Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 62 (2024) 661–668

Structural Integrity Procedia

www.elsevier.com/locate/procedia

II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

Formation of wood obstructions at bridges: processes, related problems and prediction tools

*L. Innocenti[1], F. Coscarella[2], E. Persi[3], F. Comiti[4], S. Francalanci[1], A. Larese[5], F. Macchione[2], D. Panici[6], G. Petaccia[3], S. Sibilla[3], L. Solari[1], D. Termini[7]

[1]*Dipartimento di Ingegneria Civile e Ambientale, Università degli Studi di Firenze;*
[2]*Dipartimento di Ingegneria dell'Ambiente, Università della Calabria;*
[3]*Dipartimento di Ingegneria Civile e Architettura, Università di Pavia;*
[4]*Facoltà di Scienze e Tecnologie, Università di Bolzano;*
[5]*Dipartimento di Matematica "Tullio Levi Civita", Università degli Studi di Padova;*
[6]*Università di Exeter;*
[7]*Dipartimento di Ingegneria, Università di Palermo.*

Abstract

The primary cause of many bridge collapses is related to hydraulic issues, and the Italian technical standards for constructions (NTC 2018) offer limited guidance on the design and verification criteria for bridges, especially concerning river processes. Recognizing this gap, a working group dedicated to 'Hydraulic Compatibility of Bridges' (sites.google.com/view/gii-ponti) was established in 2021. The group's objective is to develop proposals for good practices and guidelines that assess bridge hydraulic compatibility, providing a foundation for both bridge safety and flood risk analysis. Within this initiative, a working subgroup focused on 'floating debris' is striving to define a methodology for assessing the impacts of wood accumulation on bridges. While wood in rivers is environmentally beneficial, its transport and accumulation at bridges during high-stage events can lead to problematic consequences. Over the past two decades, the scientific community has actively studied wood transport dynamics, accumulation formation at bridges, and their effects on hydraulics and structural stability. Although some methodologies to assess wood-related risk have been incorporated into national legislation or practitioner reports, these implementations vary widely in defining the shape of accumulation, the wood volume assessment and the number of parameters considered. In many cases, qualitative evaluations are used for estimation due to the complexity and high site specificity inherent in wood transport dynamics. This work aims to propose a comprehensive approach, based on the latest research findings, (i) to define the wood accumulation probability at a bridge, (ii) to estimate the size and position of the accumulation, and (iii) to suggest a methodology for the estimation of bridge scour induced by wood accumulation.

Peer-review under responsibility of Scientific Board Members
10.1016/j.prostr.2024.09.092

Keywords: large wood, wood transport regime, flood risk, bridge stability, single-pier accumulation, accumulation mechanism.

1. Introduction

Wood in rivers and its transport regime strongly influence the morphological and hydrodynamic complexity of rivers (Bertoldi and Ruiz-Villanueva, 2017, Wohl et al., 2023), and provides a large set of benefits for river ecosystems (Wohl et al., 2019). In contrast, large floods can transport large quantities of wood, hazarding humans and infrastructures (De Cicco et al., 2018). In this sense, particularly important are the interactions between the wood flux and the bridges' structure (Schmocker and Hager, 2011; Gschnitzer et al., 2013; De Cicco et al., 2018, 2020; Panici and de Almeida, 2018, Schalko et al., 2018, 2019).

Wood pieces longer than 1 m with a diameter larger than 0.1 m are referred to as large wood (LW) (Gregory et al., 2003). The transport of smaller pieces of wood has received less attention so far, even if they play an important role in determining the severity of wood obstructions at bridges. The size of the LW elements and their density define the LW characteristics that represent one of the driving factor for determining the LW transport dynamics (Wohl et al., 2019, Innocenti et al., 2023a, Innocenti et al., 2023b). In addition, the hydrological and climate regimes, and the river morphology play a key role for the transport of wood along a river network (Ruiz-Villanueva et al., 2016). Fundamental for studying the accumulation of wood at bridges is the LW transport regime (Braudrick et al., 1997, Ruiz-Villanueva et al., 2019). Following the observation by Braudrick et al. (1997) the LW transport regime can be classified as uncongested, congested, and semi-congested. When single elements are moving independently without interacting with each other's, the regime is uncongested. On the contrary, when multiple LW elements are moving as a single mass the regime is congested. Finally, the semi-congested LW transport is an intermediate regime. More recently, Ruiz-Villanueva et al. (2019) provided a definition for a fourth case: in the case of unsaturated LW elements transported in bulk at the front of a flood wave, the regime can be defined as hyper-congested.

