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Wood Obstructions at Bridge Piers: Geometry Estimation Methodology and Scouring Process Analysis

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Abstract: Although wood in rivers provides environmental benefits, its transport and accumulation at bridges, especially during high-flow events, can cause significant issues regarding bridge stability and increased backwater effects. Indeed, the dynamics of wood in rivers have been investigated by the scientific community in terms of wood transport, recruitment mechanism, probability of wood accumulation at bridge piers, and its potential impacts. Nonetheless, the implementation of such scientific findings in bridge engineering practices is still poor, and only a few national legislations propose guidance for the evaluation of wood-related impacts on bridges. In this paper, the "Hydraulic Compatibility of Bridges" committee working within the Italian Group of Hydraulics is presenting a methodology for assessing the impacts of wood accumulation on bridges. This contribution aims at expanding a preliminary procedure that analyzed the effects of wood obstruction at bridges by (i) including an estimate of the potentially recruited Large Wood (LW) volume and (ii) proposing a geometrical approach for the evaluation of the accumulation dimensions. The procedure is then applied to a case study to demonstrate its implementation.

Author keywords: Large wood; flood risk; bridge stability; single-pier accumulation; accumulation mechanism

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Introduction

The presence of wood in rivers is ubiquitous, and wood-related processes play a crucial role in shaping river morphology and enhancing hydrodynamic complexity.[1,2] While these processes greatly benefit river ecosystems,[3] the transport of large quantities of wood during floods poses serious risks to human safety and infrastructure.[4] In this context, the interactions between wood flux and bridge structures are particularly critical.[4–10]

To examine the interaction between wood flux and bridges, the focus of this study is on large wood (LW), defined as wood pieces longer than 1 m with a diameter greater than 0.1 m.[11] Understanding LW transport dynamics has become increasingly important in recent decades. Studies have demonstrated that the size and density of LW elements are key characteristics influencing transport dynamics.[3,12–14] Additionally, hydrological and climatic regimes, as well as river morphology, play crucial roles in shaping the movement of wood along river networks.[15] A fundamental aspect of studying wood accumulation at bridges is the LW transport regime.[16,17] Braudrick et al.[16] were the first to classify wood transport regimes into three categories: (i) uncongested, where single elements move independently without interacting; (ii) congested, where multiple LW elements move together as a single mass; and (iii) semi-congested, representing an intermediate regime. This classification remained unchanged until Ruiz-Villanueva et al.[17] introduced a fourth regime: the hyper-congested regime, characterized by the bulk transport of LW elements at the front of a flood wave. In addition, the amount and characteristics of recruitable wood strongly depend on the recent history of high flows and the recruitment processes.[1,18,19]

At bridge locations, transported wood elements often interact with bridge piers and decks, potentially leading to the formation of LW accumulations.[20] Typically, accumulation begins with larger pieces of wood, which are more likely to become trapped.[7,10] These larger LW elements, often referred to as *key-logs*, play a critical role in increasing the blockage probability of smaller pieces, thereby acting as the foundation of the accumulation.[4,9,21] LW accumulations at bridge piers reduce the available cross-sectional flow area.

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Consequently, wood obstructions at bridges are recognized as essential processes that must be explicitly accounted for when developing flood hazard maps.[22,23] In addition, the scour depth at the bridge pier in the presence of LW accumulation increases up to 50% of that without accumulation.[24,25]

The presence of LW accumulations at bridges was a central focus for researchers and practitioners, who have developed methodologies to evaluate the likelihood of blockage accumulation. Drawing from previous studies in the United States[26], Italy (IDRAIM—System for stream hydromorphological assessment, analysis, and monitoring, Rinaldi et al.[23,27]), Switzerland,[28] and the United Kingdom (CS 469: Management of Scour and Other Hydraulic Actions at Highway Structures;[29,30]), Innocenti et al.[14] recently proposed a four-step methodology to assess the likelihood of blockage accumulation at bridges. This approach, which considers single-pier accumulations with a semicircular cone shape (Panici and de Almeida;[8] see Fig. 1), includes (i) defining the event scenario, (ii) evaluating the probability of LW accumulation at bridges, (iii) estimating the accumulation dimensions, and (iv) assessing the scour associated with LW accumulation.

