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Video monitoring of in-channel wood: from flux characterization and prediction to recommendations to equip stations

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Abstract

Wood flux (piece number per time interval) is a key parameter for understanding wood budgeting, determining the controlling factors, and managing flood risk in a river basin. Quantitative wood flux data is critically needed to improve the understanding of wood dynamics and estimate wood discharge in rivers. In this study, the streamside videography technique was applied to detect wood passage and measure instantaneous rates of wood transport. The goal was to better understand how wood flux responds to flood and wind events and then predict wood flux. In total, one exceptional wind and 7 flood events were monitored on the Ain River, France, and around than 24000 wood pieces were detected visually. It is confirmed that, in general, there is a threshold of wood motion in the river equal to 60% of bankfull discharge. However, in a flood following a windy day, no obvious threshold for wood motion

was observed, confirms that wind is important for the preparation of wood for transport between floods. In two multi-peaks floods, around two-thirds of the total amount of wood was delivered on the first peak, which confirms the importance of the time between floods for predicting wood fluxes. Moreover, we found an empirical relation between wood frequency and wood discharge, which is used to estimate the total wood amount produced by each of the floods. The data set is then used to develop a random forest regression model to predict wood frequency as a function of three input variables that are derived from the flow hydrograph. The model calculates the total wood volume either during day or night based on the video monitoring technique for the first time, which expands its utility for wood budgeting in a watershed. A one-to-one link is then established between the fraction of detected pieces of wood and the dimensionless parameter "$passing\ time \times framerate$", which provides a general guideline for the design of monitoring stations.

Keywords: Fluvial dynamics; Large wood in river; Random forest model; Wind condition; Multi-peaks discharge; Streamside video monitoring.

1. Introduction

Floating wood in rivers, known as driftwood, is a significant component of catchments, notably in forested temperate regions (Wohl, 2013; Ruiz-

Villanueva et al., 2016a). It is delivered to the rivers by a set of processes (landslides, debris flows, blowdown, bank erosion and so on) which vary from upstream to downstream (Nakamura and Swanson, 1993; Montgomery et al., 1996; Abbe and Montgomery, 2003; Gurnell and Petts, 2006). Among different recruitment processes, bank erosion probably delivers most of the large organic material into larger lowland rivers (Keller and Swanson, 1979). These large pieces of wood (i.e. greater than 1 m length and 10 cm diameter) induce variations in hydraulic and sediment dynamics, and contribute to flow resistance and obstructions within the channel (Young, 1991; Gippel, 1995; Shields and Gippel, 1995; Wilcox and Wohl, 2006; Comiti et al., 2008). Especially during a flood, the transport and deposition of large wood pieces represent a potential increase in the destructive power of floods, which increases the potential risks to human populations and infrastructures (Lassettre and Kondolf, 2012; De Cicco et al., 2018; Mazzorana et al., 2018). For instance, a flow obstruction due to wood accumulation can lead to upstream bed aggradation, channel avulsion, and local scouring processes, which can in turn cause embankment or bridge collapse and floodplain inundation (Diehl, 1997; Lyn et al., 2003; Fischer, 2006; Waldner et al., 2007; Mao et al., 2008; Mazzorana et al., 2009; Comiti et al., 2012; Ruiz-Villanueva et al., 2014a). Therefore, quantifying wood inputs, transport, deposition, and budgeting in general is crucial for understanding and

managing wood risk in rivers.

Understanding the variability and the process-scale dynamics which control wood delivery and transport rate is also a critical challenge (Martin and Benda, 2001; Benda et al., 2003; Marcus et al., 2011; Schenk et al., 2014; Boivin et al., 2015). Wood budgeting can be explored at different time scales. The wood recruitment sites are often observed close to the preferential sites of deposition (Schenk et al., 2014; Ravazzolo et al., 2015), but not systematically, as shown along the Isère River, France (Piégay et al., 2017). Some pieces of wood can be transported over very long distances during a single flood (Gurnell et al., 2002; Gurnell, 2012; Comiti et al., 2016; Kramer and Wohl, 2017). Moreover, the amount of wood can be documented at multi-annual and annual time intervals over long time periods by historical data (Seo et al., 2008; Seo and Nakamura, 2009; Ruiz-Villanueva et al., 2014b). Based on this long time scale, however, it is not possible to record continuous series and study wood transport processes during shorter but critical hydrological events such as floods, exceptional wind events, and landslides, which are known to drive wood fluxes in rivers (Lassettre and Kondolf, 2012; Ruiz Villanueva et al., 2014a).

To generate wood input series in shorter time scales, Moulin and Piégay, (2004) used weekly time steps to measure the wood stored in a reservoir. The results quantified the timing and magnitude of Large Wood (LW) export during

flood events in the reservoir and allowed the recruitment and transport processes of LW at the watershed scale to be better understood. Benacchio et al. (2017) monitored wood delivery and calculated wood weight in a reservoir by an automated image processing technique using much finer time intervals (10 min). In addition to the reservoir-based monitoring, Kramer and Wohl, (2014) showed that in high-discharge, low-velocity rivers, the deployment of monitoring cameras with coarse frame rates (≥ 1 min) enables monitoring of LW transport at large spatial and long temporal scales. However, in smaller and steeper rivers the velocity of wood pieces is higher or the field of view is too small such that low frame rate photography cannot provide accurate estimates of wood delivery.

Video monitoring of the water surface can be used to continuously monitor wood flux at a high temporal resolution. Lyn et al. (2003) were the first to apply this technique, using two stream-side video cameras to observe and detect wood accumulation on bridge pier in the Eel River, Unites States. Due to data storage issues, Lyn et al. (2003) downgraded the frame rate to 0.1 fps (frame per second) and applied image compression to the recorded frames through the monitoring period. Such issues were overcome by MacVicar et al. (2009), and MacVicar and Piégay (2012) who established a monitoring station at the Ain River, France, but transferred the full resolution images recorded at 5 fps to

a remote server for analysis. The high quality and frequency of the data, which is likely necessary in high gradient rivers, allowed them to compare LW dynamics with flood hydrograph and develop a quantitative relation between wood and water discharges. Other studies have implemented similar approaches (Boivin et al., 2015; Kramer et al., 2017; Senter et al., 2017; Ruiz-Villanueva et al., 2018; Ghaffarian et al., 2020a) but overall the technique remains undersubscribed and models of the wood flux as a function of the flow hydrograph remain poorly parameterized.

