Effect of driftwood on hydraulic head of Piano Key weirs

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ABSTRACT: Driftwood is often transported by a river course during flood events and can be problematic where it accumulates at hydraulic structures. Near obstacles, driftwood can block and thus reduces the open flow area for water passage, resulting in a lowered discharge capacity combined with increasing flow depths in the upstream region. The blocking of driftwood at weirs and spillway inlets is of particular interest, as it may affect the safety of such structures by drastically reducing the maximum spilling capacity. The high discharge efficiency of Piano Key weirs (PKWs), relative to linear weirs, may influence driftwood collection. The flow depth over a PKW for a given discharge will be less than would be required by linear structures, thus providing less flow momentum per unit weir length for flushing driftwood. If the catchment is forested, the potential effects of driftwood on the PKW head-discharge relation should be considered as part of the hydraulic design process. This paper describes systematic model tests considering the effect of driftwood on the PKW discharge efficiency. Trunks and rootstocks were supplied upstream of different laboratory-scaled PKW configurations. The test series closely approximated real-world conditions by investigating the nature of driftwood accumulations on the PKW discharge efficiency.

1 INTRODUCTION

1.1 *Driftwood*

Catchment areas of Mountain Rivers are often forested. During extreme flood-generating rain events, riverbank erosion and landslides can develop. It is common for both processes to introduce trees and brush into the watercourse. In steeper boulder-lined rivers, trees are quickly reduced to smaller fractured woody debris elements during transport. In lower zones of a catchment, infrastructure [Bezzola and Hegg 2007 (weirs); Bezzola et al. 2002, Schmocker and Hager 2011 (bridge decks); Melville and Dongol 1992, Pagliara and Carnacina 2010 (bridge piers)] along a river often limits driftwood transport capacity; urban waste can add to the problem. Near such structures, driftwood often blocks and thereby reduces the open flow area for water passage, resulting in a lowered discharge capacity combined with an increased upstream flow depth. The blocking generated by driftwood at weirs and spillway inlets is of particular interest, as it may affect the safety of such structures. Namely, the maximum spilling capacity is reduced due to obstruction.

Determination of the potential driftwood volume that might be generated by a catchment represents an important input parameter for the analysis. The nature and volume of the driftwood can vary significantly based on terrain, geographical location, season, and climate. Rickenmann (1997), however, observed a correlation between the catchment surface area and the effective driftwood production, based on several filed surveys following floods, particularly in Switzerland. The catchment area seems a suitable first-order indicator, as it can be used to approximate the size of the forested surface and the hydrologic peak flood discharge. For the catchment areas evaluated, Rickenmann (1997) proposed the following pragmatic estimate for potential driftwood volume V [m^3]:

$$V = 45A^{0.67} \tag{1}$$

where A = catchment surface in [km^2]. A significant spread was observed for small catchment areas (< 1 km^2), whereas the equation overestimated the value V for large catchments (> 1'000 km^2). Alternative methods to derived the driftwood volume at a given river section are provided by Uchiogi et al. (1996), Rimböck (2003), and Lange and Bezzola (2006).

1.2 *Piano Key weirs*

Piano Key weirs (PKWs) are a hydraulically attractive alternative to linear overflow weirs, increasing the unit discharge at the unregulated spillway inlet for given upstream heads and spillway widths. This advantage allows for operation of reservoirs at higher supply levels (less reservoir volume set aside for flood routing) thus providing an increased retention volume. In the last decade, the implementation of PKWs in practice has increased significantly, particularly in France (e.g., Laugier 2007, Laugier et al. 2009) and presently under construction in Vietnam (Ho Ta Khan et al. 2011). Lempérière et al. (2011) and Schleiss (2011) presented historical reviews on the evolution from Labyrinth weirs to PKWs, with a focus on the hydraulic characteristics of PKW operation. Note that the standard naming convention for PKWs as introduced by Pralong et al. (2011) is applied herein.