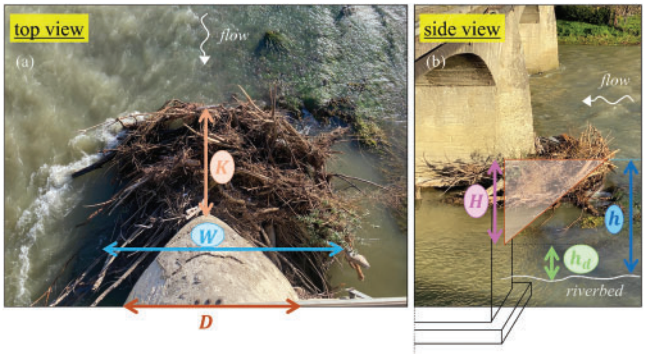

Figure 1. (a) Top-view and (b) side view of a LW accumulation at a pier, with the characteristic dimensions: the accumulation transverse width, W; the accumulation vertical high, H; and the accumulation upstream length, K (according to Panici and de Almeida[8]). In the top view, the bridge pier transverse width is indicated, D. While in the side view, the sketch reports water depth upstream the bridge, h, and the distance between the riverbed and the bottom of the wood accumulation, h_d. Photographs taken by Innocenti et al.[14,31]

In this paper, the methodology presented by Innocenti et al.[14] is extended by including a more precise definition of the LW transport scenarios. Furthermore, the methodology is applied to a selected case study, to analyze its applicability and compare the results with other existing methods.

Methodology

The four-step methodology for assessing the susceptibility of bridges to LW accumulation at bridge piers, as proposed by Innocenti et al.,[14] is schematized in Fig. 2. The probability of LW accumulation is evaluated by analyzing the interaction between the bridge piers and the transported wood regime, along with the qualitative characteristics of the LW flux for the given event scenario (e.g., ordinary, intermediate, or rare flood events). If a high probability of accumulation is identified, the methodology estimates the volume and geometry of the LW accumulation using the formulation proposed by Panici and de Almeida.[8] Finally, the impact of LW accumulation on bridge scours is calculated using the formulation developed by Ebrahimi et al.[24].

The limits of the methodology presented by Innocenti et al.[14] are that it considered three scenarios for the hydrological forcing (i.e., ordinary floods for a return period of 2–5 years, intermediate floods with a return period of 20–50 years, rare floods with a return period of 100–200 years) without including a quantification of the LW transport flux.

In the present work, the first step of the methodology is enhanced by introducing an alternative approach for estimating the LW potentially transported during the flood event (PTV_{LW}, which stands for Potential Transported Volume of LW), to define a transported LW scenario that corresponds to each hydrological forcing scenario. To this aim, the characteristics of the upstream reach of the bridge under study are evaluated, considering a specific potential LW-recruitment area (S_r) for each hydrological scenario. In particular, the following characteristics of the upstream reach are considered: (i) the presence of wooded riparian areas, (ii) the geometry of the riverbed (e.g., the presence of river bars or islands), (iii) the presence of in-channel structures (e.g., weirs and bridges), and (iv) the presence of lateral structures (e.g., embankments or bank protection structures). The area to be considered for potential LW recruitment is evaluated as follows:

$$S_r = \beta S_{bankfull} \tag{1}$$

where, $S_{bankfull}$ represents the channel area at bankfull discharge condition and β is the width ratio that depends on the hydrological forcing scenario and the channel type characteristics. Table 1 presents the values of β for cobble- and gravel-bed channels, which were adopted to estimate the potential LW-recruitment area for intermediate and rare events. Additionally, the channels were classified into three categories based on their width and slope, as shown in Table 1.

This adjustment accounts for the fact that LW is primarily recruited or mobilized from wood storage already present within the active channel during ordinary floods. However, under less probable scenarios (e.g., intermediate and rare events) in unconfined channels (i.e., no contribution from gravitational processes such as landslides), the vast majority of LW elements typically originate from floodplains and recent terraces through bank erosion processes.

