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A high-resolution inter-annual framework for exploring hydrological drivers of large wood dynamics

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Abstract

Rivers with alluvial bars store more wood than those without, supplied through channel shifting. However, wood dynamics (arrival or new deposits, departure or entrainment, and stable or immobile pieces) can vary substantially over time in response to critical hydrological drivers that are largely unknown. To evaluate them, we studied the dynamics of large wood pieces and logjams along a 12-km reach of the lower Allier River using six series of aerial images of variable resolution acquired between 2009 and 2020, during which maximum river discharge fluctuated around the dominant flood discharge ($Q_{1.5}$) that is potentially the bankfull discharge along this well-preserved not incised reach. Individual wood departure was best correlated with water levels exceeding dominant flood discharge. The duration of the highest magnitude flood was best correlated with wood depositions, with shorter floods resulting in a higher number of deposits. Finally, most of the wood remained stable when river discharge did not exceed 60% of $Q_{1.5}$ over a long period of time. Changes in inter-annual wood budget (reach-scale) depend on the duration over which discharge exceeded 60% of $Q_{1.5}$. Hydrological conditions driving jam build-up and removal were similar to those controlling individual wood piece dynamics. The results suggest that specific hydrological conditions influence the dynamics of large wood and log jams in the Allier River. Understanding the dynamics of large wood and its impact on river morphology is fundamental for successful river management and habitat restoration initiatives.

KEYWORDS

Allier River, hydrological factors, large wood, retention time, temporal dynamics

1 | INTRODUCTION

Human attitudes towards large wood in rivers are currently two-sided. On the positive side, wood is seen as an essential element of riverine ecosystems, diversifying the physical habitat conditions (e.g., flow velocity, grain size, temperature and access to light) in a way that is

valuable for macroinvertebrates (Benke & Wallace, 2010) and fish species (Jones et al., 2014; Pettit et al., 2013). Besides sediment storage, wood also provides considerable storage of carbon in river floodplains (Wohl et al., 2012). Wood promotes landscape heterogeneity through its influences on hydraulic conditions and hydrogeomorphic processes (e.g., sediment transport and deposition, shear stress) in the

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channel and on alluvial bars (Gurnell et al., 2002; Gurnell & Sweet, 1998; Piégay & Gurnell, 1997; Wohl, 2013). Moreover, wood in rivers also provides organic matter to the food chain (Elosegi et al., 2007; Guiney & Lininger, 2022).

On the negative side, wood is also perceived as a risk. It can cause direct damage to any infrastructure (e.g., bridges, dams and buildings) and also result in failure due to scour (Diehl, 1997; Mao & Comiti, 2010; Melville & Dongol, 1992). Wood accumulation can also reduce the channel cross section and induce a water level rise upstream of the jam, thereby increasing the upstream flood risk (Gippel, 1995; Ravazzolo et al., 2022; Schalko et al., 2018; Schmocker & Hager, 2011). However, there may be uncertainties about the proportional contribution of wood to the damage caused by flood events (Comiti et al., 2008a).

Most of the wood stored in medium to large river corridors is recruited through lateral bank erosion. Once wood is recruited, logs are transported downstream at varying speeds depending on their length and shape, which influences their resistance to flow (Ravazzolo et al., 2022). Tree trunks can be deposited as individual pieces or they can agglomerate and thus form logjams (Piégay, 1993). Jams can build up on bare surface, or on the upstream side of an obstacle (e.g., vegetation patch present on alluvial bars) but even a single piece of wood is capable of trapping and stabilising other logs, thereby initiating jam development; this first element of the jam is called the “key member” (Abbe & Montgomery, 1996).

Wood dynamic is an important parameter for modelling and potentially preventing hazards associated with large wood, although it can be difficult to assess. Transport rates reported in previous studies show high variability, but the studies include a wide range of stream types, sizes, measurement methods and monitoring times. On large rivers, the mean annual transport rate is over 40% and can exceed 80% (such as on the Tagliamento River in Italy) (Ruiz-Villanueva et al., 2016b). The deposition of large pieces of wood and jams can have a high residence time counted in decades, even reaching up to 200 years (Keller & Swanson, 1979). An example of relatively stable jams can be found in Australian ephemeral streams, where they are key to driving geomorphic processes (Dunkerley, 2014). The depositional form modifies wood dynamics, because individual wood pieces that become entwined within a jam obviously show much longer transit durations than free pieces of wood (Kramer & Wohl, 2017). Meanwhile a jam remains spatially stable, its size (i.e., number of logs within jam) can fluctuate, with the episodic release and capture of wood (Piégay et al., 2017). Hydrological conditions drive retention of large wood (Galia et al., 2020) and also drive changes in the size of jams. The retention of large pieces of wood in jams primarily occurs during normal flows (Hassan et al., 2016). In a reach-scale analysis of the dynamics of large wood pieces in British Columbia, Hassan et al. (2016) showed that an important proportion of the total wood accounted for is stored within logjams.

Wood dynamics at the reach scale can be analysed using information gathered through repeated field campaigns (Boivin et al., 2017; Máčka et al., 2011), but such campaigns can be very time-consuming and expensive and are sometimes not possible to undertake for

logistic or technical reasons. Aerial imagery is an alternative that has been successfully used to determine wood storage (Comiti et al., 2008b; MacVicar et al., 2009; Ulloa et al., 2015) and monitor wood jam evolution (Haschenburger & Rice, 2004), provided that the image resolution is sufficiently high (Marcus et al., 2002). Galia et al. (2022) assessed spatiotemporal variations in large wood using satellite images and found that it was not possible to make direct comparisons of volume and frequency through time because of resolution differences across the images. Raft dynamics are easier to monitor using aerial photographs or satellite images because of the greater spatial extent of rafts compared with individual pieces (Boivin et al., 2015; Kramer & Wohl, 2015). Comiti et al. (2008b) used aerial RGB images to quantify wood storage within seven sub-reaches of braided/wandering rivers in Italy, while Smikrud and Prakash (2006) used an automated method to map individual logs and wood accumulations to assess changes in wood distribution over two successive years. Lassetre et al. (2008) used two series of oblique aerial photographs, whereas Moulin et al. (2011) georeferenced video footage to manually quantify individual trunks and jams within a 36-km reach of the Ain river (France). High-resolution UAV imagery was also used to manually identify individual wood pieces and log jams with great accuracy (Sanhueza et al., 2019, 2022). Atha (2014) used 1-m-resolution satellite images in Google Earth to detect large wood over a broad spatial scale. Riparian vegetation cover may obscure deposited wood, and therefore, Atha (2013) chose to manually interpret LiDAR point clouds. Methods such as supervised or automated classifications were applied to hyperspectral and multispectral images for stream mapping (Leckie et al., 2005; Marcus et al., 2002). Automated methods were also applied to LiDAR data and aerial four-band imagery to quantify and measure individual wood pieces, although the failure to detect individual trunks limited the success of the techniques (Richardson & Moskal, 2016). In addition, the data sources used in these studies are costly and are rarely available at high frequency and over long timescales.

Today it is still difficult to predict when wood will be deposited and remobilised because we do not know the critical hydrological thresholds. There is a crucial need to understand the processes controlling wood kinetics to calibrate algorithms predicting wood dynamics and improve modelling capabilities. Moreover, to provide adequate management of large wood in large rivers, we need a good understanding of its dynamics from recruitment and through deposition and remobilisation phases. River discharge is the primary driver that governs wood transport (Gurnell et al., 2002), and multiple studies have shown a significant correlation between peak flow magnitude and wood export (Boivin et al., 2015; Moulin & Piégay, 2004; Ruiz-Villanueva et al., 2016a; Senter et al., 2017). However, the relationship appears to be nonlinear and slightly noisy (Boivin et al., 2015; MacVicar & Piégay, 2012), demonstrating the complex interactions that exist between the main channel, its margins and the alluvial plain in terms of wood exchange. Kramer and Wohl (2017) suggested that a flow duration of near or just under bankfull discharge has the greatest influence on the transport distance of large wood. One option to solve this issue is to develop a multi-date analysis showing deposits and

departures under different hydrological contexts, thereby helping to obtain an understanding of the main thresholds.

Wood surveys at reach scale frequently concentrate on one dimension, in particular the spatial dimension of wood distribution (e.g., Andreoli et al., 2007; Galia et al., 2020; Massé & Buffin-Bélanger, 2016; Piégay & Marston, 1998), but are rarely performed over multiple timepoints. Reach-scale studies that include temporal dynamics of wood are frequently undertaken within headwater reaches or cover only short reach-lengths or timescales and sometimes do not make explicit links with hydrological parameters (Daniels, 2006; Haschenburger & Rice, 2004; Iroumé et al., 2015; Jochner et al., 2015; Latterell & Naiman, 2007; Wohl & Cadol, 2011; Wohl & Goode, 2008). A recent study used hydrological proxies (discharge level, number of days exceeding geomorphologically significant flow and accumulated geomorphic work) to explain channel morphodynamics and spatiotemporal changes in the storage of large wood, but the focus was on intermittent Mediterranean rivers (Galia et al., 2023). The use of tagging technologies to monitor individual wood pieces (Dixon & Sear, 2014; Haga et al., 2002; Jochner et al., 2015; Ravazzolo et al., 2015; Schenk et al., 2014) has potential for advancing our knowledge on the motion of wood, but it does not address long-term changes in remobilisation of wood within the overall wood storage of a reach in relation to flow history.

