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Key Points:

- A logistic regression model was developed to estimate individual stem blockage probability at ogee crested spillways with piers
- The blockage probability depends markedly on the hydraulic head and stem draft, and, to a lesser extent on the stem length and bay width
- Heads greater than 1.8 times the stem draft can ensure blocking probabilities smaller than 0.20 at ogee crested spillways with piers

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Blockage Probability Modeling of Large Wood at Reservoir Spillways With Piers

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Abstract Large wood increases the morphological and hydraulic complexity of rivers, yet it may block and modify the flood discharge capacity of hydraulic structures. To assess the related risk, blockage probability estimation for hydraulic structures such as reservoir spillways is needed. This work presents unstudied parameters for blockage of large wood with a reservoir-type approach flow, where the inflow velocity has a negligible magnitude. Experiments were conducted in a channel with an ogee crested spillway equipped with piers, representing a commonly used hydraulic structure. Artificial stems were used to systematically evaluate the influence of stem length and stem draft on the blocking process. Different hydraulic conditions were evaluated by changing the water level in the reservoir. The head at the spillway crest with respect to stem draft was found to be a key parameter for blockage probability estimation at a spillway. Additionally, stem length was related to the bay width in the estimation of blockage. Larger heads tend to reduce the blocking probability of large wood, for a given stem draft, while increasing the relative stem length tends to increase the blocking probability. A logistic regression model is provided to estimate large wood blockage probability at ogee crested spillways with piers. Finally, recommendations for engineering practice are presented.

1. Introduction

In some areas, large wood (LW) is often cleared to prevent it from entering streams (Comiti et al., 2016; Wohl, 2014) regardless of its positive influence for the diversification of aquatic ecosystems. The classification of LW includes stems longer than 1 m and with a diameter larger than 0.10 m (Braudrick et al., 1997; Ruiz-Villanueva, Piégay, Gurnell, et al., 2016; Wohl et al., 2016). The transport of LW can induce dangerous obstructions at hydraulic infrastructures like bridges, weirs and spillways during floods (Allen et al., 2014; Bénet et al., 2021; De Cicco et al., 2016, 2020; Gschnitzer et al., 2017; Hartford et al., 2016; Hartlieb, 2012; Iroumé et al., 2015; Panici & de Almeida, 2018; Pfister, Capobianco, et al., 2013; Piton et al., 2020; Schalko et al., 2020; Schmocker & Hager, 2011).

Accumulations of LW in reservoirs can have significant negative impacts on the operation and functioning of a dam. During August of 1978, the Palagnedra Dam in the southern canton of Ticino (Switzerland) was overtopped. After a heavy rain event, LW reached the spillway inlet and blocked at the piers of the ogee crested spillway. The hydropower plant was obstructed with twisted tree trunks in the spiral casing of the turbines (Bruschin et al., 1982; Maggia, 1979). The large discharge combined with an unknown degree of obstruction of the spillway led to the dam overtopping which created a very dangerous situation. Even in 2015, the National Performance of Dams Program reported 23 accidents at dams in the United States involving large wood blockage of spillways (Hartford et al., 2016).

Today, engineers are more aware of the impacts of LW blockage at spillways but still, few guidelines for construction have been developed (e.g., Comité Français des Barrages et Réservoirs, 2013; Swiss Committee on Dams, 2017). In the analyses of LW interactions with structures, physical models have been used to systematically investigate different aspects of the process (Wilcox & Wohl, 2006). Godtland and Tesaker (1994) used physical model experiments to define construction recommendations for an overflow spillway. They aimed to clarify under which conditions LW and tangled trash, may cause clogging of free overflow spillways,

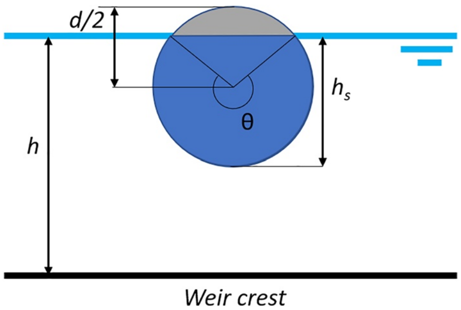

Figure 1. Schematic representation of a submerged stem with the respective stem draft (h_s) and angle (θ).

with or without a bridge structure. Based on their experiments, to avoid blocking probabilities of the drifting trees higher than 10%–20%, it is recommended to have a distance between piers of at least 80% of the length of the arriving tree.

Nonetheless, given that LW is naturally in contact with water, a physical model should realistically represent the physical changes wood can have due to water absorption (Mazzorana et al., 2017). In Schmocker and Hager (2013), the head increase upstream of a debris rack was investigated. For that, the soaking-time of the woody material was varied and analyzed. However, density was only considered for the experimental design and not related to the head increase upstream of the rack. The aim was to represent floods of some hours; therefore, it was decided to soak the woody material less than 8 h and keep a relatively constant wood density during the experiments. For the tested conditions, wood density was only influential in the head increase upstream of the structure when the stems were fully submerged. Schalko et al. (2020) used systematic experimental tests to study the accumulation probability of stems at bridge piers. In their study, they represented three wood densities by watering the stems during different time periods. One density was of 460 kg/m^3, a second of 850 kg/m^3 and a third one of 1320 kg/m^3. For the case of a bridge pier, they concluded that the blockage probability was not affected by the density as differences in blockage were inside the reproducibility range (differences smaller than 10%). Panici and de Almeida (2018), presented a brief analysis regarding the wood density influence on the shape of a jam for a bridge pier. By comparing two different wood densities they found that the depth of the jam changes as a function of the density, but the extension of the jam was not significantly influenced. According to their experiments, increasing wood density would increase up to 30% the depth of a jam. In the study of Furlan, Pfister, Matos, and Schleiss (2018), the analysis of wood density for blocking probability estimation of stems was started for spillways. Based on those experiments, it was concluded that wood density did not have a significant influence on the blocking probability for stems shorter than the bay width, in comparison to that observed for longer stems.