Overall, the success of a particular monitoring station will be determined by issues of wood size and image resolution (MacVicar and Piégay, 2012; Ghaffarian et al., 2020a). Ghaffarian et al. (2020a) monitored floods on the Isère River (France) and demonstrated the generalizability of technique to other rivers along with some limits, constraints, and methodological recommendations. The oblique angle of the camera means that it is particularly important to understand where wood will pass relative to the camera position (Ghaffarian et al., 2020a). Moreover, a problem remains that there are gaps within the data. Such gaps can occur due to the poor visibility in low light or cloudy weather, lost connections where data is transferred to a remote server for storage (Muste et al., 2008; MacVicar et al., 2009; MacVicar and Piégay, 2012; Ghaffarian et al. 2020a), or simply to the time required to extract

information about floating wood from videos. Despite some efforts at automatic extraction (Ali and Tougne, 2009; Lemaire et al., 2014), the procedure to date remains predominantly manual. Improved modeling of wood fluxes as a function of flow hydrographs or other environmental conditions could be an effective strategy to reduce sampling effort and fill in missing data such that wood fluxes could be integrated over time to support wood budgeting in watersheds.

The aim of the current study is to advance the video monitoring technique for wood flux measurement by addressing the following questions: i) is wood transported only above a discharge threshold, and if so, is the threshold a function of antecedent conditions? ii) Can wood flux be modelled as a function of the flood hydrograph? and iii) Can we accurately estimate wood flux from sampling? The analysis uses the database assembled by MacVicar and Piégay (2012) of sampled periods during three floods on the Ain River but significantly adds to this work by performing a complete analysis of the daytime videos from four new flood events and one period with low flow but an exceptional wind condition, which was then followed by a flood event. This much larger database comprises nearly 180 hours of annotated videos or around than 24,000 annotated wood pieces, which substantially expands on the 18 hours and 7800 wood pieces monitored by MacVicar & Piégay (2012). The windy day event with

35-year return period allowed us to address the first research question. A random forest (RF) model was used to answer the second question. Flux and wood measurements from the MacVicar and Piégay (2012) database combined with the data of the present study are used to resolve the third question.

2. Study site

The study site is located on the lower Ain River, a sixth-order piedmont river flowing through a forested corridor in France. The channel is typically single thread with occasional islands, and a wandering system with prominent meander scrolls and cutoff channels (Figure 1.a) (MacVicar et al., 2009). The hydrograph shows a strong seasonal pattern, with low flows in the summer and most of floods occurring between October and April. Bed material sizes are gravel–cobble mix with a median size of 2.5 cm. The unvegetated channel width is 65 m in average at the study site, actively shifting so that significant amount of wood is delivered by bank erosion. Tree species established in the floodplain are a mix of soft and hardwood species dominated by black poplar (Populus nigra) that can reach up to 75 cm in diameter and 25 m in height (MacVicar and Piégay, 2012). Along the study site, wood influx has been estimated over several decades from the analysis of aerial photographs at 18 to 38 m^3/km/yr (Lassettre et al., 2008).

Floating wood was counted on the river at Pont de Chazey, where a stream gauge is maintained by a regional authority (Figure 1.b, c). Along the river, the characteristic discharge of 1.5-year return period was $Q_{1.5} = 840$ m^3/s (Ghaffarian et al., 2020a), and at this study site, an estimated bankfull discharge (Q_{bf}) of 530m^3/s was confirmed by visual observation (MacVicar and Piégay, 2012). At this point the flow discharge is calculated based on the water elevation measured at the gauging station. These data are available online from 1959 at (www.hydro.eaufrance.fr). Mean daily wind speed is also available from the Meteorological Station of Lyon-Bron (1949-2020) (see Figure 2).