1.3 *Driftwood at Piano Key weirs*

PKW research to date has primarily focused on hydraulic efficiency (Kabiri-Samani and Javaheri 2012; Leite Ribeiro et al. 2012; Machiels 2012; Anderson and Tullis 2012a, 2012b, 2013), typically ignoring a possible negative effect of driftwood on the rating curve. Ouamane and Lempérière (2006) were among the first to conduct preliminary model tests with driftwood. They observed that no driftwood was trapped under the apex overhangs during the reservoir filling process. As soon as the PKW started to spill, however, driftwood got stuck in the inlet key at small discharges, resulting in a slight reduction in discharge efficiency. A discharge coefficient reduction of about 10% was reported for $H/P < 0.5$, with H = total upstream head measured relative to the PKW crest elevation, and P = weir height. As the discharge increased, the driftwood was eventually washed downstream.

LCH (2007) investigated the effects of floating wood on the St. Marc Dam (France) emergency PKW spillway and reported no driftwood-associated reduction in discharge capacity when the gates of the adjacent principal spillway were fully open, attracting a significant portion of the driftwood.

Laugier (2007) reported systematic model tests with driftwood of the emergency PKW spillway of Goulours Dam (France), concluding that 1) increasing head tended to remove previously blocked driftwood, 2) the principal gated spillways attracted driftwood before the PKW started operation, 3) most driftwood passed the PKW for flow depths at the PKW larger than 1 m, 4) most streamlines passed below the driftwood of a fully blocked PKW entering the inlet key, so that the water flowed “around” the blockage, and 5) the residual discharge capacity of a blocked PKW was more than 80% of the driftwood-free condition.

SOGREAH (2011) conducted model tests of the Luziere Dam (France) emergency PKW spillway. It was observed that 1) driftwood was mainly attracted by the principal spillway inlet, as it generated higher approach flow velocities than the PKW, 2) the volume of blocked driftwood decreased with increasing discharge, 3) the density of the driftwood accumulations were compact for high heads and loose for small heads, and 4) a relative head increase of some 10% occurred for a flood, with an initial head of 1.0 m.

Despite of a lack of systematic tests, one may summarize that PKWs seem prone to blockage with driftwood, particularly when a gated primary spillway isn’t available to attract the majority of the floating debris. Although the effect occurs within certain limits, an increased hydraulic head was observed, particularly for small specific discharges. This has to be considered for the design of such structures.

2 PHYSICAL MODEL TESTS

2.1 *Piano Key weir configurations*

Systematic physical model tests were conducted at the Laboratory of Hydraulic Constructions (LCH) of EPFL, Switzerland. Three different PKW configurations (Table 1, and Fig. 1) were tested at the downstream end of a 2 m wide and 10 m long channel, with an approach flow depth on the order of 0.8 m. The PKWs were installed in the opening of a vertical-walled dam (contracted-weir configuration) as shown in Fig. 1. With linear weir width W to upstream channel width ratios of 0.27 to 0.33 and the base of each PKW installed 0.5 m above the channel invert, the upstream approach flow condition approximated that of a reservoir. Additionally, no tailwater submergence occurred. The water level in the channel was measured using a point gauge (±0.5 mm). The latter measurement provided H, as the measurement was taken in a zone with stagnant water. Generally, the channel flow velocities tended to zero because the tested discharges Q were small. The latter was measured with a magnetic inductive flow meter (±0.5% at full span).

To better generalize the results, three different PKW configurations (all Type-A) were tested as detailed in Table 1. They included variations in cycle number, characteristic lengths, and abutment wall detail. The physical models were built with a geometrical scale factor of 1:30 (relative to their respective prototype structures) and operated under the similitude of Froude. Herein, only prototype values are mentioned.

Table 1. Characteristics of tested PKW configurations A to C, with W = linear transversal width, W_i = inlet key width, W_o = outlet key width, T_s = side wall thickness, B = stream-wise length, B_i = inlet key overhang length, B_o = outlet key overhang length, $P_i = P_o$ = inlet or outlet key weir height, R = parapet wall height, and W_u = cycle width.