The effect of the wood density on the movement of stems can be related to their buoyancy (Braudrick et al., 1997). In their study, Ruiz-Villanueva, Wyżga, et al. (2016), Ruiz-Villanueva, Piégay, Gaertner, et al. (2016) performed a sensitivity analysis of wood density and its influence on transport. Wood density showed a significant influence on the likelihood of LW movement, as it affects the buoyancy and mobility of the piece.

A theoretical submerged height or stem draft can be calculated as a function of the wood density and stem diameter (Equation 1, e.g., in Quintela, 2005).

$$h_s = \frac{d}{2} \cdot \left(1 - cos\left(\frac{\theta}{2}\right)\right) \tag{1}$$

Here, h_s is the stem draft, d the stem diameter and θ is the angle relative to a circular segment as indicated in Figure 1. The wood density will influence h_s through θ. If the density is increased, the stem will submerge more, lowering its center of gravity and changing the θ angle.

The prediction and quantification of LW blockage at hydraulic structures remains a major challenge due to the complexity involved in the process. Density, and thus stem draft, has been a key parameter for movement estimation, quantification of wood budgets and transport studies (Braudrick et al., 1997; Dixon & Sear, 2014). Nevertheless, stem draft has not been considered an influential parameter for blockage at hydraulic structures like reservoir spillways. The aim of this study is to evaluate blockage probability of LW at an ogee crested spillway equipped with round nose piers, by relating LW characteristics (i.e., stem length and stem draft) to geometric and hydraulic parameters relevant to the spillway. A statistical approach was adopted herein to study the interaction of the variables, using a Generalized Linear Model (GLM) to estimate large wood blocking probability. This work was done in the framework of Furlan (2019).

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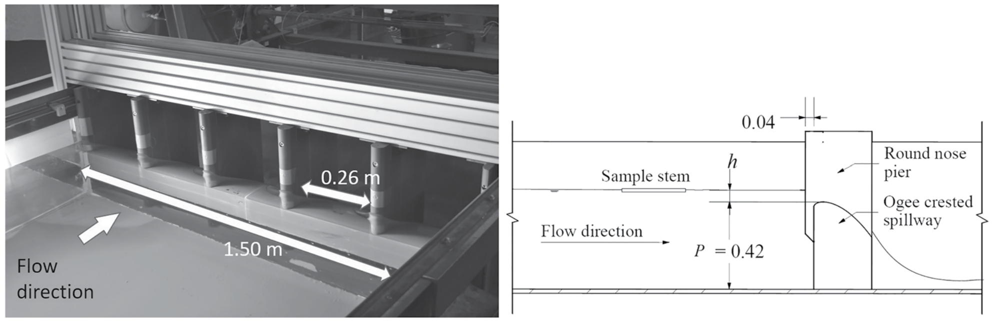

Figure 2. Experimental set-up. Left: Front view of the physical model; Right: Longitudinal schematic view of the physical model (dimensions in meters).

2. Methods

2.1. Experimental Set-Up

Experiments were carried out in a 10 m long and 1.50 m wide straight flume assembled at the Laboratory of Hydraulic Constructions (LCH) of the Ecole Polytechnique Fédérale de Lausanne (EPFL). Water was conveyed from a tank through a flow-straightener into the channel, ensuring homogeneous flow distribution. An ogee crested spillway (U. S. Army Corps of Engineers, 1987) was located at the end of the reservoir channel with five symmetrical bays of width $b = 0.26$ m (Figure 2). A design head (defined as the summation of the head above the spillway crest and the velocity head) of $H_d = 0.15$ m was used for the design of the ogee crest. For low flow velocities, as adopted in the present study with a reservoir approach flow, the total head (H) is practically equal to the head (h). Round nose piers were chosen due to their broad use in practice. The pier-nose protrudes 0.04 m into the reservoir, with a transversal thickness of 0.04 m.

Artificial plastic stems with constant cylindrical geometry were chosen to represent LW in the experiments, excluding geometrical irregularities to restrict and simplify the model. Stems were fabricated using PVC and PE pipes with endcaps attached to the stems ends. To increase the weight of stems without changing their size, the endcap's length was increased while decreasing the middle part. Five different stem lengths L were studied and compared to the bay width b by calculating a relative stem length L/b (Table 1).

