Partial Driftwood Rack at Gated Ogee Crest: Trapping Rate and Discharge Efficiency

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Abstract: Driftwood belongs to natural rivers just like water and sediment do. A sound ecosystem requires driftwood, although it might jam at civil structures, altering the flow section and rise the backwater. Safety considerations suggest removing wood from rivers, whereas ecological experience asks for its presence. The situation might become critical if spillways clog during floods, so that their discharge capacity reduces. For narrow bays, full racks mounted upstream of the weir or overhanging piers trap the driftwood distant from the flow control section. The hydraulic capacity is then maintained, but the driftwood has to be removed after the event. We thus investigated herein with a physical model a novel partial rack, motivating the driftwood for uncongested appearance to partially pivot and pass, but ensuring a high discharge capacity under hypercongested appearance. The partial rack configuration was specified, together with the related trapping rate and discharge efficiency. **DOI: 10.1061/(ASCE)HY.1943-7900.0001994.**

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Introduction

Driftwood is a natural part of riverine ecosystems. It alters the flow pattern and affects the hydraulic characteristics as well as the morphology. Driftwood provides spaces to hide, nutriments, and shadow (Naiman et al. 2002; Dolloff and Warren 2003; Benke and Wallace 2003; Bisson and Wondzell 2003). Braudrick et al. (1997) stated: “Restoring streams to improve aquatic habitat requires the reintroduction of wood into streams.”

Hydraulic engineers also experience the risks related to driftwood-loaded rivers (Piégay et al. 2009). Being mobilized during floods and transported to a structure that alters the flow cross section—as bridge piers, weirs, or culverts—large trunks may block, accumulate, and reduce the open flow area. Flooding and erosion are frequent consequences. Approaches to handle driftwood are the (1) maintenance of the riparian vegetation, (2) construction of in-stream (Schmocker and Weitbrecht 2013) or on-site (Bénet et al. 2021b) retention structures where the wood is removed after a flood, or (3) implementation of transfer structures provoking a (partial) passage.

The risk related to driftwood occurrence is particularly pronounced at dam spillways. They must discharge their maximum capacity under extreme floods, without a limitation by driftwood. The case of Palagnedra Dam in Switzerland (Bruschin et al. 1981) and other critical situations proved that an uncontrolled reservoir-level rise may lead to dam overtopping with related damages.

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Several studies proposed structures or countermeasures to avoid an interference of driftwood with the flow section fixing the undisturbed rating curve. Alternatively, the effect of driftwood on the rating curve or its trapping rate (or blocking probability) were described (Hartung and Knauss 1976; Perham 1986; Johansson and Cederström 1995; USACE 1987, 1997; Le Lay and Moulin 2007; Hartlieb 2012; Pfister et al. 2013; Yang 2013; Schmocker 2017; STK 2017; Walker and Shinbein 2020; Schalko et al. 2018; Lassus et al. 2019; Furlan et al. 2019, 2020, 2021; Piton et al. 2020).

Two studies seem particularly interesting in the present context:

- Godtland and Tesaker (1994) conducted model tests considering a linear ogee weir with and without piers. Single trees typically passed the crest without piers if the head exceeded 85% of the trunk diameter (Pfister et al. 2013; Furlan et al. 2021). With piers, the bay width b had to be larger than 80% of the maximum (subscript M) trunk length L_M to induce passage of most trees (USACE 1997). This means that trunks typically block and provoke a backwater-level rise if the bays are narrower.
- Bénet et al. (2021b, a) investigated the reservoir-level rise upstream of an ogee crest with piers under an extreme driftwood arrival. For narrow bays ($0.40 \leq b/L_M \leq 0.77$) and without countermeasures, the discharge coefficient was reduced to around $C_d \approx 0.36$, as compared to $C_{dR} \approx 0.49$ for free conditions and the design discharge. Three countermeasures were presented: pier overhang (flow orientation, trapped driftwood), absence of piers (possible without gates, flaps, or bridge piers, transfer of driftwood), and racks (supplementary structure, trapped driftwood). They assured globally a discharge efficiency of around 95% with driftwood.

Most of the cited studies so far focused on a retention (and removal) of the driftwood. Its ecological potential remains unexploited in the downstream water course. The following conflict arises: The critical flow section defining the rating curve must remain free of driftwood, whereas the driftwood must pass this section to remain in the water course. If allowing the driftwood to approach that section, clogging may occur. A combination of dam safety and the passage of driftwood over the spillway appears challenging.

The study of Godtland and Tesaker (1994) has shown that wide bays ($b/L_M \geq 0.80$) are ideal: The driftwood passes with a high

Fig. 1. Physical model: (a) ogee, piers, and partial rack without water; and (b) impression for hypercongested driftwood appearance (Test 280), both seen from upstream.

probability, the weir remains (almost) free, and the discharge efficiency is hardly affected. New spillway inlets should thus, whenever possible, respect that criterion. Existing spillways often include narrower bays, so alternative approaches are required.