	A	B	C	
W	16.35	16.65	19.95	[m]
W_i	2.46	1.32	1.20	[m]
W_o	1.50	1.17	0.99	[m]
T_s	0.25	(0.03)	0.30	[m]
B	9.75	5.70	9.75	[m]
B_o	3.54	1.65	3.00	[m]
B_i	2.70	1.50	2.25	[m]
Crest type	half rounded	sharp	half rounded	
$P_i = P_o$	2.88	2.52	4.50	[m]
R	0.00	0.50	0.60	[m]
W_u	4.44	2.55	2.79	[m]
L/W	5.20	5.50	7.80	[-]
W_i/W_o	1.64	1.13	1.21	[-]
B/P	3.39	2.26	2.17	[-]
B_i/B	0.28	0.26	0.23	[-]
B_o/B	0.36	0.29	0.31	[-]

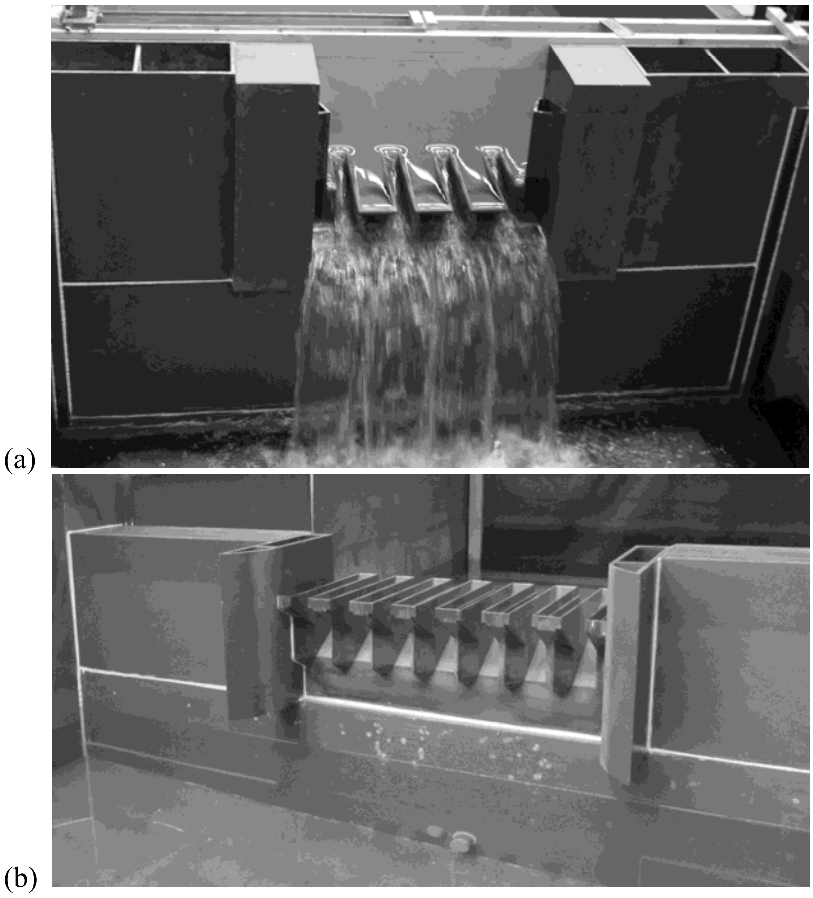

Figure 1. Photos of PKW configurations (a) A, and (b) C (Table 1).

2.2 *Driftwood*

The tested driftwood was chosen based on two approaches, namely: A large spectrum of trunk lengths to find sensitive dimensions and to allow for a general application of the results; and to cover common flood-related driftwood element sizes as determined by Bezzola and Hegg (2007), based on survey after major flood events in Switzerland. Herein, seven trunk length T classes were derived from the latter reference, namely $T = 1.0$, 3.0, 5.0, 7.0, 9.0, 11.0, and 13.0 m. Small values T represent tree branches, and large values entire trunks not yet fractured by the transport processes. The ratio between individual trunk length and diameter D was constant as $T/D = 20$. The trunk lengths compared with the cycle width W_u of the herein investigated PKWs (Table 1) ranges between $0.23 \leq T/W_u \leq 5.10$. Furthermore, rootstocks were included, with a trunk length of 5.0 m and a root-diameter of 2.5 m, defined perpendicular to the trunk axis.