Wood density values (ρ_w) were normalized with respect to water density ρ ($\rho_s = \rho_w / \rho$). Four ranges of wood density were represented with the stems: ρ_{s1} = [0.40–0.47] represents the density of light wood (Chave et al., 2009); ρ_{s2} = [0.47–0.67] average dry wood in Europe (Chave et al., 2009) or instream wood (Ruiz-Vil-

Table 1
Physical Characteristics of Artificial Stems Used for the Experiments

Length L (m)	Relative stem length L/b (-)	Diameter d (m)	Relative stem density ρ_s (-)	Stem draft h_s (m)
0.210	0.80	0.010	0.59	0.0057
			0.79	0.0074
			0.99	0.0097
0.260	1.00	0.012	0.56	0.0066
0.300	1.20	0.016	0.43	0.0072
			0.56	0.0088
			0.97	0.0149
0.400	1.50	0.020	0.63	0.0121
0.520	2.00	0.025	0.40	0.0105
			0.54	0.0134
			0.76	0.0178
			0.99	0.0242

Table 2
Experimental Test Conditions

N°	L/b (-)	h_s (m)	h (m)	h/h_s (-)	N°	L/b (-)	h_s (m)	h (m)	h / h_s (-)
1	0.80	0.0057	0.009	1.58	19	1.20	0.0088	0.025	2.84
2			0.012	2.11	20	1.20	0.0149	0.015	1.01
3			0.015	2.64	21			0.017	1.14
4	0.80	0.0074	0.010	1.35	22	1.50	0.0121	0.016	1.32
5			0.012	1.62	23			0.020	1.66
6	0.80	0.0097	0.010	1.03	24			0.025	2.07
7	1.00	0.0066	0.009	1.36	25	2.00	0.0105	0.019	1.81
8			0.012	1.82	26			0.025	2.38
9			0.015	2.28	27	2.00	0.0134	0.016	1.20
10	1.20	0.0072	0.017	2.37	28			0.019	1.42
11	1.20	0.0088	0.009	1.02	29			0.020	1.50
12			0.012	1.36	30			0.021	1.57
13			0.015	1.70	31			0.024	1.80
14			0.015	1.70	32			0.025	1.87
15			0.016	1.82	33			0.025	1.87
16			0.016	1.82	34	2.00	0.0178	0.019	1.07
17			0.017	1.93	35	2.00	0.0242	0.019	0.79
18			0.020	2.27	36			0.025	1.03

lanueva, Piégay, Gaertner, et al. [2016] found that a representative wood density value can be 660 kgm^{-3} with a standard deviation of 200 kgm^{-3}); ρ_{s3} = [0.67–0.88] green wood (Ruiz-Villanueva, Piégay, Gaertner, et al. [2016] found that a representative value can be 800 kgm^{-3} with a standard deviation of 170 kgm^{-3}); and ρ_{s4} = [0.88–0.99] waterlogged large wood (Buxton, 2010). Based on the stem diameter and stem density, the stem draft (h_s) was calculated for all stems (Table 1).

The experiments were designed to investigate key variables identified for the blocking probability of stems at hydraulic structures (Table 2). Ratios of the head (h) to the stem draft (h_s) (h/h_s, relative head) ranged between 0.79 and 2.84. These limits were based on preliminary tests. The experiments were carried out with constant L/b and h_s while increasing h and therefore h/h_s. Some combinations were duplicated. Thus, two different but statistically acceptable results are presented in Section 3, for identical L/b and h/h_s. These duplications were performed to study the statistical accuracy of probability estimations as a function of the experimental repeatability for LW experiments in a reservoir environment (Furlan, Pfister, Matos, Amado, & Schleiss, 2018).

The head h, prior to blockage, was measured without stems as the initial condition using a point gauge (±0.5 mm) located 2.60 m upstream of the ogee crest. The discharge Q was measured with a magnetic inductive flow meter (±0.5% at full span). The surface tension effect on the rating curve is negligible if the flow depth exceeds some 0.025 m (Ettema et al., 2000) and 0.02 m particularly for standard ogee spillways (Breitschneider, 1978). Pfister, Battisacco, et al. (2013) state that a head of 0.015 m generates an error of 5% only in terms of discharge coefficient at a piano key weir. More recently, Tullis et al. (2018) found negligible scale effects in labyrinth weirs for minimum heads ranging from 0.008 to 0.016 m, for half-round crests, and from 0.007 to 0.009 m, for round crests. Similarly, no single minimum upstream head limit was found that characterized a scale effect limit for all nonlinear weirs analyzed in Tullis et al. (2020). In the present study, heads ranging from 0.009 to 0.025 m were tested. As such, the rating curve of some tests may not have been exempted from scale effects. However, the evaluation of the stem blockage probability was the focus of our study and not the determination of the rating curve of the ogee crested spillway.

Stems were supplied individually, approximately 4 m upstream of the spillway, and it was noted if they passed the ogee crest or not. Stems were introduced in the flume center axis parallel to the flow direction. When a stem blocked, it was removed to avoid interactions with next stems, and the procedure was repeated with the same initial conditions 30 times for statistical accuracy (Furlan, Pfister, Matos, Amado, & Schleiss, 2018).

2.2. Statistical Analysis

The blocking probability of LW, π, is an unknown value that we try to estimate herein based on the physical model results. In order to estimate π, the maximum likelihood estimator, $\hat{\Pi}$, has been used, given by (Equation 2):

$$\hat{\Pi}(n) = \frac{X}{n} \tag{2}$$

where X is the number of blocked stems and n is the total number of repetitions (30 for each experiment). Confidence intervals were calculated using the Clopper-Pearson method, considering 90% confidence (Furlan, Pfister, Matos, Amado, & Schleiss, 2018).

