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ORIGINAL PAPER

Identifying bridges prone to instream wood accumulation: insights from bridges across the UK

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Abstract

Accumulation of instream large wood (i.e., fallen trees, trunks, branches, and roots) at bridges during floods may exacerbate flooding, scour and cause structural failure. Yet, explaining and predicting the likelihood of a bridge trapping wood remains challenging. Quantitative data regarding wood accumulation at bridges are scarce, and most equations proposed to estimate the accumulation probability were derived from laboratory experiments, and include variables such as flow velocity, Froude number, and approaching wood volume or size which are difficult to obtain. Other evaluations based on technical reports and information regarding wood removal have been proposed but are mostly qualitative. Until now, a data-driven approach combining multiple quantitative accessible variables at the river reach and catchment scales remains lacking. As a result, the controlling parameters explaining whether a bridge is prone to trap wood are still unclear. This work aims to fill this gap by analysing a database of 49 bridges across the United Kingdom (UK) classified as prone and not prone to wood accumulation. The database contained information regarding the geometry of the bridge (i.e., number of piers and pier shape) and we added parameters describing the upstream river channel morphology, the riparian land-cover, and high-flow characteristics. We applied multivariate statistics and a machine learning approach to identify the variables that explained and predicted the predisposition of bridges to wood accumulation. Results showed that the number of bridge piers, the unit stream power, the pier shape, and the riparian forested area explained 87% of the total variability for the training dataset (0.87 training accuracy), and the selected model had a testing accuracy of 0.60 (60%). Although limited by the sample size, this study sheds light on the identification of bridges prone to wood accumulation and can inform bridge design and management to mitigate wood-related hazards.

Keywords Instream large wood · Driftwood · Wood accumulation · Bridge clogging · Blockage probability · Flood risk

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1 Introduction

The presence of instream large wood, in the form of fallen trees, trunks, branches, and roots, influences a river's physical characteristics and boosts biodiversity by providing habitat, shelter, and food for a wide range of aquatic and terrestrial organisms. Hence, instream large wood plays a major role in sustaining diverse and healthy river ecosystems (Shumilova et al. 2019). However, instream large wood might be transported during floods in significant amounts (VanDine 1985; Lagasse et al. 2010; Comiti et al. 2016) and can also represent a hazard (Ruiz-Villanueva et al. 2014a; Wohl et al. 2016; De Cicco et al. 2018).

This is due to the fact that wood trapped at bridge piers increases the so-called effective pier width (Lagasse et al. 2010) and reduces the flow area under the bridge. The reduced area and usually associated backwater effect upstream of the bridge affect the flow velocity and turbulence around the piers. As a consequence, processes like the acceleration of sediment dislodge, scour at pier foundations, structural instability/failure and inundation of surrounding areas are exacerbated (Diehl 1997; Hoffmans and Verheij 1997; Lagasse et al. 2010; Pagliara and Carnacina 2011; De Cicco et al. 2015; Ruiz-Villanueva et al. 2017; Carnacina et al. 2019; Ebrahimi et al. 2020).

In the United Kingdom (UK) or the United States (US) for example, wood-related failures of bridges alone cost the governments millions of pounds and dollars every year (Chang 1973; RSSB 2004; Lassettre and Kondolf 2012; Benn 2013; Lamb et al. 2016). In recent times, severe flood events and the resulting transport of large amounts of instream wood have caused the collapse of bridges in various parts of Europe (Comiti et al. 2016; Steeb et al. 2017; Lucía et al. 2018; Ruiz-Villanueva et al. 2018), one of the last cases being the floods in the central region of Marche of Italy in September 2022 (Floodlist.com 2022) or those in Germany in July 2021 (Fekete and Sandholz 2021), when 67% of the bridges located in just 40 km of river length were destroyed or heavily damaged (Koks et al. 2021). Therefore, identifying bridges that are prone to accumulate wood is crucial for river and flood risk management.

Multiple variables influence the accumulation of wood and clogging of bridges, such as flow, discharge, wood supply and wood characteristics, wood transport mode, and bridge design (Diehl 1997; Lagasse et al. 2010; Gschnitzer et al. 2017; Ruiz-Villanueva et al. 2017; De Cicco et al. 2020; Schalko et al. 2020). Yet, data regarding wood accumulation at bridges are scarce, and most previous studies on instream wood accumulation at bridges were based on flume experiments, mainly focused on the hydrodynamics at the bridge section (e.g., Schmocker and Hager 2010, 2011; Khwairakpam et al. 2012; De Cicco et al. 2018; Hemdan et al. 2016; Ebrahimi et al. 2017; Panici and de Almeida 2018) or on the impacts of clogging (Ruiz-Villanueva et al. 2014b; Rasche et al. 2019). Despite the knowledge gathered by these previous works, the controlling parameters explaining whether a bridge is prone to trap wood are still unclear.