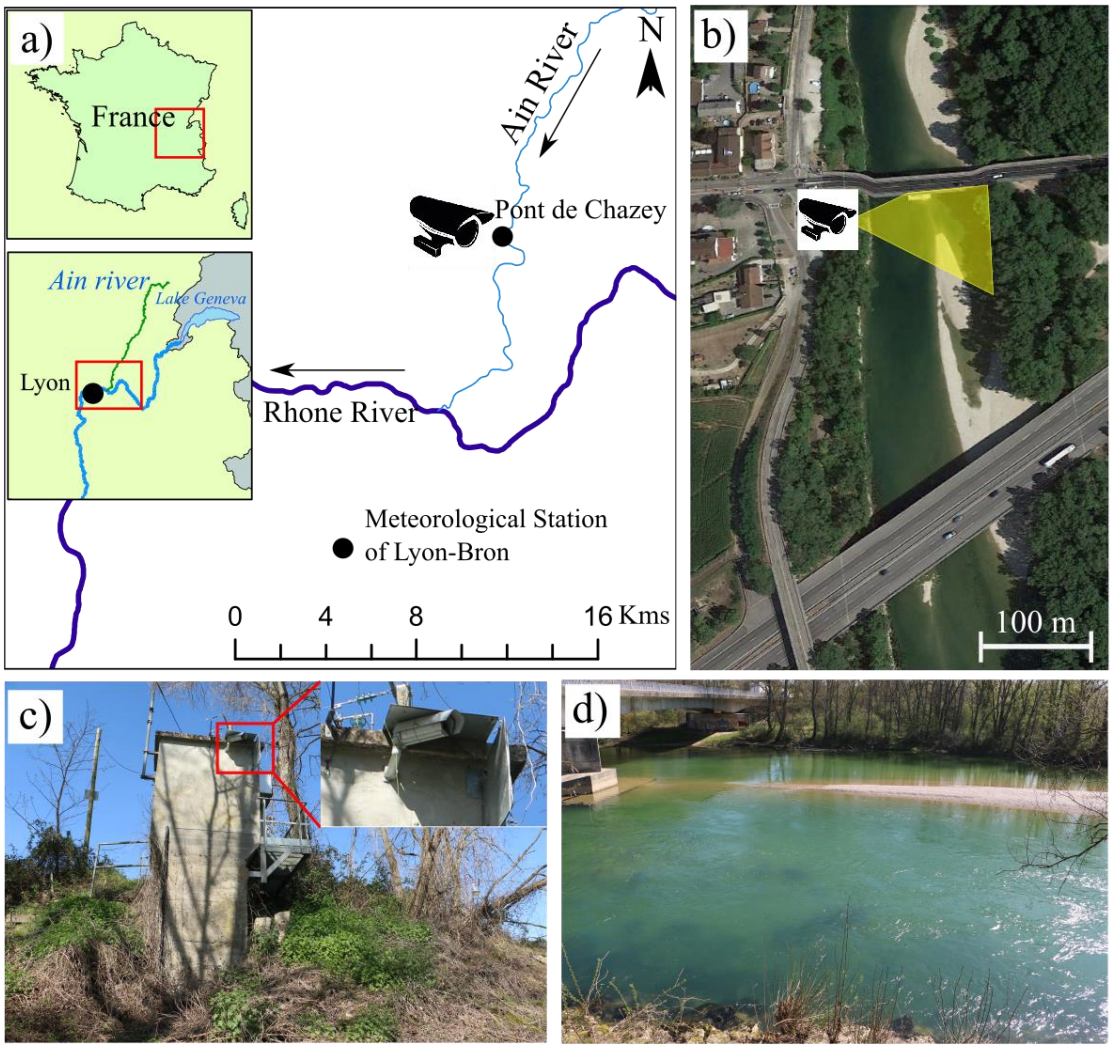

Figure 1. Study site at Pont de Chazey: a) Location of the Ain River course in France and location of the gauging and meteorological stations, b) camera position and its view angle in yellow, c) overview of the gauging station with the camera installation point, d) view of the River channel from the camera

3. Material and Methods

3.1. Stream-side video camera

Wood pieces were monitored at Pont-de-Chazey gauging station using an AXIS P221 Day/Night™ fixed network camera installed in the spring of 2007. Figure 1.d shows the camera field of view on the river surface. The video

camera can supply high resolution (HDTV720P) surveillance even in extreme low-light, though not at night time. The camera was located on the side of the river closest to the thalweg to provide a maximum resolution where the majority of wood pieces are observed. The camera elevation is 9.84 m above the base flow surface at a sufficiently wide angle to afford a view of the entire river width during most periods. Ethernet connectivity enables the automatic transfer of recorded videos to a central server where located at CNRS UMR 5600 – Environment Ville et Société, Site of École Normale Supérieure, Lyon, France. Videos were recorded continuously at a maximum frequency of 3 to 5 fps. Data was recorded with this camera from 2007 to 2011 at a resolution of 640×480 pixels and from 2012 to 2016 at 768×576 pixels. The first three floods (events F1 to F3) thus have a lower resolution than the final four floods and windy period (events F4 to F7 and W1). At minimum compression, each video segment occupied approximately 94Mb of memory and approximately 15 minutes so that a 4TB hard drive stored approximately one year of video. Flood levels were reviewed every few days and videos of interest were saved for later analysis.

3.2. Monitored events

In total, 7 flood events were monitored in this study (Table 1). Three flood events from 2007 to 2008 were collected from MacVicar & Piégay (2012),

referred to herein as events F1 to F3 (Figure 2.a, red lines). A video camera has been recorded video at this location more or less continuously from 2007. For the current work, four additional flood events between 2012 to 2014 were selected for study and sampling and are referred to as events F4 to F7 (Figure 2.a, blue lines). The floods range from 578 m^3/s ($\cong Q_{bf}$) to 1020 m^3/s ($\cong 2Q_{bf}$). Event F7 was selected to assess whether wind has an effect on the wood delivery because it occurred just two days after an exceptional windy day. The windy day occurred on December 24, 2013 and is referred to herein as event W1 (Figure 2.b). The average daily wind speed on this day was 13.6 m/s, which is considered to be a one in 35 year event based on a Gumbel distribution of the over 70 years of record (Yue et al., 1999).

Table 1 Wood sampling statistics at the Pont de Chazey for different events.

Flood periods	Events	Peak flows (m3/s)		Daily wind velocity(m/s)	Analyzed video (hr)	Monitored fraction*	Number of floating woods	
		total	daylight				Rising limb	falling limb
22 to 24-Nov-2007	F1	578	576	6.6	06:15	09%	2800	38
10 to 12-Dec-2007	F2	616	616	6.3	03:45	05%	968	93
10 to 13-Apr-2008	F3	1050	1007	3.8	07:45	08%	3331	584
01 to 07-Jan-2012	F4	808	807	4.9	57:00	34%	3681	1641
15 to 16-Dec-2012	F5	932	821	4.9	17:15	36%	6901	798
01 to 06-Feb-2013	F6	701	701	8.5	56:30	39%	1040	473
24 to 25-Dec-2013	W1	134	134	13.6	08:45	37%	8	-
25 to 27-Dec-2013	F7	600	580	5.6	25:45	36%	1443	43