A logistic regression is a generalized linear model that allows one to estimate or predict the probability of an outcome, based on a set of observed explanatory variables (Hosmer & Lemeshow, 2000; Montgomery & Runger, 2011). The response variable is the occurrence of a stem getting blocked at the ogee crested spillway, having a value of 1 for blockage or 0 for passage. Using the statistical tool R (R Core Team, 2017), logistic regressions were performed to model the relation of the explanatory variables (Equation 3).

$$\pi(x_1, x_2, \cdots, x_p) = \frac{exp^{\beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p}}{1 + exp^{\beta_0 + \beta_1 x_1 + \ldots + \beta_p x_p}} \tag{3}$$

Here, β_0 is a constant parameter (intercept), $\beta_{1,\ldots,p}$ are the regression coefficients for the explanatory variables, determined with the maximum-likelihood estimation method, and $x_{1,\ldots,p}$ are the explanatory variables. A positive coefficient (β) indicates that the explanatory variable increases the log odds ratio, assuming that the other variables are held constant.

3. Results

The systematic approach chosen for the experiments, aimed to isolate the influence of each explanatory variable in the blockage process of individual stems at an ogee crested spillway with piers. The complete set of results (values after 30 independent repetitions), represents 1080 individual experimental results. A 90% confidence interval was calculated for the blocking probability obtained experimentally using the Clopper-Pearson method (Clopper & Pearson, 1934).

3.1. Relative Stem Length

For a small head and small approach flow velocity, the driving mechanism of blockage consists of stems touching the crest of the spillway, pivoting to one side and blocking between the crest and a pier (or, otherwise, touching first the pier, pivoting to one side, and blocking between the pier and the spillway crest). In general, stems blocked in three main modes, namely bridging between two piers perpendicular to the flow direction (Figure 3a), leaning against one pier and touching the spillway crest oblique to the flow direction (Figure 3b) and leaning against one pier and touching the spillway crest parallel to the flow direction (Figure 3c). The first mode (stems bridging between two piers) occurred for $L/b > 1.00$, with a significantly lower frequency, as compared to the other modes (less than 15 times from the 1080 individual results).

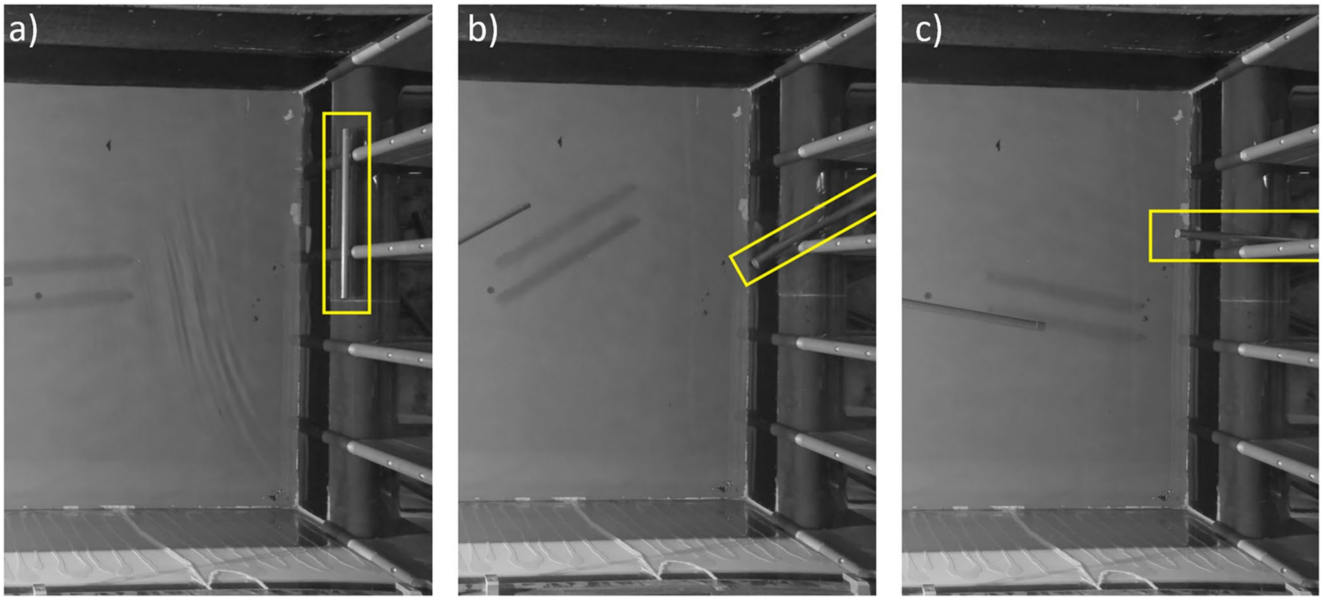

Figure 3. Photos of different modes of stem blockage. View from above, flow from left to right. (a) Bridging between two piers, perpendicular to flow direction; (b) Leaning against one pier and touching the spillway crest, oblique to flow direction; (c) Leaning against one pier and touching the spillway crest, parallel to flow direction.

3.2. Relative Head

The resulting blocking probability ($\hat{\Pi}$) from the physical experiments can be seen in Figure 4 as a function of the relative head (h/h_s). As previously mentioned, the relative head (h/h_s) is the ratio of the head (h) to the stem draft (h_s) (Figure 1). For all relative stem lengths, there is a decreasing trend of blockage with the increase of h/h_s, for h/h_s ranging approximately between 1 and 2.3 (Figure 4). For $h/h_s > 2.3$, the blocking probability was almost zero, as stems would not touch the ogee crested spillway.