The off-channel areas relevant for LW recruitment, estimated by Eq. (1), have to be reduced by excluding those protected by structures—whether in-channel or external, to prevent bank erosion.

Determining the potentially mobilized LW volume (PTV_{LW}) requires characterizing the forested riparian areas

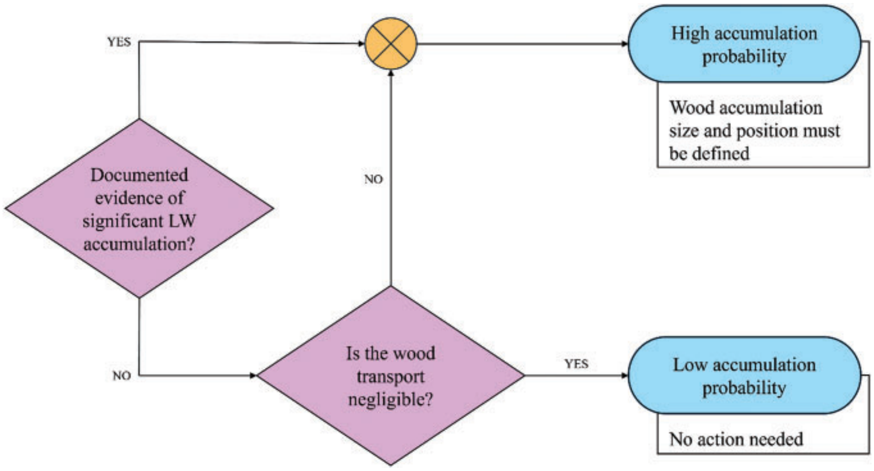

Figure 2. Flowchart for wood accumulation probability

Table 1. Width ratio (β) for cobble- and gravel-bed channels

Channel type (cobble- and gravel-bed only)	β	
	Intermediate events	Rare events
Wide (>100 m) or low slope (<0.5%) of any width	1.2	1.5
Intermediate width (10–100 m) if slope >0.5%	2.5	5
Narrow (<10 m) or steep (>4%) of any width	5	10

within the flooded zone, particularly in terms of tree density (number of trees per unit area) and average size (i.e., average diameter and length). This information can be obtained through various methods: (i) consulting a forest inventory, (ii) performing field surveys, (iii) performing a GIS-based analysis,[32] or (iv) applying empirical formulas to determine the expected wood volume during a flood.[33] This step also includes the identification of the characteristic size of the *key-log* (L_{LW}), which will be used in subsequent calculations.

Once the PTV_{LW} is determined, the second step involves calculating the volume of wood that can potentially accumulate at a single bridge pier. The procedure assumes that LW is uniformly distributed across the upstream cross-sectional width of the bridge. This assumption is reasonable under conditions of congested or hyper-congested LW transport regimes, and when LW is recruited far upstream of the critical bridge, allowing sufficient time for the material to spread across the entire width irrespective of the point of recruitment. However, under uncongested or semi-congested transport regimes, or when LW is recruited near the bridge, this hypothesis may not hold. Despite these limitations, given the significant uncertainties in this field, this approach provides a practical estimate of the potentially accumulated volume for these scenarios. Thus, the LW volume interacting with a single bridge pier (i.e., the volume of potential LW accumulation, PAV_{LW}) is calculated as:

$$PAV_{LW} = 1.4\,PTV_{LW}\frac{2L_{LW}}{W_{surf}} \tag{2}$$

where, W_{surf} is the cross-section-free surface width upstream of the bridge, and the coefficient 1.4 is included to consider the overall porosity of LW accumulation. Various studies have reported measurements of the porosity of wood accumulations in rivers. Among these, we refer to the work of Livers et al.,[34] which reports an average porosity value of 0.4.

