A high-resolution temporal framework to understand the reach-scale controls on wood budgeting

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A high-resolution temporal framework to understand the reach-scale controls on wood budgeting

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Hydrological control of wood budget

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Abstract

Large active channels usually store more wood than channels with a narrow flow because of the availability of large unvegetated bars for wood deposition and inner functioning that usually supplies more wood through channel shifting. However, the dynamics of the wood supply (wood input, output, or stability) can vary substantially over time and the drivers are largely unknown. To explore them, we studied the temporal variability 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 biannual (Q_2) flood magnitude. We show that the wood budget was controlled by specific hydrological conditions. Wood output was best explained by water levels exceeding bankfull discharge ($Q_{1.5}$). The duration of the highest magnitude flood (over bankfull discharge) was the best predictor of wood inputs, with shorter floods resulting in higher input rates. Finally, most of the wood remained stable when the river discharge did not exceed 60% of the bankfull discharge over a long period of time. Hydrological conditions driving jam build-up and removal were similar to those controlling individual wood piece dynamics. A succession of floods of similar (relatively low ~ Q_2) magnitude and decreasing flood duration since 2016 have probably reinforced the filtering effect of wood obstacles, leading to positive feedback, which has been strengthened by riparian vegetation colonisation of the active channel.

Keywords

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

1. Introduction

Human attitudes towards large wood in rivers are currently two-sided. On the positive side, in-channel 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 channel and on alluvial bars (Gurnell et al., 2002; Gurnell & Sweet, 1998; Piégay & Gurnell, 1997; Wohl, 2013). Moreover, in-channel wood also provides organic matter for the food chain (Elosegi et al., 2007; Guiney & Lininger, 2022). On the negative side, wood is perceived as a risk for infrastructure such as bridges and dams when individual pieces form obstructions (Ruiz-Villanueva et al., 2014; Schmocker & Hager, 2011). Wood accumulation can also reduce the channel section and induce a water level rise upstream from the jam, thereby increasing the upstream flood risk. Wood jam-induced high water velocity around an obstacle leads to scouring and can increase the fragility of infrastructure. Furthermore, large floating logs during floods can cause direct damage to houses and other infrastructure (Le Lay et al., 2013).

Most of the wood stored in medium to large river corridors is recruited through lateral bank erosion, and is strongly controlled by land cover (the availability of wood on the banks) (Iroumé et al., 2014; Massé & Buffin-Bélanger, 2016), channel morphology, and hydrology (Gurnell & Petts, 2002; Piégay et al., 1999). Wood recruitment has been studied at the local (Piégay & Marston, 1998) and watershed scales (Boivin et al., 2017b), and over short interannual (Boivin et al., 2017a) to decadal time scales (Lassettre et al., 2008).

The above mentioned studies and other works (e.g. Wohl & Cadol, 2011) emphasise the controlling role of geomorphology in wood recruitment and wood storage. Once wood is recruited, logs are transported downstream at various speeds and frequencies depending on their length and shape (which effect resistance to flow), and their position within the catchment (e.g., the flow conditions allowing transport are related to flow depth over space and time).

Model simulations by Ruiz-Villanueva et al. (2016) demonstrated that it is mainly water depth, rather than surface roughness, that determines preferential sites for wood deposition in different geomorphic units. Tree trunks can be deposited as individual pieces or they can form logjams (Piégay, 1993). A single piece of wood is capable of trapping and stabilising other logs, and thereby initiating jam development; this first element of the jam is called the “key member” (Abbe & Montgomery, 1996).

Wood stability is an important parameter for modelling and potentially preventing hazards associated with large wood, although it can be difficult to assess. The 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, Wyżga, et al., 2016). The deposition of large pieces of wood and jams can have a high residence time counted in decades, even reaching up to 200 years, and they can generate significant morphological changes (Keller & Swanson, 1979). Wood tends to be more mobile in low gradient channels, but highly mobile large pieces of wood and jams can also influence channel morphodynamics and downstream hydrology. An example of relatively stable jams can be found in Australian ephemeral streams, where they are key to driving geomorphic processes (Dunkerley, 2014). Gregory et al. (1985) demonstrated the role of wood jams in slowing down the travel time of water, and thereby influencing a river's hydrography. Individual wood pieces that become entwined within a jam obviously show much longer transit durations than free pieces of wood (Kramer & Wohl, 2017). Jam size can fluctuate, with the episodic release and capture of wood (Piégay et al., 2017). One of the elementary parameters determining jam size is the size of the recruited trees or transported logs (Likens & Bilby, 1982). 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 accounted wood is stored within logjams.

Wood input and output at the reach-scale can be analysed using information gathered through repeated field campaigns (Boivin et al., 2017a; 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., 2008; B. J. 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. (2008) 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. Lassettre 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). Atha (2014) used 1-m-resolution satellite images from 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 time-scales.

Even if we know both where wood is potentially coming from and the preferential sites for storage, wood budgeting at the reach-scale remains a complex question: it is still difficult to predict when and how much wood will arrive and depart from a specific river reach, as well as its duration of residency. There is a crucial need to understand the processes controlling wood kinetics to calibrate algorithms predicting wood mobility 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 to export. 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, Piégay, et al., 2016; Senter et al., 2017). However, the relationship appears to be nonlinear and slightly noisy (Boivin et al., 2015; B. 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 input and output under different hydrological contexts, thereby helping to obtain an understanding of the main controlling factors.

Wood surveys at reach scale frequently concentrate on one dimension, 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 time-scales, 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, 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 inputs and outputs of wood within the overall budget in relation to flow history.

Our aim with this paper is to achieve a better understanding of the drivers that control wood budgets at the reach-scale, considering individual wood pieces and jams in terms of inter-annual inputs, outputs, and stability. To accomplish this, we designed a comparative approach based on a high frequency inter-annual survey strategy to evaluate geomorphological and hydrological factors controlling wood input, output, and storage at the reach-scale. 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 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). The 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 m^3/s, with Q_2 and Q_{10} of 560 and 940 m^3/s, respectively.