For stems with a length larger than the bay width ($L/b \geq 1.20$) and for h/h_s lower than 1.50, except in one case, the blocking probability was equal to or greater than 0.60. For h/h_s greater than 1.8, the blocking probability was generally smaller than 0.20.

This is equivalent to say that blockage tends to decrease with higher heads or smaller stem drafts. With smaller heads, the odds of blockage would increase as interactions between stems and the ogee crested spillway increase. Also, with larger stem drafts, thus larger stem density, stems may be transported close to

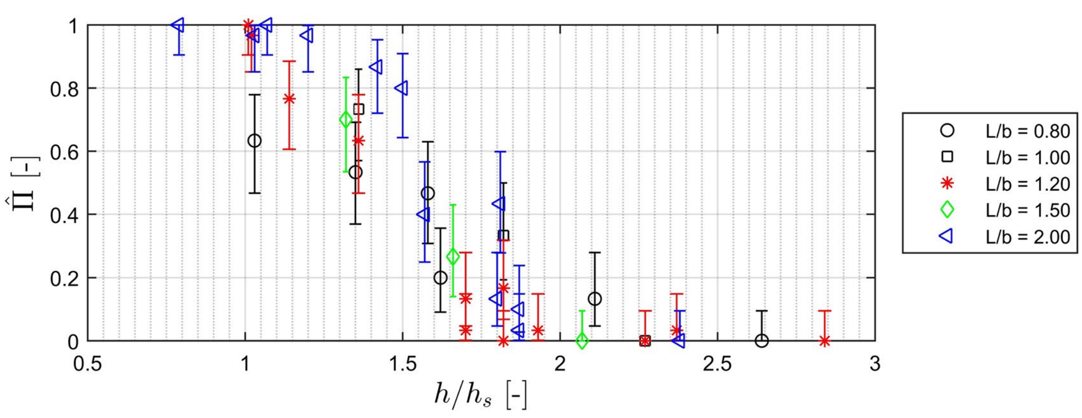

Figure 4. Blocking probability ($\hat{\Pi}$) as a function of relative head (h/h_s), separated by relative stem length (L/b) and obtained from the physical model experiments. Confidence intervals were obtained with Clopper-Pearson method, considering 90% confidence.

Table 3
Estimated Parameters of the Generalized Linear Model (GLM) Given by Equation 4

Explanatory variable	Model coefficients		Wald's test	
x_p	$\hat{\beta}_p$	Std error	z	Significance level
Constant	7.12	0.54	13.00	<0.001
h/h_s	−5.61	0.34	−16.56	<0.001
L/b	0.93	0.19	4.81	<0.001

the ogee crested invert and interact more with it, thereby increasing the blocking probability. Although the data are scattered, the general trend corresponds to an S-shape distribution.

3.3. Generalized Linear Model

To understand the effect of the studied variables on the blocking probability $\hat{\Pi}$, a logistic regression was performed (Equation 3). All parameters were considered as continuous variables.

The model (Equation 4) evaluates the independent influence of each variable. In Table 3 the regression diagnosis for the generalized linear model is presented.

$$\hat{\Pi}_{GLM} = \frac{e^{7.12-5.61 \cdot h/h_s + 0.93 \cdot L/b}}{1 + e^{7.12-5.61 \cdot h/h_s + 0.93 \cdot L/b}} \quad (4)$$

The negative sign of the estimated coefficient for h/h_s, indicates that an increase in the relative head decreases the blocking probability. The positive sign of the estimated coefficient for L/b, indicates that on increasing the relative stem length, the blocking probability increases. The absolute value of these coefficients indicates that the influence of the relative head on the blocking probability is considerably greater than that of the relative stem length. Hence, with constant relative stem length and draft, the increase of the head (h) leads to a decrease of the blockage probability, namely for h/h_s ranging approximately between 1 and 2.

4. Discussion

4.1. Influence of the Studied Variables on the Blockage Probability

To date, the blockage probability of LW at hydraulic structures (π), in reservoirs or rivers, remains experimentally estimated for a reduced set of possible scenarios. The proposed model (Equation 4) is based on a fairly large set of experimental conditions (36 different combinations of studied parameters, repeated 30 times each for statistical accuracy, resulting in 1080 individual results) and it can be considered valid under similar conditions (Table 2). The selection of 30 experimental repetitions was based on the findings of Furlan, Pfister, Matos, Amado, and Schleiss (2018). Thus, to pursue results that are statistically significant (errors smaller than 0.10), the amount of tested parameters had to be restricted.

In the case of a reservoir approach flow, in contrast to a river approach flow, stems do not interact with the bottom of the channel upstream of the ogee crested spillway. Furthermore, when slowly approaching from the reservoir to the spillway, the stems are not yet oriented or markedly influenced by the flow velocity field as it is the case of a river approach flow.

A larger head, represents less possible (or even the absence of) interactions with the spillway crest, reducing the probability of blockage as the stems may be "free" to pass. The blocking probability tends to increase with the reduction of the stream power (for an ogee crested spillway this is equivalent to the reduction of the head). Another way to increase the blocking probability is with a higher wood density (equivalent to a larger stem draft), as it increases the chances of stems interacting with the spillway crest.