Design equations have been proposed to estimate the wood accumulation probability, using variables related to the hydraulic conditions, the bridge geometry, and the dimensions of the approaching wood (Gschnitzer et al. 2017; Schalko et al. 2020). However, the information required to apply such equations, for example flow velocity, approaching wood volume or size, might be flood event-dependant, and are often not available or difficult to predict. To deal with the lack of data, Mazzorana and Fuchs (2010) proposed a scenario-based framework. Other studies adopted a simplified approach, based on the principle of incremental pier width adjustment (i.e., effective pier width), to account for wood blockage (Lagasse and Schall 1980; Richardson and Davis 2001; Lagasse et al. 2010), or were based on qualitative evaluations of technical reports and aerial imagery (Panici et al. 2020).

However, the factors controlling the accumulation of instream large wood at a bridge section show complex interrelationships which depend on the bridge and its surroundings, but also on its upstream riparian areas and catchment hydrological characteristics. Thus, a thorough assessment of bridge wood accumulation predisposition needs to account for all the above mentioned factors, their relative importance and their interrelations (De Cicco et al. 2018).

This is the goal of this work, to disentangle the variables at the local and the catchment scales that control the predisposition of bridges to trap wood, and to identify bridges prone to accumulate wood. To do so, 49 bridges across the UK for which information about wood accumulation was available were analysed. It is worth noting that part of the used database (the wood-prone subset from the Devon County Council-owned stock of bridges) has been analysed in a previous study by Panici et al. (2020). This study looked at the likelihood of wood accumulation at bridges in a qualitative manner based on evidence from inspection reports, photographic imagery, accumulation removal works, and land cover in the vicinity of the bridge. Our work made a step further, by identifying the critical parameters influencing bridge clogging including quantitative variables such as the bridge span, number of piers, location and characteristics, catchment hydrological properties (i.e., stream power), channel morphology and riparian landcover.

2 Materials and methods

In this study a dataset of 49 bridges across the UK was analysed. Bridges were initially classified as wood-free or wood-prone, as explained in Sect. 2.1.2. Then, for each bridge, parameters describing their geometry, upstream river reach morphology, catchment land use and hydrology (e.g., stream power) and forest characteristics were extracted. Finally, machine learning techniques were used to examine the capacity of these descriptors to predict wood accumulation predisposition. Figure 1 summarises our approach, while the methodology is detailed in the following subsections.

2.1 Studied bridges

2.1.1 Location and catchment characteristics

The studied bridges and their catchments are scattered across England, although they are more concentrated at the Southern region, as shown in Fig. 2. The selection of these bridges was greatly influenced by the availability and reliability of data in the form of bridge inspection records. They are particularly concentrated in the county of Devon, which has the largest bridge stock in the UK, with frequent and organised inspection records in relation to instream wood accumulation (Panici et al. 2020). 18 of the Devon study bridges are wood-prone, while 18 wood-free ones were selected near the wood-prone ones for comparison purposes. In general, the bridge catchments sizes vary widely, ranging between 2 and 2277 km^2. The 36 catchments within Devon mostly range in size from 116k to 812 km^2 apart from 5 which have areas of 2 km^2, 3 km^2, 42 km^2, 47 km^2 and 53 km^2