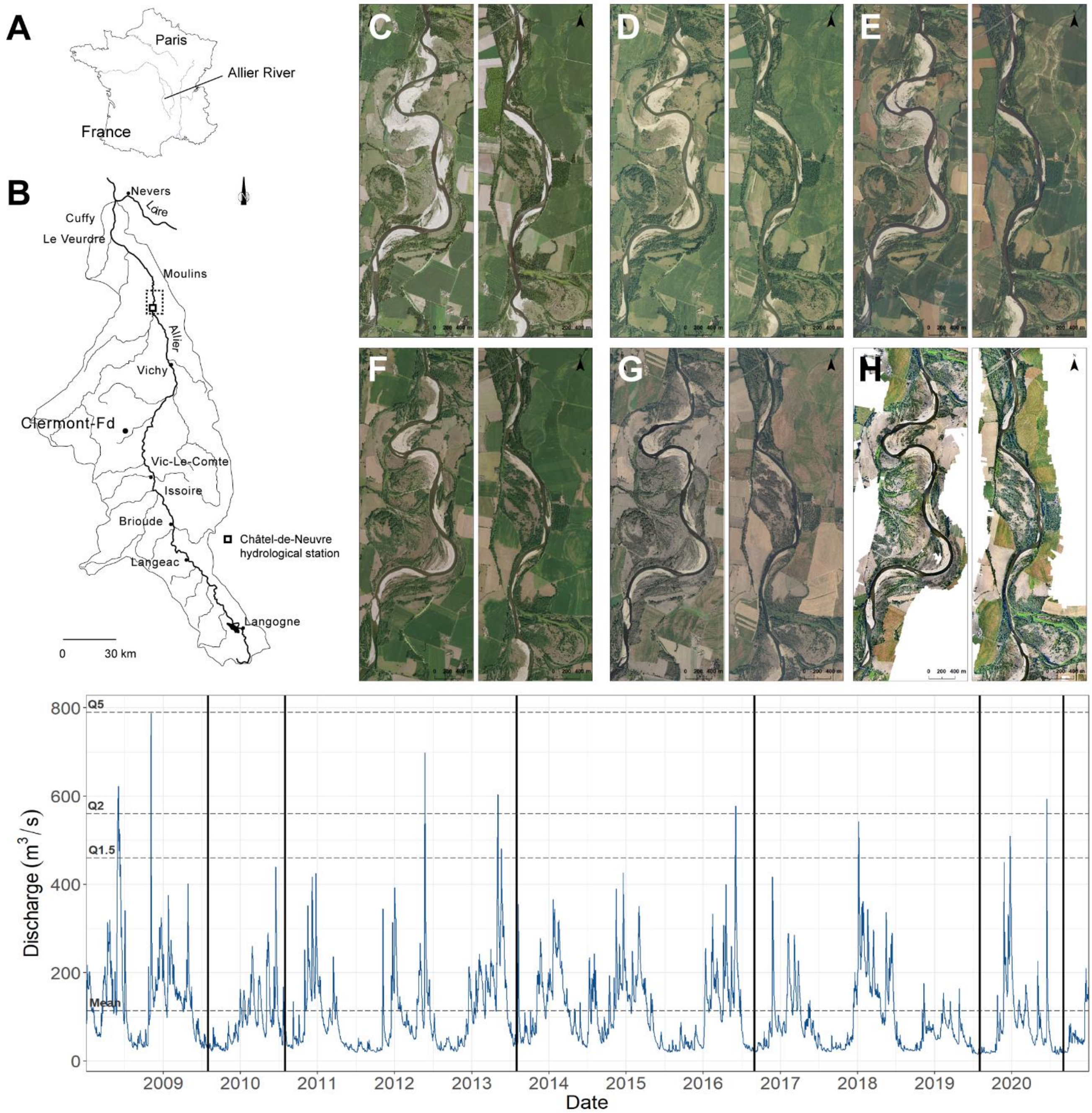


Figure 1. (A) Location of the Allier River within France. (B) River basin of the Allier River and the location of the study reach within the dotted rectangle. (C)-(H) The six aerial images (2009, 2010, 2013, 2016, 2019 and 2020) analysed to sense individual wood pieces and jams. The left image corresponds to the upstream part of the study site, 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.

2.2. Survey of wood input and output

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). We generated three groups of information from the six maps: (i) the total number of wood pieces; (ii) the number of imported, exported, and stable wood pieces at each date; and (iii) the retention time of each wood piece. Groups (ii) and (iii) were estimated used the spatial join tool of ArcGIS.

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, Piégay, et al., 2016). We identified which jams had been created, destroyed, or were stable from one period to the next. In addition to the number of jams present at each survey 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 when the decrease or increase in size was at least 50%, with this definition being chosen to reduce possible quantification error and to focus on substantial changes. The size of a jam was considered be stable 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 reporting of false increase in jam size due to wood breakage within jam structures. The proportion of wood stored within jams in relation to the total amount of wood quantified within the reach was calculated for each survey date.

2.4. Correction of image resolution bias for wood sensing

The aerial photographs were acquired during low-flow periods and had a resolution varying from 0.5 to 0.07 m/pixel. 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. Comparisons between the different resolutions revealed a linear relationship between image resolution and the number of detected wood pieces (Figure 2A), which meant that a simple correction factor could be applied to quantify changes in wood storage across the years.

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, with both of these parameters showing a similar linear relationship with resolution (Figure 2B, C).

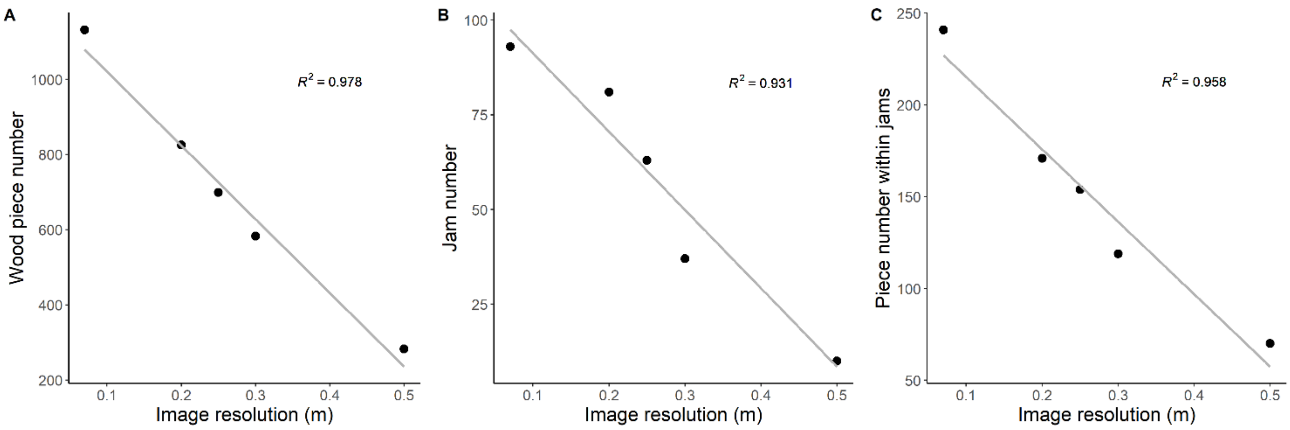


Figure 2. Relationship between aerial image resolution and (A) the number of wood pieces detected, (B) the number of jams, and (C) the number of wood pieces forming jams.