If the bays are narrow, then the driftwood has to be oriented when approaching the spillway. Such transfer structures are known from rivers, where the flow momentum permits a partial pivoting of trunks. McFadden and Stallion (1976) introduced an alignment system installed upstream of an outlet structure. Most of the longest trunks were reported to pass. Federal Highway Administration (FHWA 2005) presented a debris fin installed upstream of a constriction to orient the wood. Lange and Bezzola (2006) detailed transfer structures and presented a pier with an inclined and sharp-edged front. Clogging was avoided under uncongested wood appearance, whereas jams appeared for a congested arrival. Schalko et al. (2020) focused on bridge piers, reviewing current approaches and conducting tests with fins and sills. The fins did not increase the passage, whereas the sills reduced the accumulation probability. De Cicco et al. (2020) investigated bridge piers, particularly the link between front shape and driftwood blockage.

Countermeasures in reservoir thus incorporate driftwood retention, whereas a transfer via an alignment of the wood is feasible in rivers. We combine both approaches, i.e., to pivot trunks despite the small flow momentum in reservoirs, and to simultaneously limit the impact of those yet blocked on the discharge capacity. The tests of Bénet et al. (2021b) showed that the partial rack configuration [Figs. 1(a and b)] was promising in this context. The wide span of the partial rack [$2b/L_M > 0.8$, Figs. 2(a and b)] sporadically initiated trunk rotation and passage. It retained the trunks yet blocked distant form the weir so that the rating curve quasi-persisted.

Experimental Setup

Physical Model

Physical model tests were performed at the Platform of Hydraulic Constructions (PL-LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL). The configuration of Bénet et al. (2021b) was used: a 10-m-long and $B = 1.5$-m-wide horizontal flume. At its end, a linear ogee crest with a design (subscript D) head of $H_D = 0.15$ m and a vertical front was transversally mounted. Its crest level was at $W = 0.42$ m above the channel bottom to eliminate an effect of the approach flow on its rating curve (Vischer and Hager 1999). The crest was equipped with 0.04-m-thick and round-nosed piers. They were fixed on a flexible frame, so that $n = 4$–5 open bays resulted. All bays had the same width b for a test, whereas the bay width was varied between tests. The upstream pier front was aligned with the vertical weir front (except for the combined tests where a pier overhang of $p = 0.08$ m into the reservoir was installed). No gates were installed (fully open bays), so free overflow conditions appeared.

The discharge was measured by a magnetic inductive flowmeter (Krohne, Switzerland) up to ±0.5% full-scale. A point gauge fixed roughly 2 m upstream of the weir crest measured flow depths up

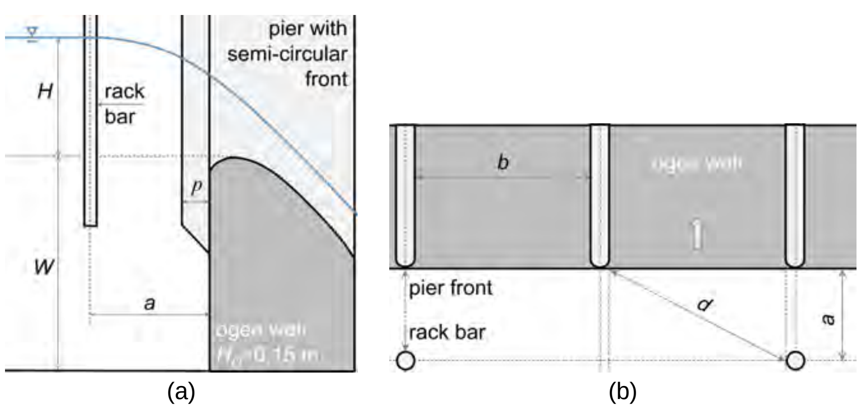

Fig. 2. Parameter definition: (a) streamwise section; and (b) plan view.

to ±1 mm. There, the maximum kinematic head (for H_D) was in the order of the measurement accuracy and thus negligible, so a reservoir-type approach flow may be assumed. An implicit validation of the measured parameters via the theoretical rating curve was conducted, underlining the accurate operation of the model.

Scale effect affecting the rating curve are negligible because $H \geq 0.05$ m for all tests (Hager et al. 2021). As for the driftwood, scale effects are probably present but not determinant. The trunk stiffness was overestimated (less fracturing), and fine elements (leaves and branches) were absent. Small driftwood fractions or fine material would not cause additional blocking, but potentially make existing blocking less permeable.