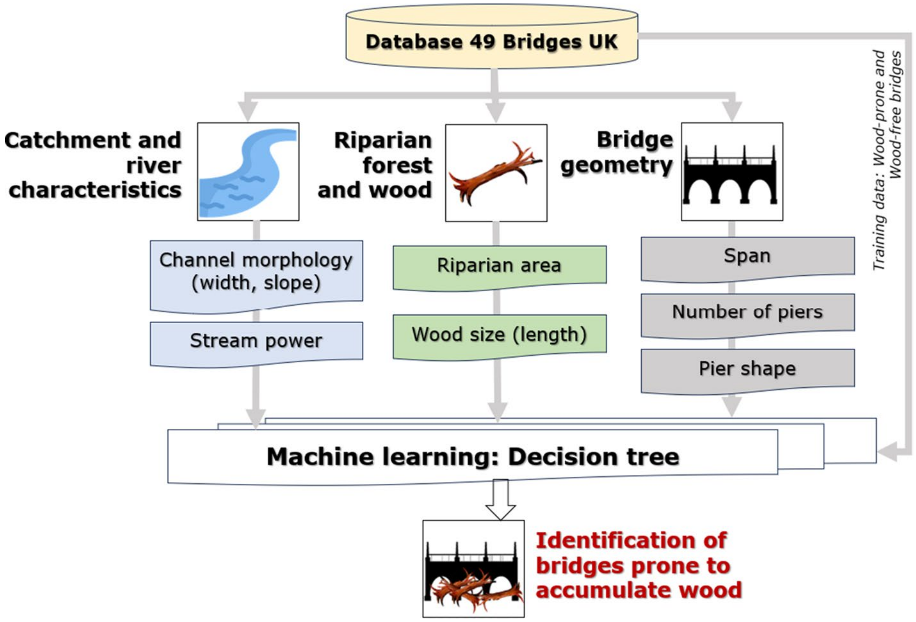

Fig. 1 Flow chart showing the framework developed in this study

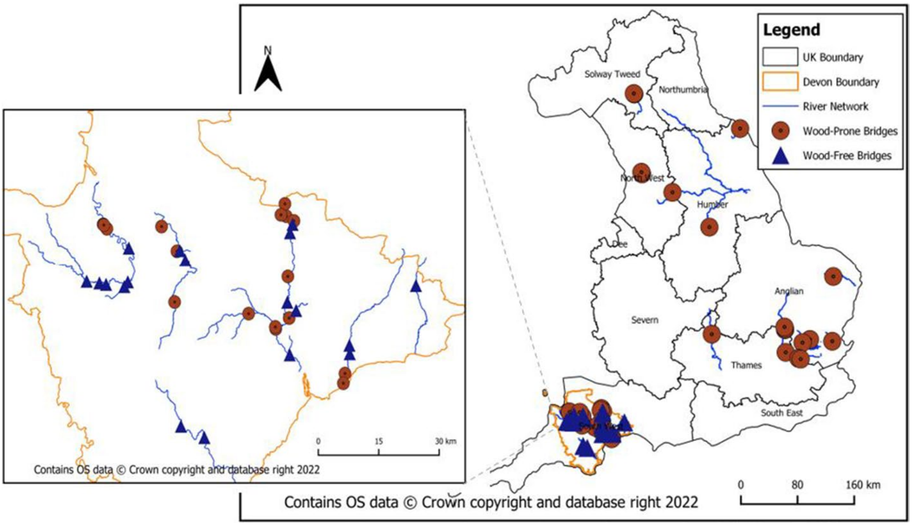

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Fig. 2 UK river basin districts map showing study bridge locations

respectively. On the other hand, the 19 catchments outside of Devon range between 2 and 271 km^2 with exception of one which is 2277 km^2 in size.

Devon is located within the South–West River Basin District of the UK. Covering an area of over 21000k m^2 with the lowest population density of all regions in England, but with significant seasonal population fluctuations due to a thriving tourism industry. This region is predominantly rural with noticeably hilly topography and sandy shores (Environment Agency 2011, 2019). Land use in the region is mainly agriculture of which arable and dairy farming form the greater proportion (Environment Agency 2011, 2019). The river network of 130 rivers extends to a sum length of approximately 1000 km (Environment Agency 2011, 2019). The wettest period of the year in the region occurs between the months of December and January while April to July is usually the driest with total annual rainfall in the range of 900–1000 mm (Met Office 2016).

Outside of Devon, the rest of the study bridges are scattered across the Anglian, Thames, Humber, North–West and Solway Tweed River basin districts (See Table S1 of Supplementary Sheet) with a bulk of them located in the Anglian River basin district which is 27,900 km^2 in area. Like the South–West River Basing District, this region is predominantly rural, with over 50% of land use made up of agriculture. This region is known for the presence of a wide diversity of wildlife species with the Norfolk Broads being the largest protected wetland in Britain (Environment Agency 2016). Although rainfall is evenly distributed throughout the year, the region only receives about 70% (less than 600 mm per year) of the UK national average and is considered as the driest in the country (Globaqua 2018).

2.1.2 Evidence of wood accumulation

To classify a bridge as either wood-prone or wood-free, we used long-term bridge inspection reports including photographic evidence of instream wood accumulation, as well as records of wood clearance operations (as done by Panici et al. 2020). These reports were obtained from various bridge owners including Network Rail, Devon, and Essex County Councils (Network Rail 2017; Devon County Council 2018; Essex County Council 2018). Figure 3 shows images from the photographic catalogue illustrating typical wood-prone bridges.

The available photographs and reports served as qualitative evidence of the predisposition of these bridges to instream wood accumulation rather than as a quantitative

Fig. 3 Images of wood accumulation at some of the study bridges. The arrows indicate the direction of river flow. Source: Devon County Council (2018)

description of bridge blockage or wood characteristics. Bridges were classified as wood-prone if their inspection records indicated present or historic wood accumulation requiring mechanical clearance at least once.

2.1.3 Bridge geometry

Bridge geometrical information including bridge span (i.e., pier-to-pier and/or pier-to-abutment widths), pier shape (i.e., flat, circular, oval, or pointed) and pier location (i.e., inside, or outside of river channel) was mostly extracted from bridge design drawings obtained from the various bridge owners and from photographs in the inspection reports, with the help of Google Earth imagery in some cases.