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 imaging obtained at fixed timepoints, several hydrological variables were derived from river discharge to explain wood budget variability. Ten hydrological parameters and two parameters related to erosion processes were evaluated to determine the conditions influencing the exported, imported, and stable wood quantities across periods. For each period, the time over which the water discharge exceeded a given threshold or was within two characteristic discharge levels was calculated. The parameters estimated in “hours” considered the cumulative sum over the entire period 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 m^3/s), wood motion threshold (270 m^3/s), bankfull discharge (in this paper $Q_{1.5}$ is used; 460 m^3/s), and Q_2 (560 m^3/s). The wood motion threshold was determined using video monitoring at Châtel-de-Neuvre. 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 and the total shrub- and forest-covered eroded surfaces (ha) were quantified. Pearson correlations were performed to test which of the eleven parameters modulated wood input and output, jam stability, and the amount of wood in jams. R software (R Core Team, 2022) was used for this analysis.

3. Results

3.1. Temporal changes in the storage of individual wood pieces

3.1.1. Inter-annual change in storage of individual wood pieces

The corrected number of individual wood pieces detected 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 3).

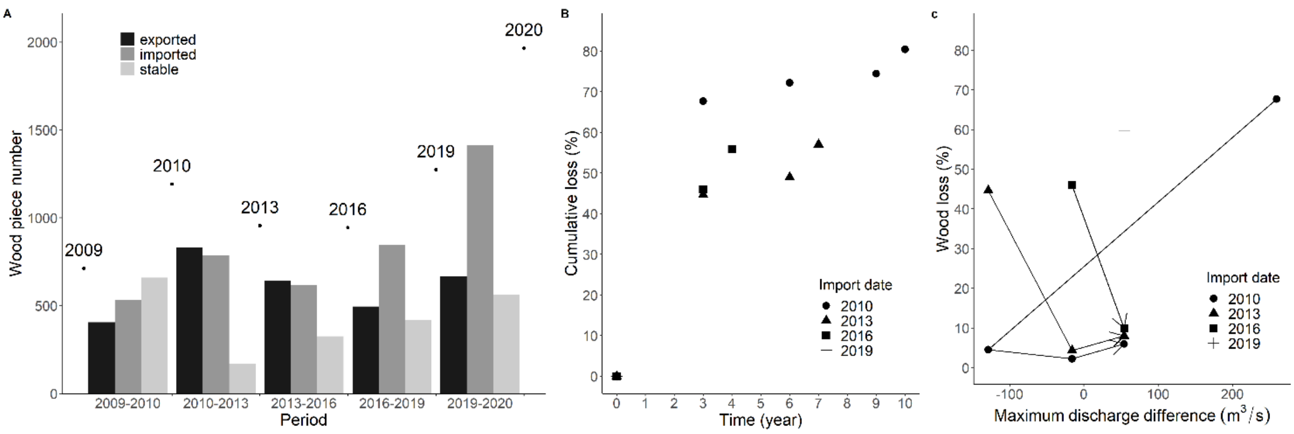


Figure 3. (A) Total number of wood pieces per year (dots), and number of exported, imported, and stable wood pieces per period (bars), all corrected for resolution bias. (B) Cumulative wood loss in relation to time (100% = all imported wood over a given time). (C) Relative change in wood loss (100% = all imported wood over a given time) in relation to the difference in maximum discharge between successive periods.

The amount of imported wood pieces was always higher or very similar to the exported amount (Figure 3). The periods 2016–2019 and 2019–2020 were the most favourable for wood import. Between 2013 and 2016, wood import and export were approximately balanced. Wood export increased from 2010 to 2013, then decreased until 2019, when it then increased again. The highest wood export occurred in 2013. Between 2009 and 2010, a higher number of wood pieces remained stable than were either imported or exported. The amount of stable wood pieces then increased progressively from 2013 onwards.

3.1.2. River discharge as a parameter for predicting storage of individual wood pieces

The best explanatory variables for the number of stable wood pieces were the cumulative number of hours when the discharge exceeded 60% of bankfull discharge ($r = -0.99$; p-value < 0.005) and cumulative energy ($r = -0.98$; p-value < 0.005; Table 1, Figure 4A, B), with both variables showing negative correlations. There were also significant and strong negative correlations with erosion rate and vegetated eroded surface (Table 1, Figure 4C, D). The parameters best-explaining wood export were maximum discharge ($r = 0.96$; p-value < 0.05), the cumulative number of hours when the discharge exceeded bankfull discharge ($r = 0.98$; p-value $= 0.005$), and erosion rate ($r = 0.95$; p-value < 0.05; Table 1, Figure 4E, F, G). The only parameter showing a significant association with the amount of imported wood was the duration of individual floods (the highest flood if multiple floods occurred) higher than bankfull discharge ($r = -0.99$; p-value < 0.05; Table 1, Figure 4H). Note that only four points are presented in Figure 4H because the flow did not exceed bankfull discharge in 2010. The longest floods above bankfull discharge occurred in 2013 and 2016 (both 4 days; Figure 4I). 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 imported more wood and exported 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 ($Q2012 > Q_2 > Q2018$, see Figure 1I, Figure 4I).

Table 1. Pearson correlation coefficients (and p-values) between the tested hydrological parameters and (i) the amount of stable, exported, and imported wood, (ii) the stable, destroyed, and created jams and (iii) the proportion of wood pieces forming the jams (100% = total number of wood pieces per year).