For the tests, ten different driftwood batches (i.e., accumulations) were prepared, which included 19 to 22 trunk elements of varied sizes and two rootstocks (RS) (Table 2). Further, the trunk dimensions within a driftwood batch were chosen in an effort to be consistent with the natural driftwood size distribution statistics presented by Bezzola and Hegg (2007). The ten driftwood batches were added sequentially at random stations across a common reservoir cross-section located 2 m upstream of the PKW, for a constant Q. Without removing the driftwood trapped on the PKW from previous batches, subsequent driftwood batches were introduced upstream of the flume; this was repeated for all ten driftwood batches. All three PKW configurations (Table 1) were tested under four different discharge rates (discharge was held constant during a test) spanning a dimensionless upstream head spectrum of $0.07 \leq H_i/P \leq 0.49$, where H_i = initial upstream head prior to adding driftwood. For each discharge, the ten batches were added sequentially and their effect on H measured. Thus, 40 values of H resulted per PKW geometry, giving a total of 120 data points for all PKWs collectively.

Table 2 indicates the supplied integral driftwood volume V supplied according to the individual batch number. In total, approximate driftwood volume associated with the 10 batches was 144 m^3. This volume describes exclusively the effective wood volume, assuming the trunks and rootstocks to be linear cylinders. The total volume of a loosely formed batch (low heads) including void spaces exceeded the related wood volume.

Table 2. Batch characteristics, indicating number of elements per trunk class.

T [m] →	13	11	9	7	5	3	1	RS	Els. per batch	V [m^3]
Batch 1	1	2	2	4	7	4	2	2	24	18
Batch 2	1	1	1	4	6	4	2	2	21	31
Batch 3	1	1	2	5	7	5	0	2	23	47
Batch 4	1	1	1	4	6	4	2	2	21	60
Batch 5	1	1	2	5	7	4	2	2	24	76
Batch 6	1	1	1	5	7	5	0	2	22	90
Batch 7	1	1	2	4	6	4	2	2	22	105
Batch 8	1	1	1	5	7	4	2	2	23	119
Batch 9	0	1	2	5	7	4	0	2	21	130
Batch 10	0	2	2	5	6	4	2	2	23	144

2.3 *Test range*

In order to generalize the resulting observations, some key figures are given as semi-normalized values. The specific discharge ranged from $1.63 \leq q = Q/W \leq 12.45$ m^3/sm. The corresponding head-specific discharge curves are shown in Fig. 2, along with some higher discharges for validation. Configuration C had the highest discharge efficiency of the three PKWs tested, followed by B then A. This order is in agreement with L/W given in Table 1, which represents the dominant parameter regarding discharge efficiency (Leite Ribeiro et al. 2012). Similarly, the specific driftwood supply is defined as $V_s = V/W$, with V from Table 2. The parameter V_s describes thus the driftwood volume arriving at the PKW per weir width. The first batch of configuration C ($V_s = 0.88$ m^3/m) represented the minimum specific driftwood supply; the tenth batch of configuration A ($V_s = 8.79$ m^3/m) represents the maximum value tested herein.

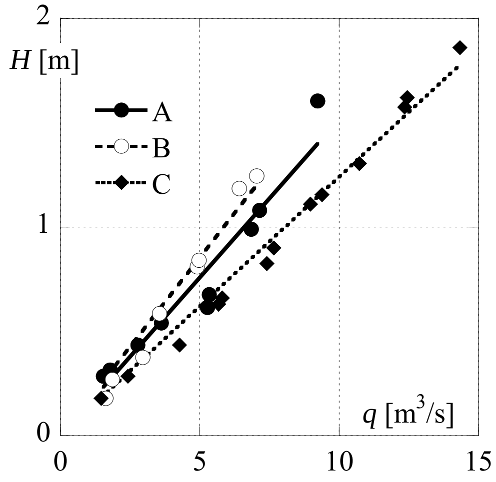

Figure 2. Rating curves of PKW configurations A to C.