The hydrological regime (i.e., magnitude, frequency, and duration) is one of the most important factors influencing LW transport regime. The recent history of high flows strongly determines the amount of available mobilizable wood deposited in the river corridor (Millington and Sear, 2007). In addition, LW is often recruited during the falling limb of the hydrograph when entered by bank erosion (Ruiz-Villanueva et al., 2016). These processes determine the LW characteristics, since the recruitment dynamics mostly determine the shape of recruited LW elements in terms of presence of branches and roots (Benda et al., 2003).

The in-channel structures (i.e., check-dams, weirs, bridges) often trap most of the transported LW during intense flood events (Comiti et al., 2016). These in-channel elements reduce the available cross-sectional flow area, inducing a backwater effect which may cause hazards to people and infrastructures (Mazzorana et al., 2011; De Cicco et al., 2018; Schalko et al., 2018). Indeed, wood obstructions at bridges have been recognised – along with morphological changes – to be essential processes that have to be explicitly accounted for when establishing flood hazard mapping (Mazzorana et al., 2012; Rinaldi et al., 2015).

LW accumulation at bridges, that is the focus of the present work, can occur as a "single-pier accumulation" or as a "span-blockage accumulation" (Diehl, 1997). When the single-pier mechanism occurs, the wood accumulation is limited to a portion of the bridge structure (De Cicco et al., 2018, Schalko et al., 2018) and is usually represented with a semicircular cone shape (Panici and de Almeida, 2018). On the opposite, if the maximum wood length is greater than the effective opening between bridge piers, the wood is entrapped between two piers ("pier-to-pier accumulation"), or between a pier and other obstacles (e.g., the riverbank, an existing bar).

The bridge shape determines the LW accumulation by influencing the accumulation probability (Schalko et al., 2019; De Cicco et al, 2020). For this reason, the estimation of LW accumulation probability is fundamental for an integrated flood hazard assessment, as it directly affects the damage potential. Recently, Panici and de Almeida (2018) provided further information about the accumulation and failure mechanism, i.e., the detachment process of the LW accumulation. The authors defined three stages that were conceptually classified as unstable, stable, and critical conditions. The unstable condition is typical of the wood accumulation formation, particularly when the accumulation rapidly grows, and few individual elements can easily break free and continue downstream. The stable condition starts once a robust framework is formed, and only moderate changes occur to the LW accumulation structure. The third condition (i.e., critical) appears when the accumulation starts to rotate, which eventually leads to the failure of the accumulation.

In the present work a methodology is presented to evaluate the likelihood of blockage accumulation at a bridge. Previous experiences in the U.S.A. (Diehl, 1997), Italy (IDRAIM, Rinaldi et al. 2014, 2015), Switzerland (Hunzinger, 2014) and United Kingdom (CS 469, Management of scour and other hydraulic actions at highway structures; Takano and Pooley, 2021; Pregnolato et al. 2022) provided the basis for the development of a comprehensive approach in 4 steps that includes (i) the definition of the event magnitude that may be significant for a specific structure, (ii) the probability of wood accumulation, (iii) the evaluation of the accumulation dimension and (iv) a preliminary estimation of the scour connected to wood accumulation.