A linear partial rack was mounted at a streamwise distance a from the vertical weir front. The rack axis was parallel to the weir crest. The rack consisted of a bar upstream of every second pier only [Fig. 1(a)], aligned with the axis of the latter [Fig. 2(b)]. The bar diameter was 0.04 m, same as the pier thickness. The distance a was defined in function of the bay width b and the maximal trunk length L_M, resulting in four rack positions. These are denominated as:

1. Distant from the weir front, so that the longest trunk L_M (herein $L_M = 0.433$ m) might theoretically pass between the rack bar and the pier (Fig. 2) after pivoting partially, as

$$a_1 = \sqrt{L_M^2 - b^2} \tag{1}$$

2. Intermediate as

$$a_2 = \frac{1}{2}\left[\frac{b}{2} + \sqrt{L_M^2 - b^2}\right] \tag{2}$$

3. Close to the weir front, in agreement with the configuration of Bénet et al. (2021b), as

$$a_3 = \frac{b}{2} \tag{3}$$

4. Absent, i.e., no partial rack was installed, so that $a_4 = 0$ m.

The distance a is set in a context to b and L_M in Table 1 to enable a comparison with prototype.

Driftwood Characteristics

Driftwood-related measures can potentially encounter all wood appearances during the rising part of a flood hydrograph (Ruiz-Villanueva et al. 2019). Therefore, three different driftwood supply modes were tested:

1. Sporadic appearance: 20 batches of three trunks each were supplied (60 trunks in total, all of $L_M = 0.433$ m) at arbitrary locations at the model entrance. This corresponded to an un- or semicongested mode.
2. Congested appearance: six batches of 30 trunks each were supplied (180 trunks in total, all of $L_M = 0.433$ m) at arbitrary locations at the model entrance.
3. Hypercongested appearance: 2,840 trunks and rootstocks were supplied in one single batch covering the full model width. The trunks were of variable lengths (0.100 m to $L_M = 0.433$ m) and followed the characteristics Rickli and Hess (2009) derived from an in situ survey. The herein used driftwood is the same used by Bénet et al. (2021b) (extreme volume $4V$).

All trunks had a natural surface and shape and were watered several hours before conducting the tests. As for the trunk diameter D, the assumption of $L/D \approx 20$ was made. With a scale factor of $\lambda = 35$, for instance, prototype trunk lengths of 3.5 m $\leq L \leq$ 15.2 m were reproduced.

Parameters and Test Procedure

All driftwood batches were supplied progressively for a defined discharge, weir, and rack configuration. After several minutes, when stable conditions were achieved, the resulting head H (Fig. 2, under the influence of the totally supplied wood) was measured, and the number of blocked trunks was counted. For the tests related to the sporadic and congested appearance, trunks that passed the rack and the weir were removed from the model, whereas trunks that passed under the hypercongested appearance were added again to the reservoir to maintain an extreme situation. As stated by Bénet et al. (2021b), this was rarely necessary.

The measured head H under driftwood impact was used to compute a disturbed and thus lowered discharge coefficient C_d. The latter was compared to the reference (subscript R) discharge coefficient C_{dR} derived before in separate tests without driftwood (giving Q_R, H_R, χ_R, and C_{dR}). The discharge coefficient followed from the Poleni equation

$$C_d = \frac{Q}{nb_e\sqrt{2gH^3}} \tag{4}$$

where Q = discharge; and n = number of open bays. The hydraulically active bay width $b_e = b-(2K_pH)$ was used because it was slightly smaller than the geometrical width b, with K_p as pier parameter according to Vischer and Hager (1999).

The remaining (clogged) discharge efficiency followed consequently as

$$\eta = \frac{C_d}{C_{dR}} \tag{5}$$

In the following, the discharge was expressed as relative reference head χ_R. Practically, the head corresponding to a certain discharge was calculated based on Eq. (4) for the reference case without driftwood. This reference head H_R was then divided by the ogee design head H_D (herein $H_D = 0.15$ m), so that

$$\chi_R = \frac{H_R}{H_D} \tag{6}$$

The application of the relative reference head χ_R allows for a nondimensional expression of the discharge, as used hereafter.

Table 1. Overview of distances a of the partial rack upstream of the weir front

Bay width, b (m)	Rack position [Eqs. (1)–(3)]	Distance, a (m)	Relative distance, a/b	Relative diagonal length, d/L_M
0.175	1	0.40	2.26	1.00
0.260	1	0.35	1.33	1.00
0.335	1	0.27	0.82	1.00
0.175	2	0.24	1.38	0.69
0.260	2	0.24	0.92	0.81
0.335	2	0.22	0.66	0.93
0.175	3	0.09	0.50	0.45
0.260	3	0.13	0.50	0.67
0.335	3	0.17	0.50	0.86
0.175	4	0	0	$b/L_M = 0.40$
0.260	4	0	0	$b/L_M = 0.60$
0.335	4	0	0	$b/L_M = 0.77$

Note: For model dimensions, see Figs. 2(a and b).

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Table 2. Summary of test program

Driftwood supply mode	Value	χ_R Eq. (6)	b/L_M	C_d Eq. (4)	C_{dR} Eq. (4)	a (m) Eqs. (1)–(3)
Sporadic	Minimum	0.34	0.40	0.365	0.433	0.00
	Maximum	1.01	0.77	0.496	0.496	0.40
Congested	Minimum	0.33	0.40	0.334	0.433	0.00
	Maximum	1.01	0.77	0.475	0.496	0.40
Hypercongested	Minimum	0.17[a]	0.40	0.372	0.411	0.00
	Maximum	1.01	0.77	0.495	0.496	0.40

[a]Data from Bénet et al. (2021b).