† *Cumulative values computed for the entire study periods*

‡ *Values were calculated individually for each flood and only the highest flood was used for the correlation if multiple floods occurred over the study period.*

Type	**Dynamic**	**Max discharge†**	**Duration over which discharge exceeded mean annual discharge†**	**Duration over which discharge exceeded bankfull discharge†**	**Duration over which discharge exceeded 60% of bankfull discharge†**	**Duration over which discharge was between mean annual and bankfull discharge†**	**Duration over which discharge exceeded Q_2 discharge†**	**Cumulative energy†**	**Erosion (ha) †**	**Eroded shrub and forest surface (ha) †**	**Flood duration above a threshold of 270 m^3/s‡**	**Flood duration above a threshold of bankfull discharge‡**
Individual wood	Stable	−0.8 (0.100)	−0.8 (0.090)	−0.8 (0.093)	**−0.99 (<0.005)**	−0.8 (0.096)	−0.9 (0.126)	**−0.98 (<0.005)**	**−0.9 (<0.05)**	**−0.9 (<0.05)**	−0.6 (0.288)	−0.7 (0.312)
	Exported	**0.96 (<0.05)**	0.5 (0.438)	**0.98 (0.005)**	0.7 (0.198)	0.4 (0.453)	0.9 (0.093)	0.8 (0.105)	**0.95 (<0.05)**	0.7 (0.225)	0.0 (0.970)	−0.1 (0.935)
	Imported	0.4 (0.475)	−0.5 (0.449)	0.3 (0.620)	−0.2 (0.740)	−0.5 (0.439)	−0.4 (0.571)	−0.0 (0.973)	0.0 (0.956)	−0.2 (0.815)	−0.6 (0.297)	**−0.99 (<0.05)**
Jam	Stable	−0.7 (0.210)	−0.7 (0.158)	−0.8 (0.134)	**−0.9 (<0.05)**	−0.7 (0.165)	−0.9 (0.090)	−0.9 (0.068)	−0.9 (0.056)	−0.7 (0.154)	−0.5 (0.388)	−0.6 (0.392)
	Destroyed	0.8 (0.084)	0.1 (0.903)	**0.9 (<0.05)**	0.4 (0.478)	0.1 (0.922)	0.8 (0.221)	0.5 (0.367)	0.8 (0.109)	0.3 (0.675)	−0.3 (0.611)	−0.3 (0.716)
	Created	−0.3 (0.623)	**−0.95 (<0.05)**	−0.3 (0.612)	−0.9 (0.058)	**−0.95 (<0.05)**	−0.5 (0.522)	−0.8 (0.134)	−0.5 (0.348)	−0.9 (0.067)	**−0.9 (<0.05)**	**−0.99 (<0.05)**
Proportion of wood pieces forming the jams	-	−0.3 (0.636)	−0.2 (0.733)	−0.3 (0.574)	−0.1 (0.923)	−0.2 (0.740)	**−0.96 (<0.05)**	−0.2 (0.781)	0.2 (0.692)	0.4 (0.523)	0.2 (0.768)	−0.1 (0.837)

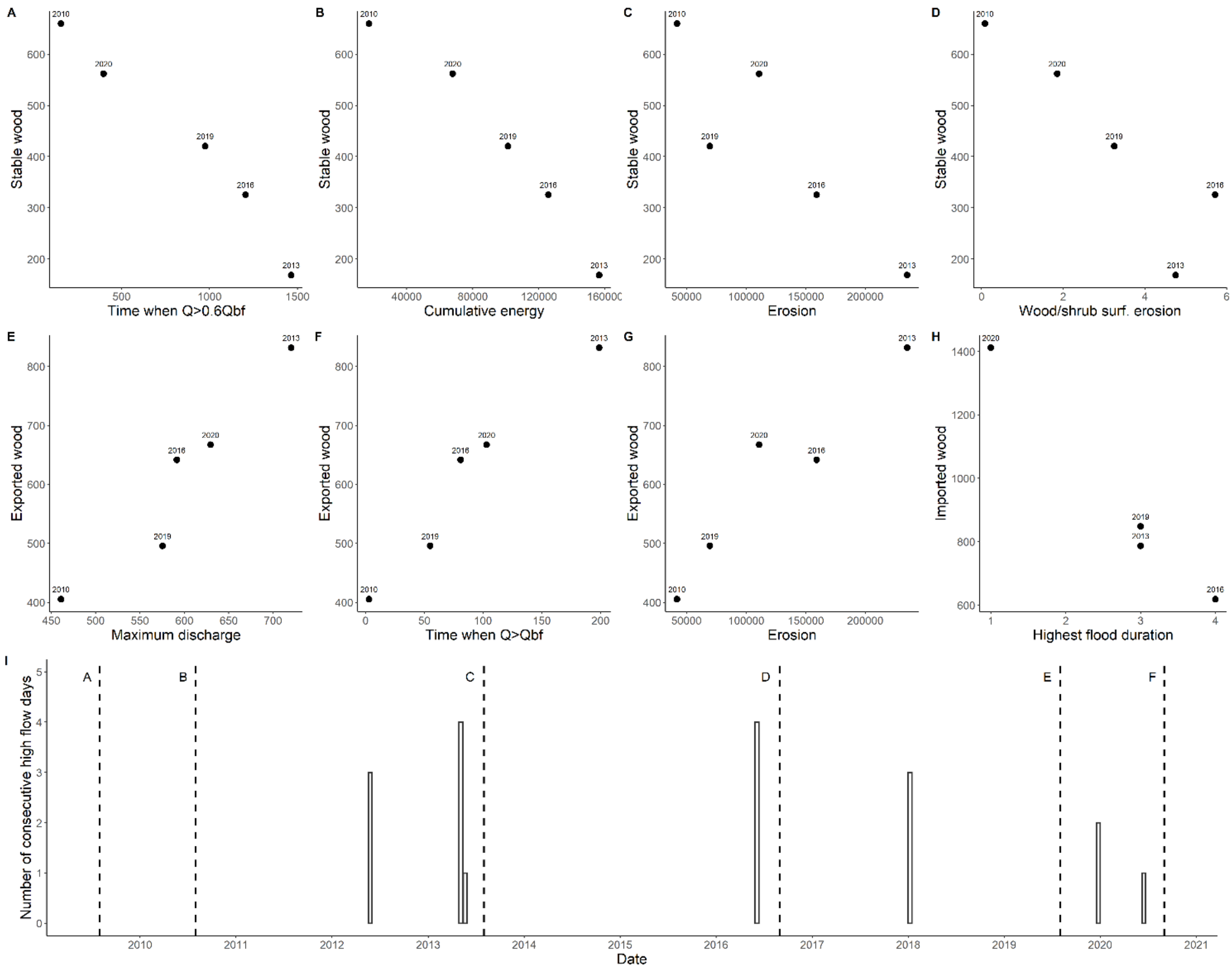


Figure 4. Relationships between: the number of stable wood pieces and (A) the cumulative time (hours) over which discharge exceeded 60% of bankfull discharge, (B) cumulative energy, (C) erosion rate, (D) eroded wood/shrub surface; between the number of exported wood pieces and (E) the maximum discharge, (F) cumulative time (hours) over which discharge exceeded bankfull discharge, and (G) erosion rate; and between (H) the number of imported wood pieces and the duration of the highest flood (in days) above of bankfull discharge. (I) Duration of all floods above bankfull discharge.