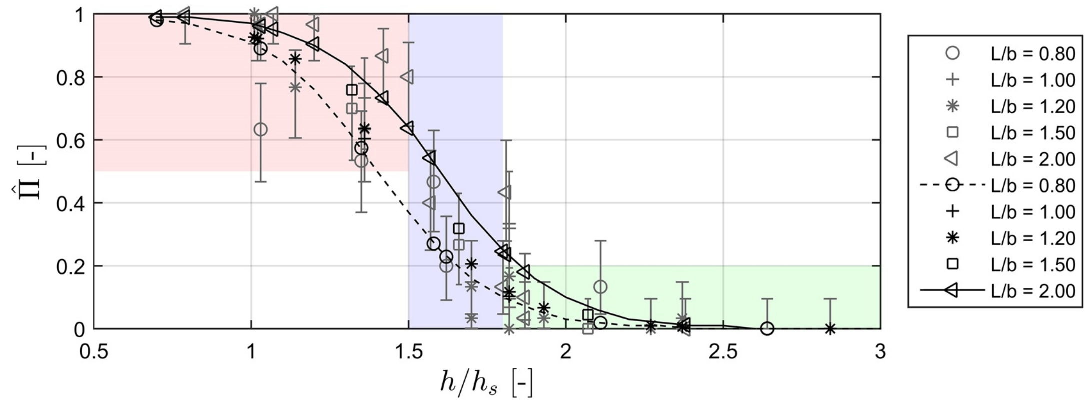

Figure 5. Blocking probability ($\hat{\Pi}$) as a function of the relative head (h/h_s). Experimental results with confidence intervals in gray color; Generalized Linear Model (GLM) results in black color (the dashed line is for the smaller relative stem length and the solid line for the larger one). Green area, low blockage; red area, high blockage; blue area, transition zone.

Stems touched the ogee crested spillway for $h/h_s < 1$ to 1.5 (Figure 5), this scenario led mainly to blockages of stems touching the crest and leaning against one pier, parallel or oblique to the flow direction (Figures 3b and 3c). However, particularly for small relative stem lengths ($L/b = 0.8$), the stems could touch the crest, rotate without leaning against one pier, and pass. This may explain the occurrence of blocking probabilities considerably smaller than the unity (e.g., $\hat{\Pi} \approx 0.6$, for $h/h_s = 1$). Stems were not expected to touch the ogee crest for large relative heads (e.g., $h/h_s > 2$) and this led to smaller blockages overall. It was also observed that the influence of L/b on the blocking probability was considerably small for $h/h_s > 2$. This may be explained by the fact that the first mode of blockage (stems bridging between two piers, Figure 3a) occurred with a much lower frequency, compared to the other modes (namely stems leaning against one pier and touching the spillway crest, oblique to flow direction, Figure 3b, and stems leaning against one pier and touching the spillway crest, parallel to the flow direction, Figure 3c).

From Figure 5, some interesting trends can be obtained. When considering blockage as a function of the hydraulic conditions at a reservoir spillway with piers, the head should be greater than 1.80 times the stem draft to ensure blockage probabilities lower than 0.20 (Figure 5, green shaded area). On the other hand, blocking probabilities greater than 0.50 are likely to occur for $h/h_s < 1.50$ (Figure 5, red shaded area). There is a transition zone where blocking probabilities between 0 and 0.50 occurred (Figure 5, blue shaded area). It can also be observed from Figure 5 that for $h/h_s > 1.80$, the blocking probability is lower than 0.20, irrespective of the relative stem length.

The relative stem length was expected to play an important role in blockage of stems at a reservoir spillway equipped with piers, however, compared to h/h_s, L/b had a secondary effect within the evaluated conditions (Table 3). The first mode of blockage (bridging between two piers, perpendicular to flow direction) was found to be considerably less relevant than the other modes, even for $L/b = 2.00$. This is in agreement with previous experiments done by Furlan (2019) where different release angles were tested for a reservoir approach flow. Regardless of the release angle, stems would rotate as they moved downstream (Lyn et al., 2003) and at the vicinity of the spillway (approximately 1 m upstream of the ogee crest) most stems would align themselves with the flow direction. Therefore, from our observations during the experiments, we conclude that a reservoir approach flow may increase the complexity of the blockage process, compared to a river approach flow. This is because stems are oriented by the flow velocities mostly in the vicinity of the crest, due to the velocity increase, in contrast to a river approach flow, where stems may align with the flow direction far upstream of the structure.

The proposed model (Equation 4) is valid for single stem blockage only. Certainly, during a flood, large volumes of wood are transported. However, it must be considered that a single stem can become a key member of a jam, defined as that piece or pieces which initiated the formation of an accumulation of LW (Abbe & Montgomery, 1996; Bénet et al., 2021). Once a key element is blocked at the structure, it can start collecting other elements (Panici & de Almeida, 2018). We found it important to establish the initial conditions of

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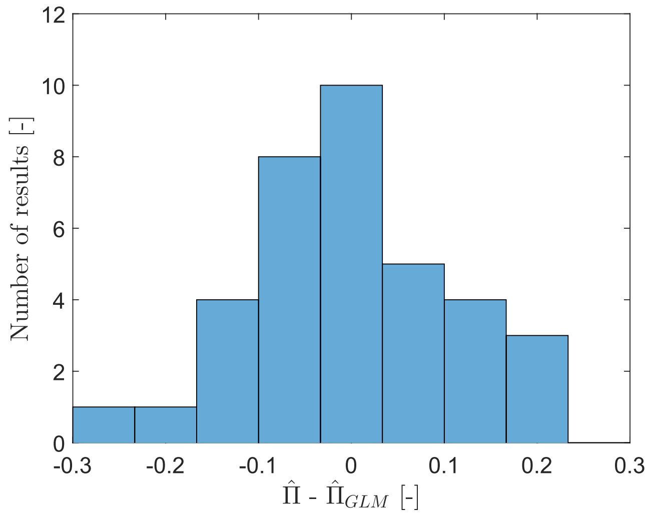