Finally, the trapping rate P followed from the number of clogged trunks (cumulated at the rack and the weir), divided by the number of totally supplied trunks (60, 180, or 2,840).

Key elements were systematically varied to identify their effect on η and P (Fig. 2):

- The bay width as $b = 0.175$, 0.260, and 0.335 m. Relative bay widths of $b/L_M = 0.40$, 0.60, and 0.77 followed, all being below the recommendation of $b/L_M > 0.80$ (Godtland and Tesaker 1994). The bays of many existing weirs are narrow, so the installation of a rack (or another measure) becomes necessary. Such cases were considered herein. Given the model width of 1.5 m, four open bays of $b = 0.335$ m could be installed, and five bays of $b = 0.175$ or 0.260 m.
- The discharge within $0.019\ \mathrm{m^3/s} \leq Q_R \leq 0.170\ \mathrm{m^3/s}$, expressed nondimensionally as $\chi_R = 0.33$, 0.67, and 1. The discharge was fixed based to the reference heads $H_R = 0.05$, 0.10, and 0.15 m $(= H_D)$, and always corresponded to the reference situation (without wood).
- Three different driftwood supply modes were tested, as described previously.
- A partial rack was inserted, at different distances a upstream of the weir [Eqs. (1)–(3)].
- The pier front was aligned with the weir front ($p = 0$ m) for the basic tests, but exceptionally overhanging ($p = 0.08$ m) for some supplementary tests.

Furlan et al. (2019) recommended repeating identical driftwood tests several times to achieve statistical relevance. Based on Furlan et al. (2019) and Bénet et al. (2021b), we conducted every test related to a sporadic appearance 10 times, to a congested appearance five times, and to a hypercongested appearance twice.

The test program comprised 573 experiments, including the repetitions. Without counting the repetitions, 90 configurations were investigated, which were completed by selected data of Bénet et al. (2021b). Table 2 summarizes the tested parameters in function of the wood supply mode, and Tables 3 and 4 give the outcomes in terms of P and η.

Performance of Partial Rack (without Pier Overhang)

Sporadic Driftwood Appearance

Per test, 60 driftwood elements of L_M were consecutively supplied in 20 batches of three trunks each. Such small batches had few piece-to-piece interactions and were thus relatively free to pivot at the partial rack. First batches usually passed, whereas subsequent batches might encounter some blocked trunks from previous batches, limiting the ability to rotate.

For a partial rack being installed distant of the weir (Position 1), most trunks passed and only few were blocked, often at the piers

Table 3. Remaining discharge efficiency η

Driftwood supply mode	Rack position	Without pier overhang, b/L_M 0.40	Without pier overhang, b/L_M 0.60	Without pier overhang, b/L_M 0.77	Without pier overhang, Average	With pier overhang, b/L_M 0.60
Sporadic	1	0.94 (0.03)	0.94 (0.04)	0.97 (0.01)	0.95 (0.03)	0.99 (0.01)
	2	—	0.92 (0.03)	—	0.92 (0.03)	0.98 (0.01)
	3	—	0.94 (0.03)	—	0.94 (0.03)	—
	4	0.80 (0.04)	0.88 (0.05)	0.95 (0.02)	0.88 (0.04)	0.97 (0.01)
Congested	1	0.94 (0.04)	0.87 (0.03)	0.93 (0.04)	0.91 (0.04)	0.98 (0.01)
	2	—	0.89 (0.04)	—	0.89 (0.04)	0.98 (0.01)
	3	—	0.90 (0.02)	—	0.90 (0.02)	—
	4	0.79 (0.04)	0.77 (0.03)	0.83 (0.06)	0.79 (0.04)	0.95 (0.02)
Hypercongested	1	0.95	0.96	0.98	0.96	0.99
	2	—	—	—	—	0.99
	3	0.97	—	0.97	0.97	—
	4	0.86	0.85	0.81	0.84	0.97

Note: Mean values of test repetitions and discharges are on top, standard deviation is below in brackets.

Table 4. Trapping rate P

Driftwood supply mode	Rack position	Without pier overhang b/L_M 0.40	0.60	0.77	Average	With pier overhang b/L_M 0.60
Sporadic	1	0.22 (0.20)	0.06 (0.08)	0.01 (0.02)	0.10 (0.10)	0.20 (0.17)
	2	—	0.16 (0.15)	—	0.16 (0.15)	0.26 (0.24)
	3	—	0.30 (0.20)	—	0.30 (0.20)	—
	4	0.41 (0.20)	0.18 (0.13)	0.05 (0.04)	0.21 (0.12)	0.32 (0.19)
Congested	1	0.94 (0.06)	0.68 (0.18)	0.59 (0.22)	0.74 (0.15)	0.82 (0.14)
	2	—	0.76 (0.13)	—	0.76 (0.13)	0.82 (0.13)
	3	—	0.82 (0.15)	—	0.82 (0.15)	—
	4	0.80 (0.12)	0.72 (0.18)	0.52 (0.20)	0.68 (0.17)	0.81 (0.13)
Hypercongested	1	≈1	≈1	≈1	≈1	≈1
	2	—	—	—	—	≈1
	3	≈1	—	≈1	≈1	—
	4	≈1	≈1	≈1	≈1	≈1