2.2 Catchment and river data

The surface catchments contributing runoff to the study bridges and their hydrological descriptors (e.g., area, slope, intensity–duration–frequency of precipitation, percentage of urban landcover) were obtained from the Flood Estimation Handbook Web Service (https://fehweb.ceh.ac.uk/Map, FEH; CEH 2020). A comprehensive list of the catchment descriptors for each study bridge is included in Supplementary Material (Table S4).

2.2.1 Riparian corridor land cover

The 2015 version of UK-Wide Landcover map (i.e., LCM2015 Vector Data), comprising 21 unique land use/landcover classes, was obtained from the Centre for Ecology and Hydrology (CEH) for the characterisation of the catchment and riparian corridors landcover (CEH 2019). The river network shapefile required for delineating the riparian corridors and channel slope calculations was obtained from the Ordnance Survey (OS) data hub (OS 2018). The channel width 30 m upstream of the bridge was obtained from bridge risk assessment reports in the case of the Network Rail-owned bridges. The widths of rest of the channels were measured using high-resolution imagery from Google Earth.

The riparian vegetation characterisation involved, first delineating the riparian corridor, which encompasses two 30m-wide land strips at each side of the river banks, extending 1.5 km along the river upstream of the bridge. This area was delineated and the land cover type inside was calculated from the CEH UK landcover map using ArcGIS version 10.5.1 (ESRI 2017). The selected riparian width of 30 m was inspired by previous observations in the Northwest of the United States, where a significant proportion of the woody material (70% to 90%) delivered into a river came from within a 30 m distance of the river banks (Van Sickle and Gregory 1990; Fetherston et al. 1995). The "Dominant Forest Type" is defined here as the forest type forming the greater proportion of the total "Forested Area" while "Dominant Landcover" is defined as the vegetation or landcover type forming the greater proportion of the overall landcover of the catchment.

2.3 Flow characterisation

The unit stream power was calculated for each study site, assuming a 10-year return period flood and per channel width as follows:

$$\omega = \Omega/\mathrm{w} \tag{1}$$

where ω = unit stream power (Wm^{-1}). Ω = stream power (W). W = channel width (m).

and:

$$\Omega = \rho \mathrm{gQS} \tag{2}$$

where ρ = Density of water (1000 kg m^{-3}). g = is the acceleration due to gravity (9.8 m s^{-2}). Q = peak discharge for a 10-year return period ($\mathrm{m}^3\mathrm{s}^{-1}$). S = channel slope (m/m).

In order to compute the peak discharge for a 10-year return period, we applied the so-called revitalised FSR/FEH (ReFH) rainfall-runoff method (Kjeldsen 2007), implemented within the Flood Modeller Pro software version 4.6. The ReFH method uses long historical records of rainfall and flow discharge from the extensive hydrometric network in the UK for the hydrological parametrization of catchments, which inform their design storms and unit hydrographs. The ReFH uses the unit hydrograph concept to transform effective rainfall into overland runoff at the catchment outlet, while the baseflow is simulated using an exponential decay recession curve. The application of the ReFH method requires four model parameters for the study catchments: time-to-peak (Tp) for the routing model; the loss model parameter Cmax; the baseflow model parameters BL and BR. These parameters were estimated based on the catchment descriptors, using the equations proposed in (Kjeldsen 2007).

The catchment specific unit hydrograph was combined with the 10-year return-period design rainfall, winter profile, to estimate the 10-year peak discharge. Table S5 in Supplementary Material lists the calculated model parameters, 10-year peak discharge and unit stream power for all the study catchments.

Details of the riparian corridor, river channel and bridge geometrical data used in this study are presented in Table 1.

2.4 Relating parameters to in-stream wood accumulation

The various bridge, river and catchment parameters presented above were compared for wood-prone and wood-free bridges. Initially, the Wilcoxon–Mann–Whitney (MW) test was used to investigate which of the parameters had significantly different values for wood-prone and wood-free bridges. The test was performed using the *ggpubr* and *ggplot2* packages of R version 4.2.0 in RStudio version 2022.02.2 (RStudio 2022). Statistical significance was considered at p values ≤ 0.05. Non-parametric tests were used as they do not assume any distribution of the data and are preferred for small data samples. Then, a factor analysis on mixed Data (FAMD) was applied to 9 bridge variables to identify which ones best explained the bridge predisposition to accumulate wood (i.e., distinguishing between wood free and wood prone bridges). The FAMD was conducted using the *Factoshiny*, *FactoMineR*, *FactoInvestigate* and *missMDA* packages of R version 4.2.0 in RStudio version 2022.02.2 (RStudio 2022). The 9 variables used in the FAMD are: Forested, Arable and Horticulture Cover (*FAH.Cover*) (%), Riparian Forest Cover (ForestCover) (%), Bridge Span (*BridgeSpan*) (m), Number of in-channel piers (*ChannelPiers*), Bridge Span to Channel Width Ratio (*BSC.W.R*), Pier Nose Shape (Flat = 1, Circular = 2, Oval = 3, Pointed = 4), Standard annual average rainfall (*SAAR*) (mm), Bridge Span to Average Sturdy Wood Length Ratio (BSW.L.R), and Unit Stream Power (*U.StreamPower*) (Wm^{-2}).