At this stage, the event scenarios are defined, enabling progression to the second step of the methodology: evaluating the probability of LW accumulation at the bridge pier. As illustrated in Fig. 2, in cases where a low probability of accumulation is identified, no actions are needed. On the contrary, when the probability is high, the methodology requires two more steps. The third step involves estimating the geometry of the LW accumulation. This can be achieved using the formula proposed by Panici and de Almeida,[8] as detailed in Innocenti et al.[14] Alternatively, the PAV_{LW} can be used to derive the dimensions of the wood accumulation (i.e., H, K, and W, as shown in Fig. 1) by modeling it as a semicircular cone.[8]

The fourth step of the methodology involves the characterization of the bridge pier scours in case of LW accumulation. This task is achieved by adopting the formulation proposed by Ebrahimi et al.,[24] following which the LW accumulation increases the scour at the pier of a factor Φ_{LW} that depends on the geometry of the accumulation:

$$\phi_{LW} = \frac{d_s}{d_{s,0}} = f\left(\frac{K}{D}, \Delta A, \frac{h_d}{h}\right) \tag{3}$$

where, d_s is the local scour depth considering the wood accumulation, $d_{s,0}$ is the maximum local scour depth without wood accumulation, $\Delta A = (WK/Bh)$ is effectively the percentage of the flow cross-section blocked by the wood accumulation. To calculate the ϕ_{LW} factor, the authors proposed the following approximation on the basis of laboratory observations,

$$\phi_{debris} = K_1^{0.24} K_2^{0.6} K_3^{0.25} \tag{4}$$

where,

$$K_1 = \frac{1.33\,(K/D)^2 - 2K/D + 6}{(K/D)^2 - 3K/D + 6} \tag{5}$$

$$K_2 = 1 + 0.002\Delta A^{1.5} \tag{6}$$

$$K_3 = -0.76\left(\frac{h_d}{h}\right)^3 + 0.6\left(\frac{h_d}{h}\right)^2 + 0.28\frac{h_d}{h} + 0.88 \tag{7}$$

Case Study

The selected case study is located in northern-western Italy and involves the bridge on the A4 Turin–Trieste highway (located at km 68+367 and km 68+687), crossing the Sesia River (see Fig. 3a).

The Sesia River basin at the bridge site covers an area of 1050 km^2. In this reach, the Sesia River exhibits a predominantly multi-thread channel under low-flow conditions, transitioning to a straight planform during flood events when the river bars are completely submerged by the flow. The studied reach is embanked, and a noticeable narrowing of the river can be observed near the bridge.

The bridge comprises two separate parallel decks, one for each traffic direction. Each deck is 17 m wide and constructed using a composite steel-concrete structure. The beam consists of five spans, with the two lateral spans measuring 54.10 m and the three central spans measuring 69.60 m (see Fig. 3c). The minimum underside elevation of the bridge low chord is 168.53 m above the sea level The piers have a portal-frame geometry and are inclined (approximately 25°) relative to the beams to reduce the surface area exposed to the river flow. Each pier consists of a row of four circular columns, each with a diameter of 2.50 m, spaced approximately 10 m apart (see Fig. 3b).

The selected highway bridge is currently managed by Sina S.p.A. for structural safety and maintenance purposes. The company provided data from numerical simulations conducted to study the interaction between the Sesia River and the bridge. Specifically, two numerical models were shared: a large-scale one-dimensional model at the basin scale and a local two-dimensional model at the reach scale. These models simulate the hydraulic conditions at the bridge section without accounting for the presence of large wood.

The selected river reach flows entirely within the Piemonte Region, which provides online data on flooded areas for various flood event scenarios, as well as information on vegetation in riparian areas. These data are made available through a WebGIS portal (https://www.geoportale.piemonte.it) from which they were downloaded for the purposes of the present study. Specifically, the vegetation data includes information on the shape of wooded areas (provided as polygons), as well as the sizes and species of living trees.

Results

The methodology first requires the determination of the forcing scenarios, corresponding to: (i) ordinary (return period of 2–5 years), (ii) intermediate (return period of 20–50 years), and (iii) rare event (return period of 100–200 years) scenario. For each of the three scenarios, the volume of the potential wood accumulation (PAV_{LW}) was determined following the method described in Section 2 and reported step-by-step below.