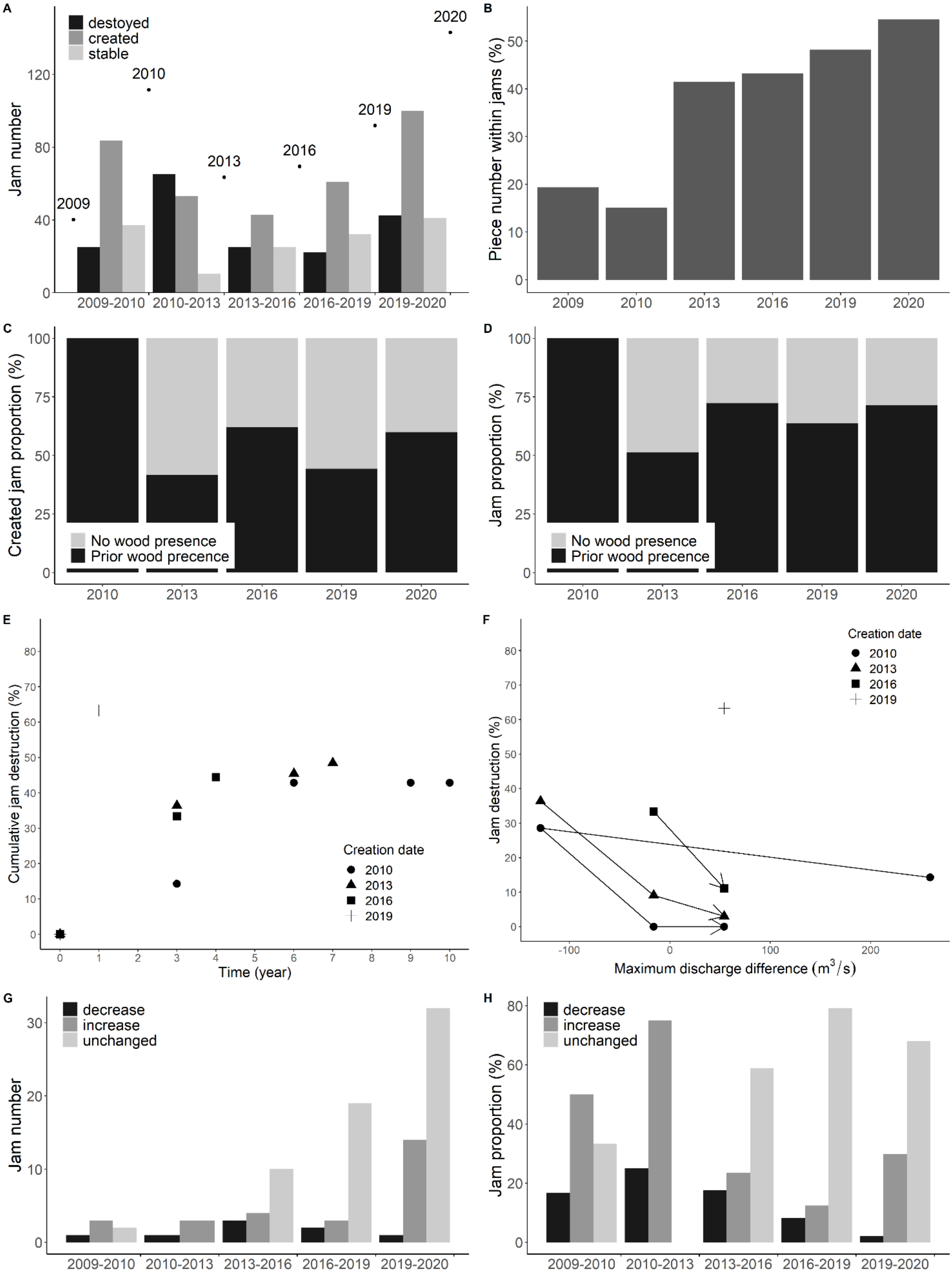
We analysed the arrival year and export year of each wood pieces to quantify how fast imported wood was exported from the reach and how long it remained within the reach. We found that between 45% and 68% of wood pieces were straight away remobilised within one to three years (Figure 3B) and that 20% of the wood imported in 2010 and approximately 40% of the wood imported in 2013, 2016, and 2019 remained stationary. The proportion of imported wood that was remobilised was much higher (over 40%) during the period immediately succeeding a deposition phase than in following periods (below 10%) (Figure 3B). Between 56% and 80% of imported wood was exported before the last studied period. Maximum discharge influenced how fast the imported wood was remobilised. The changes in imported wood over time were dependent on the relative magnitude of successive floods.

Wood loss remained below 50% (45% and 46% of the import 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 import in 2019 and 2010, respectively) when maximum discharge exceeded the peak discharge that occurred during the preceding period (Figure 3C). Thus, a relative negative discharge balance ($Q_{max}^{t} > Q_{max}^{t+1}$) also resulted in lower wood loss (in 2010 and 2013) than the opposite situation ($Q_{max}^{t} < Q_{max}^{t+1}$, in 2016). Wood loss increased when a positive discharge balance followed a negative one (the last period of import in 2010 and 2013).

3.2. Temporal changes in wood jams

3.2.1. Inter-annual change in wood jam storage

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, then increased again from 2013 to 2020 (Figure 5A).


A
destoyed
created
stable
Jam number
2009
2010
2013
2016
2019
2020
2009-2010
2010-2013
2013-2016
2016-2019
2019-2020
B
Piece number within jams (%)
C
Created jam proportion (%)
No wood presence
Prior wood precence
D
Jam proportion (%)
No wood presence
Prior wood precence
E
Cumulative jam destruction (%)
Time (year)
Creation date
F
Jam destruction (%)
Maximum discharge difference (m^3/s)
Creation date
G
decrease
increase
unchanged
Jam number
H
decrease
increase
unchanged
Jam proportion (%)

339

Figure 5. (A) Total number of jams per year (dots) and number of destroyed, created, and stable jams per period (bars), corrected for resolution bias. (B) The proportion of wood stored within jams in relation to the total amount of wood quantified within the reach at each survey date. (C) Proportions of newly built (created) jams with and without prior wood presence. (D) Proportions of all jams with and without prior wood presence. (E) Cumulative jam destruction in relation to time (100% = all jams created over a given duration). (F) Relative change in jam destruction (100% = all imported jams over a given time) in relation to the difference in maximum discharge between successive periods. Size fluctuation of stable jams represented as (G) absolute values and (H) as relative proportion for the period.