* Monitored fraction = monitored duration / total duration of an event

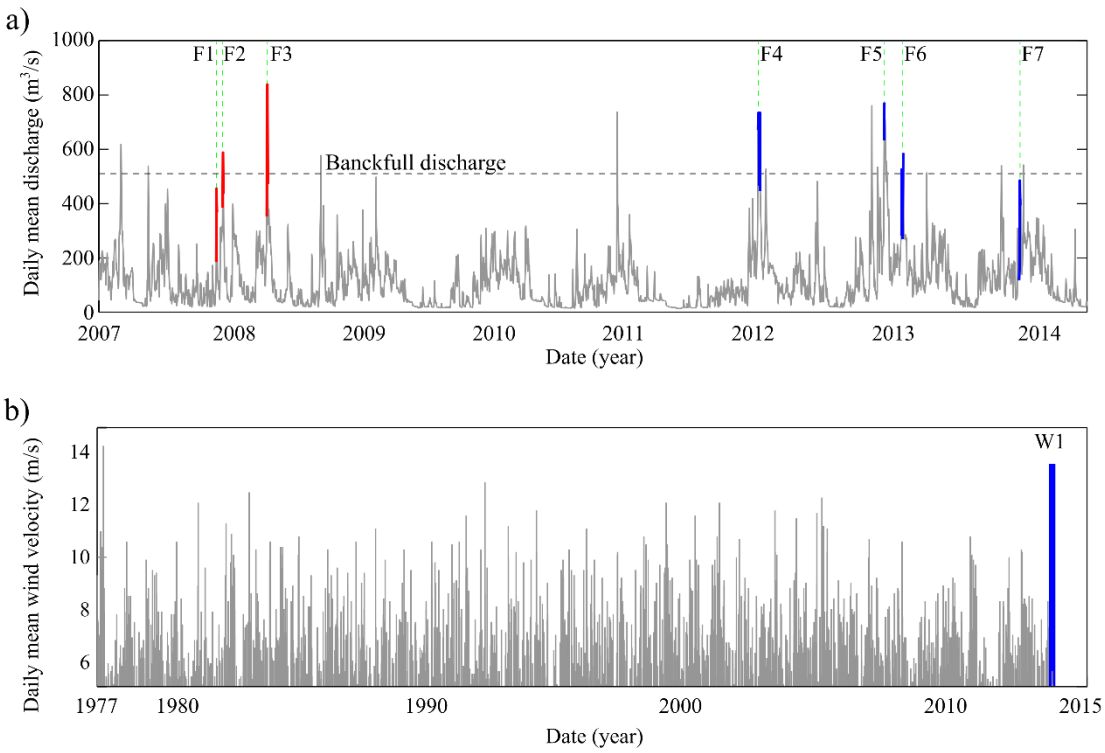

Figure 2. Monitored events a) the daily mean discharge series monitored by MacVicar & Piégay (2012) (red lines) and monitored in this work (blue lines) on the discharge series from 2007 to 2014. b) The daily mean wind velocity series from 1977 to 2013.

3.3. Monitoring process

In total 183 hours of video was analyzed, including 18 hours monitored by MacVicar & Piégay (2012) (Table 1). For this analysis, floating wood was visually detected by an operator and the position of each piece of wood was digitally annotated frame by frame via a graphical user interface.

Two methods were applied for event monitoring: (i) 15-minute monitoring intervals for events F1 to F3; and (ii) continuous monitoring for events F4 to F7 and W1. In the first approach, applied by MacVicar and Piégay (2012), a 15-minute video segment was monitored for each daytime hour (e.g. from 8:30 to

8:45, 9:30 to 9:45, etc. to ~5:30) and, by multiplying the number of detected pieces by four, the wood flux per hour was extrapolated to be compared with other studies. A problem with this sampling strategy was noted by Ghaffarian et al. (2020a), who showed that a 15 min interval may not be sufficient to reliably estimate the hourly wood flux due to short term variability. For this reason, all daytime periods were monitored by an operator for the flood events added as part of the current analysis.

By extracting the detection time for each piece of wood (indicated on top of each frame, see Figure 4.a), wood flux was calculated as the number of wood pieces within a time interval. In the current study, an hour time interval was selected to model the wood fluxes through the flood events (sections 4.1, and 4.2), again for the reasons highlighted by Ghaffarian et al. (2020a). One and 10-minute time intervals were used for analysis in section 4.3 to assess the importance of shorter-term pulses on overall wood fluxes.

3.4. Observer bias

The analyzed events in this work are based on two different operators (MacVicar and Zhang). During the detection process, the operator bias can play a role in the quantity of wood fluxes. To check this effect, 13 segments of 15-minute videos from events F1 to F3 were selected and wood was detected by

both operators following the process used by Ghaffarian et al. (2020a). These video segments were selected such that they cover different light conditions (e.g. sunshine or cloudy weather or different day times) to evaluate the operator visions in this range of conditions. Also, the amount of wood pieces varies greatly among the videos (from 0 to more than 300 pieces), which allowed us to assess whether bias was affected by wood frequency. Overall, there was a ~7% difference in wood flux estimates between the two observers, with most discrepancies occurring when many small wood pieces pass through the image within a short time interval.

3.5. Modeling wood flux

A random forest (RF) non-linear regression algorithm was applied to model the link between wood flux and flow discharge in this study. It produces multiple decision trees (here, 500), each of which is trained on a randomly selected subset of the data (in-bag portion) while the remaining subset is used to test the regression and assess its performance (out-of-bag portion)(Breiman, 2001; Hastie et al., 2009; Belgiu and Drăguţ, 2016). The RF error corresponds to the residual sums of squares averaged across all the out-of-bag portions of the regression trees. The importance of a variable in the RF model can be assessed through a score that corresponds to the total decrease in error due to splits on

that particular variable, averaged across all trees (Breiman, 2001).

For the current study, the response variable was the wood flux and the predictor variables were all derived from the flow time series. We considered three predictors that could influence the wood flux during flood including: (i) flow discharge $Q(t)$, (ii) the time elapsed since the last time that Q was higher or equal to $Q(t)$, known as T_Q, and (iii) the gradient of discharge over a time lag (5 min) dQ/dt. The application of these predictors in the model is presented in the results (section 4.2). Due to gaps in sampling (e.g., during night time), periods where the time interval between two consecutive detections exceeded 10 hr were removed from the data. In cases when several pieces of wood were annotated in the same image frame, we assume a time interval of 0.5 s between wood pieces.

The RF and all related data-wrangling were carried out using the R software (R Core Team, 2019) and the Random Forest package (Liaw and Wiener, 2002). The random forest consisted of a default number of trees set to 500 and the sampling of in-bag/out-of-bag samples was made with replacement. The R notebook gathering all RF-related commands is available from https://github.com/lvaudor/wood_flux.

3.6. From wood flux to wood discharge

In the study by MacVicar and Piégay (2012), wood discharge was calculated as m^3/s by estimating the length and diameter of all detected floating wood pieces. This process is time consuming, and a decision was made for the current study that, rather than completing the size measurements, the wood pieces would only be counted for floods F4 through F7. The wood count allowed the calculation of the wood flux as a frequency (pieces/minute). This approach was justified by considering Figure 3, which shows that there was a strong correlation between wood flux and wood discharge for the 15 min video segments (see section 3.3) sampled by MacVicar and Piégay (2012) for F1, F2 and F3 ($R^2 = 0.83$). This strong relation gives confidence that wood discharge and the total wood volume can be reliably estimated from the wood flux to allow comparison with other studies and models of the wood budget. Extrapolating this relation for other rivers would be an open question that can be the objective of future comparative works.