Figure 6. Histogram of the residuals (difference of the blocking probability ($\hat{\Pi}$) estimated with the physical model minus that estimated from the Generalized Linear Model (GLM)).

blockage for single LW at an ogee crested reservoir spillway with piers, as a first step to understand how greater blockages can be triggered. In order to have a systematic approach that allows to separate the effect of different variables, like relative head or relative stem length, it was found paramount to work with single stems and simplify the model. This methodology is important for reservoir approach flow conditions which have a significant effect on the randomness of the blockage process. Furthermore, considering the relatively small flow velocities in a reservoir approach, the process of stem compaction is dissimilar to that for river weirs.

To challenge the proposed model, blocking probability estimates with distinct LW characteristics and transport conditions should be compared to those estimated with Equation 4. The optimal would be to test it against prototype data but which may be difficult to obtain.

4.2. Evaluation of the Generalized Linear Model

Overall, the generalized linear model (Equation 4), is able to represent reasonably well the experimental results. Figure 6 presents the histogram of the residuals between the blocking probability estimated with the physical model and with Equation 4. Of the complete set of experiments, 23 (more than 60%) showed a difference, in relation to the physical model, below 0.10.

In Figure 5, the values estimated with the physical model and from Equation 4 are presented. Specific cases can be singled out where the estimations made with Equation 4 are outside the confidence interval of the physical model estimations. An underestimation is noticeable for $L/b = 2.00$ and $h/h_s \sim 1.0$ to 1.5, but the estimated values from Equation 4 are still inside the confidence intervals of the blocking probability obtained with the physical model. Equation 4 overestimates the blocking probability for $L/b = 0.80$ and $h/h_s \sim 1$ because it reproduces the main trend of blockage from larger stems. This is an outcome based on the amount of results with $L/b \geq 1.20$ and higher blockage that are “forcing” the regression toward estimating higher blockage probability. Additional results with $L/b = 0.80$ are required to fully understand this specific case. However, the general behavior of Equation 4 is in accordance to the physics of the blockage process.

As stated before, with the experimental campaign it is obtained a maximum likelihood estimator, $\hat{\Pi}$, of the unknown blocking probability π. With the physical model we may yield two different blocking probabilities for identical experimental conditions as stems do not behave in exactly the same way at each repetition. For example, the experiments with $L/b = 1.20$ and $h/h_s = 1.70$ or $h/h_s = 1.82$ (Figure 4) were duplicated and gave different blockage probability estimations. As π is unknown, taking into account the confidence intervals and their overlap, it can be stated that both estimates are statistically acceptable with 90% confidence. This represents a problem for Equation 4 as the GLM has to select which one to consider “valid” (normally the closest one to other blocking estimations for similar scenarios) and therefore the other falls outside the prediction. For one combination of parameters, the GLM is only able to predict one blocking probability.

The proposed logistic regression model for blocking probability estimation does not include aspects like different number of open bays, asymmetrical currents, and pier shape influence. To the best of our knowledge, this is the first probability analysis that includes the effect of different wood density through the relative head, in conjunction with relative stem length, on blockage probability estimation for a reservoir-type approach flow.

4.3. Comparison With Other Studies

This model results in a significant advancement in relation to the findings of Furlan, Pfister, Matos, and Schleiss (2018). In that study, a first approach to understand the effect of stem density on the blockage probability of single stems with a reservoir-type approach flow was undertaken. Therein, the relative stem density was singled out as one blockage variable, independent of the relative head. Herein, such analysis has been enhanced by working with the relative head. In addition, the influence of the stem density (or

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stem draft) on the blocking probability, namely for stem lengths smaller than the bay width, was reviewed, considering the results of the GLM.

The findings of this study, for constant stem density, are in agreement with the observations of Schmocker and Hager (2011), Gschnitzer et al. (2017) and Schalko et al. (2020) for bridges and a river approach flow, and of Pfister, Capobianco, et al. (2013) for Piano Key Weirs (PKW) with a reservoir approach flow. Once the stream power is increased, the blockage probability of stems decreases. The critical flow depth at an ogee crested spillway is considered as $2/3h$. Based on Figure 4, if the stem draft is smaller than the critical flow depth ($h/h_s > 1.5$), then it can be expected that the stem tends to pass (in general this situation resulted in $\hat{\Pi} < 0.50$ in our experiments). If the stem draft is larger than the critical depth ($h/h_s < 1.5$), then it can be expected that the stem tends to get blocked (normally $\hat{\Pi} > 0.50$). This is in agreement with the findings of Pfister, Capobianco, et al. (2013) for PKW (without piers) with a reservoir approach flow.

Schalko et al. (2020) described similar situations observed in their experiments but for single piers with much higher flow velocities. In that case, for scenarios with low flow velocities, stems would tend to block when some part of it touched the pier. On the contrary, with higher flow velocities stems could touch the bridge pier and pass. Therein, the authors indicated that this was due to increased turbulence and waves that facilitated the passage. Additionally, in Schalko et al. (2020) they tested three values of wood density. It was noted that, with a river approach flow and for a bridge pier, the blockage probability was not affected by changes of stem density, considering densities smaller than 1000 kg/m^3. For densities above the water density, they observed a small increase in the blockage probability, as stems were transported at the channel bottom. Nonetheless, the differences found on the blockage probability were inside the reproducibility range and were considered negligible. When comparing these results to a reservoir approach flow, some behavior are similar. If stems have an interaction with the bottom of a channel or the crest of the spillway, blockage can increase. If LW density increases, the stem draft increases and a greater stream power (or larger head) is needed to avoid blockages compared to smaller LW densities.