2. Methodology

2.1. Event scenarios definition

Three event scenarios were defined to be used for assessing the LW accumulation at bridges, differing in the return period of the flood events. The methodology was developed by considering not only the flow magnitude but also the processes connected to the flood, e.g., bank erosion or the generation of landslides. The three scenarios are listed below:

- Scenario I: ordinary flood

The ordinary flood is here considered as a flood with a return period of 2 – 5 years. The wood material potentially transported during such events is only the one deposited in the riverbed upstream of the bridge under consideration, as typically, for relatively mild floods, the contribution of wood material eroded from the slopes or the floodplain is negligible. The upstream distance from the bridge to be considered for estimating the dimensions and volumes of the wood material present in the riverbed is constrained by the presence of longitudinal disconnections (weirs capable of retaining the material). In any case, the maximum length of transportable wood elements can be considered at most equal to the width of the active riverbed immediately upstream of the bridge. The motion conditions of the wood material typically appear to be uncongested.

- Scenario II: Intermediate flood

The intermediate flood is here considered as a flood with a return period of 20 – 50 years. The wood material potentially transported during such events depends on the quantity and dimensions of LW elements available in the riverbed upstream of the bridge (as described for Scenario I). In this case, larger LW elements from bank erosion processes can be added with respect to Scenario I, especially in the case of semi- or non-confined reaches with erodible banks. The identification of the maximum dimensions of transportable wood elements needs to consider the plants in the riverbed and on the floodplains and recent terraces. To determine the extension of these areas outside of the riverbed, the lateral and longitudinal connectivity needs to be considered (i.e., downstream of any transverse retaining structures and within any longitudinal defence works). The LW transport regime still appears to be uncongested as for Scenario I.

- Scenario III: rare flood

The rare flood is here considered as a flood with a return period of 100 – 500 years. During floods of exceptional magnitude, the wood material present in the riverbed upstream of the bridge provides no information regarding transportable volumes and maximum dimensions. For such events, it is crucial to consider the characteristics of forest population s both on the slopes connected to the riverbed, likely subject to gravitational phenomena (landslides, debris flows), and across the entire floodplain. In this case as well, it is necessary to evaluate only the forested areas connected longitudinally and laterally to the reach upstream to the selected bridge. However, attention must be paid to the reliability of defence structures that could be damaged or completely destroyed by such rare events. The motion of LW elements for such flood scenarios typically ranges from semi-congested to congested transport regimes. The maximum size of transportable LW needs to be defined by considering the potential production areas, as stated above, while it cannot be limited to the width of the current active riverbed (pre-event) since, during exceptional flood events, riverbeds are often subject to significant widening processes, unless they are planimetrically very stable (rocky).

2.2. Large wood accumulation probability at bridges

The probability of LW to accumulate at bridges is assessed by a three-phase procedure, described in the following:

- Phase 1: Understanding the potential interaction between the bridge structures and the transported LW

In this phase, it is necessary to verify whether there could be potential contact between floating LW elements and the bridge structures for the selected event scenario. For bridges without piers in the riverbed, it is essential to evaluate the distance between the free surface and the bridge deck, considering the possibility that the riverbed elevation may rise during the event due to sediment deposition. In the case that the free surface does reach the bridge deck, then it is necessary to move on to phase 2. In the case of bridges with piers in the riverbed, it is always necessary to proceed to phase 2.

- Phase 2: Characterization of transported wood flux

The quantity and expected dimensions related to the transport of wood elements during a flood event in a specific river section depend on the source areas activated by the flood event (as discussed in the previous section) and the connectivity along the hydrographic network. The transport regime (uncongested, semi-congested, congested), the LW size (maximum lengths), along with the hydrodynamic conditions of the flow, are among the key factors governing the likelihood of accumulations forming at bridges. Similarly to the CDE – IDRAIM methodology (Rinaldi et al., 2014, 2015), it is required to classify the extent of wood material transport into three different levels (intense, moderate, negligible) based on the characteristics of the river reach upstream of the analysed bridge. Intense transport involves the transport of large wood volumes, entrained from the highly wooded floodplains or due to landslides or debris flow, in high slope reaches (1-3%). Congested or semi-congested transport of wooden elements is observed, with high transport velocity. Moderate transport level is expected when the basin upstream of the bridge presents an abundance of wooded areas, and potentially unstable banks or islands. Finally, a negligible level occurs if the banks and the slopes are stable, if there is little or no presence of wood in the floodplain, or if other bridges or retention structures exist upstream of the considered bridge. For further information on the morphological terminology or detail on transport characteristics, refer to the IDRAIM manual.