Note: Mean values of test repetitions and discharges are on top, standard deviation is below in brackets.

and rarely at the rack. Installing the partial rack closer to the weir (reducing a) increased the trapping rate, and trunks clogged by trend rather at the rack and less at the piers (Position 3). However, the blocked trunks rarely aligned with the weir but were positioned obliquely between weir and rack, leaving space for the flow (Fig. 3). Without a rack, the trunks block parallel to the weir, limiting the discharge capacity.

Fig. 3. Typical jam pattern for sporadically arriving driftwood ($b/L_M = 0.60$, Partial Rack Position 3, $\chi_R = 0.33$, Test 371).

The ability of single trunks to pivot increased with the discharge χ (flow momentum at the rack) and the distance a (room to pivot). In parallel, the increasing flow momentum compacted and stabilized jams. Therefore, few trunks blocked under small and large discharges ($\chi_R = 0.33$ and 1), and more under a medium discharge ($\chi_R = 0.67$). Fig. S1 gives a representative overview of the trapping rates P for $b/L_M = 0.60$ and various discharges (reference heads χ_R) as well as rack positions (1–4). Small values of P were observed for maximum discharges and racks mounted on Positions 1 and 2 (distant and intermediate). Globally (Table 4, all b/L_M), partial racks reduced the trapping rate on average by a factor of 0.48 (= 0.10/0.21, Position 1) to 0.76 (= 0.16/0.21, Position 2) as compared to a setup without rack (Position 4).

Fig. 4 includes all tested a, b, and H_R, showing P and η versus the relative partial rack position a/H_R. This normalization was significant in Bénet et al. (2021b) regarding the effect of pier overhang on the clogged discharge capacity, and the rack might be considered somehow as an overhanging pier. The normalization could alternatively be referred to the critical flow section on the weir crest, so that $(a + 0.28H_D)/H_R$ would result for ogees (Bénet et al. 2021a).

Fig. 4(a) shows that the trapping rate without rack (Position 4) and with a partial rack at Position 3 (close) resulted by trend in high values P, whereas Positions 2 and 1 generated lower P (Table 4). One has the impression that P reduced to a minimum at $a/H_R \approx 6$ (trunks jam oblique, Fig. 3), and then increased because the trunks passed the rack and clogged directly at the weir. Fig. 4(b) indicates that the discharge efficiency without partial rack (Position 4) was around $0.65 < \eta < 1$. With the rack, it significantly increased to $0.80 < \eta \leq 1$. Rack Positions 1 and 2 performed well, especially for large a/H_R values.

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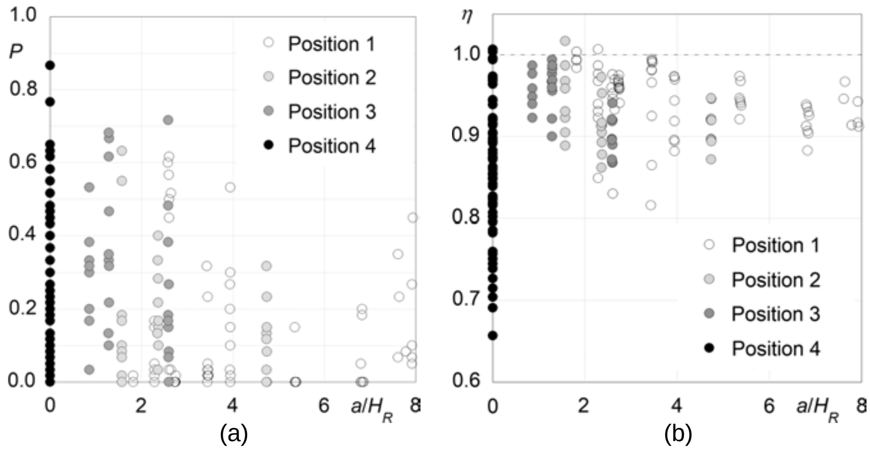

Fig. 4. Results for sporadically arriving driftwood in function of a/H_R: (a) P; and (b) η.

Congested Driftwood Appearance

Per test, 180 driftwood elements of L_M were consecutively supplied in six batches of 30 trunks each. Such large batches had many piece-to-piece interactions and traveled as a compact unit. The latter feature made them clog by trend at the first obstacle encountered, which was a rack bar. Relatively few trunks approached the weir and persisted there obliquely, so that the flow section remained quasi-open (Fig. 5). A rotation or alignment of trunks was rarely observed.

Fig. 5. Typical jam pattern for congested driftwood appearance ($b/L_M = 0.60$, Partial Rack Position 1, $\chi_R = 0.34$, Test 211).