Our aim with this paper is to achieve a better understanding of the drivers that control wood dynamics, considering individual wood pieces and jams in terms of inter-annual depositions (or arrivals), departures (or entrainment or remobilisation) and stability (immobility). This inter-annual piece-scale dynamic is also compared with the reach-scale budget. To accomplish this, we designed a comparative approach based on a high-frequency inter-annual survey strategy to evaluate hydrological thresholds above or below which wood arrival, remobilisation and storage are observed. We applied our approach on a 12-km reach of the Allier River in France because it is characterised by active lateral erosion and intense exchanges of wood between the main channel and its floodplain.

2 | METHODOLOGY

2.1 | Study site and hydrological context

The Allier River originates at 1485 m altitude, drains 14,400 km² and travels 410 km before joining the Loire River at an altitude of 140 m (Figure 1a,b). Our study area is located in the Natural Reserve of Val d'Allier. This meandering reach of 12 km spans the length between the bridges of Châtel-de-Neuvre and the N79 road. It is characterised by active shifting, with an average channel width of 60 m (sd = 15) and a mean annual erosion rate between 0.2 and 0.9 ha/km/year (between 2009 and 2020). The upstream section shows a higher channel migration rate than the downstream straighter section. The hydrograph displays a strong seasonal pattern: the mean annual discharge at Châtel-de-Neuvre where the Allier drains 12,430 km² is 114 m³/s, with Q₂ and Q₁₀ of 560 and 940 m³/s, respectively.

2.2 | Survey of wood deposition, departure and stability

We used six series of aerial photographs (2009, 2010, 2013, 2016, 2019 and 2020) to analyse the spatial distribution of large wood pieces (Figure 1c-h). Wood pieces were manually delineated on each aerial image by drawing a line in ArcGIS (v10.0). The six series of aerial photographs were acquired during days with low-flows and had a resolution varying from 0.5 to 0.07 m/pixel. With the exception of the latest image series, all earlier ones were produced by the French Geographical Institute (IGN: *Institut national de l'information géographique et forestière*) as part of the national aerial survey programme. The aerial photographs of 2020 were taken from an ultra-light vehicle and an orthomosaic was constructed using Metashape software. The shortest piece of wood measured is 0.4 m, but only a negligible amount of wood was sensed below one meter length (0.23%). Consequently, this insignificant proportion below one meter was not considered to meet the traditional criterion for defining large wood. No field data were used to validate any of the images, because the ratio between detected and undetected logs is likely to vary between images, related for example to the expansion of the riparian vegetation cover.

We generated three groups of information from the six maps: (i) the total number of wood pieces; (ii) the number of newly deposited, departed and stable wood pieces at each date; and (iii) the residence time of each wood piece (i.e., the time over which a piece did not move). Groups (ii) and (iii) were estimated using the spatial join tool of ArcGIS. We finally estimated the reach-scale changes in the total amount of wood pieces to determine if the reach gains or loss wood pieces between two surveys (delta stock).

2.3 | Survey of wood jams

Jams were also quantified on the six series of aerial images, with a jam being defined as a wood accumulation including at least three wood pieces (Ruiz-Villanueva et al., 2016a) and marked by a point geometry in GIS. We identified which jams had been created, destroyed, or remained stable (stayed present at the same location) from one period to the next. We computed the proportions of jams built over a given period that occurred with or without one or two wood pieces being previously observed (as called key member). In addition to the number of jams present at each date, the number of wood pieces forming each jam was quantified, providing an estimate of the growth or decline of stable jams. Stable jams were considered to show size fluctuation (i.e., evolution of the number of pieces within a jam) when the decrease or increase in size was at least of 50%, in order to reduce possible quantification error and to focus on substantial changes. If a previously identified jam has disappeared (i.e., was absent on one or more images) and built up later at the same place, it was considered as a new one. The size of a jam was considered unchanged when the number of wood pieces at two consecutive survey dates did not differ by more than ± 3 pieces. This interval-based definition was used to minimise possible quantification error.

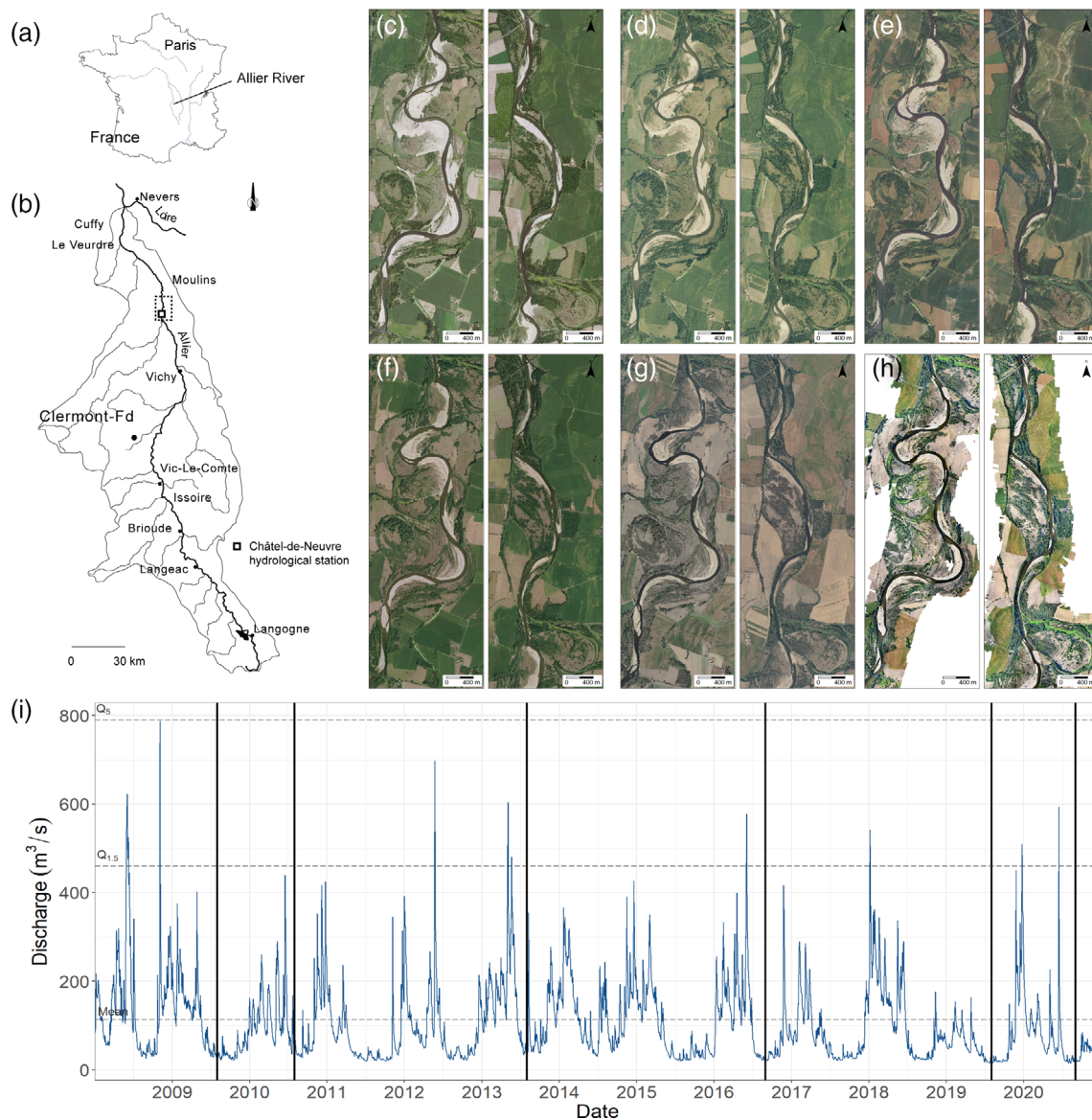


FIGURE 1 (a) Location of the Allier River within France. (b) River basin of the Allier River and the location of the study reach within the dotted rectangle. (c)–(h) The six aerial images (2009, 2010, 2013, 2016, 2019 and 2020) analysed to sense individual wood pieces and jams. The left image corresponds to the upstream part of the study site and the right one to the downstream part. (i) Mean daily discharge at Châtel-de-Neuvre. The dates of aerial images used for the analysis are indicated by vertical black lines. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