In addition to the transport level (intense, moderate, negligible), it is necessary to estimate the maximum dimensions of the transported wood elements. To determine the approximate values of the maximum lengths transported (i.e., the dimensions of the key element of an accumulation, also known as *key-log*), the operator must identify the likely source areas of wood material during the reference event and assess/estimate the "dominant" height (i.e., the average height of the tallest plants forming the upper layer of the forest cover). In riverbeds confined by slopes (typically mountainous riverbeds), the source areas of wood material are primarily unstable slopes and tributaries subject to debris flow processes. In not-confined or semi-confined riverbeds (typically piedmont and plain riverbeds), source areas include banks, river islands, and the peri-fluvial strip that may be eroded during the event. In general, in the Italian context, the potential maximum lengths of wood material are on the order of 30-40 m. However, as with assessing the wood transport regime, it is crucial to evaluate the connectivity of wood material transport upstream of the analysed bridge. In general, it is reasonable to expect that the maximum lengths of transported LW are not greater than the width of the riverbed. However, this width must be carefully assessed because in the presence of semi- or non-confined reaches during exceptional flood events, widening may occur, increasing the possibility of larger-sized elements.

- Phase 3: Probability to LW accumulation formation at bridges

The LW accumulation probability at bridges in the present methodology can be “Low” or “High”. Once established the potential interaction between the wood flux and the bridge in Phase 1, and estimated the LW transport regime in Phase 2, the LW accumulation probability is determined from the flowchart reported in Fig. 1.

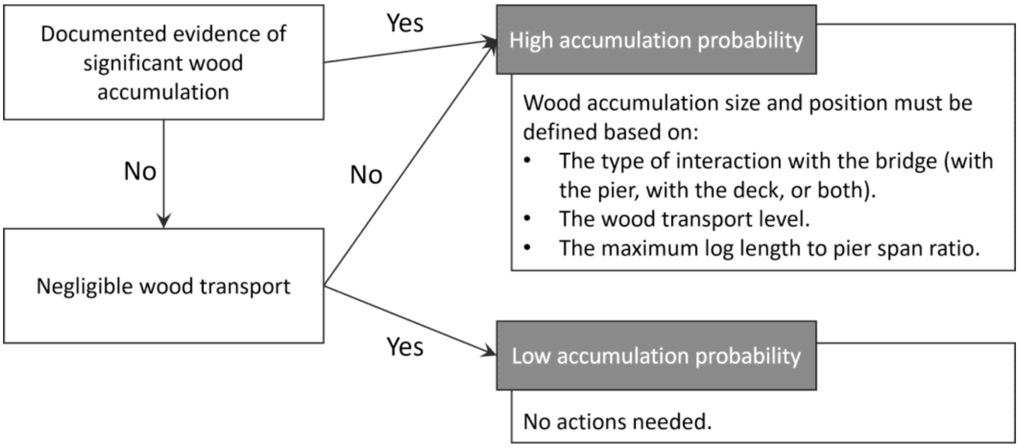

Fig. 1. Flowchart to define the wood accumulation probability.

2.3. Determining the geometry of accumulations at bridges

In case of "High" probability to wood accumulation, the evaluation of the position and size of the wood accumulation is required for the assessment of the additional force exerted on the bridge due to the accumulation presence. According to the recent experimental observations by Panici and de Almeida (2018), the expected LW accumulation has a semicircular cone shape characterized by three dimensions: (i) the accumulation transverse width, W, (ii) the accumulation vertical high, H, and (iii) the accumulation upstream length, K (Fig. 2). The geometry of the accumulation is expressed in terms of the dimensionless Froude number of the key element, defined as:

$$Fr_L = \frac{U}{\sqrt{gL}} \tag{1}$$

where U is the undisturbed flow velocity upstream of the pier, and L is the *key-log* length.