- Identification of the riparian areas with the potential to produce LW during flood events is illustrated in Fig. 4. These areas were determined by considering the potential LW-recruitment area S_r and the presence of in-channel structures. Specifically, S_r for the ordinary event was obtained from the Piemonte Region resource “mappe PAI Regione Piemonte”

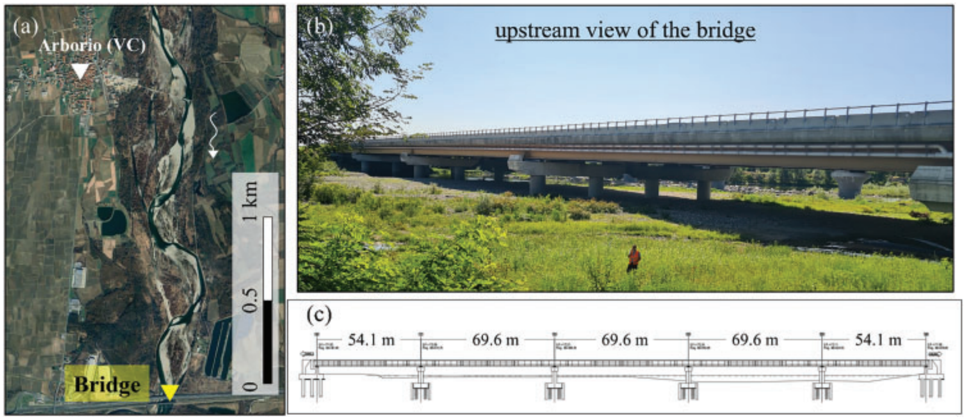

Figure 3. The bridge of the A4 Turin–Trieste highway: (a) overview of the upstream river reach, (b) upstream view of the bridge, and (c) sketch of the bridge geometry. The base map source for panel (a) is Google Earth

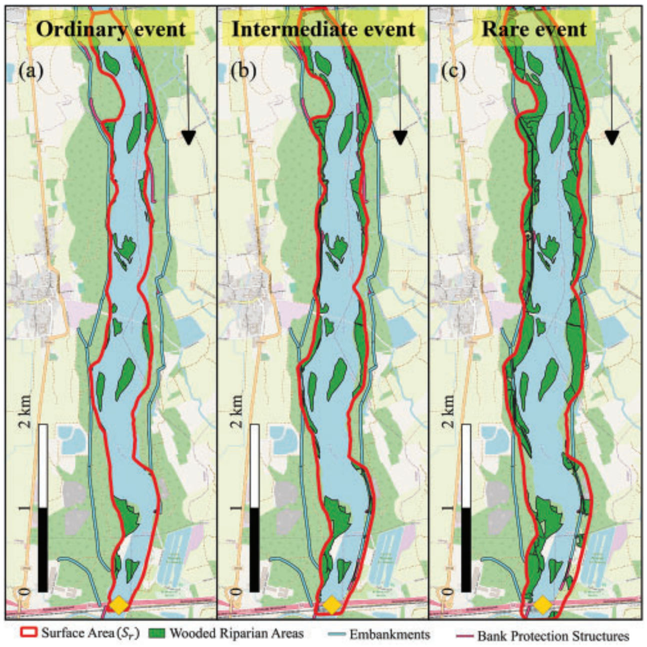

Figure 4. Riparian areas for the three scenarios: (a) ordinary event, (b) intermediate event, and (c) are event. The yellow diamond at the bottom of each panel represents the highway bridge location

Table 2. Characteristics of wooded riparian areas (source: Piemonte region)

Dominant species	*Robinia pseudoacacia*
Tree density	40 elements/ha
Average tree height	5 m
Maximum tree height (L_{LW})	10 m
Average tree diameter	0.12 m

Table 3. Potentially Accumulated Volume of large wood for the three scenarios

Scenario	PAV_{LW} [m^3]
Ordinary (2–5 years flood)	11
Intermediate (20–50 years flood)	21
Rare (100–200 years flood)	35

(available online at https://www.geoportale.piemonte.it), while it was identified for intermediate and rare events by using the width ratio β for low slope channels (see Table 1). The S_r areas were then refined by excluding regions protected by in-channel structures, based on data provided by the Piemonte Region's map "Catasto Opere Regione Piemonte" (also available at https://www.geoportale.piemonte.it). As shown in Fig. 4, the wooded riparian area increases from the ordinary scenario to the rare scenario, amounting to 0.57 km^2 for the ordinary scenario, 1.04 km^2 for the intermediate scenario, and 1.72 km^2 for the rare event scenario.