Finally, a supervised machine learning approach, decision tree learning, was adopted due to its predictive capabilities. Decision tree learning is a method increasingly used in

Table 1 Description of the riparian corridor, river channel and bridge geometrical parameters used in this study

Parameter	Unit	Description
Catchment area	km^2	Extent of the surface drainage catchment at the bridge location
Riparian corridor area	km^2	Land strips 1.5km long upstream from bridge and 30m wide from each side of the river channel
Dominant forest type	Class	Forest type with the largest coverage in the catchment or riparian corridor
Riparian forest cover (*ForestCover*)	%	The percentage area of the riparian corridor covered by forest
Forested, Arable and Horticulture Cover (*FAH.Cover*)	%	The percentage area of the riparian corridor which is forested or arable and horticulture land
River channel width	m	Bank-to-bank width of river channel measured 30m upstream of bridge
Channel slope	m/m	Average slope of the river channel upstream of the bridge
Bridge span (*BridgeSpan*)	m	Distance from pier-to-pier (for multi-span bridges) or flow area under single span bridge
Pier nose shape (*PierShape*)	Flat/circular/oval/pointed	Shape of pier facing upstream
Number of piers		Number of pier(s)
In-channel piers (*ChannelPiers*)		Number of bridge piers located inside river channel
Bridge span to channel width ratio (*BSC.W.R*)	Dimensionless	The ratio of bridge span to the upstream channel width
Bridge span to average sturdy wood length ratio (*BSW.L.R*)	Dimensionless	The ratio of bridge span to average sturdy wood length. Note: The sturdy log length refers to the maximum length at which a log is strong enough to be able to support an accumulation over its entire length (Diehl 1997). This is determined by the mature height of the dominant forest type
Standard annual average rainfall (*SAAR*)	mm	A component of the FEH catchment descriptors referring to the annual average rainfall in the bridge catchment
Unit Stream Power (*U.StreamPower*)	Wm^{-1}	Flow power per channel width of the 10-year return period peak discharge

data sciences because allows for the prediction of a target variable (wood-prone vs. wood-free bridges, in our case) based on several input variables, quantitative or categorical. The advantage of this approach is that the resulting tree-structured model is illustrative and easy to interpret, identifies the important variables and makes prediction fast (de Ryckel 2019).

Thus, a classification decision tree was developed based on the relevant variables obtained from the FAMD to identify wood-prone or wood-free bridges. This was done using the *rpart* version 4.1.16 (Thernaeu and Atkinson 2022) and *rpart.plot* version 3.1.1 (Milborrow 2022) of R version 4.2.0 in RStudio version 2022.02.2 (RStudio 2022). The decision tree model was trained with 80% of the data and then tested with the remaining 20%.

3 Results

The results showed that the number of in-channel piers, bridge span to channel width ratio, bridge span and bridge span to average sturdy wood length ratio were significantly different between wood-prone and wood-free bridges (Fig. 4).

10 out of the 31 (32%) wood-prone bridges have spans shorter than 4.2 m and 11 (35%), shorter than or equal to 6.3 m (Fig. S3 in Supplementary Material). On the contrary, 72% of the wood-free bridges have spans of 6.3 m and longer, with none being shorter than 4.2 m. In addition, bridges with 2 or more piers located within the river channel were mostly classified as prone to wood accumulation compared to those with less than 2 in-channel piers. Also, all but one of the wood-prone bridges have a bridge span to channel width ratio below 0.8 compared to 55% of wood-free bridges. No significant differences were found between the two groups of bridges for stream power, although in general wood-prone bridges were related to higher values of this parameter. The shape of the bridge piers also differed between the two groups. Bridges with flat, circular, and oval-shaped piers were more susceptible to wood accumulation while those with pointed piers were less (Fig. 4).

The FAMD showed that the most important quantitative variables explaining the variance in our dataset were: the number of in-channel piers, bridge span to channel width ratio, unit stream power, percentage riparian forested area and bridge span to wood length ratio (Fig. 5) with the first three dimensions explaining more than 50% of the variance (See Fig. S3 of Supplementary Sheet). Also, the FAMD revealed pier shape as one of the most important variables (Fig. 5b).

The decision tree learning was applied to the 6 variables identified by the FAMD as the most important (i.e., number of in-channel piers, riparian forest cover, unit stream power, bridge span to channel width ratio, pier nose shape, and bridge span to average sturdy wood length ratio). The resulting decision tree presented in Fig. 6 indicates that the number of in-channel piers is the most important variable influencing the classification, followed by forest cover, pier shape, unit stream power etc., with a prediction accuracy on the training dataset of 87% and 60% on the testing dataset.