2.4 | Correction of image resolution bias for wood sensing

Image resolution clearly affects the quantification of wood storage and results in uncertainty in periodic comparisons of wood quantities. Instead of reducing the resolution of all images to the lowest resolution, we first analysed images at their original resolution. Then, in a second step, we reduced the resolution of the highest resolution 2020 image series to the lower resolutions of the older series (e.g., 0.2, 0.25, 0.3 and 0.5 m/pixel). We selected a representative area within the upstream dynamic section of the river that included alluvial bars, banks and the main channel, and the wood storage within this

area was quantified for each decreased-resolution image of the 2020 series. The amount of wood pieces within this area represented close to 50% of the total amount found over the entire study area based on the original image of 2020. Comparison of the five resolutions showed a linear relationship between image resolution and the number of wood pieces detected (Figure 2a), which meant that a simple proportional correction could be applied to correct for this resolution bias and confidently quantify changes in wood storage across the years (Table 1). No field-based counting of wood pieces was deemed necessary as our goal was to assess bias in wood quantification with differences in image resolution. In addition, field truth data could only be obtained for the most recent image. Instead, we focused on

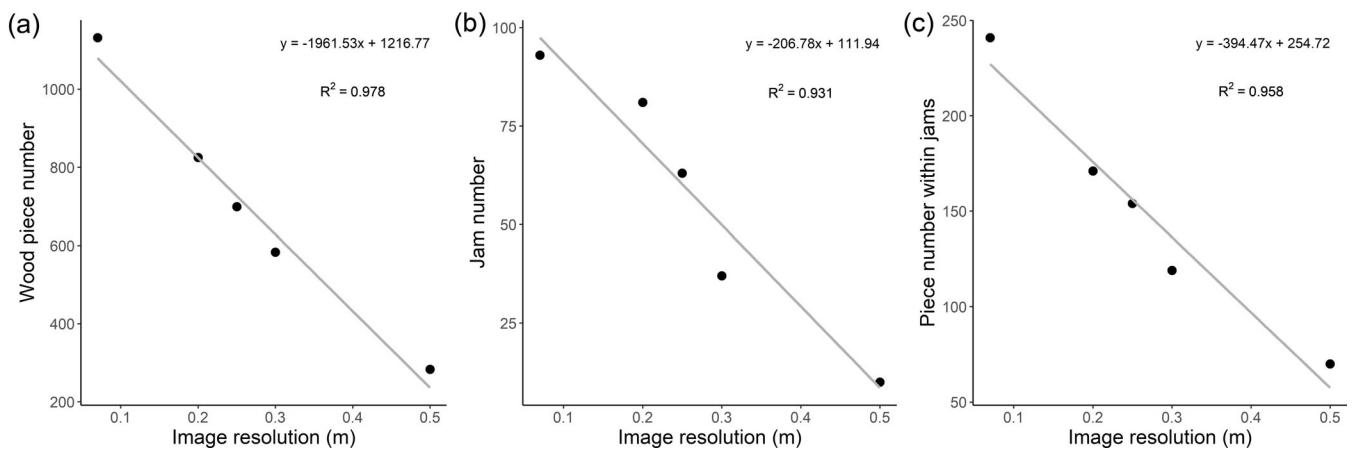


FIGURE 2 Relationship between aerial image resolution and (a) the number of wood pieces detected, (b) the number of jams, and (c) the number of wood pieces forming jams.

assessing how the number of wood pieces observed on aerial images changed with the lowering of image resolution.

The jam number and the number of wood pieces forming the jams were corrected in the same manner as the total number of wood pieces (Table 1), with both of these parameters showing a similar linear relationship with resolution (Figure 2b,c). The proportion of jams built on a key member in 2013, 2019 and 2020 were probably underestimated because the lower image resolution of the previous year's imaging resulted in lower detection of wood. Unfortunately, this error cannot be corrected.

2.5 | Hydrological conditions during the studied period

In 2008, the year before the earliest aerial image analysed, the river experienced a 5-year return-period flood. The discharge was then very low between the first and second aerial images (2009–2010). In 2012 and 2013, two 2-year floods occurred, and maximum discharge then decreased between each study periods until the 2-year return-period flood of 2020 (Figure 1i).

Using this time series of flow discharge and images obtained at fixed timepoints, several hydrological variables were derived from this series for each studied period to explain variability in individual wood piece dynamics and reach-scale budget (delta stock). Eight hydrological parameters were tested to determine the conditions influencing the departed, deposited and stable wood quantities across periods (Table 2). For each period, the time over which discharge exceeded a given threshold or was within two characteristic levels was calculated. The parameters estimated in “hours” considered the cumulative sum over the entire period (seen also as “cumulative time”) between two aerial images, whereas the ones estimated in “days” refer to individual floods that occurred during a given period. In this latter case, when more than one flood occurred within a given period, only the peak flood was considered. The following thresholds were used: mean annual discharge ($114 \text{ m}^3/\text{s}$), wood motion threshold ($270 \text{ m}^3/\text{s}$) and

frequent flood discharge ($Q_{1.5}$: $460 \text{ m}^3/\text{s}$). The threshold for wood motion was determined using video monitoring at Châtel-de-Neuvre (Robert, 2020). It is an average value corresponding to sudden wood flux increase based on the observation of four floods in 2019 and 2020. Cumulative energy was calculated by summing the discharge values during each of the rising limbs within a given period. In addition, the maximum discharge during the period was quantified. Pearson correlations were performed to test which of the eight flow parameters potentially control individual wood piece deposition, departure and stability, reach-scale budget of individual pieces as well as jam creation, destruction and stability. Analyses were run in R (R Core Team, 2022).

3 | RESULTS

3.1 | Temporal changes in the storage of individual wood pieces

3.1.1 | Inter-annual dynamics of individual wood pieces

In total, 4732 pieces were digitalised on the six aerial images with high dissimilarities between years (i.e., min and max of 298 and 1966 individuals). The corrected number of individual wood pieces detected (stored within the reach) varied between 712 (2009) and 1966 (2020), corresponding to 59 and 164 trunks per km of river, respectively. The number of wood pieces increased from 2009 to 2010, decreased between 2010 and 2016, then increased again from 2016 to 2020 (Figure 3a). This stock variability is also represented as a difference between years (Δ stock) (Figure 3a). Regarding individual piece dynamics, 2019 and 2020 were the most favourable years for wood deposits (Figure 3b). Between 2009 and 2010, a higher number of wood pieces remained stable compared with other periods and the amount of stable wood pieces increased progressively from 2013 onwards. During the period of 2009–2010, a limited number of pieces

TABLE 1 The quantified pieces and jams according to resolution and the applied correction factor.

Image date	Resolution (m)	Individual pieces			Jams			Piece number within jams		
		Detected wood pieces number	Detected proportion (%)	Correction factor	Detected jam number	Detected proportion (%)	Correction factor	Detected wood pieces number	Detected proportion (%)	Correction factor
2009	0.3	583	52	1.94	37	40	2.51	119	49	2.03
2010	0.5	283	25	4.00	10	11	9.30	70	29	3.44
2013	0.25	699	62	1.62	63	68	1.48	154	64	1.56
2016	0.25	699	62	1.62	63	68	1.48	154	64	1.56
2019	0.2	825	73	1.37	81	87	1.15	171	71	1.41
2020	0.07	1132	100	1.00	93	100	1.00	241	100	1.00

departed, opposite to the period of 2010–2013 when the proportional remobilisation (out of the total wood stock) was the highest.

3.1.2 | River discharge and dynamics of individual wood pieces

The highest correlation was found between the number of stable wood pieces and the cumulative number of hours when discharge exceeded 60% of $Q_{1.5}$ ($r = -0.98$; p -value < 0.005) and cumulative energy ($r = -0.98$; p -value < 0.005 ; Figures 4a and 5a,b), with both variables showing negative correlations. The only parameter showing a significant association with the amount of deposited wood was the duration of individual floods (the highest flood if multiple floods occurred) higher than $Q_{1.5}$ ($r = -0.99$; p -value < 0.05 ; Figures 4a and 5c). Note that only four points are presented in Figure 5c because the flow did not exceed $Q_{1.5}$ in 2010. The longest floods above $Q_{1.5}$ occurred in 2013 and 2016 (both 4 days; Figure 5g). For the periods of 2010–2013 and 2019–2020, the highest floods were used when performing the correlations, although these floods were not the ones with the longest duration (3 days and 1 day, respectively). The 2018 flood had a slightly lower magnitude than the one in 2016, which lasted one day longer, but it deposited more wood and remobilised less wood than the flood in 2016. In contrast, the 2012 and 2018 floods had the same duration but showed a large difference in magnitude ($Q_{2012} > Q_2 > Q_{2018}$, see Figures 1i and 5g). The parameters best associated with wood departure were the maximum discharge ($r = 0.96$; p -value < 0.05), the cumulative number of hours when the discharge exceeded $Q_{1.5}$ ($r = 0.98$; p -value < 0.005 ; Figures 4a and 5d,e). The Δ stock showed a significant correlation with the cumulative number of hours when discharge exceeded 60% of $Q_{1.5}$ ($r = -0.9$; p -value < 0.005 ; Figures 4b and 5f).