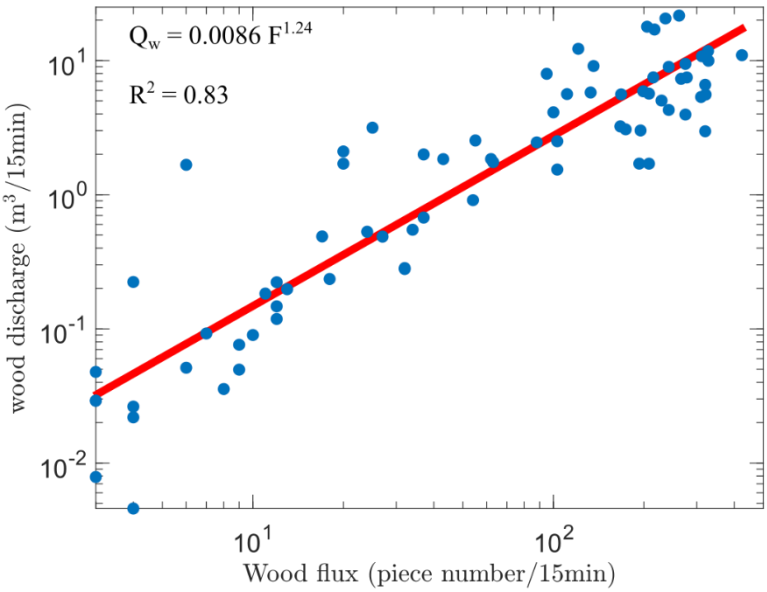

Figure 3. Wood discharge as a function of wood flux

3.7. Sampling strategy

Taking advantage of high temporal resolution videography, it is possible to capture all variations of wood flux during a critical event, while low frame rate photography can be used to detect only a fraction of wood fluxes in the river. To understand the link between the detected wood fluxes and the frame rate, here the concept of passing time (PT) is introduced as the time that one piece of wood passes through the camera field of view. As the camera has a large oblique view, PT varies a lot from the foreground to background (right side of Figure 4.a). Therefore, to measure PT, the position where most of wood pieces' pass is used. As it is seen in the left side of Figure 4.a, more than 75% of wood pieces pass from 150 to 250 pixels on j direction. The passing time at this region is around $PT \cong 5s$ (right side of Figure 4.a). Theoretically, in one snapshot of

the camera corresponds to time t_i, this object can be detectable from $t_i - \frac{PT}{2}$ to $t_i + \frac{PT}{2}$.

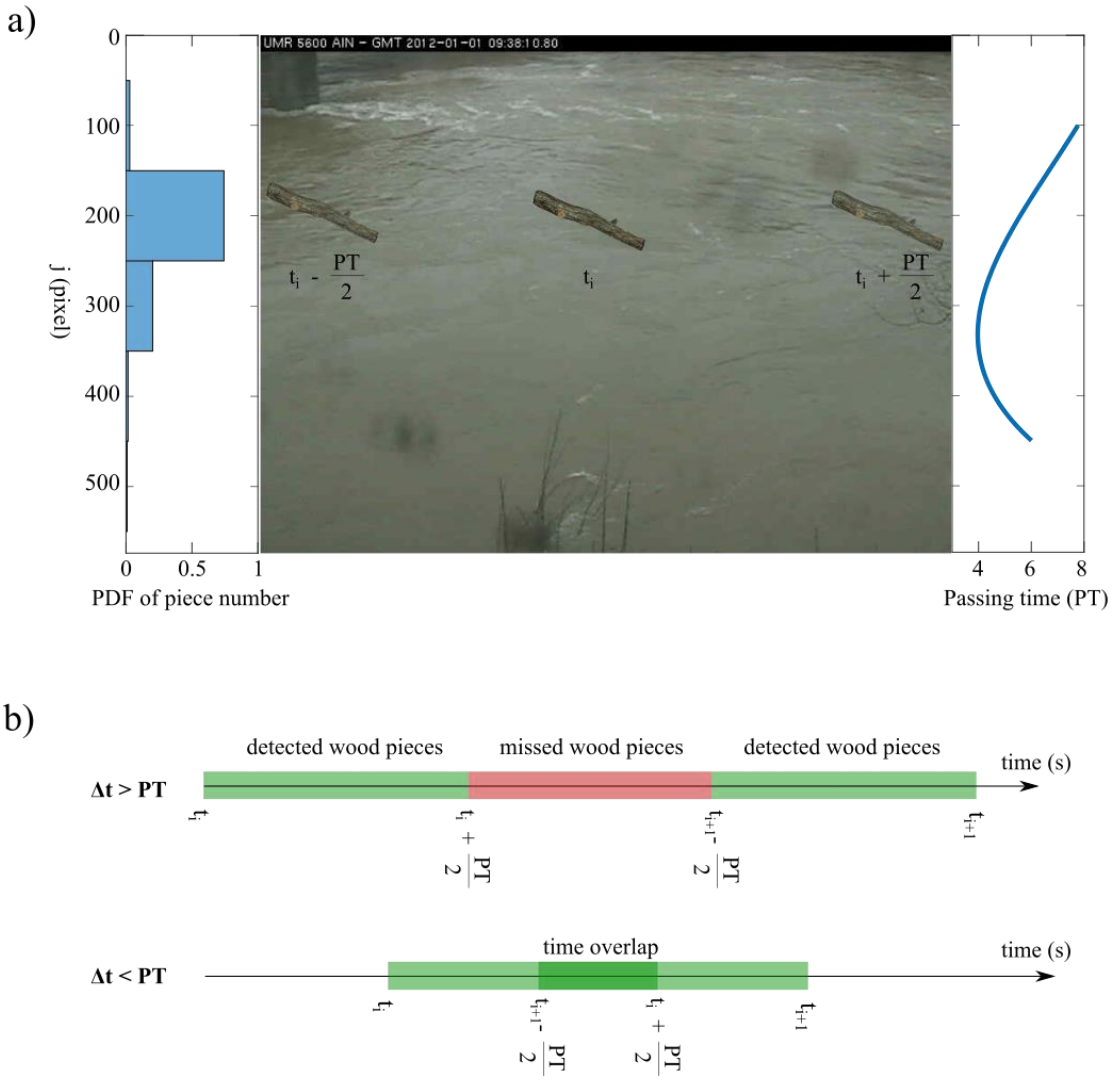

Figure 4. a) wood flux position on video frame b) link between video time laps Δt and the passing time *PT*

