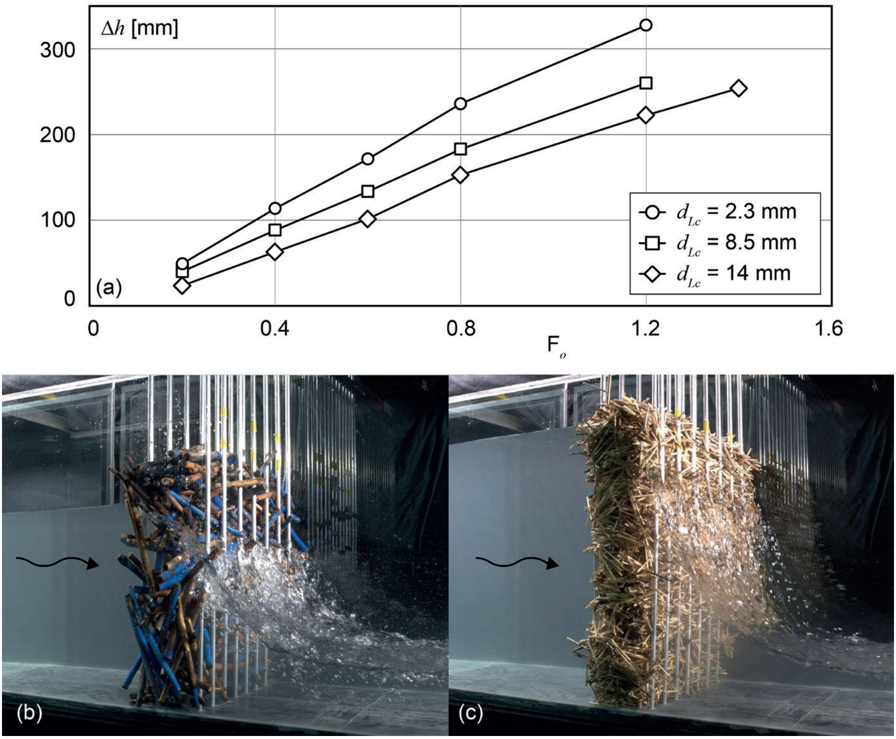


Figure 4: (a) $\Delta h$ for $h_o$ = 100 mm, $L_A$ = 100 mm and $a$ = 3.6, (b) $\Delta h$ for $d_{Lc}$ = 14 mm and $F_o$ = 1.2, (c) Δh for $d_{Lc}$ = 2.3 mm and $F_o$ = 1.2.

Therefore the driftwood accumulation contains a higher number of logs, which leads to a higher flow diversion when water is passing through. Test Series IV for the impact of $d_{Lc}$ on $\Delta h$ were conducted for $F_o$ = 0.2-1.4 and wood classes A, B and D (Fig. 2). The backwater rise for $d_{Lc}$ = 2.3 mm, 8.5 mm and 14 mm (i.e. wood classes A, B, D) with $a$ = 3.6, $L_A$ = 100 mm and $h_o$ = 100 mm is plotted in Fig. 4a. Two pictures from the model tests for class A, $F_o$ = 1.2, $a$ = 3.6, $L_A$ = 100 mm, $d_{Lc}$ = 14 mm and $d_{Lc}$ = 2.3 mm are shown in Fig. 4b and Fig. 4c. The backwater rise $\Delta h$ for $F_o$ = 0.8 equals 236 mm for $d_{Lc}$ = 2.3 mm compared to $\Delta h$ = 153 mm for $d_{Lc}$ = 14 mm. Consequently, $\Delta h$ increases with decreasing $d_{Lc}$.

## CONCLUSIONS

Hydraulic flume experiments were conducted to identify the relevant parameters affecting the backwater rise due to driftwood accumulation. During the experiments the approach flow conditions as well as the driftwood accumulation characteristics were systematically varied. The results show that the backwater rise increases with increasing Froude number $F_o$ and driftwood accumulation length $L_A$ as well as with decreasing characteristic log diameter $d_{Lc}$ and bulk factor $a$. Recently, numerical models have been developed to simulate driftwood transport, the accumulation processes and the resulting backwater rise. The results of this study may be used to validate these numerical models.

The fine material like branches and leaves in the driftwood accumulation was neglected within this study. Further work at VAW aims to model the effect of fine material on the backwater rise and to combine all results in a design diagram for the expected backwater rise. This allows to estimate the backwater rise and consequently to design the height of a planned driftwood retention rack. Regarding bridge clogging, the estimated backwater rise helps to assess the hazard potential of existing bridges or river crossing structures during flood events with high driftwood transport.

## REFERENCES


- Bezzola G.R. and Hegg C. (2007). Ereignisanalyse Hochwasser 2005 Teil 1: Prozesse, Schäden und erste Einordnung (Analysis of 2005 flood event, Part 1: Processes, damages and classification). Federal Office for the Environment FOEN, Swiss Federal Institute for Forest, Snow, and Landscape Research WSL. Umwelt-Wissen: 0825 (in German).
- Bradley J.B., Richards D.L., Bahner C.D. (2005). Debris control structures: Evaluation and countermeasures. Report No.: FHWA-IF-04-016. U.S. Dept, Transportation, Federal Highway Administration, Washington, D.C.
- Hartlieb A. and Bezzola G.R. (2000). Ein Überblick zur Schwemmholzproblematik (Overview of problems associated with driftwood). Wasser, Energie, Luft 92 (1/2): 1-5 (in German).
- Hartlieb A. (2014). Maßgebende Parameter für den Aufstau durch Schwemmholz-verklausungen (Decisive parameters for backwater effects caused by floating debris jams). Proc. Intl. Symposium "Wasser- und Flussbau im Alpenraum", VAW-Mitteilung 228 (R. Boes, ed.), ETH Zurich: 485-493 (in German).

- Knauss J. (1995). Von der oberen zur unteren Isar (From the upper to the lower Isar). Report 76: 23-66. TU Munich, Germany (in German).
- Lange D. and Bezzola G.R. (2006). Schwemmholz: Probleme und Lösungsansätze (Driftwood: problems and countermeasures). VAW-Mitteilung 188 (H.-E. Minor, ed.), ETH Zurich (in German).
- Perham R. E. (1987). Floating debris control: A literature review. Rep. REMR-HY-3, U.S. Army Corps of Engineers. Washington, DC.
- Rimböck A. (2003). Schwemmholzrückhalt in Wildbächen (Driftwood retention in mountain torrents). Report 94. TU Munich, Germany (in German).
- Schmocker L. and Weitbrecht V. (2013). Driftwood: Risk analysis and engineering measures. Journal of Hydraulic Engineering 139 (7): 683-695.
- Schmocker L. and Hager W.H. (2013). Scale modelling of wooden debris accumulation at a debris rack. Journal of Hydraulic Engineering 139 (8): 827–836.
- Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW). (2008). Ereignisanalyse Hochwasser 2005: Teilprojekt Schwemmholz (Analysis of the 2005 flood event: Sub-project drift). Bericht 4240. ETH Zurich, Switzerland (in German).
- Waldner P., et al. (2010). Schwemmholz des Hochwassers 2005 (Driftwood during the 2005 flood event). Final Rep., Federal Office for the Environment FOEN, Swiss Federal Institute for Forest, Snow and Landscape Research WSL. (in German).
- Wallerstein N.P., Thorne C.R., Abt S.R. (1996). Debris control at hydraulic structures - management of woody debris in natural channels and at hydraulic structures. Report prepared for the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.