The number of jams created was higher than the number of destroyed ones, except during the period 2010–2013 (Figure 5A). 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. The number of stable jams was highest during the first and last studied periods.

Jams can build up on bare surfaces or because of obstacles such as riparian vegetation, man-made structures, and previous wood deposits. We computed the proportions of jams built over a given period that occurred with or without wood being previously present (Figure 5C). The proportions estimated for 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. 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 higher than the biannual maximum (2013), 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, 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 5D). The proportion of wood stored within jam structures increased from 2010 (Figure 5B). Over 2010 to 2013, the proportion more than doubled, reaching 42%. From 2013 it then increased gradually, reaching 55% in 2020.

3.2.2. River discharge as a parameter for predicting storage of wood in jams

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 bankfull discharge (for both: $r = -0.95$; p-value < 0.05), and the duration over which the flood was above a threshold of bankfull discharge ($r = -0.99$; p-value < 0.05) (Table 1, Figure 6A, B, C). There was also a significant negative correlation with the duration of flooding above a threshold of 270 m^3/s, but the relationship was not as strong. The parameter that best explained jam destruction was the cumulative number of hours over which the discharge exceeded bankfull discharge (for both: $r = 0.9$; p-value < 0.05) (Table 1, Figure 6D). The variable best explaining stable jams was the cumulative number of hours over which the discharge exceeded 60% of bankfull discharge ($r = -0.9$; p-value < 0.05) (Table 1, Figure 6E). The changes in the proportion of jammed wood could be explained by the duration over which the discharge exceeded the biannual discharge ($r = -0.96$; p-value < 0.05) (Table 1, Figure 6F).

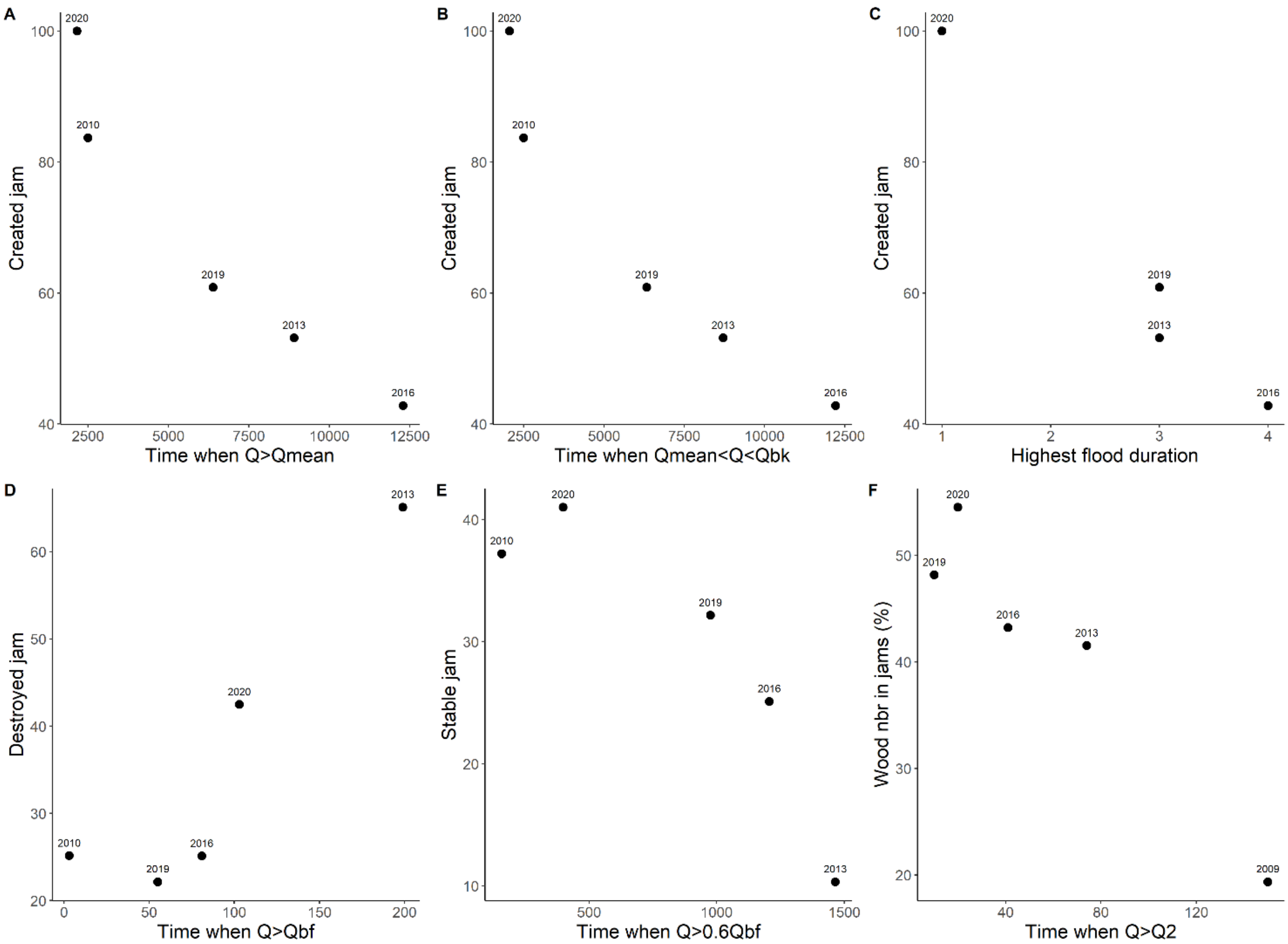


Figure 6. Relationships between: the number of created jams and (A) the cumulative time (hours) over which discharge exceeded mean annual discharge, (B) the cumulative time (hours) over which the discharge was between the mean annual discharge and the bankfull discharge, and (C) the duration over which the highest flood (in days) was above bankfull discharge; between (D) the amount of destroyed jams and the cumulative time (hours) over which discharge exceeded bankfull discharge; (E) between the number of stable jams and cumulative time (hours) over which discharge exceeded 60% of bankfull discharge; (F) between the proportional number of wood pieces forming jams (100% = total number of wood pieces per year) and the cumulative time (hours) over which discharge exceeded the biannual discharge.

We also analysed the dynamics of each jam (i.e., the creation year and the destruction year) 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 5E). 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; approximatively 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 5F). 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 (the latest import period of 2010 and 2013).

As explained above, jams could stay in place for several years. Over this time, their size could fluctuate or stay unchanged. Figure 5G, H 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 highest 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 amounts at a reach scale if differences in image resolution are carefully considered and relative proportions are used rather than absolute values. The bias related to image resolution can be easily overcome, and we propose a correction coefficient that can be used for future analysis using aerial imagery with a resolution 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 bypassing the resolution issues mentioned by Galia et al. (2023).