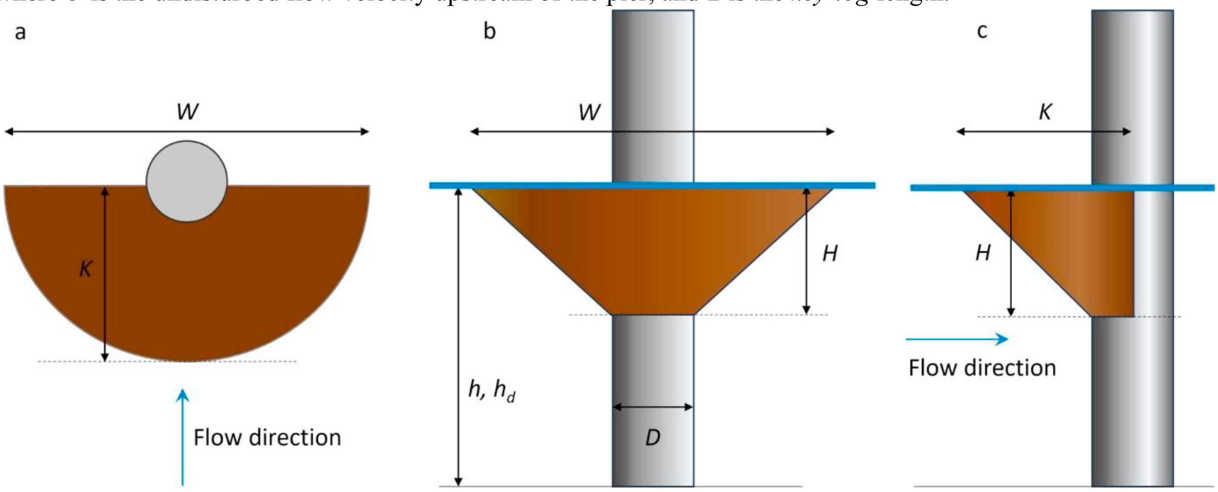

Fig. 2. (a) Top-view, (b) frontal-view and (c) side view of a wood accumulation at a pier, with the characteristic dimensions, as in Panici and de Almeida (2018). The debris elevation (h_d) coincides with the water elevation (h).

For single-pier wood accumulation, the critical size of the accumulation is provided by the relations found by Panici and de Almeida (2018). In particular, considering accumulations of nonuniform-size debris, with Fr_L = 0.10-0.40, the critical width ω_c, height η_c, and length κ_c are:

$$\omega_c = 0.774 + 0.939^{-6.139FrL} \quad (2)$$

$$\eta_c = 0.394 - 0.458^{-5.770FrL} \quad (3)$$

$$\kappa_c = 0.246 + 1.178^{-15.039FrL} \quad (4)$$

Given these non-dimensional values, the effective width, height, and length of the accumulation are obtained from the following relations: $\omega_c = W/L$, $\eta_c = H/L$, $\kappa_c = K/L$.

Regarding multiple-pier bridges, if the *key-log* is larger than the distance between the bridge piers or between the piers and the abutment of the bridge, the accumulation is expected to span between two piers, between a pier and the abutment of the bridge, or between a pier and a previous accumulation. The vertical size is still computed using Eq. 4.

When the freeboard is limited, accumulations at the bridge deck are also possible. The following ranges for accumulation at decks are identified:

- Freeboard < 1 m: accumulations are possible if wood with rigid root wads and/or branches is likely to be observed. Such parts can rise above the water surface, reaching the bridge and anchoring to the structure.
- Freeboard < 0.5 m in case of bare logs, without branches and root wads.

It is worth noting that in most of the large floods, especially rare ones, that are likely to generate the smallest freeboard at bridges, the wood flux composition is various. In fact, live trees are often added to the LW deposited elements due to slope erosion or from uprooting processes from floodplains. The deposited ones are usually devoid of branches due to collisions during previous transport events or due to decay, while the live trees mostly have a more complex shape due to the presence of branches and roots.