4 Discussion

Our results revealed that wood-prone and wood-free bridges significantly differed in terms of the number of piers in the channel, their opening span and the percentage of the riparian forest cover. The decision tree indicated that for our dataset, the number of bridge piers

Fig. 4 Boxplots of Bridge Span (*BridgeSpan*), Number of In-channel Piers (*ChannelPiers*), Unit Stream ▶ Power (*U.StreamPower*), Bridge Span to Channel Width Ratio (*BSC.W.R*), Forest Cover (*ForestCover*), Pier Nose Shape (*PierShape*), and Bridge Span to Average Sturdy Wood Length Ratio (*BSW.L.R*) for all bridges classified as wood-prone and wood-free. The p-value shows the result from the Mann-Kendal test. [Pier Shape: Flat = 1, Circular = 2, Oval = 3, Pointed = 4]

explained 79% of the classification into wood-prone and wood-free bridges (Fig. 6). Our approach also identified unit stream power as the next most important parameter after pier characteristics and forest cover in the classification of bridges as wood-prone or wood-free (Fig. 6). This is in line with previous studies revealing that discharge and other hydraulic parameters significantly affected bridge blockage probability (Ruiz-Villanueva et al. 2017; Schalko et al. 2020). The site high-flow characteristics might be one of the most important factors explaining bridge predisposition to trap wood during floods. We used a well-known and tested method in the UK, the ReFH method, to estimate the 10-year return period discharge and related stream power. Our goal was to include one variable that reflected the energy of the flow, without using one specific flood event discharge. Different return periods could have been used, and this aspect could be further explored in future works.

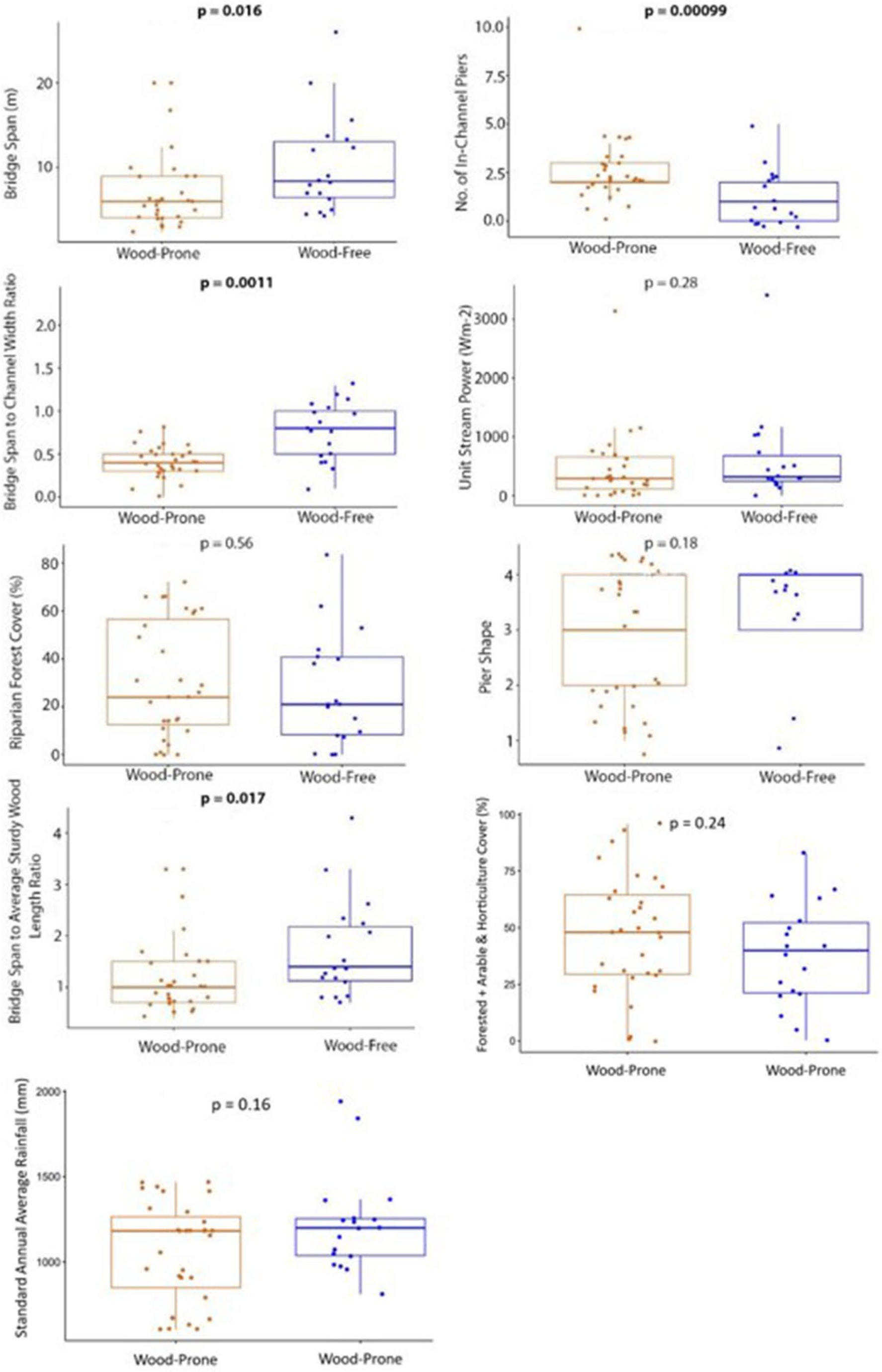
The bridge span to channel width ratio and bridge span to average wood length ratio were also fundamental variables discriminating bridges prone to wood from wood-free bridges (Fig. 5). This was not unexpected, as existing studies indicated that upstream channel width and wood size were key factors in influencing instream wood accumulation at bridges (Triska and Cromack 1980; Bilby and Ward 1989, 1991; Benke and Wallace 1990; Lagasse et al. 2010).