Fig. S2 gives P in function of the rack position and χ_R for $b/L_M = 0.60$. Without rack [Fig. S2(d)], the average P was around 0.70–0.80 for all tested χ_R. A distant partial rack [Position 1, Fig. S2(a)] reduced P for $\chi_R = 1$ to an average of around 0.35, whereas it was increased to around 0.90 for $\chi_R = 0.33$. The probability to clog was heterogenous but on average (for all χ_R and b/L_M) by trend slightly increased with the presence of the rack (particularly for the Positions 2 and 3, Table 4).

Much more efficient than the presence of the partial rack were wide bays in terms of wood passage. Bays with $b/L_M = 0.77$ reduced the trapping by a factor of 0.87 ($= 0.59/0.68$, Table 4, Position 1) as compared to $b/L_M = 0.60$, whereas narrower bays ($b/L_M = 0.40$) increased the blockage by a factor of $1.38 (= 0.94/0.68)$.

Fig. 6 includes all varied parameters, showing P and η versus the relative partial rack position a/H_R. A high spread of trapping rates ($0 \leq P \leq 1$) is visible in Fig. 6(a) within $0 \leq a/H_R < 4$, and $0.8 \leq P \leq 1$ for $a/H_R \geq 4$. Some rack-induced trapping rates were on average even above those without rack (Table 4). Thus, the partial rack on Positions 1 or 2 hardly influenced the wood blockage as long as $a/H_R < 4$, but increased the latter if the rack was mounted further upstream. Fig. 6(b) shows a discharge efficiency without

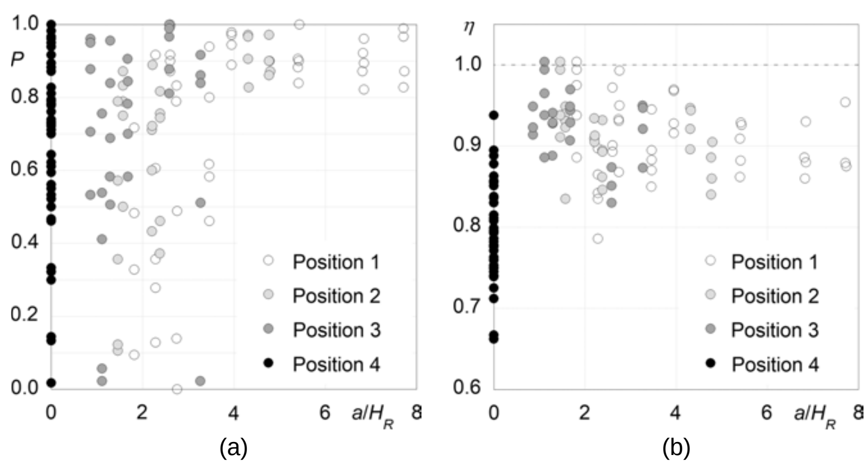

Fig. 6. Visualization of results for congested driftwood appearance in function of a/H_R: (a) P; and (b) η.

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partial rack of around $0.65 < \eta < 0.95$, and of approximately $0.80 \leq \eta \leq 1$ with the partial rack.

Hypercongested Driftwood Appearance

The extreme driftwood appearance included one single batch of 2,840 trunks and rootstocks of variable length and diameter. It represented a test case for the discharge capacity η, but less for the driftwood blocking. The latter is known to be around $P \approx 1$ from Bénet et al. (2021b), a value that was confirmed herein. The batch was coherent and clogged at the partial rack (Fig. 7). Only a few trunks touched the weir, so its capacity was largely maintained.

The presence of the partial rack did not amplify the driftwood passage. The entire batch clogged, as it would do without a rack. However, Fig. 8 shows that the discharge efficiency remained around $0.90 < \eta \leq 1$ with the partial rack (for all a, b, and H_R tested), whereas it would be $0.70 \leq \eta \leq 0.95$ without a rack. If installing the rack at a relative distance of $1 \leq a/H_R < 4$, then even $0.95 < \eta \leq 1$ was achieved (Table 3).

Fig. 7. Typical jam pattern for hypercongested driftwood appearance ($b/L_M = 0.60$, Partial Rack Position 1, $\chi_R = 1.01$, Test 287).

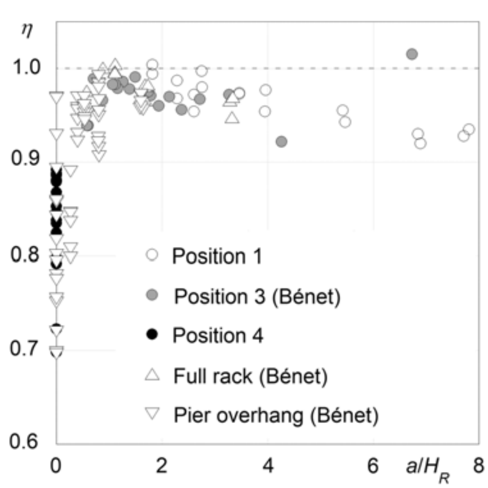

Fig. 8. Visualization of results for hypercongested driftwood appearance: η versus a/H_R. (Data from Bénet et al. 2021b.)