The height of the accumulation can be computed based on Eq. 4 if the vertical span between the bridge deck and the river bottom is smaller than the *key-log* length. In this case, logs may get stuck touching the bottom and the bridge, behaving like a bridge pier and fostering the accumulation. Otherwise, a superficial accumulation is considered, i.e., an accumulation height equal to the sum of the bridge deck height and of the railing/parapet height, that may be occluded by the transported material.

The proposed dimensions are based on literature results and on reasonable approximations. If additional information is available, for a specific bridge geometry or event, in the same river or similar hydraulic conditions, different accumulation geometries may be adopted.

2.4. *Bridge scour in case of wood accumulations*

The existing formulae for the assessment of the maximum local scour depth around piers account for flow and pier characteristics, like pier shape, flow depth, flow velocity, and angle of attack relative to the pier to find the aforementioned scour depth (Melville and Coleman, 2000).

In order to consider the effect of debris accumulation on the scour at piers, Ebrahimi et al. (2020) proposed adding a further factor called "debris factor", Φ_{debris}, which is fundamentally the ratio of the maximum local scour depth with debris (d_s) to the maximum local scour depth without debris ($d_{s,0}$). The factor was derived by analysing the literature laboratory datasets by Ebrahimi et al. (2018), Lagasse et al. (2010) and Melville and Dongol (1992). As reported by Ebrahimi et al. (2020), the local scour depth due to debris varies on debris sizes (i.e., streamwise length of debris upstream of the pier centre, K; spanwise length of debris, W, and submerged thickness of debris, H) and its elevation in the water column (h_d). For safety purposes, considering clear-water conditions, the flow depth h, the pier diameter D, and the flume width B have a significant impact on the scour depth due to debris (Ebrahimi et al., 2020). Using Buckingham's π Theorem Ebrahimi et al., 2020 argued that

$$\phi_{debris} = \frac{d_s}{d_{s,0}} = f\left(\frac{K}{D}, \Delta A, \frac{h_d}{h}\right) \quad (5)$$

where $\Delta A = (W\ K/B\ h)$ is effectively the percentage of the flow cross-section blocked by debris. Based on this reasoning Ebrahimi et al., 2020 found a functional link between Φ_{debris} and each of the ratios L_d/D, ΔA and h_d/h

denoting the influence of the relative independent variable while the other ratios are constant. Regarding the relation between Φ_{debris} and ΔA, Melville and Dongol (1992), Lagasse et al. (2010) and Pagliara and Carnacina (2011) illustrated that scour depth varies highly on debris width multiplied by debris thickness. Finally, Ebrahimi et al. (2020) carried out a multiple linear regression using literature data, concluding that the maximum local scour depth around piers considering the effect of debris accumulation, d_s, from the scour depth without wood accumulation, $d_{s,0}$, can be assumed equal to:

$$d_s=\phi_{debris}\ d_{s,0} \tag{6}$$

3. Conclusions

The paper drafts a methodology for the evaluation of the effects of wood accumulation at bridges as a proposal for an update of the Italian technical standards for constructions (NTC 2018). The main aim is filling a gap of knowledge on the wood-related hydraulic issues that can pose under risk the bridge safety.

First, the reference events for the evaluation of wood accumulation must be defined, based on the return period and on the potential wood entrainment caused by erosion or landslides. The probability of wood accumulation at bridges, then, depends on the possible interactions between LW and the structure, on the characteristics of the wood flux and of LW elements, and on the evidence of previous wood accumulation. In case of high probability of accumulation, the accumulation dimensions can be determined based on empirical relations that account for the flow velocity and the *key-log* maximum length. Finally, the scour at a bridge pier induced by wood accumulation can be derived considering the potential scour, without wood, and a correction factor that depends on the log dimension, submergence and blockage ratio.

The application of the methodology requires hydraulic computations to identify the main hydraulic variables, i.e., water elevation and flow velocity upstream of the bridge, and the acquisition of technical information about maintenance and past events, as well as a careful evaluation of the expected log dimensions. Collaboration with bridge management authorities and local experts is foreseen to collect all the required information.