In river approach conditions, more parameters have been already studied. In Gschnitzer et al. (2017), they evaluated the blocking probability of stems at bridges with and without piers. They compared the blockage probability of stems with and without irregular geometries. In such case, it was observed that the blocking probability highly increased for irregular stem geometries. Other studies like Schalko et al. (2020) also describe the effect of LW with irregularities on the blockage probability of single stems for a bridge pier. It was stated that for uncongested regimes (like herein), the effect of branches on the blocking probability is negligible. However, in our experiments cylindrical artificial stems were used, under different approach flow conditions, so conclusions about the influence of irregular stem geometry cannot be drawn. Based on the work done in De Cicco et al. (2016, 2020), where they investigated the effect of the pier shape in the accumulation of LW at bridges for river approach flows, it was concluded that the round nose piers are less prone to LW blockage when compared to other geometries. On the contrary, in Schalko et al. (2020) they concluded that only a minor effect was observed for bridge pier shapes in terms of blocking probability. In our experiments, a rounded pier nose, commonly used at reservoir spillways, was used so conclusions about the influence of other geometries cannot be drawn.

4.4. Practical Recommendations

The recommendations by Godtland and Tesaker (1994), for reservoir spillways equipped with piers, state that the blocking probabilities should be lower than 20% for a bay width equal to 80% of the tree length (i.e., $L/b \leq 1.25$). Nevertheless, almost half of our experiments (11 out of 21) resulted in higher blockage probability ($\hat{\Pi} > 0.20$) (Figure 4). Thus, we recommend to also consider the effect of the relative head, given as the ratio between the head and the stem draft. For a small head and small approach flow velocity, the driving mechanism of blockage consists of stems touching the crest of the spillway, pivoting to one side and blocking between the crest and a pier (or, in alternative, touching first the pier, pivoting to one side and blocking between the pier and the spillway crest).

From the analysis of Figure 5, the following Table 4 can be used as a guide to regulate the water level over a spillway crest, based on the acceptable blockage probability of stems. This new available knowledge may guide practitioners to a safer management of LW in reservoirs during spillway operation.

Table 4
Blockage Probability of a Stem as a Function of the Relative Head

h/h_s	$\hat{\Pi}$
>1.80	0.00–0.20
1.50–1.80	0.00–0.50
<1.50	0.50–1.00

A linear relation (Equation 5 with $R^2 = 0.97$) was found to fit well to the data for wood densities greater than or equal to 400 kg/m^3. Hence, under such conditions, Equation 5 may be adopted to calculate, in a simple and practical manner, the draft as a function of the relative stem density and stem diameter.

$$h_s = 0.97\, d\, \rho_s \tag{5}$$

Considering that $h/h_s > 1.80$ would lead to blockage probabilities lower than 0.20 (Figure 4), the application of Equation 5 indicates that the spillway should be operated with a head greater than 1.75 $d\, \rho_s$ (assuming a small number of arriving trees without branches). For example, when considering green wood with $\rho_s \sim 0.70$, a head of 1.20 d would lead to a blockage probability lower than 0.20. Due to the high stem draft a waterlogged large wood can have, trees with this high wood density (≥1000 kg/m^3) should be considered key elements for initializing jams, possibly leading to the obstruction of the spillway.

5. Conclusion

The interactions between LW and structures like spillways are a complex process, and thus, different outcomes can be expected even for identical conditions. Such behavior requires the use of statistical tools in order to understand the effects and probabilities of LW blockage. In this study, relations between key explanatory variables and blockage probabilities at ogee crested spillways with piers were established for reservoir approach flows. The results provide new insights but also reveal the limited predictive capacity of statistical models for LW processes. The present research quantified the relation of relative stem length and relative head with blockage probabilities. To the best of the authors' knowledge, this is the first time stem draft is included as a relevant parameter in the estimation of LW blockage at ogee crested spillways with piers, with reservoir approach flow conditions.

According to the experiments, the explanatory variables have different effects on the stem blockage probability at ogee crested spillways with piers. The relative head was found to be particularly influential in the process of blockage, being a key parameter which may have a significant effect on the randomness of the blocking process. The influence of the relative stem length on blockage was comparatively smaller.

To improve the prediction capacity of LW blocking probability, additional experiments with varying stem and hydraulic characteristics, as well as transport regimes, are needed. Furthermore, the GLM presented herein has a limited applicability that can be improved for other conditions and even for other type of structures (e.g., for broad crested weirs with piers, check dams with racks, bridges with piers). In continuity of this work, further efforts should be made to make direct use of the available experimental results in numerical models such as those presented in Ruiz-Villanueva et al. (2014), Persi et al. (2017) and Kimura et al. (2021). Our experimental results and probabilistic analysis may be very useful to validate any numerical models in future, which could be used to study the effect of congestion by multiple stems or to incorporate LW blockage at hydraulic structures like spillways with reservoir approach flows.

Data Availability Statement

Data sets for this research are published in Furlan (2019).

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