Bridge upstream channel widths were obtained from inspection reports in the case of the Network Rail-owned bridges. For the rest of the bridges, channel widths were measured using available high-resolution aerial and satellite imagery from Google Earth. There might be certain inaccuracies when digitalizing channel widths using aerial or high-resolution satellite imagery, and other data could be used or combined to reduce errors, for example using high resolution digital elevation models or topographical maps. Whether the channel upstream from bridges was channelized or reinforced was not considered in our analysis, and might be a relevant aspect. Unfortunately, information was not readily available from the sources of our dataset. Channelized reaches may prevent bank erosion and supply of wood, however, in many cases, the wood is being transported from far upstream (farther than 1.5 km). Therefore, it would be difficult to estimate the influence of channelized river banks on the wood accumulation. Therefore, by not considering it, we assumed a worst-case scenario in terms of wood supply and hence being more conservative in our predictions.

According to Diehl (1997), instream wood jams were more likely to occur at bridges where wood pieces are shorter than upstream channel width but long enough to span bridge openings or trapped at piers. Therefore, bridge design should consider this important aspect. The challenge might be related to identifying the expected wood size. To do so, information about the riparian vegetation is key (Mazzorana 2009; Lagasse et al. 2010).

In our work, we explored the riparian forested area within a certain distance from the riverbanks. We defined a buffer of 30 m, following a study in the Pacific Northwest in the USA, where the authors observed that a significant proportion of the woody material (70% to 90%) delivered into a river was within 30 m from the river banks (Van Sickle and Gregory 1990; Fetherston et al. 1995).

According to the available information, the dominant forest cover in the riparian area upstream of all the bridges was broadleaved woodland, with a matured height of over 5 m


p = 0.016
Bridge Span (m)
20
10
Wood-Prone
Wood-Free
p = 0.00099
No. of In-Channel Piers
10.0
7.5
5.0
2.5
0.0
Wood-Prone
Wood-Free
p = 0.0011
Bridge Span to Channel Width Ratio
2.0
1.5
1.0
0.5
0.0
Wood-Prone
Wood-Free
p = 0.28
Unit Stream Power (Wm-2)
3000
2000
1000
0
Wood-Prone
Wood-Free
p = 0.56
Riparian Forest Cover (%)
80
60
40
20
0
Wood-Prone
Wood-Free
p = 0.18
Pier Shape
4
3
2
1
Wood-Prone
Wood-Free
p = 0.017
Bridge Span to Average Sturdy Wood Length Ratio
4
3
2
1
Wood-Prone
Wood-Free
p = 0.24
Forested + Arable & Horticulture Cover (%)
100
75
50
25
0
Wood-Prone
Wood-Prone
p = 0.16
Standard Annual Average Rainfall (mm)
2000
1500
1000
Wood-Prone
Wood-Prone