In addition to low resolution, other parameters can interfere with wood detection and inter-annual analysis of wood budgets. Vegetation can limit wood detection when it grows on or overhangs wood deposits, such as on alluvial bars and banks. Thus, the retention time can be underestimated and wood export 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, resulting in false negative detections. Export appeared more important than it really was because of vegetation development and growth.

4.2. Discharge as a factor controlling wood storage over time

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, Lassettre 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 (71–202 trunks/km). A likely explanation for this is the higher volume of wood recruited through lateral erosion: 17–36 m^3/km/year on the Ain River vs. 58 m^3/km/year on the Allier River. In comparison, Moulin et al. (2011) performed a georeferenced aerial survey on a meandering river in the U.S. 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. 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.

Multiple factors control wood recruitment and storage in rivers, including (i) the availability of riparian vegetation, (ii) channel patterns, and (iii) river flow (Lassettre et al., 2008). In this study, we focussed on testing river discharge as a factor controlling wood jams and storage within a channel reach. The proportions of wood and jam inputs and outputs varied over the study period; thus, the factors controlling the two aspects probably differ. This is in line with the asynchronous wood import and export observed over a 10-year period within small low-order reaches in Chile (Iroumé et al., 2020). The relationship between peak flows and wood export described in previous studies at the basin scale (Moulin & Piégay, 2004; Ruiz-Villanueva et al., 2019) seems to also be observed when studying wood budgets at the reach-scale. Higher maximum discharges result in higher amounts of wood export. However, wood export correlates best with the duration over which discharge exceeds bankfull 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 slightly higher (40%) jam removal rate. The duration of the highest magnitude flood (over bankfull discharge) was found to be the best predictor of wood import and the occurrence of new jams. When the water level exceeds the statistical bankfull discharge (Q1.5) over a long period, wood import and jam build-up decrease. Most wood pieces and jams remained stable when river discharge remained below 60% of bankfull 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; B. MacVicar & Piégay, 2012). Our results are in line with this finding because the amount of stabilised wood on the Allier River decreased when the number of days exceeding 0.6 Q_{bf} during a given period increased. Thus, these three hydrological conditions ($Q > Q_{bf}$, duration of the highest magnitude flood, and 0.6 Q_{bf}) can determine the mobility 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: bankfull discharge and the 0.6 Q_{bf} threshold (Figure 7). A discharge over bankfull level over a relatively long period is necessary to activate wood export, and also to promote individual log deposition. Between 2009 and 2010, the mean daily discharge did not exceed bankfull discharge, resulting in the lowest import of individual wood pieces and the only period over which more wood pieces remained stable than were either imported or exported (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. We hypothesise that the high magnitude flood of 2009 (Q_5) left easily accessible wood that could be transported, even by such a low magnitude flood as the one in 2010. This wood was mostly filtered out of the flow by existing logs located at low elevation, and therefore, compared with other periods, proportionally more new jams were 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. Whether wood is organised within jams or deposited as isolated pieces seems to depend on discharge conditions; wood has an increasing tendency to be organised into jams when the cumulative time with discharge above Q_2 is shorter.

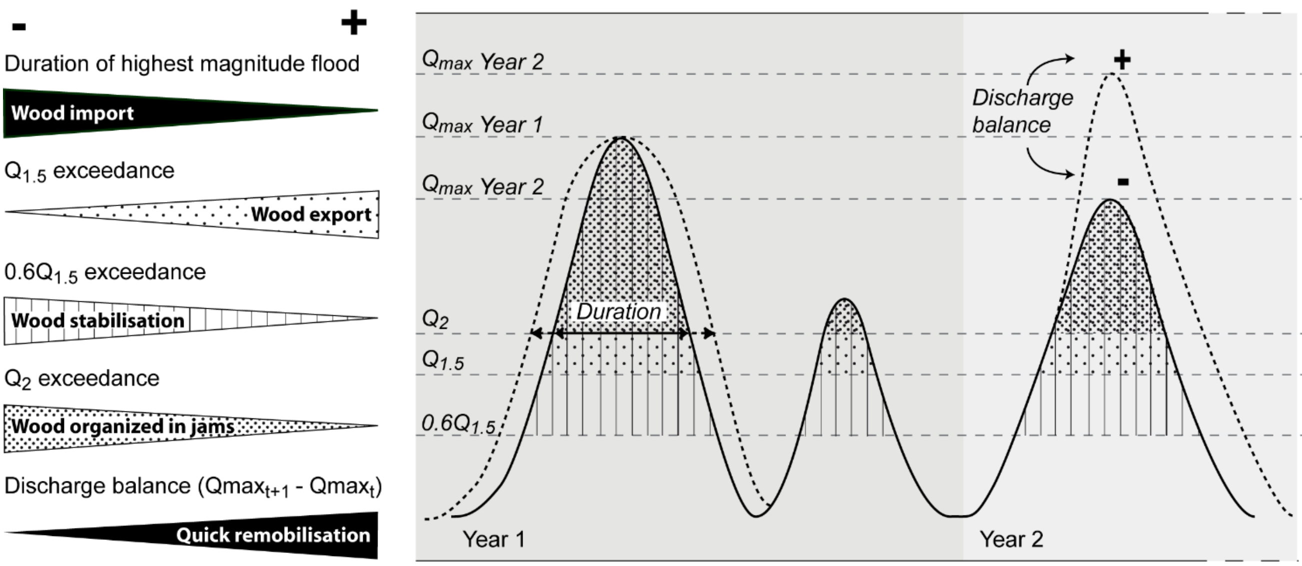


Figure 7. Conceptual model summarising key results from this study.

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 to 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 would be 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 imported and exported 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 U.S., wood export 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 export rates can reach 80% or higher at discharge equal to or exceeding bankfull level (Kramer & Wohl, 2017). In line with previous findings, the export 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 imports, between 45% and 68% of newly imported trunks are rapidly transported downstream within a timespan of one or three years (depending on aerial image frequency). Monitoring mobility relative to wood import, allows the flood history of imported wood pieces to be taken into account, and therefore allows the retention time to be related to the hydrological conditions experienced by wood pieces during import and the succeeding period until export conditions occur (if this happens within the studied period). It appears that at least 45% (and up to 60%) of wood is exported from the reach by floods of lower, identical, or slightly higher energy than the one that deposited it (Figure 3C). Whether wood is actually exported can be questioned when high sediment deposition is observed. Wood can potentially be buried in such cases, instead of being exported, but this phenomenon is difficult to accurately define on aerial imagery (and sometimes even in the field). Some clues suggest that this situation happened between 2019 and 2020 (Figure 8), although we were unable to determine whether this is a common or occasional process, and whether it is linked to specific hydrological conditions.