3 RESULTS

Figure 3 shows the blockage process of driftwood at two different PKW configurations (left configuration B, right configuration C), subjected to two different specific discharges (left $q = 2.96$ m^2/s, right 9.39 m^2/s), as a function of the specific driftwood supply (increasing supply from Fig. 3a to 3e).

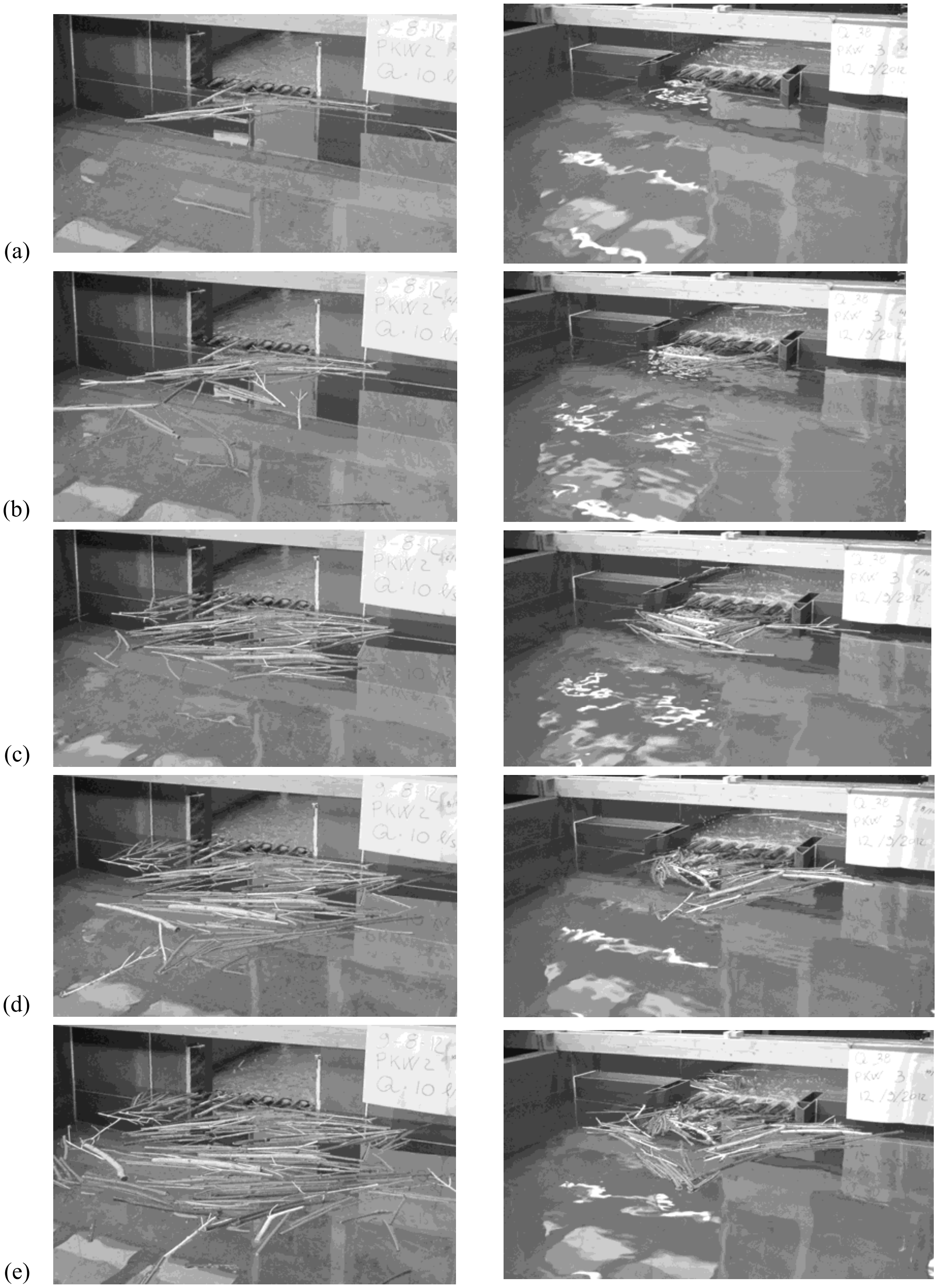

Figure 3. Progressive driftwood blockage at PKW configuration B for q = 2.96 m^2/s (left), and configuration C for 9.39 m^2/s (right), after supply of batch (Table 2) (a) 2, (b) 4, (c) 6, (d) 8, and (e) 10.

Figure 3 indicates that:

- the driftwood volume trapped at the PKW increases with increasing supplied driftwood volume V_s.
- large specific discharges (right) generate a smaller blockage than small values (left). Or, vice-versa, the probability to be washed over the PKW increases for large specific discharges.