We analysed the arrival year and the remobilisation year of each wood piece to quantify how fast after its arrival a wood piece was remobilised or, in other words, how long it remained at the same location. We found that between 45% and 68% of wood pieces were remobilised straight away within one to three years (Figure 3c) and that 20% of the wood which arrived in 2010 and approximately 40% of the wood which arrived in 2013, 2016 and 2019 remained stationary. The proportion of newly deposited wood that was remobilised was much higher (over 40%) during the period immediately succeeding a deposition phase than in following periods (below 10%) (Figure 3c). Between 56% and 80% of newly deposited wood was remobilised before the last studied period. Maximum discharge influenced how fast the deposited wood was remobilised. The changes in deposited wood over time were dependent on the relative magnitude of successive floods. Wood departure remained below 50% (45% and 46% of the deposit in 2013 and 2016, respectively) when maximum discharge was lower than the peak flow of the preceding period and over 50% (60% and 68% of the deposit in 2019 and 2010, respectively) when maximum discharge exceeded the peak discharge that occurred during the preceding period (Figure 3d). Thus, a relative negative discharge balance ($Q_{\max}^t > Q_{\max}^{t+1}$) also resulted in lower wood

TABLE 2 The tested hydrological parameters.

Parameter	Method	Time scale	Unit
Max discharge	Maximum discharge during the period	Period	m ³ /s
Duration over which discharge exceeded mean annual discharge	Cumulative values		Hour
Duration over which discharge exceeded Q _{1.5}			
Duration over which discharge exceeded 60% of Q _{1.5}			
Duration over which discharge was between mean annual and Q _{1.5}			
Cumulative energy	Sum of the discharge values during each of the rising limbs		
Flood duration above a threshold of 270 m ³ /s	Cumulative values	Calculated individually for each flood and only the highest flood was used if multiple floods occurred over the study period	Day
Flood duration above a threshold of Q _{1.5}			

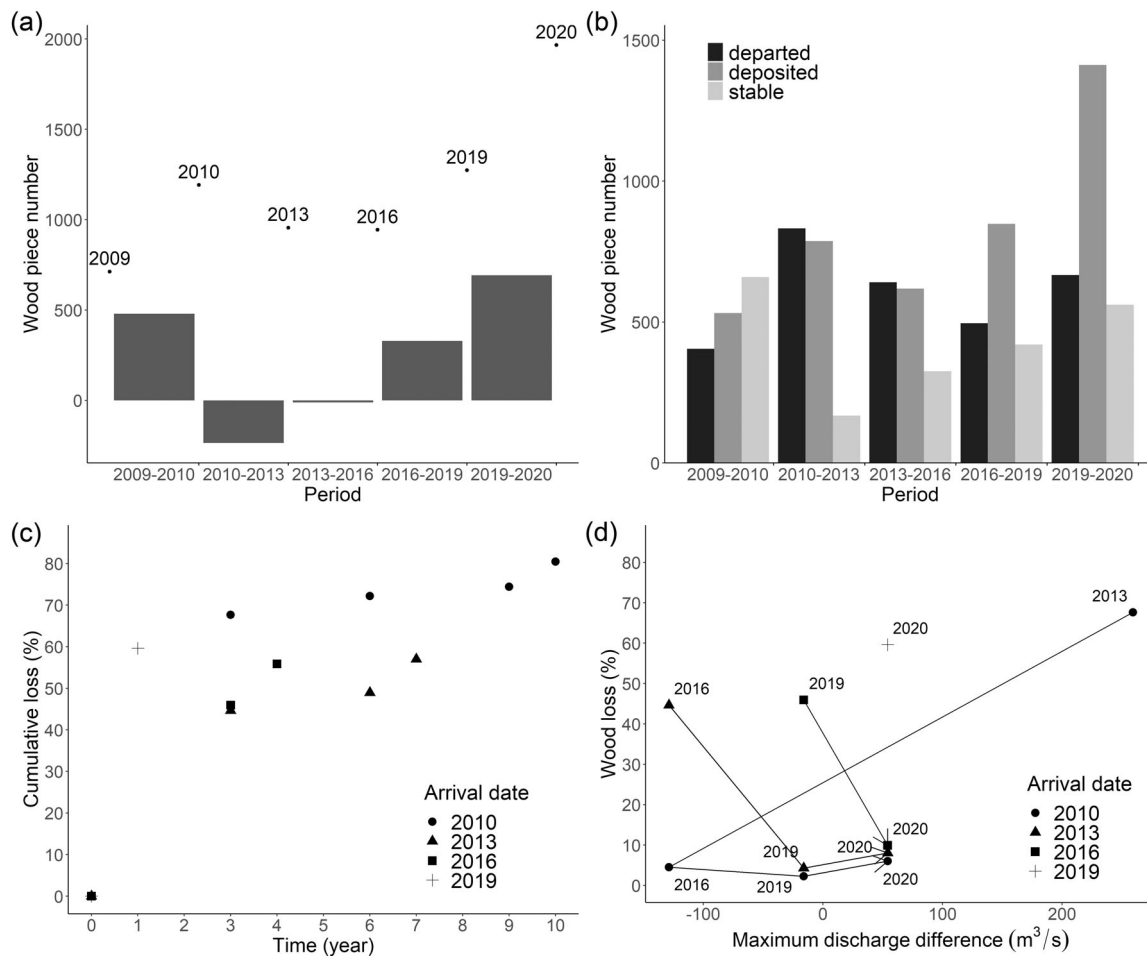


FIGURE 3 (a) Total number of wood stock per year (dots) and the changes in stock between years (Δ stock), corrected for resolution bias. (b) The number of departed, deposited and stable wood pieces per period, all corrected for resolution bias. (c) Cumulative wood loss in relation to time (100% = all deposited wood over a given time). (d) Relative change in wood loss (100% = all deposited wood over a given time) in relation to the difference in maximum discharge between successive periods. Arrows connect measurement points in order of time, departing from the initial amount of deposited wood.

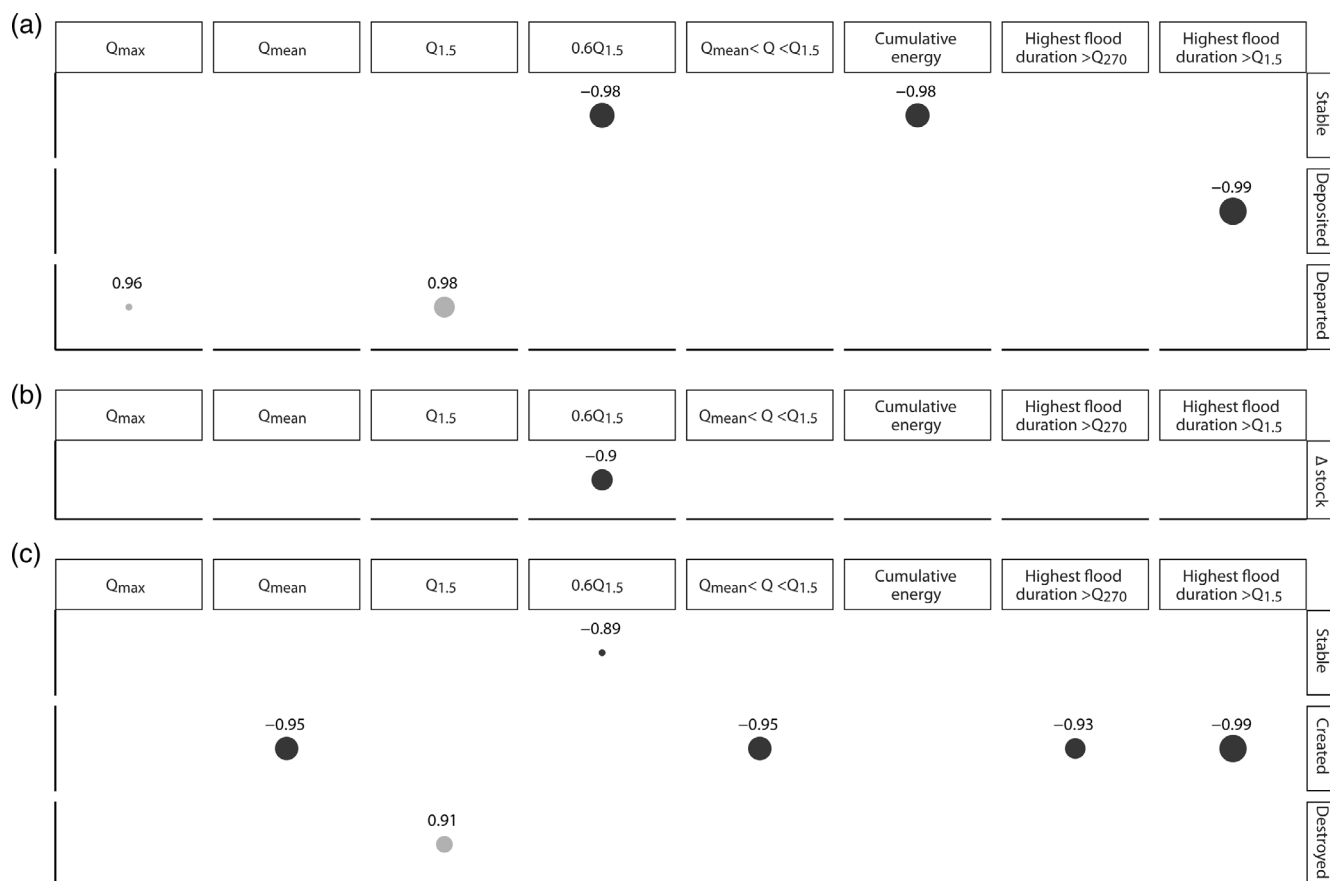


FIGURE 4 Pearson correlation coefficients (when p -values < 0.05) between the tested hydrological parameters and (a) the amount of stable, deposited and departed wood, (b) the Δ stock (difference of total wood number between two following periods), (c) the stable, created and destroyed jams. The more detailed description of the hydrological parameters are the following: Max discharge, Duration over which discharge exceeded mean annual discharge, Duration over which discharge exceeded $Q_{1.5}$, Duration over which discharge exceeded 60% of $Q_{1.5}$, Duration over which discharge was between mean annual and $Q_{1.5}$, Cumulative energy, Flood duration above a threshold of $270 \text{ m}^3/\text{s}$, Flood duration above a threshold of $Q_{1.5}$.