Performance of Partial Rack Combined with Pier Overhang

The three driftwood supply modes that have been tested so far resulted in different outcomes (Tables 3 and 4):

- For a sporadic appearance, the driftwood passage was high either for wide bays (e.g., $b/L_M > 0.80$) or for narrow bays with a partial rack (Positions 1 or 2, within $a/H_R < 6$). The discharge efficiency increased from $0.65 < \eta < 1$ without to $0.80 < \eta \leq 1$ with partial rack.
- For a congested appearance, wide bays (e.g., $b/L_M > 0.80$) performed best in terms of driftwood passage. Narrower bays combined with a partial rack installed close to the weir amplified clogging (as compared to the situation without rack), whereas distant racks indicated an indifferent behavior if $a/H_R < 4$. The discharge efficiency was $0.65 < \eta < 0.95$ without and $0.80 \leq \eta \leq 1$ with partial rack.
- For a hypercongested appearance, the driftwood jammed, independent of the tested conditions. The partial racks did not enhance the wood transition. Nevertheless, the rack noticeably increased the discharge efficiency to $0.95 \leq \eta \leq 1$ if installed within $1 \leq a/H_R < 4$, as compared to $0.70 \leq \eta \leq 0.95$ without a rack.

A spillway inlet might be subjected to various driftwood appearances during its lifetime. Narrow bays ($b/L_M < 0.80$) profit from the presence of a partial rack because the driftwood passage of un- and semicongested wood is amplified. These transport regimes appear frequently in rivers (Wohl et al. 2019). Under congested and hypercongested conditions, the rack retained the driftwood—as would the weir without a rack.

In parallel, the partial rack maintained a discharge efficiency of $\eta \geq 0.80$, which was above $\eta \geq 0.65$ for a weir without rack. Particular spillways might nevertheless require an efficiency of $\eta \approx 1$. We thus conducted supplementary tests combining the partial rack with overhanging piers (Bénet et al. 2021b), with the objective to maintain the elevated driftwood passage and to further increase the discharge efficiency. The same model configurations were used, except that a pier overhang of $p = 0.08$ m was installed [Figs. 2(a) and 9]. Such a pronounced value is efficient following

Fig. 9. Typical jam pattern for overhanging piers combined with partial rack (hypercongested appearance, $b/L_M = 0.60$, Partial Rack Position 1, $\chi_R = 1.01$, Test 528).

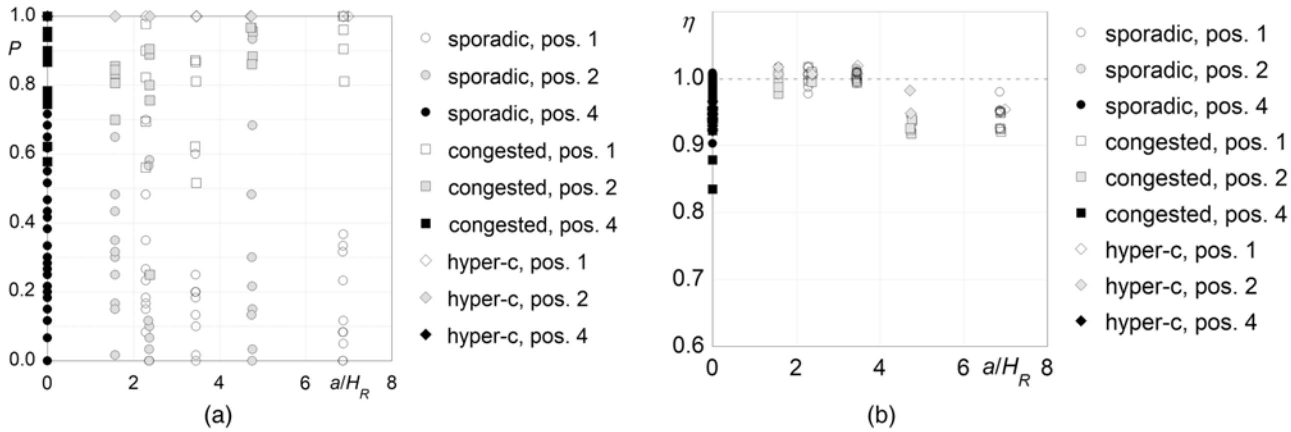

Fig. 10. Visualization of results ($b/L_M = 0.60$) for pier overhang and partial rack in function of a/H_R: (a) P; and (b) η.

Bénet et al. (2021b, a). Consequently, Partial Rack Position 3 [close, Eq. (3)] was in conflict with the pier front and was not tested. We limited the test program here to $b/L_M = 0.60$.

The behavior of the driftwood was basically similar to the setup without pier overhang, although the resulting η and P changed. The main differences were first that trunks being blocked at the piers were distant from the discharge control section, so η remained comparably high (Table 3), and second that P was higher (Table 4) because the trunks arriving at the piers were subjected to a lower flow momentum, reducing their alignment potential.