- for small specific discharges, most of the trunks from the initial batches get trapped (Fig. 3b, left); for larger specific discharges, most of the trunks from the initial batches passed (Fig. 3b, right), given that no blockage was present at their arrival.
- Generally, the accumulations appear loose for small specific discharges (due to the reservoir approach flow type), and denser for higher specific discharges. For the latter, the flow momentum is comparably higher, supporting the passage of trunks as well as the tighter "packing" of trapped trunks.
- The trunks in direct contact with the PKW weir crest are mostly orientated parallel to the flow (perpendicular to the weir axis), whereas those further upstream were arranged more tangentially.

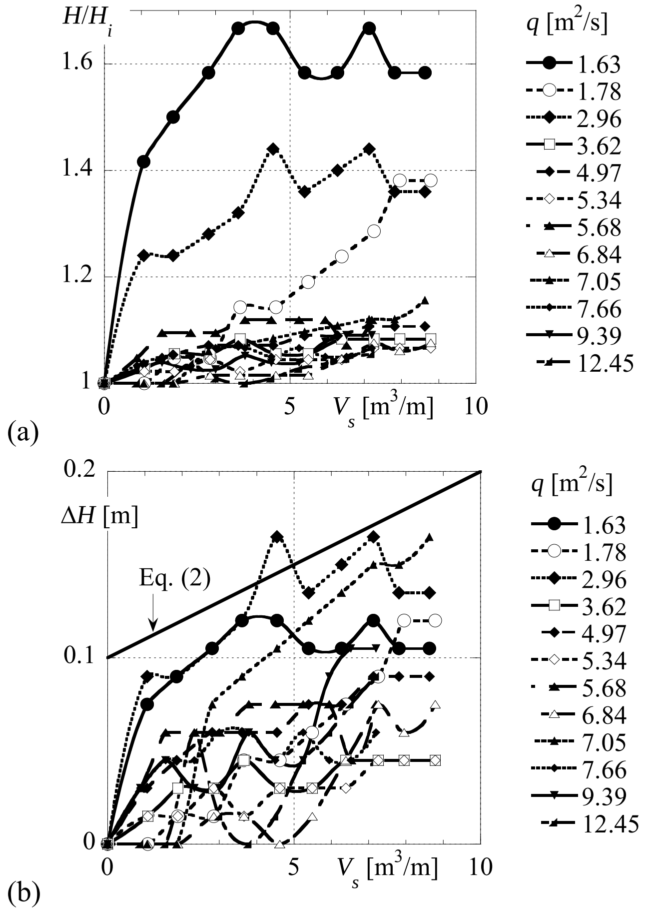

Figure 4. Effect of V_s and q on (a) relative H/H_i, and (b) absolute ΔH head increase.