remobilisation (in 2010 and 2013) than the opposite situation ($Q_{\max}^t < Q_{\max}^{t+1}$, in 2016). Wood remobilisation increased when a positive discharge balance followed a negative one (the last period of deposit in 2010 and 2013).

3.2 | Temporal changes in wood jams

3.2.1 | Inter-annual change in wood jam dynamics

The corrected number of jams per survey date varied between 40 (2009) and 144 (2020), corresponding to 3.3 and 12 jams per km of river, respectively. The number of jams increased from 2009 to 2010, decreased between 2010 and 2013 and then increased again from 2013 to 2020 (Figure 6a).

The number of jams created was higher than the number of stable ones (Figure 6a). The number of stable jams was highest during the first and last studied periods (Figure 6a). The periods 2009–2010 and 2019–2020 were the most favourable for jam formation. Jam

destruction was highest over the periods 2010–2013 and 2019–2020 (Figure 6b).

Jam build-up can be facilitated by previous wood deposits. The proportions of jams built over a given period that occurred with or without wood being previously present acting as key element is shown on Figure 6c. We estimated the proportions of new jams that were built on a key member (an already present wood piece) to be 100% in 2010, >40% in 2013, 62% in 2016, >43% in 2019 and > 60% in 2020. These results indicate that deposited wood plays a facilitating role in jam formation. Even at floods close to Q_4 (period 2010–13), 40% of created jams formed where at least one wood piece was present. The proportion of jams that were built on a key member accounted for at least 43% following biannual floods (2016, 2019 and 2020). When all jams measured on an aerial image were considered (newly created and previously existing), at least 51% of jams were built on a key member (Figure 6d). The proportion of wood observed in the study reach that was stored within jam structures accounted for 55% in 2020, when no correction related to image resolution was necessary.

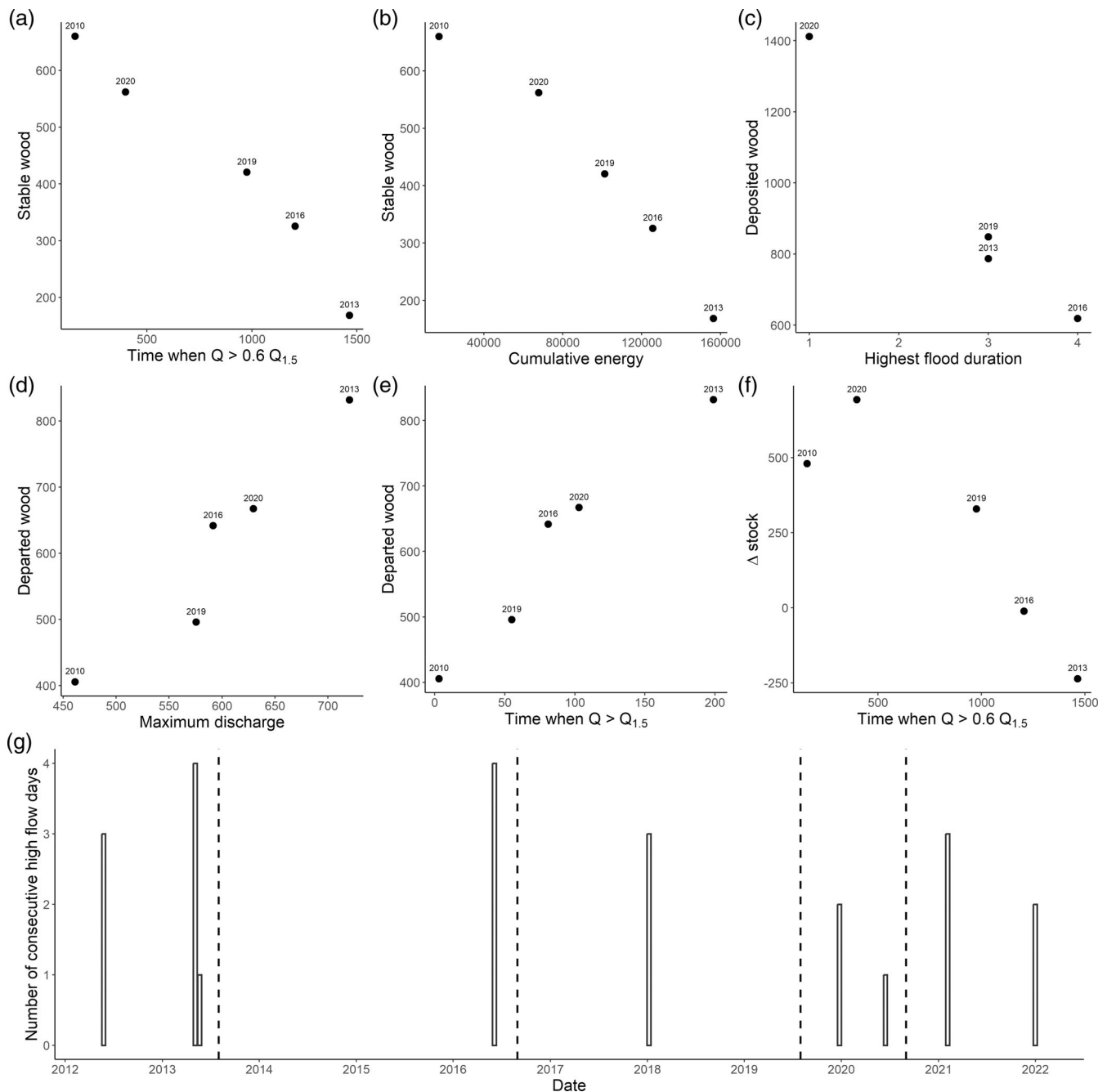


FIGURE 5 Relationships: between the number of stable wood pieces and (a) the cumulative time over which discharge exceeded 60% of $Q_{1.5}$, and (b) cumulative energy; (c) between the number of deposited wood pieces and the duration of the highest flood above of $Q_{1.5}$; between the number of departed wood pieces and (d) the maximum discharge, (e) cumulative time over which discharge exceeded $Q_{1.5}$; and (f) between the Δ stock and the cumulative time over which discharge exceeded 60% of $Q_{1.5}$. (g) Duration of all floods above $Q_{1.5}$.

3.2.2 | River discharge and dynamics of wood in jams

The variable the most correlated with stable jams was the cumulative number of hours over which the discharge exceeded 60% of $Q_{1.5}$ ($r = -0.9$; p -value < 0.05) (Figures 4c and 7a). The number of jams created correlated strongly with the duration over which discharge exceeded mean annual discharge, the duration over

which discharge was between mean annual and $Q_{1.5}$ (for both: $r = -0.95$; p -value < 0.05), and the duration over which the highest flood was above a threshold of $Q_{1.5}$ ($r = -0.99$; p -value < 0.05) (Figures 4c and 7b-d). There was also a significant negative correlation with the duration of flooding above the wood motion threshold of $270 \text{ m}^3/\text{s}$, but the relationship was not as strong (Figures 4c and 7e). A strong correlation was found between jam destruction and the cumulative number of hours over which