Fig. S3 shows the trapping rates P for the combined installation. As compared to the situation without pier overhang, an increased P occurred for all rack positions and relative heads. Nevertheless, the partial rack again reduced the driftwood trapping on its Position 1 for a sporadic wood appearance, now by a factor of 0.63 (= 0.20/0.32, Table 4), as compared to the setup without rack (but with pier overhang). For the congested and hypercongested appearance, the partial rack generated approximately the same blockage as the configuration with an overhang only.

Fig. 10(a) specifies the effect of the relative distance a/H_R on P, indicating the absence of a clear trend. A sporadic driftwood appearance tended to request large distances ($a/H_R > 4$), whereas a congested appearance requested short distances ($a/H_R < 4$) for low P. The discharge efficiency [Fig. 10(b)] was, for all driftwood appearances, typically $\eta \geq 0.90$ without rack, around $\eta \approx 1$ with a partial rack at $0 < a/H_R < 4$, and $\eta > 0.90$ for a rack at $a/H_R \geq 4$.

The combination of a partial rack with a significant pier overhang maintained herein the quasi-full discharge capacity under all driftwood appearances (Rack Position 1, $a/H_R < 4$). The driftwood passage was globally smaller than at the setup with a partial rack but without a pier overhang. However, if a pier overhang was foreseen, then the presence of the rack amplified the passage of sporadically appearing trunks. No significant difference in terms of wood passage was observed for other driftwood appearances.

Conclusions

It seems challenging to maintain a free weir rating curve under various types of driftwood appearances if piers are present, and to simultaneously transit the wood over the weir. The present study highlighted the following issues in this regard:

1. Wide bays seem the most efficient measure to maintain the rating curve and to let driftwood pass simultaneously. Although not explicitly tested herein, our results indicated that $b/L_M > 0.80$ for new spillways or removing piers on existing spillways was promising.
2. If narrow bays are considered ($b/L_M \leq 0.80$) and driftwood represents a threat but should be kept as far as possible within the river downstream of the spillway, then:
   - If the discharge capacity should be maintained ($\eta \geq 0.95$ for all scenarios tested), then a pier overhang ($p/H_R > 0.35$) could be combined with a partial rack ($a/H_R < 4$). The presence of the rack reduced the trapping of sporadically occurring driftwood on average by a factor of 0.63 (= 0.20/0.32, Table 4). Congested and hypercongested driftwood appearances remained uninfluenced in terms of blockage.
   - If there is a flexibility with regard to the discharge capacity or a limited reservoir-level rise might be acceptable, then a partial rack is adequate (without pier overhang). The discharge efficiency is then $\eta \geq 0.80$. For a hypercongested driftwood appearance, it was $0.95 \leq \eta \leq 1$ if the partial rack was provided at Position 1 and within $1 \leq a/H_R < 4$. That rack reduced the trapping rate of sporadically arriving wood by a factor of 0.48 (= 0.10/0.21, Table 4), as compared to the situation without rack. The rack did, however, not increase the driftwood passage for congested and hypercongested appearances. Significantly less driftwood was blocked (factor of 0.74 for all wood appearances) with the rack only, as compared to the combined setup with pier overhang.
3. If narrow bays are considered ($b/L_M \leq 0.80$), driftwood represents a threat and should be removed from the downstream river (e.g., flooding of city), then a full rack might be installed at the weir for instance (e.g., Bénet et al. 2021b).

The tested partial rack (possibly with overhanging piers) enhanced the transition for sporadically arriving driftwood, maintaining a high discharge capacity. Under congested and hypercongested appearances, the wood was mostly trapped. This might be favorable because frequently arriving trunks remain as deadwood in the river, whereas batches transported during floods block and can be removed after the event.

Tables 3 and 4 give an overview of η and P. They include mean values per discharge, repetition, and standard deviation for the sporadic (10 test repetitions) and congested (five test repetitions) appearance. The typical standard deviation for η is small (typically 4%), indicating minor variability. The standard deviation of P is similar to the mean for the sporadic appearance, and around 23% of the mean for the congested appearance.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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Notation

The following symbols are used in this paper:

a = streamwise distance between weir front and rack axis (m);
B = total channel width (m);
b = individual bay width (m);
C_d = discharge coefficient;
D = trunk diameter (m);
d = diagonal open length between rack bar and pier (m);
g = acceleration of gravity (m/s^2);
H = upstream weir head (m);
K_p = pier parameter (Vischer and Hager 1999);
L = trunk length (m);
n = number of open bays;
P = trapping rate (blocking probability);
Q = discharge (m^3/s);
W = vertical offset between channel bottom and weir crest (m);
η = discharge efficiency;
λ = geometrical scale factor;
ρ = water density (kg/m^3); and
χ = relative head.

Subscripts

D = design;
M = maximum; and
R = reference (without driftwood).

Supplemental Materials

Figs. S1–S3 are available online in the ASCE Library (www.ascelibrary.org).

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