Figure 4a shows the relative head increase H/H_i versus the driftwood supply V_s. Generally, the relative head increased with increasing V_s, with few exceptions for small specific discharges. For these cases, the arrival of additional driftwood at the PKW provided sufficient momentum to remobilize some of the previously trapped debris clusters and pass them over the PKW. As the trapped debris was liberated, H/H_i subsequently decreased. Furthermore, smaller discharges ($q < 3.0$ m^2/s) produced larger relative head increase ($1.4 < H/H_i < 1.7$), whereas large specific discharges above the aforementioned limit resulted in $H/H_i < 1.2$. The latter values apply for V_s between 4 to 9 m^3/m approximately. However, the conclusion that a large value q is less sensitive regarding the effect of driftwood on H might be misleading, as Fig. 4b indicates. There, the absolute head increase $\Delta H = H - H_i$ is given as a function of q and V_s.

An envelope of the data in Fig 4b indicates that the maximum hydraulic head ΔH_M in [m] additionally generated by driftwood can be expressed pragmatically as

$$\Delta H_M = E + 0.01 V_s \tag{2}$$

where V_s = specific driftwood volume transported to the considered section in in [m^3/m]. Note that the limits of the model tests apply, namely related the PKW configurations, $q \leq 12.45$ m^2/s and $V_s \leq 8.79$ m^3/m. The variable E covers the initial and pronounced head increase occurring as soon as driftwood arrives at a PKW, and is $E = 0.10$ for $q \leq 3$ m^2/s, and $E = 0.05$ for $q > 3$ m^2/s. In Fig. 4b, Eq. (2) is shown with $E = 0.10$. For a design discharge of $q_D \leq 3$ m^2/s, the ΔH_M from Eq. (2) with $E = 0.10$ represents the additional reservoir freeboard required to account for debris accumulation. For larger design discharges, the larger value ΔH_M from Eq. (2) either with $E = 0.10$ or with $E = 0.05$ has to be provided. This is necessary, as PKWs are unregulated weir structures, imperatively spilling small discharges at the first phase of every flood passage.

For PKWs, the hydraulic head is frequently expressed relative to the weir height as H_i/P. Figure 5 includes basically the same information as Fig. 4, i.e., shows that the relative head increase H/H_i generated by driftwood is significant (H/H_i up to 1.7) for $H_i/P < 0.2$, and small ($H/H_i < 1.2$) for $0.2 < H_i/P < 0.5$. As for the absolute head increase ΔH (Fig. 5b), the trend is again less significant, however, the maximum additional head becomes $\Delta H_M < 0.2$ m.

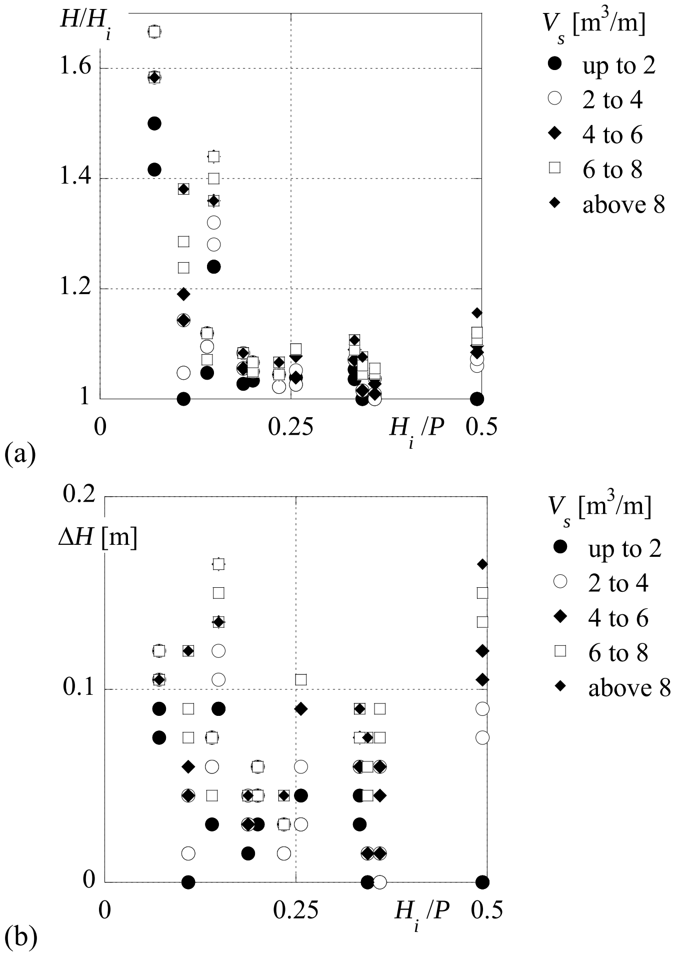

Figure 5. Effect of H_i/P and V_s on (a) relative H/H_i, and (b) absolute ΔH head increase.