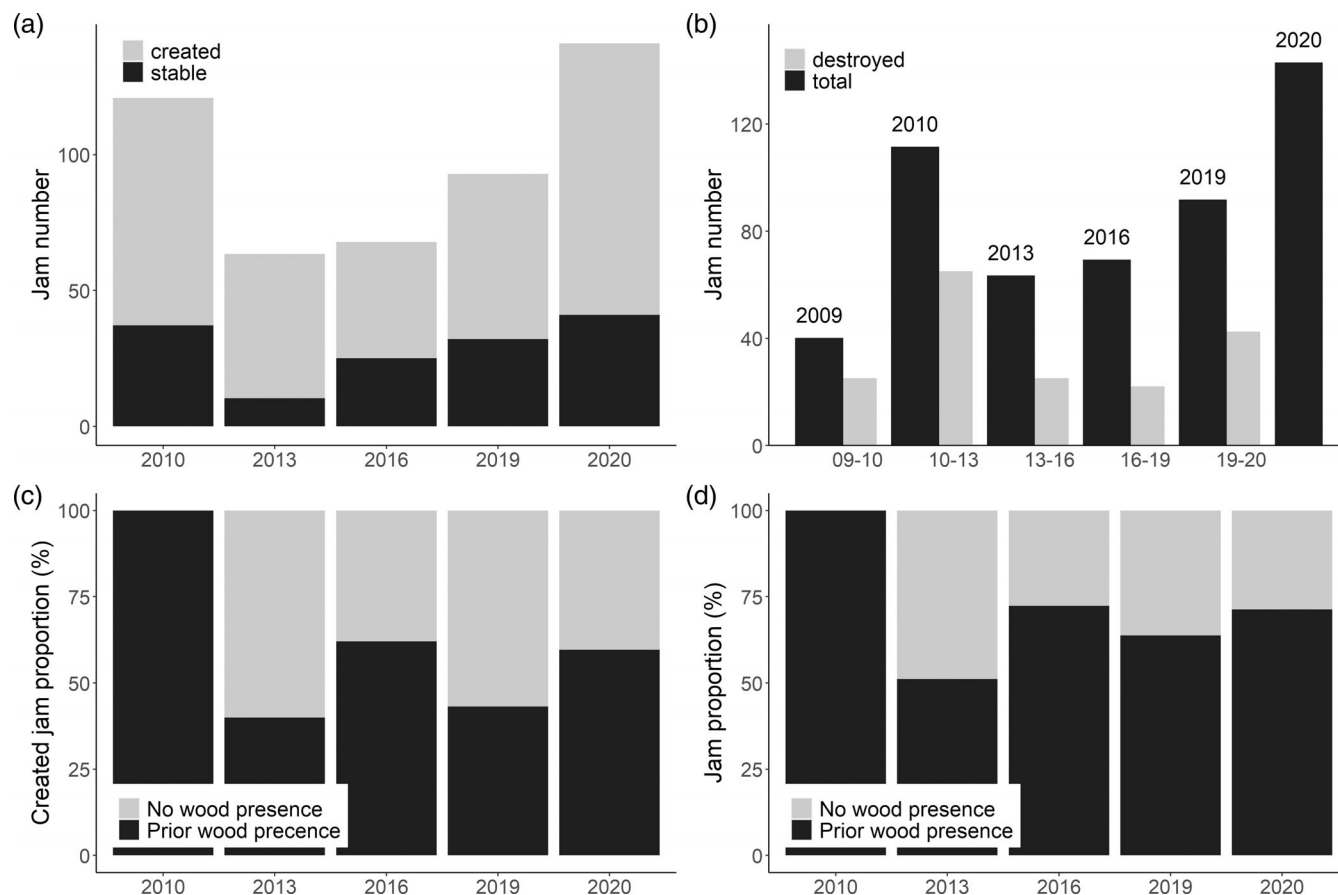


FIGURE 6 (a) Total number of jams per year composed of newly created, and stable jams, corrected for resolution bias. (b) Total number of jams per year and the number of destroyed jams during the following period. (c) Proportions of newly built (created) jams with and without prior wood presence. (d) Proportions of all jams with and without prior wood presence.

the discharge exceeded $Q_{1.5}$ (for both: $r = 0.9$; p -value < 0.05) (Figures 4c and 7f).

We also analysed the dynamics of each jam (i.e., the year of creation and the year of destruction) to quantify how fast the created jams were destroyed or how long they remained in place. We observed large differences in the proportion of jams being destroyed within one or three years, with the proportion ranging from 14% to 63% (Figure 7g). A higher proportion of jams (over 30%) were remobilised directly after their build-up (i.e., within one or three years) than during later periods (within 6–10 years; approximately 10%), as in the cases of jam creation in 2013 and 2016. However, the temporal trajectory of the jams created in 2010 was different: fewer jams were destroyed over the first period (14%) than over the second period (29%), although it is important to note that the numbers of jams represented by these percentages were very low (1 and 3, respectively). Approximately 55% of the jams created in 2010, 2013 and 2016, and 40% of the jams created in 2019, were still in place at the end of the study period. The destruction of jams in relation to discharge balance was similar to that of individual wood pieces, with the exception of 2010 (Figure 7h). A negative discharge balance during the first remobilisation period resulted in lower wood loss than the positive discharge balance. However, contrary to the pattern for individual wood pieces,

when a positive discharge balance followed a negative one, the proportion of jams destroyed decreased, or at least no further jam destruction occurred.

As explained above, some jams could remain in place for several years. Over this time, their size could fluctuate or stay unchanged. Figure 7i represents the size fluctuation of stable jams that showed a variation in size of at least 50%. The first two periods are not representative because there were only six or four jams per period. From 2013, most of the stable jams did not vary in size (at least 60%), and fewer jams decreased in size. The largest size increase was observed over the period 2019–2020, and the lowest over the period 2016–2019.

4 | DISCUSSION

4.1 | Methodology

We showed that accessible resources in the form of aerial photographs can provide valuable information on changes in wood abundance at a reach scale if differences in image resolution are carefully considered. We suggest a proportional correction of the wood count

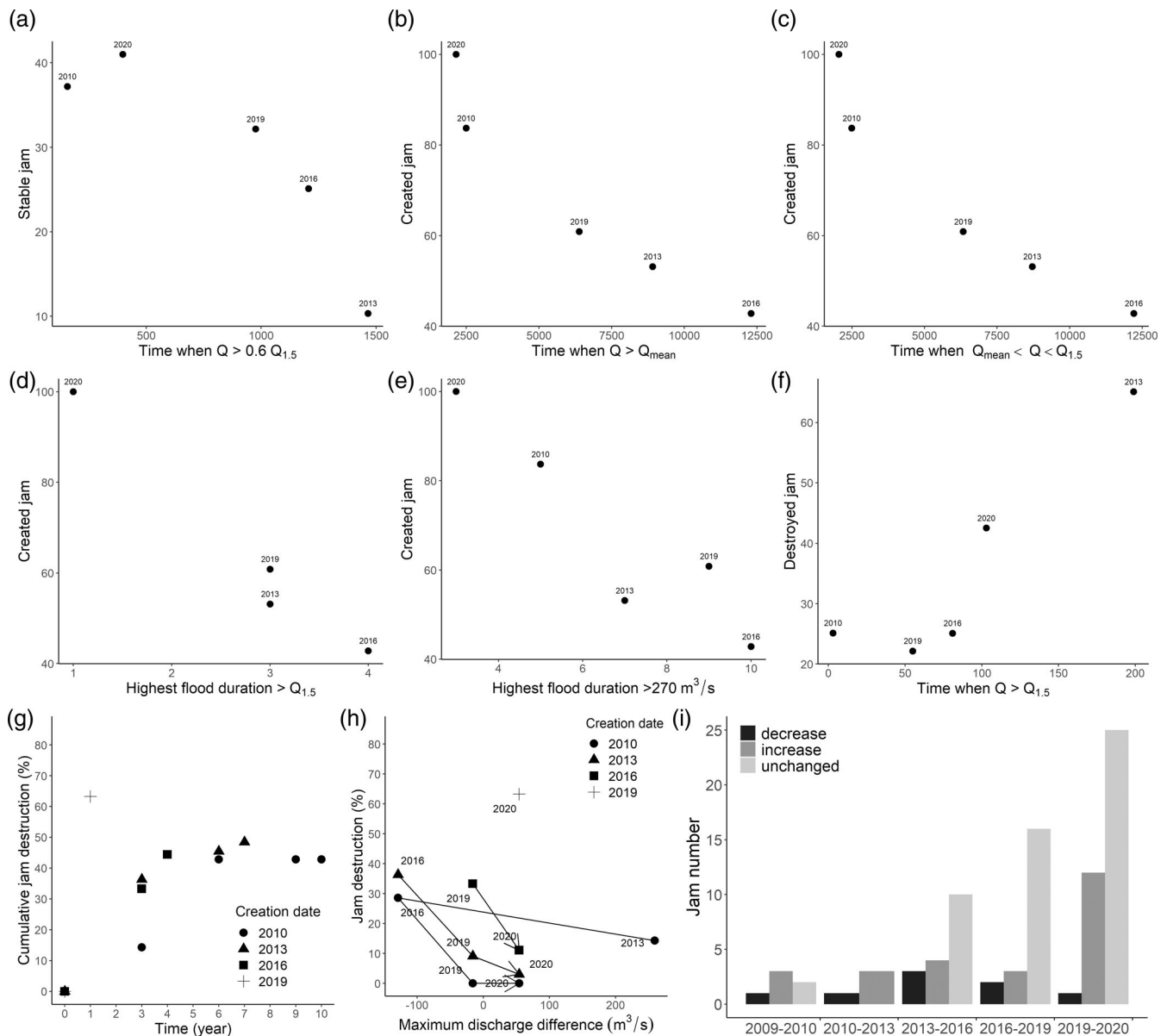


FIGURE 7 Relationships (a) between the number of stable jams and cumulative time over which discharge exceeded 60% of $Q_{1.5}$; between the number of created jams and (b) the cumulative time over which discharge exceeded the mean annual discharge, (c) the cumulative time when the discharge was between the mean annual discharge and the $Q_{1.5}$, (d) the duration of the highest flood above of $Q_{1.5}$, and (e) the duration of the highest flood above a threshold of $270 \text{ m}^3/\text{s}$; (f) between the amount of destroyed jams and the cumulative time over which discharge exceeded $Q_{1.5}$; (g) Cumulative jam destruction in relation to time (100% = all jams created over a given duration). (h) Relative change in jam destruction (100% = all created jams over a given time) in relation to the difference in maximum discharge between successive periods. Arrows connect measurement points in order of time, departing from the initial number of created jams. (i) Size fluctuation of stable jams represented as absolute values.