By introducing the frame rate (of frame per second fps) as one over the time between two consecutive frames ($fps = \frac{1}{\Delta t} = \frac{1}{t_{i+1} - t_i}$), all the objects that pass from $t_i - \frac{PT}{2}$ to $t_i + \frac{PT}{2}$ or from $t_{i+1} - \frac{PT}{2}$ to $t_{i+1} + \frac{PT}{2}$ can be detected by the observer at each camera snapshot (see Figure 4.b). Consequently, if $\Delta t > PT$,

there can be some pieces that cannot be detected by the camera (red region in Figure 4.b, top), while if $\Delta t < PT$, we can be sure that no wood piece is missed between each pair of frames (Figure 4.b, bottom). Therefore, the fraction of the detected wood pieces can be defined as the ratio between detected wood pieces in the green region in Figure 4.b and the summation of detected (green region) and missed pieces (red region). To study the link between the frame rate and the fraction of detected wood pieces, all detections in Table 1 were used. Knowing $\Delta t = 0.2s$ ($5\ fps$) and $PT \cong 5\ s$ on the Ain river, we know that $\Delta t \gg PT$ means that there is enough overlap between each pair of frames (the condition presented in the bottom of Figure 4.b) and wood can be detected. Note that while PT changes both with discharge conditions and the transvers position of detection, the value $PT \cong 5\ s$ is a rough value for estimating the ratio between frame rate and passing time. Moreover, the 'detectability' of wood pieces does not account for wood that is not clearly visible in the frame (for e.g. small pieces far from the camera), which is a separate issue related to image resolution and camera angle/position. Given the detection time for each piece of wood (as recorded on top of each frame - see Figure 4.a), the effect of the frame rate on the number of detectable wood pieces was assessed by artificially changing the frame rate from 0.001 to $5\ fps$ ($0.2s < \Delta t < 1000s$). Results are presented in section 4.3.

4. Results

4.1. Estimate of wood fluxes during critical events

Overall, the results show 3-stages of (i) rising from a threshold of motion, (ii) high but flat at discharges above the bankfull, and then (iii) around one order of magnitude lower on the falling limb (Figure 5 and Table 1). In Figure 5 the blue scatters from the new events are quite consistent with the events in red from MacVicar and Piégay (2012) which validates the sampling technique.

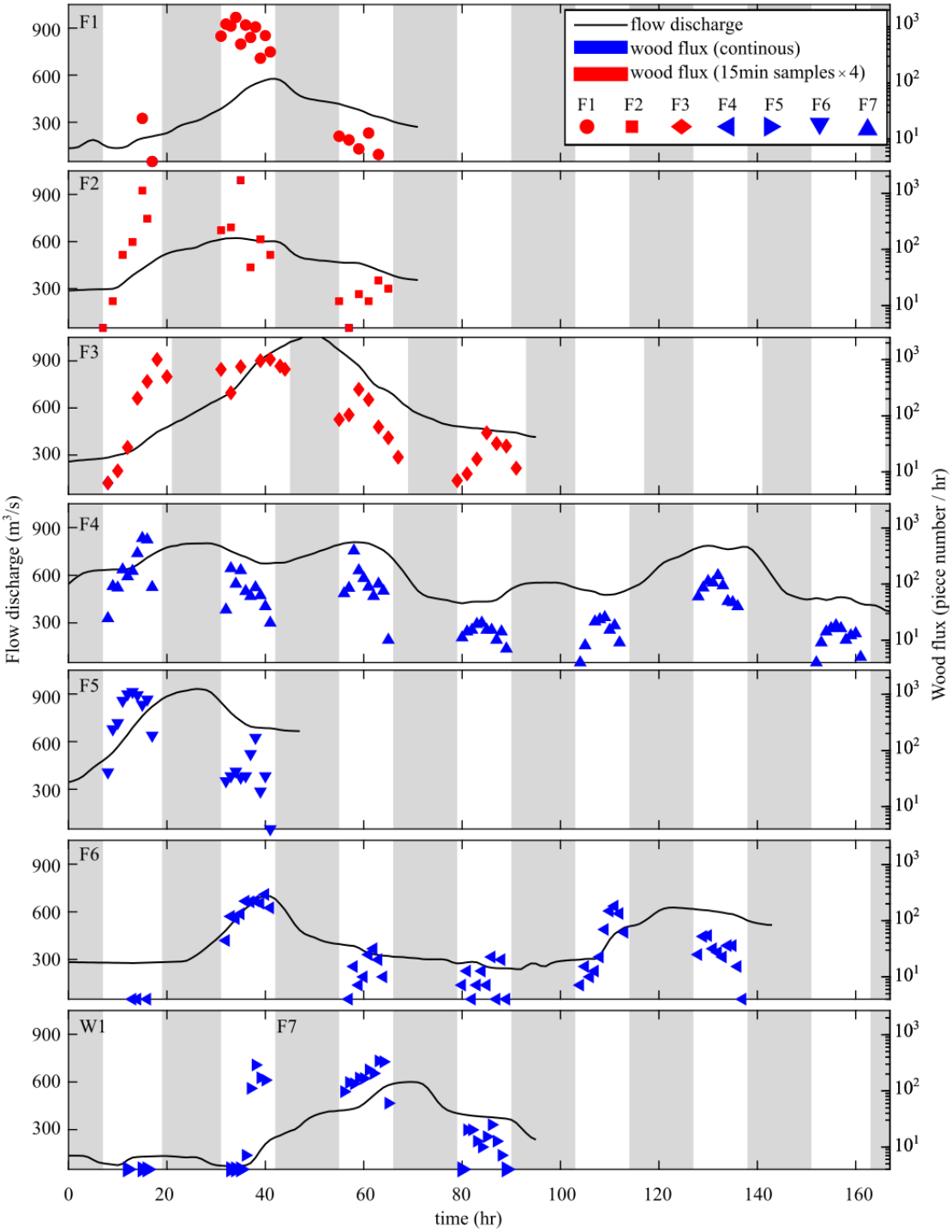

Figure 5. Comparison between wood flux based on sampling (red) and continuous (blue) monitoring and flood hydrograph (black line). The gray boxes show the night time when video monitoring was impossible. Different symbol shapes show different events and are consistent with some of the next figures.