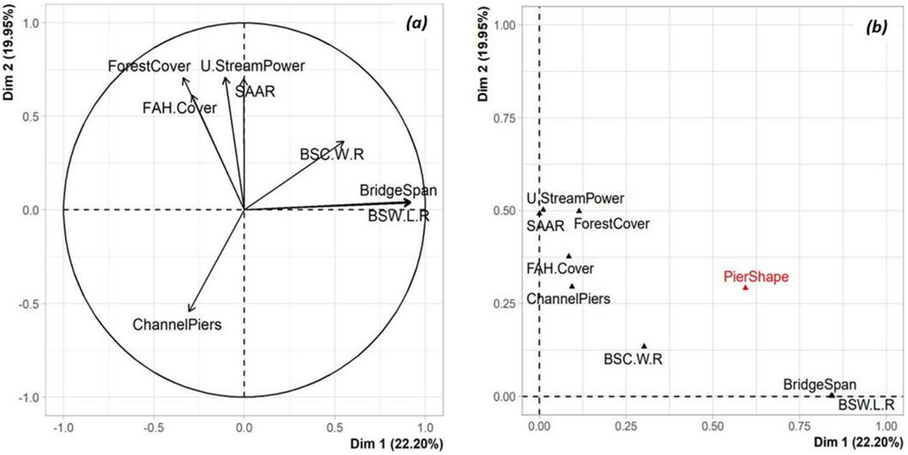


Fig. 5 FAMD Plots: **a** Biplot of the selected variables explaining > 50 of the variance in the data; **b** Plot of the selected variables (including the only categorical variable pier shape) [Bridge Span (BridgeSpan), Number of In-channel Piers (ChannelPiers), Unit Stream Power (U.StreamPower), Bridge Span to Channel Width Ratio (BSC.W.R), Forest Cover (ForestCover), Pier Nose Shape (PierShape), and Bridge Span to Average Sturdy Wood Length Ratio (BSW.L.R), Forested, Arable and Horticulture Cover (FAH.Cover), Standard annual average rainfall (SAAR)]

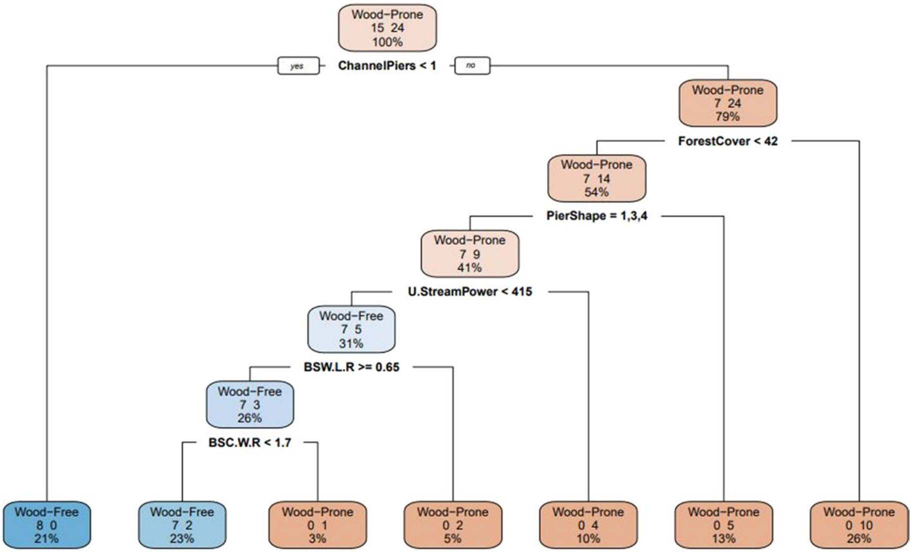


Fig. 6 Decision tree classification of bridges based on parameters influencing wood accumulation at bridges [Pier Shape (PierShape): Flat = 1, Circular = 2, Oval = 3, Pointed = 4], Number of In-channel Piers (ChannelPiers), Forest Cover (ForestCover), Unit Stream Power (U.StreamPower), Bridge Span to Average Sturdy Wood Length Ratio (BSW.L.R), and Bridge Span to Channel Width Ratio (BSC.W.R)

(NFI 2017; CEH 2019). However, the level of detail in the available database was limited. Other type of information, such as tree species, stand stage or management practices, or a more detailed distribution of tree heights (for example derived from LiDAR data) could be used to define this parameter better. Unfortunately, this information was not available at the time of this study. This is an important aspect, and future work should consider acquiring this information.

Finally, we acknowledge that the representativeness of our database is limited to certain conditions and would not cover the full range of natural variability. The relatively small size of the dataset used in this study and the uneven distribution of the study bridges undoubtedly influence the obtained results. Therefore, our results, and the proposed model can be enhanced using a much larger dataset. We thus call for further studies, and more important, for compiling the required information and data, over a wider range of conditions.

5 Conclusions

Our analysis based on data collected for 49 bridges across England reveals that the number of in-channel piers, pier nose shape, unit stream power, and the percentage of riparian forested area are able to distinguish between wood-free brides and those prone to wood accumulation, and hence, these variables could be used to identify wood-prone bridges elsewhere.

Bridges with 2 or more piers, with a bridge Span to Average Wood Length Ratio lower than 0.65, and a Bridge Span to Channel Width Ratio < 1.7 were all grouped as wood-prone. This indicates that under similar conditions of wood supply, bridge design is key in controlling wood accumulations.

This study provides a novel model based on a classification decision tree, that is easy to interpret and apply elsewhere, and can be used to distinguish bridges prone to accumulate wood, informing bridge design as well as river and flood management strategies to mitigate wood-related hazards.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11069-023-06174-9.

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Declarations

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