Despite being only theoretically depicted, the methodology is based on sound literature formulations separately derived from experimental evidence and already applied to real test cases. A systematic application to additional test cases will help identify the most suitable approaches (e.g., 1D or 2D hydraulic modelling) and the expected confidence ranges for the accumulation size and connected scour.

4. Online license transfer

Acknowledgements

L. Innocenti's and L. Solari's contributions were supported by the project "A new interdisciplinary approach to advance understanding of sediment and large wood TRANSport in FORested Mountain catchments - TRANSFORM" - PNR - NextGenerationEU (DM 737/2021 - DR 1395 del 15/11/2022).

References

Benda, L., Miller, D., Sias, J., Martin, D., Bilby, R., Veldhuisen, C., Dunne, T., 2003. Wood Recruitment Processes and Wood Budgeting. American Fisheries Society Symposium, 37(January), 49–73.

Bertoldi, W., Ruiz-Villanueva, V., 2017. Physical and Numerical Modelling of Large Wood and Vegetation in Rivers. Gravel-Bed Rivers: Process and Disasters, 729–753.

Braudrick, C.A., Grant, G.E., Ishikawa, Y., Ikeda, H., 1997. Dynamics of Wood Transport in Streams: A Flume Experiment. Earth Surf. Process. Landforms, 22: 669-683.

Comiti, F., Lucía, A., Rickenmann, D., 2016. Large wood recruitment and transport during large floods: A review. Geomorphology 269: 23–39.

De Cicco, P.N., Paris, E., Solari, L., Ruiz-Villanueva, V., Stoffel, M., 2018. In-channel wood-related hazards at bridges: A review. River Res Applic. 2018; 34: 617–628.

De Cicco, P.N., Paris, E., Solari, L., Ruiz-Villanueva, V., 2020. Bridge pier shape influence on wood accumulation: Outcomes from flume experiments and numerical modelling. Journal of Flood Risk Management, June 2018, 1–16.

Diehl, T.H., 1997. Potential Drift Accumulation at Bridges. US Department of Transportation, Federal Highway Administration, Research and Development, Turner-Fairbank Highway Research Center, April, 45.

Ebrahimi, M., Kripakaran, P., Prodanović, D. M., Kahraman, R., Riella, M., Gavin, T., Arthur, S., and Djordjević, S. 2018. Experimental Study on Scour at a Sharp-Nose Bridge Pier with Debris Blockage. Journal of Hydraulic Engineering, 144(12), 04018071.

Ebrahimi, M., Djordjević, S., Panici, D., Tabor, G., & Kripakaran, P. 2020. A method for evaluating local scour depth at bridge piers due to debris accumulation. In Proceedings of the Institution of Civil Engineers-Bridge Engineering (Vol. 173, No. 2, pp. 86-99).

Gregory, V., Meleason, M.A., Sobota, D.J., 2003. Modeling the Dynamics of Wood in Streams and Rivers History of Wood Models. In The Ecology and Management of Wood in World Rivers (pp. 315–335).

Gschnitzer, T., Gems, B., Aufleger, M., Mazzorana, B., Comiti, F., 2013. Physical scale model test on bridge clogging. In H.w. Zhaoyin & S. Jizhang (Eds.), Proceedings of the 35th IAHR world congress (pp. A11817:1–11). Beijing: Tsinghua University PressPaper

Hunzinger, L., 2014. Freeboard analysis in river engineering and flood mapping—New recommendations. Conf. on Fluvial Hydraulics, RIVER FLOW 2014, Taylor & Francis, London, 31–37.

Innocenti, L., Branß, T., Zaid, B., Aberle, J., Solari, L., 2023a. Characterization of trajectories and drag coefficients of large wood in sharp river bends from flume experiments. Earth Surface Processes and Landforms, 48(4), 770–781.