to overcome bias in image resolution. This can aid future analyses that utilise aerial imagery with resolutions ranging between 0.07 and 0.5 m/pixel. This methodology could also be applied to assess the spatiotemporal dynamics of large wood pieces from satellite images, thereby overcoming the resolution issues mentioned by Galia et al. (2023). While it is true that some uncertainties will inevitably arise when correcting such data, and that aerial images cannot fully replace field surveys, they still provide valuable insights into historical wood dynamics at scales that would be impossible to assess solely with field

surveys. In relative terms, a “truth” is provided by the image with the highest spatial resolution (0.07 m). Additionally, the truncation of the pieces of wood selected above 1 m long, that is, much coarser than image resolution, makes field-based validation of lesser necessity to undertake this sort of studies.

In addition to low resolution, other parameters can interfere with wood detection and inter-annual analysis of wood dynamics. Vegetation can limit wood detection when it grows on or overhangs wood deposits, such as on alluvial bars and banks. Thus, the retention time

may be underestimated and wood departure overestimated. For alluvial bars, a solution would be to integrate vegetation cover into the analysis as an indicator of stability. Between 2013 and 2016, we observed relatively important vegetation growth on alluvial bars, which probably lead to an underestimation of detections. Thus, departure could appear more important than it really was because of vegetation development and growth. Using only aerial photographs, this error can hardly be corrected. Field prospection can specify proportion of wood storage under vegetation cover and within visible areas, but there is no reason to think that the same proportions are valid for another years (or set of images).

4.2 | The Allier River, a system that stores a significant amount of wood

Studies on the frequencies of individual wood jams report large variability in storage over space and time. On a 36-km-long reach of the meandering Ain River, Lassetre et al. (2008) observed frequencies of 20 and 43 pieces of wood per km at different timepoints, locally attaining 72 pieces per km. On the Allier River, wood storage can be three times higher (59–164 trunks/km). A likely explanation for this is the higher volume of wood recruited through lateral erosion: 17–36 m³/km/year on the Ain River vs. 58 m³/km/year on the Allier River. In comparison, Moulin et al. (2011) performed a georeferenced aerial survey on a meandering river in the United States and found 55 individual wood pieces/km and 59 pieces/km forming jams, giving a total of 114 trunks/km. On an intermittent Mediterranean river, between 7.7–23.9 pieces/km and 0.4–11 jams/km were observed using 0.5-m resolution satellite imagery (Galia et al., 2023). Piégay and Landon (1997) observed up to 36–40 individual wood pieces/500 m on the Drôme river. A much higher, up to 479 trunk/km frequency was measured in the field within Alpine catchments, but authors included pieces as small as 0.3 m (Comiti et al., 2006). The jam frequency on the Allier River is between 3.3 and 12 jams/km. In comparison, Dunkerley (2014) measured (in the field) 3 jams/km on the Fowlers Creek ephemeral river, and great spatial and temporal variability (0.9–4.1 jams/km) in jams was observed on the low gradient San Antonio River in Texas (Curran, 2010). Field surveys on the Gregory and Riley creeks (British Columbia), where wood recruitment is dominated by mass movement and bank erosion, found 6 and 8.8 jams/km (Hassan et al., 2016). Because we know that the detection rate of remotely sensed data has a resolution that is significantly lower than observed field data, the remote sensing performed on the Allier shows that the amount of wood stored is fairly high and provide a very good set of samples to explore inter-annually the wood and jam dynamics.

4.3 | The critical hydrological thresholds of wood dynamics

Wohl et al. (2019) defined the wood regime as a set of components describing the complex wood transfer in river systems including wood

recruitment, transport and storage in river corridors. They indicated each of these components can be characterised in terms of magnitude, frequency, rate, timing, duration and mode and that wood regimes vary across space and through time. Inter-annual wood dynamics is evidently part of the wood regime, looking at a specific aspect of the wood regime, that is, the critical discharge that is needed to significantly entrain or deposit wood piece or, in other words, the threshold differentiating wood conditions (stored vs transported). This critical hydrological threshold can be seen as a duration or a frequency (Figure 8). It can be really meaningful to improve and validate wood entrainment rate or deposit rate in real conditions with two-dimensional hydrodynamic models that are based on a Lagrangian model for wood dynamics such as the one used by Ruiz-Villanueva et al. (2016b) on the Czarny Dunajec River or by Ruiz-Villanueva et al. (2014a).

The proportions of wood and jam deposition or creation and departure or destruction varied over the study period; thus, the factors controlling the two aspects probably differ. This is in line with the asynchronous wood deposit and departure observed over a 10-year period within small low-order reaches in Chile (Iroumé et al., 2020). The relationship between peak flows and wood remobilisation described in previous studies at the basin scale (Moulin & Piégay, 2004; Ruiz-Villanueva et al., 2019) seems to be also observed when studying wood dynamics at the reach scale. Higher maximum discharges result in higher amounts of wood remobilisation. However, wood departure correlates best with the duration over which discharge exceeds dominant flood discharge. This also corresponds to the discharge condition that facilitates jam removal. Observations on Chilean low-order rivers also suggested higher large wood mobility when flow discharge exceeds bankfull discharge (Iroumé et al., 2015). Gregory et al. (1985) monitored wood jams over a year on a small river in England. Over that period, one high-flow event approached bankfull discharge and removed 36% of the jams. Probably the most similar hydrological conditions observed on the Allier River were those between 2009 and 2010, when it had a similar (40%) jam removal rate. The duration of the highest magnitude flood (over $Q_{1.5}$) had the strongest correlation with wood deposition and the occurrence of new jams. When the water level exceeds $Q_{1.5}$ over a long period, wood deposition and jam build-up decrease. Following Iroumé et al. (2015) and the hydraulic geometry theory of dynamic adjustment, we would argue $Q_{1.5}$ corresponds to bankfull discharge on the Allier. Estimating real bankfull discharge is clearly challenging, especially as it can vary locally within a river reach but there are several evidence that bankfull is frequent (no significant incision of the river, field observations showing frequent overbank flows within the floodplain). Overpassing bankfull discharge can influence flow conditions, and interactions with the riparian forest can influence wood dynamics and this could be potentially the case on the Allier. Most wood pieces and jams remained stable when river discharge remained below 60% of frequent flood discharge over a long period of time. Analysis of video recordings of the Ain river allowed quantification of the wood motion threshold, which is approximately when discharge reaches that threshold (Ghaffarian et al., 2020; MacVicar & Piégay, 2012). Our

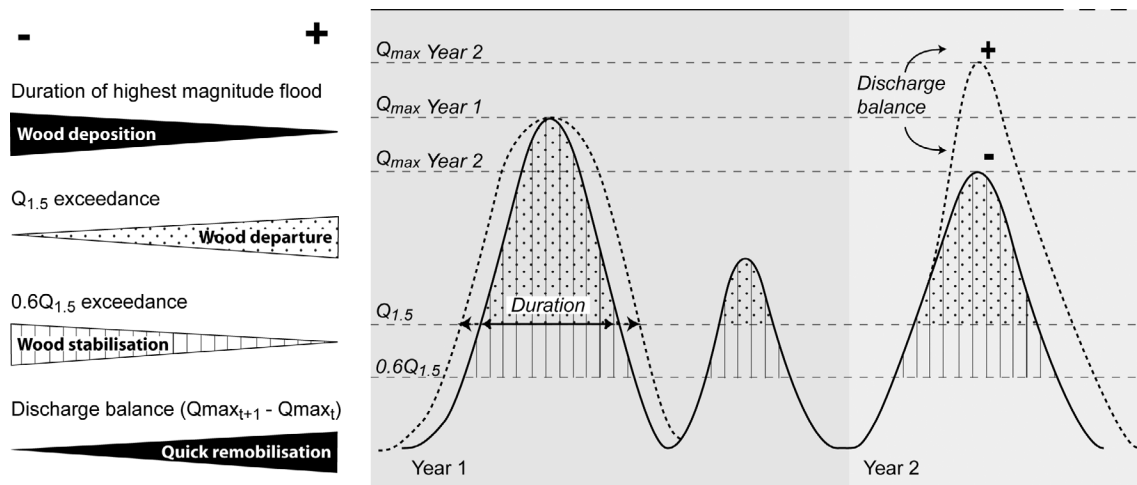


FIGURE 8 Conceptual model summarising key results from this study.