During the exceptional windy day (W1 from 8 to 17 hr) almost no wood was

detected on the river (Table 1). This means that the wood flux is only observed during flood events. As it is seen in Figure 5 in all cases but F7, there are almost no wood pieces in the river for flow discharge less than ~300 m^3/s. In the case of the flood event F7 following W1 (the exceptional wind event), however, the threshold appears to be much lower or non-existent. For this event only, the wood flux increases immediately following the increase in flow discharge, which demonstrates the potential effect of W1, not in terms of transport of floating wood downstream, but in the wood transfer from the river banks to the channel where it can be readily mobilized in the subsequent flood.

In Figure 5, events F4 and F6 are characterized by multi-peak hydrographs. Event F4, for example, is characterized by three peaks with similar discharges (Table 2), during which 3098, 1134 and 839 pieces of wood were observed respectively in the first to third peaks. Event F6 is characterized by two slightly lower peaks, and 995 and 427 pieces of wood were observed in two peaks, respectively (Table 2). Despite some differences in the timing of the floods with respect to daylight hours, these results do indicate that around two-thirds of the wood are mobilized in the first peak of a multi-peak flood. As the number of peaks increases, it also appears that the amount of transported wood progressively decreases.

Table 2 Wood flux in multi peak floods F4 and F6

Flood event	F4.1(Peak1)	F4.2(Peak2)	F4.3(Peak3)	F6.1(Peak1)	F6.2(Peak2)
Q_{max} (m^3/s)	801	808	786	701	627
Pieces number	3098	1134	839	995	427
Fraction*	61%	23%	16%	71%	29%
Flux on rising limb (num/hr)	268	211	82	97	35

* Fraction = piece number during one peak / total piece number during an event.

4.2. Predicting wood fluxes from the flow hydrograph

As described in section 3.5, three predictors derived from the flow hydrograph that were thought to influence the wood flux during the flood were used to develop a RF model. Figure 6 shows the link between (i) flow discharge ($Q(t)$) (Figure 6.a), (ii) the gradient of discharge over 5 min time lag (dQ/dt) (Figure 6.b), and (iii) the time elapsed since the last time that Q was higher or equal to $Q(t)$ (T_Q) (Figure 6.c) from one hand, and the wood flux from the other hand. Regarding the first predictor, as is seen in Figure 6.a, $Q(t)$ has a non-linear positive relationship with the wood flux. Wood flux starts to respond to $Q(t)$ from a threshold almost equal to 450 m^3/s and reaches its maximum value at around 850 m^3/s. These values agree with observed values in Figure 5. For the second predictor, a comparison between positive and negative values of dQ/dt (rising and falling limb) in Figure 6.b shows that while there is a strong effect of flow discharge gradient on the rising limb, there is almost no effect of the discharge gradient on the falling limb. Finally, as seen in Figure 6.c even with a strong initial fluctuation, the wood flux increases with increasing inter-

flood time.

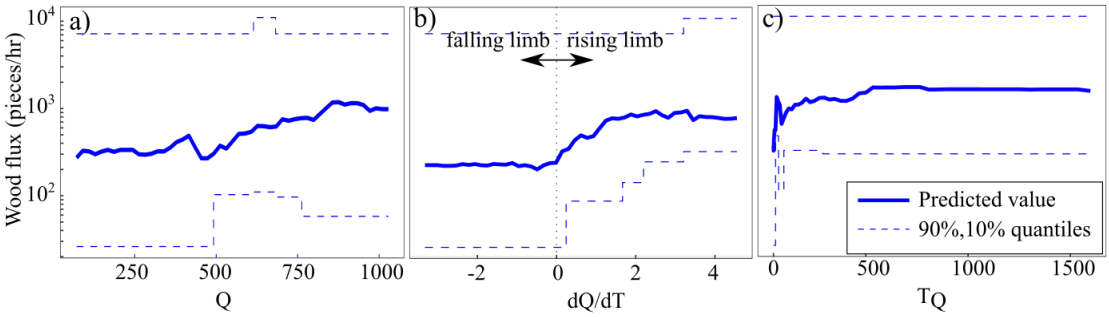

Figure 6 Predicted value of wood flux (in blue) as a function of a) flow discharge Q (m3/s), b) discharge gradient dQ/dt (m3/s/1hr) and c) the time elapsed since the last time that Q was higher or equal to $Q(t)$, T_Q (days). Dashed lines indicate the 90% and 10% quantiles of the data.

Figure 7 compares the observed and the modelled wood fluxes time series (aggregated by hour) for continuous (blue) and sampled (red) videos. The clear strength of the model is that the modelled flux is continuous and provides information during the night and other gaps in the wood sampling database. In terms of performance, the number of trees in the RF model (500) was sufficient to show a convergence on the minimum error possible from this data set. The final average R^2 for the out-of-bag portion across all trees was 49.5%. When carrying out cross-validation for the RF as a whole (with 80% of the data randomly sampled –without replacement- as the training set and 20% as the test set) the R^2 for training set was also 49.5% on average across all trees for the training set (estimated on the out-of-bag data) and 69.8% on the test set. The most important predictor is T_Q (responsible for 41% of the total increase in

node purity –as measured by the residual sum of squares-), followed by Q (32%) and dQ/dt (27%). To assess the efficiency of the model more objectively, Figure 8 compares observed and modelled data on the rising and falling limbs of the hydrograph at each event. Each data point represents the sum of wood flux values over the entire limb of the flood during the daylight. As shown, the model predicts the observations with a precision estimated to about 95%.