Innocenti, L., Bladé, E., Sanz-Ramos, M., Ruiz-Villanueva, V., Solari, L., Aberle, J, 2023b. Two-dimensional numerical modelling of large wood transport in bended channels considering secondary current effects. Water Resources Research, 59, e2022WR034363.

Lagasse, P. F., Clopper, P. E., Zevenbergen, L. W., Spitz, W. J., Girard, L. G., Ayres Associates, Inc., and Fort Collins, CO. 2010. Effects of debris on bridge pier scour. Transportation Research Board, Washington, D.C.

Mazzorana, B., Comiti, F., Volcan, C., Scherer, C., 2011. Determining flood hazard patterns through a combined stochastic-deterministic approach. Nat. Hazards, 59(1), 301–306.

Mazzorana, B., Comiti, F., Scherer, C., Fuchs, S., 2012. Developing consistent scenarios to assess flood hazards in mountain streams. Journal of Environmental Management, 94,112-124.

Melville, B. W., and Coleman, S. E. 2000. Bridge Scour. Water Resources Publication.

Melville, B. W., and Dongol, D. M. 1992. Bridge Pier Scour with Debris Accumulation. Journal of Hydraulic Engineering, 118(9), 1306–1310.

Millington, C.E., Sear, D.A., 2007. Impacts of river restoration on small-wood dynamics in a low gradient headwater stream. Earth Surface Processes and Landforms, 32(July), 1204–1218.

Pagliara, S., and Carnacina, I. 2011. Influence of Wood Debris Accumulation on Bridge Pier Scour. Journal of Hydraulic Engineering, 137(2), 254–261.

Panici D., de Almeida G.A.M., 2018. Formation, growth, and failure of debris jams at bridge piers. Water Resources Research, 54, 6226–6241.

Pregnolato, M., Giordano P.F., Panici D., Prendergast L.J., Limongelli M.P., 2022. A comparison of the UK and Italian national risk-based guidelines for assessing hydraulic actions on bridges, Structure and Infrastructure Engineering

Rinaldi M., Surian N., Comiti F., Bussettini M., 2014. IDRAIM – Sistema di valutazione idromorfologica, analisi e monitoraggio dei corsi d'acqua – ISPRA – Manuali e Linee Guida 113/2014. Ro-ma, giugno 2014.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydro-morphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology, 251,122-136.

Ruiz-Villanueva V., Wyżga B., Zawiejska J., Hajdukiewicz M., Stoffel, M., 2016. Factors controlling large-wood transport in a mountain river. Geomorphology, 272, 21–31.

Ruiz-Villanueva V., Mazzorana B., Bladé E., Bürkli L., Iribarren-Anacona P., Mao L., Nakamura F., Ravazzolo D., Rickenmann D., Sanz-Ramos M., Stoffel M, Wohl. E., 2019. Characterization of wood-laden flows in rivers. Earth Surf. Process. Landforms, 44, 1694–1709.

Schalko, I., Schmocker, L., Weitbrecht, V., Boes, R.M., 2018. Backwater Rise due to Large Wood Accumulations. Journal of Hydraulic Engineering, 144(9), 04018056.

Schalko, I., Schmocker, L., Weitbrecht, V., Boes, R.M., 2019. Laboratory study on wood accumulation probability at bridge piers, Journal of Hydraulic Research.

Schmocker, L., Hager, W. H., 2011. Probability of Drift Blockage at Bridge Decks. Journal of Hydraulic Engineering, 137(4), 470–479.

Takano, H., Pooley, M., 2021. New UK guidance on hydraulic actions on highway structures and bridges. Proceedings of the Institution of Civil Engineers – Bridge Engineering 174(3): 231–238.

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., Piegay, H., Lininger, K.B., Jaeger, K.L., Walters, D.M., Fausch, K.D., 2019. The Natural Wood Regime in Rivers, BioScience, Volume 69, Issue 4, 259–273.

Wohl, E., Uno, H., Dunn, S. B., Kemper, J. T., Marshall, A., Means-Brous, M., Scamardo, J. E., & Triantafillou, S. P., 2023. Why wood should move in rivers. River Research and Applications, 1–12.