- Characterization of the vegetation in the identified riparian areas. It was characterized using data from Piemonte Region ("Catasto Opere Regione Piemonte," available online at https://www.geoportale.piemonte.it). A summary of the tree information is shown in Table 2.
- The potentially accumulated volume of wood (PAV_{LW}) was calculated for the three scenarios considering Eq. (2); results are reported in Table 3. It should be noted that this result represents the volume that could potentially be accumulated at each of the bridge piers. Volumes follow the trend observed for riparian surfaces, so they increase from the ordinary to the rare scenarios.

Given these scenarios, the probability of observing LW accumulation at the bridge piers was evaluated following the procedure proposed by Innocenti et al.[14] and schematized in the flowchart reported in Fig. 2. Information was collected regarding the past formation of LW accumulation at the bridge piers and regarding the LW transport in general along the Sesia River. Additionally, field surveys conducted during Summer 2023 provided further insights. Based on this information, the probability of observing LW accumulation was determined to be high. Consequently, as indicated in Section 2, the methodology proceeds to the estimation of the LW accumulation geometry (step three) and the assessment of pier scour induced by LW accumulation (step four).

Step three of the methodology is here achieved, considering both the formulation proposed by Panici and de Almeida[8] for non-uniform length wood pieces accumulation and deriving the dimensions of the wood accumulation by knowing the PAV_{LW}. For both approaches, the accumulation was considered as having a semicircular cone shape (as represented in Fig. 1). The use of Panici and de Almeida's formulas required the knowledge of the flow velocity approaching the bridge. The latter information was provided for each scenario by numerical simulations, as described in Section 3. A summary of the resulting LW accumulation geometries at the bridge piers is reported in Table 4. Using both approaches the accumulation transverse width, W, is the largest dimension, while H and K are smaller and comparable to each other.

The last step of the methodology was the evaluation of the bridge pier scour associated with LW accumulation. This was performed by applying Eq. (3) and assuming the maximum local scour depth without the wood accumulation ($d_{s,0}$) equal to two times the transverse width of the bridge pier (D). Table 5 reports the factor ϕ_{LW} obtained by applying the two approaches. According to the Panici and de Almeida[8] approach, scouring associated with LW accumulation is greater for ordinary events and decreases as the return period of the event increases. In contrast, scouring associated with LW accumulation derived from PAV_{LW} demonstrates the opposite behavior, with scouring increasing as the return period grows. This divergence reflects differences in the predicted sizes of wood accumulations, particularly in the

Table 4. Estimated geometry of the potential accumulation at bridge piers

Scenario: Ordinary event (2–5 years flood)		
Dimension	Panici and de Almeida[8]	Derived from PAV_{LW}
W [m]	11.0	5.0
H [m]	2.2	1.7
K [m]	3.4	2.5
Scenario: Intermediate event (20–50 years flood)		
Dimension	Panici and de Almeida[8]	Derived from PAV_{LW}
W [m]	9.7	6.2
H [m]	2.9	2.1
K [m]	2.7	3.1
Scenario: Rare event (100–200 years flood)		
Dimension	Panici and de Almeida[8]	derived from PAV_{LW}
W [m]	9.0	7.4
H [m]	3.3	2.5
K [m]	2.5	3.7

Table 5. Estimated bridge pier scour considering the wood accumulation

	ϕ_{LW} [%]	
Scenario	Panici and de Almeida[8]	Derived from PAV_{LW}
Ordinary (2–5 years flood)	11.4	8.0
Intermediate (20–50 years flood)	9.0	12.5
Rare (100–200 years flood)	8.3	13.5

accumulation width (W), which increases with the return period in PAV_{LW}'s approach but decreases in the Panici and de Almeida[8] approach for larger return periods.

Discussion

The methodology presented in this study represents an update to the approach developed by Innocenti et al.[14] Its application to the case study of the highway bridge over the Sesia River represents the first practical implementation of this methodology.