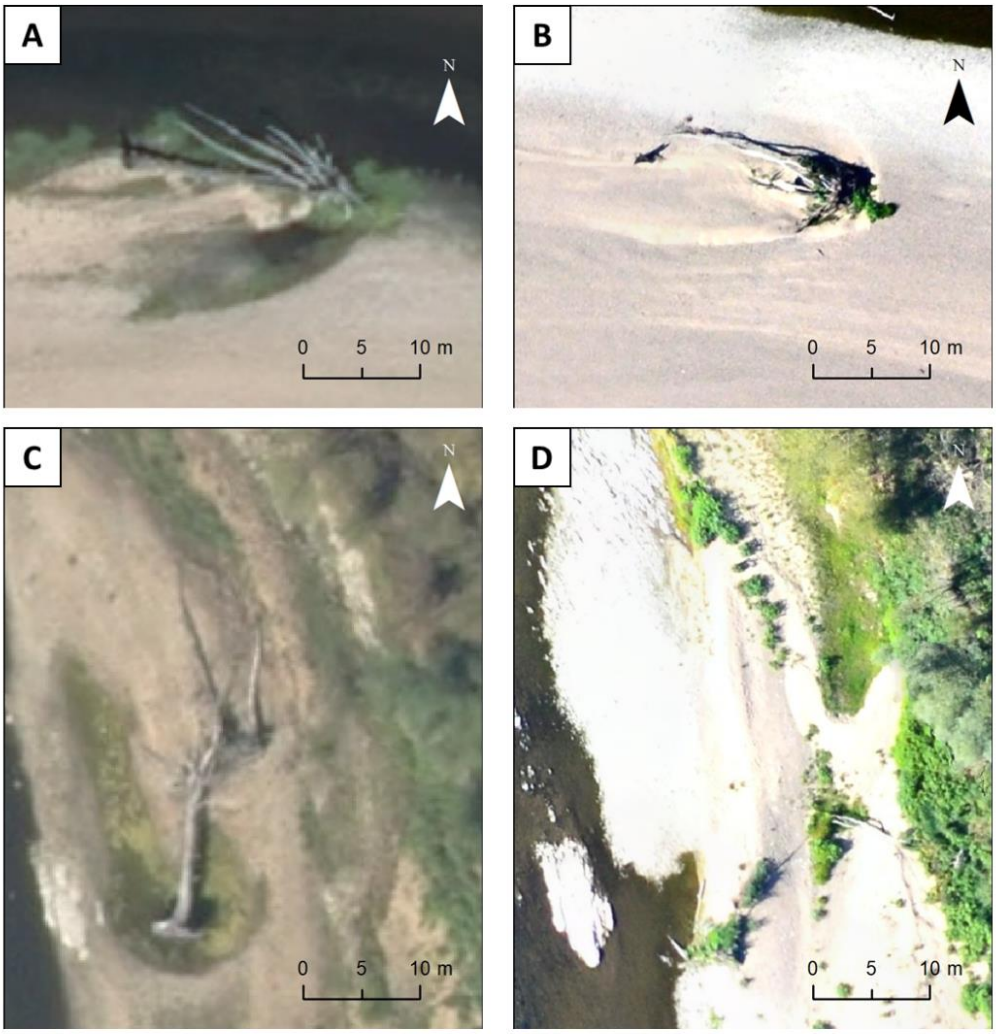


Figure 8. Aerial photographs of two identical locations in (A) and (C) 2019, (B) and (D) 2020.

We did not find a positive correlation between wood recruitment occurring through bank erosion and increasing wood storage, as suggested by several authors (Kramer & Wohl, 2017), or between wood storage and erosion rate (which considers all type of landcover). The wood import in 2016 was one of the lowest recorded, despite the highest recruitment of wood through lateral erosion. Leaving 2010 out of the computation (very low flow conditions with low import), we observed an inverse tendency compared with the one found in the literature: more individual pieces were imported and more jams were built over periods characterised by low recruitment, which was an unexpected finding. Furthermore, even though the highest erosion rate, associated with the highest flood magnitude, was found during the period 2010–2013, wood import was virtually the same as over the period 2016–2019. Our results indicate that events with high erosion capacity also have a high wood export capacity. Conversely, Galia et al. (2023) observed a high individual wood export rate in association with a lack of lateral erosion. This potentially means that, on the Allier River, wood influx originating from local bank erosion is exported from the reach instead of being deposited nearby. The highest wood import on the alluvial bars occurred in 2020, despite a low wood influx. We suggest several explanations for this phenomenon.

(i) Wood influx was more important in the earlier years within reaches located upstream from the study site, and the wood arrived in the study reach through a cascading process (Lassettre et al., 2008; Piégay et al., 2017).

(ii) 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 mobility. In this study, we showed that flood duration also plays an important role in the wood budget. 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 4). 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 import during shorter floods probably (at least partially) originated from nearby sources, as demonstrated on the Tagliamento river (Bertoldi et al., 2013). The higher wood influx was accompanied by a higher export rate during the earlier years: in 2020, even though wood influx was low, the discharge conditions were not favourable to export of wood, but were more beneficial to import of wood.

(iii) Another possible explanation is that the succession of floods of similar discharge (around Q_2) and the decreasing flood length since 2016 have reinforced the filtering effect of wood obstacles, thereby leading to positive feedback. Therefore, although a lower amount of wood was introduced from the banks, the wood was deposited on alluvial bars, resulting in an increase in the wood budget. Boivin et al. (2017a) 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 filters, resulting in a situation where floods of around 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 filtered by riparian vegetation cannot be estimated through analysis of aerial images.

Model simulations made by Ruiz-Villanueva et al. (2014) demonstrated that water depth over a particular surface plays an important role in the control of wood deposition. In this context, the exporting 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 export, with potential counter-effects in terms of blockage at downstream-located infrastructure and overflooding 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 how hydrological conditions control large wood dynamics within a 12-km-long reach of the Allier River. Overall mobility 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 predicting wood import, export, and storage, with there being three key parameters: $Q > Q_{bf}$, duration of peak flow, and $Q < 0.6Q_{bf}$. Imported wood has, on average, a 50% chance of being remobilised immediately, depending on whether relative discharge is positive (i.e., $Q_{remobilisation} > Q_{installation}$) 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 mobility 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, BH, upon reasonable request.

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