The tests were conducted under a constant discharge q, and the increased head H as a function of the driftwood supply was measured. Formulating the related discharge coefficients C_d gives

$$\frac{q}{q_i} = \frac{C_d\sqrt{2gH^3}}{C_{di}\sqrt{2gH_i^3}} = 1 \tag{3}$$

where the subscript *i* refers to initial conditions prior to adding driftwood. Equation (3) can be reformulated as

$$\frac{C_d}{C_{di}} = \left(\frac{H}{H_i}\right)^{-3/2} \tag{4}$$

Considering the herein measured maximum $H/H_i = 1.7$ results is $C_d/C_{di} = 0.45$, and $H/H_i = 1.1$ in $C_d/C_{di} = 0.87$. If $q > 3.0$ m^2/s then generally $H/H_i < 1.2$ (Fig. 4a), so that minimally $C_d/C_{di} = 0.76$. For the latter (typical) situation, one may thus assume a reduction of the discharge coefficient up to $C_d = (3/4)C_{di}$, serving as basis for a rough estimation.

The hydraulic load on the PKW increases due to the presence of driftwood. For the reservoir approach flow type as investigated herein, mainly the augmented hydrostatic pressure (by ΔH) seems relevant, whereas the dynamic impact of the trunks is small due to negligible approach flow velocities.

4 CONCLUSIONS

To develop a better understanding of the potential impact of driftwood accumulation upstream of PKWs, laboratory-scale testing was conducted featuring three different in-reservoir PKW geometries and varying sizes of driftwood trunks consistent those commonly found in alpine and pre-alpine catchments (Bezzola and Hegg 2007). Each PKW was tested at four different specific discharges; each test included the addition of ten sequential batches of tree trunks of distributed diameter and length upstream of the PKW. The driftwood elements were allowed to pass or collect at the PKW as flow conditions dictated. Trapped driftwood elements were not removed prior to the addition of the subsequent batches. The changes in the upstream reservoir level were noted with the addition of each batch. Based on the results of these tests, the following conclusions are made:

1. In general, the amount of driftwood collecting at the PKWs increased with decreasing unit discharge (q). In some low specific discharge cases, however, the momentum provided by the later driftwood batch additions, along with the increased reservoir level (ΔH) caused by the driftwood accumulation, was sufficient to liberate some of the previously trapped trunks and pass them over the PKW.
2. The driftwood volume trapped at the PKW increases with increasing supplied driftwood volume (V_s). The density of the trapped driftwood debris field increased with increasing q, as shown in Fig. 3.
3. The probability of driftwood trunks being washed over the PKW increased with increasing q.
4. The trunks in direct contact with the PKW weir crest were mostly orientated parallel to the flow (perpendicular to the weir axis); trapped trunks located further upstream in the reservoir were arranged more parallel to the PKW axis.
5. Eq. 2 provides a first-order approximation of the increase in upstream reservoir head (ΔH) caused by driftwood accumulation at a PKW. The nature and volume of the driftwood will likely vary significantly, however, with terrain, geographical location, season, and climate.
6. The discharge coefficient (C_d) decreases due to driftwood collection at the PKW. It is typically around (3/4) of the value without drift wood occurrence for specific discharges (q) exceeding some 3 m^2/s.

Future research areas regarding driftwood and PKW interaction should include characterizing the influence of adjacent gated spillway operation as a means of controlling driftwood collection at PKWs following flood events. Additionally, the influence of the crest shape is of interest. Besides, Eq. (2) has to be expressed dimensionless, based on a dimensional analysis.

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