results are in line with this finding because the amount of stabilised wood on the Allier River decreased when the number of hours exceeding $0.6 Q_{1.5}$ during a given period increased. The same tendency was observed for the reach-scale budget (Δ stock). Thus, these three hydrological conditions ($Q > Q_{1.5}$, duration of the highest magnitude flood, and $0.6 Q_{1.5}$) can determine the dynamics of individual wood pieces and jams at the same time, which tend to fluctuate in parallel. This means that there are two critical discharge levels: $Q_{1.5}$ and the $0.6 Q_{1.5}$ threshold. A discharge over bankfull level over a relatively long period is necessary to activate wood departure, and also to promote individual log deposition. Between 2009 and 2010, the mean daily discharge did not exceed $Q_{1.5}$ discharge, resulting in the lowest amount of deposited individual wood pieces and the only period over which more wood pieces remained stable than were either deposited or departed (i.e., low dynamism). However, this was not the case for logjams, because we recorded the second highest jam creation rate over the same period. All the newly formed jams were built around so-called key members, that is, wood was mostly retained by existing logs. Compared with other periods, more new jams were proportionally formed than isolated deposits. Kramer and Wohl (2017) hypothesised that the greatest influence on large wood transport distance was the flow duration near or just under bankfull discharge and also suggested that a shorter travel distance due to shorter floods can lead to increasing jam build-up.

Most of the stable jams did not show significant changes in size between 2013 and 2020. This can be related to the relatively low maximum discharge, which fluctuated around Q_2 , and the increasing distance of jams from the river channel due to lateral erosion. Many jams seemed to decrease in size between 2013 and 2016, but their actual number was quite low, and vegetation colonisation over stable jams (as observed) can reduce visibility leading to false estimates of wood loss. Between 2019 and 2020, a significantly higher number of jams expanded in size compared with other periods, in line with preferential organisation of wood into jam structures during the shorter biannual floods explained above. Even if the methods were

adapted to reduce errors, it is possible that the jam size expansion was overestimated when several wood pieces break down into smaller pieces within the same jam. At the same time, a stable jam can be considered as unchanged when the numbers of deposited and departed pieces are equal. This situation was rarely observed in this case study. However, in some cases, a slight change in orientation or a few upstream pieces were noted without a global fluctuation in jam size.

On the braided Queets River in the United States, wood remobilisation within a 5-year period was estimated at 50% (Latterell & Naiman, 2007). On the Arly and Isère Rivers, 60%–70% of wood pieces were remobilised, despite the absence of significant floods, which was not the case on the Arc River (France), which showed lower wood mobility over the same period (Piégay et al., 2017). An analysis based on multiple studies showed that the remobilisation rate of stored wood remained below 30% when discharge did not exceed bankfull level and that departure rates can reach 80% or higher at discharge equal to or exceeding bankfull level (Kramer & Wohl, 2017). In line with previous findings, the departure rate of individual wood pieces in the Allier River was between 38% and 83%, and ranged from 40% to 86% for jams. If we look at wood dynamics relative to wood deposits, between 45% and 68% of newly deposited trunks are rapidly remobilised downstream within a timespan of one to three years (depending on aerial image frequency). Monitoring dynamics relative to wood deposits allows the flood history of deposited wood pieces to be taken into account, and therefore, retention time can be related to the hydrological conditions experienced by wood pieces during arrival and the succeeding period until departure conditions occur (if this happens within the studied period). It appears that at least 45% (and up to 60%) of wood is entrained by floods of lower, identical or slightly higher energy than the one that deposited it (Figure 3d). Whether wood is actually departed can be questioned when high sediment deposition is observed. Wood can potentially be buried in such cases, instead of being remobilised, but this phenomenon is difficult to accurately define on aerial imagery (and sometimes even in the



FIGURE 9 Aerial photographs of two identical locations in (a) and (c) 2019, (b) and (d) 2020 showing potential wood burial. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/raa.4242)]

field). Some clues suggest that this situation happened between 2019 and 2020 (Figure 9), although we were unable to determine whether this is a common or occasional process, and whether it is linked to specific hydrological conditions.

Several authors (Haga et al., 2002; Moulin & Piégay, 2004; Ruiz-Villanueva et al., 2019) suggested that the order and frequency of flood occurrence play an important role and that two successive floods of similar magnitude do not always have the same effect on wood dynamics. The peak discharge in 2020 reached a higher level than in 2013, 2016 and 2019, but the floods in 2020 and at the end of 2019 were of shorter duration (Figure 5). It has already been argued that flood duration can influence log transport distance (Kramer & Wohl, 2017; Piégay et al., 2017; Ravazzolo et al., 2015) and thus that the duration of flow above a critical discharge determines transport distance, rather than flow magnitude (Piégay et al., 2017). If this is also the case on the Allier River, wood deposit during shorter floods probably (at least partially) originated from nearby sources, as demonstrated on the Tagliamento river (Bertoldi et al., 2013). Our results indicate that hydrological parameters, such as time when river discharge remained below or exceed 60% of frequent flood discharge conditions stability at the two spatial scales, that is, reach (storage) and individual/jam scales, at least at our study site within this relatively low flow conditions. Another possible explanation of the increasing stability is that the succession of floods

of similar discharge (around $Q_{1.5}$ - Q_2) and the decreasing duration of flood events since 2016 have reinforced the trapping effect of wood obstacles, thereby leading to positive feedback. Boivin et al. (2017) suggested that individual wood pieces introduced by high-flow events are transported towards already existing jams during subsequent floods. Once a logjam is formed, it then becomes an efficient trapping element for individual wood logs (Dixon & Sear, 2014; Millington & Sear, 2007). A study by Pettit et al. (2005) demonstrated that the majority of jams that are initiated by a key member have a greater size than those that are not initiated by a key member. In line with this, the number of jams increased after 2016, and since 2013, proportionally more wood was stored within jams than was deposited in the form of individual logs. Furthermore, a one-year duration with a complete absence of high flows preceded the floods of 2019–2020, a situation that is very favourable to the generation of high wood flux (Zhang et al., 2021). Moreover, the colonisation of alluvial bars by vegetation creates additional natural retention sites, resulting in a situation where floods of around $Q_{1.5}$ - Q_2 are insufficient to remove wood. This is clearly visible on the aerial images (Figure 1), where active channel width can be seen to decrease over time, in line with the alluvial landscape dynamics of 1964 to 2000 (Petit, 2006). However, as explained earlier, the exact amount of wood retained by riparian vegetation cannot be estimated through analysis of aerial images.

Model simulations made by Ruiz-Villanueva et al. (2014b) demonstrated that water depth over a particular surface plays an important role in the control of wood deposition. In this context, the remobilising process can be hindered if positive biogeomorphic feedback between wood, sediment and living vegetation creates the conditions for the emergence of biogeomorphic units, which in turn lead to rising topographic level (Collins et al., 2012; Corenblit et al., 2011; Gurnell, 2014). The increasing amount of stabilised wood since 2013 is also a sign of an increasingly steady system. Considering these findings in the context of climate change, we can ask the question whether longer low-flow periods accompanied by an absence or low frequency of large floods result in an increased opportunity to trap wood on bars and slow down its downstream remobilisation, with potential counter effects in terms of blockage at downstream-located infrastructure and flooding in the case of smaller rivers. Several studies (Curran, 2010; Wohl & Goode, 2008) revealed direct links between increasing wood residence time or persistent jams and increased influence on ecology, channel hydraulics and geomorphology. We also showed that wood can remain stable over several years, depending on hydrological conditions. Local conditions of sediment texture, topographic evolution and water temperature modification in relation to large wood should be analysed and related to habitat conditions at variable channel gradients to achieve integrative river management solutions.

5 | CONCLUSION

In this study, we determined which hydrological drivers are best correlated with large wood dynamics within a 12-km-long reach of the Allier River. Overall, dynamism patterns were found to be similar to those observed in other studies at the basin scale, with features being shared between individual pieces and logjams. Both flow magnitude and duration are important considerations when investigating wood deposit, departure and storage, with there being three key parameters: $Q > Q_{1.5}$, duration of peak flow and $Q < 0.6Q_{1.5}$. Newly deposited wood has, on average, a 50% chance of being remobilised immediately, depending on whether relative discharge is positive (i.e., $Q_{\text{remobilisation}} > Q_{\text{installation}}$) or not. Jams are more durable elements of the river landscape than isolated wood pieces, and about half of jams are built up on so-called key members. The Allier River shows a rather high density of large wood, and the stability of wood deposits has risen over the last decade, with an increasingly high proportion of wood being trapped in jams. It is likely that a potential positive feedback loop has occurred between wood, sediment and riparian vegetation, because the successive floods around Q_2 have progressively increased stability. Knowledge on large wood dynamics and the potential effects of wood on channel morphology can be useful for river management actions, including wood reintroduction. Our understanding of the retention time should be extended in future research with related habitat analysis, which could help in the design of habitat restoration projects.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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