The definition of the LW transport scenario, linked to the chosen hydrologic forcing, needs significant effort to complete the first step of the methodology. The identification of the forested areas can be carried out through satellite image analysis, but the procedure also requires the availability of flooded areas for the selected scenarios, which must be obtained through hydrodynamic modeling. This effort, however, ensures that users obtain a comprehensive understanding of the study case, which is crucial for subsequent steps.

In the case study, at the second step, the methodology identified a high probability of LW accumulations at the bridge piers, confirming that, according to Fig. 2, the estimation of accumulation geometries is needed. The geometry of the accumulations was estimated using two distinct approaches, which can be considered alternative methods, requiring different information. The Panici and de Almeida's methodology, for instance, requires hydraulic condition data for the upstream section of the bridge (flow velocity, Froude number, and, eventually, water level), which, again, requires that hydrodynamic modeling is performed for the selected reach. On the contrary, estimating accumulation's dimensions using the volume of Potential LW Accumulation (PAV_{LW}) calculated in the first step does not require additional information.

The differences between the two methods is apparent from the comparison between the accumulation sizes presented in Table 4. Panici and de Almeida's formula computes results based on a nonlinear relationship between the Froude number of the *key-log* and the characteristic dimensions of the accumulation. In contrast, deriving the accumulation geometry from the PAV_{LW} employs a linear model that relates the estimated volumes to the accumulation dimensions. This results in contrasting trends in dimension increase and decrease with the return period. It is important to emphasize that the procedures are based on different approaches. Panici and de Almeida[8] derived accumulation sizes from flume experiments under varying hydraulic conditions, using a constant number of LW elements (input LW volume), which may or may not accumulate at the pier. Larger accumulations were observed at smaller Froude numbers, while both the overall volume and the transverse dimension decreased for higher Froude numbers, likely due to a reduction in accumulation porosity. In contrast, the proposed methodology employs a fixed porosity value (0.4) and an increasing LW volume for events with higher return periods. Unfortunately, due to the scarcity of real-world data on accumulation sizes and dimensions, it is not possible to determine which factor is more significant: whether the increase in LW potentially recruited outweighs the increase in accumulation dimensions, or if the higher hydrodynamic forces exerted by faster flows dominate, leading to a reduction in accumulation porosity, overall volume, and dimensions. Therefore, this step requires further investigation by the scientific community.

The calculated ϕ_{LW} for local scour increase are in contrast to the two considered approaches used to estimate the LW accumulation geometry. Using Panici and de Almeida's formula the ϕ_{LW} decreases from the ordinary to the rare scenarios, the opposite using PAV_{LW} method. This is a result of Ebrahimi's model (see Eqs. (4)–(7)) that, for the present case, follows the ratio K/D; it appears that using Panici and de Almeida's formula, the upstream protrusion of LW accumulation decreases upstream from ordinary to rare scenarios, while the opposite happens in case the PAV_{LW} method.

Conclusions

This paper presents an enhanced version of the four-step methodology introduced by Innocenti et al.[14] for evaluating the effects of wood accumulation at bridge piers. The primary objective of the study is to address a gap in knowledge regarding wood-related hydraulic issues, which are insufficiently addressed in the Italian technical standards for construction.[35]

The methodology presented and applied in this paper introduces two main changes compared to its original version: (i) it provides a more detailed definition of the forcing scenarios in the first step, and (ii) it offers an alternative approach to estimate LW accumulation in the third step, which complements Panici and de Almeida's formula (included in the original version).

The application of the methodology to the selected case study was facilitated by the availability of the necessary data. This enabled a clear demonstration of the method's characteristics, particularly through a comparison of the two approaches defined for estimating the geometry of the accumulations. By comparing the results obtained in steps three and four, a distinct trend emerges depending on whether Panici's formula or the PAV_{LW} method is used. As discussed in Section 5, further studies are needed to better understand and characterize the mechanism of large wood accumulation at bridge piers, which is critical for estimating the effects of such features on the bridge structure and the local river hydraulics.

Acknowledegments

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Data Availability Statement

The data that support the findings of this study are openly available, in addition to the Supporting Information file, the data could be requested to the corresponding author.

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