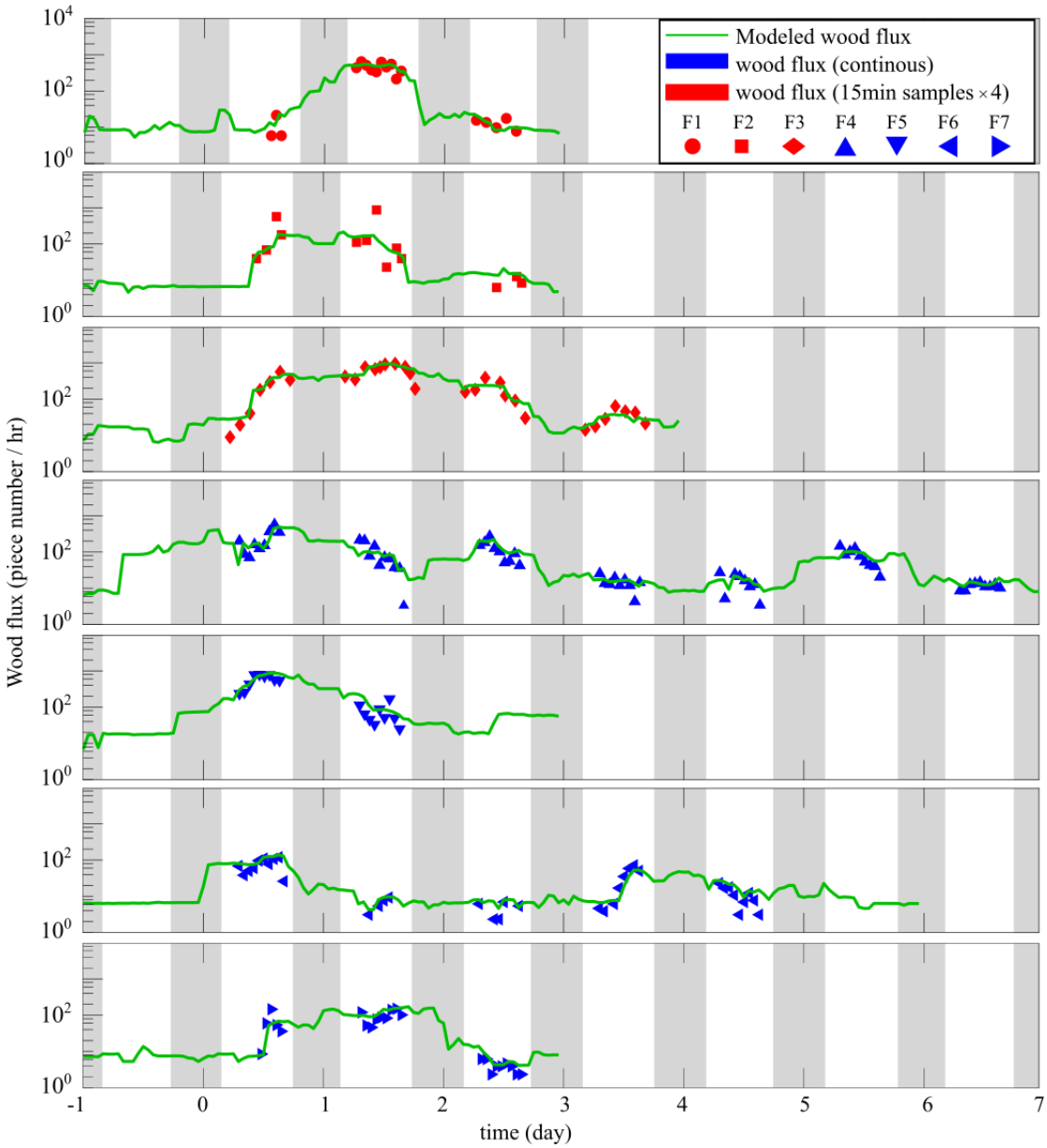

Figure 7. Wood fluxes based on continuous (blue) and sampled (red) videos and

modelled wood fluxes (green line) using RF model as a function of time.

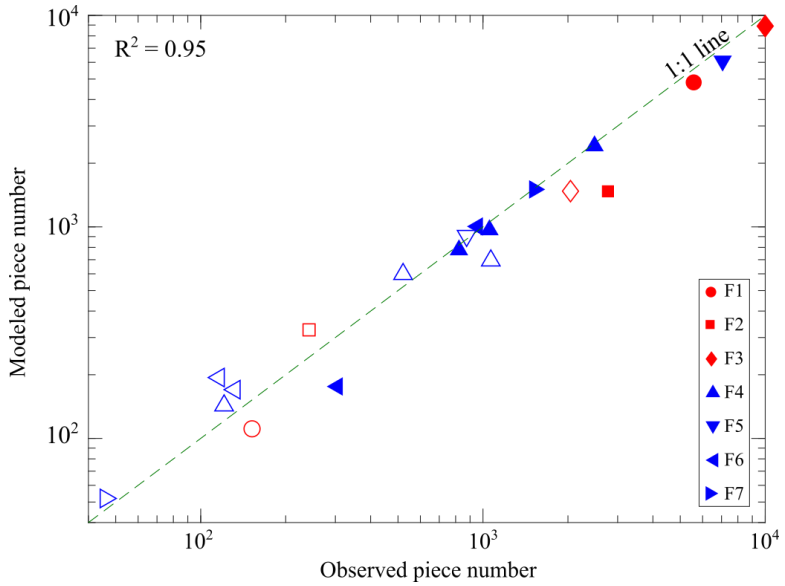

Figure 8. Comparison between observed and modelled piece number: filled and empty scatters show data on the rising and falling limbs of the hydrograph, respectively. Data are compared with a 1:1 line. There are 3 points for F4 and 2 points for F6 due to multiple peak floods.

Based on the field observations and the RF modelled wood fluxes, it is possible to check both the wood mobility during the night and the critical threshold of motion. The critical threshold of motion is defined by the discharge which initiates the mobility of wood flux on the rising limb of the flood. Moreover, to be able to compare the wood volume in two different approaches (observation and model) the process described in section 3.6 was used.

The new phenomenon that is observed here is the exceptional windy day W1 with low flow ($Q < 0.18Q_{bf}$) which is followed by a flood ($Q > Q_{bf}$) F7. During this wind event, almost no wood flux was detected at the video monitoring station (only 2 m^3). In the subsequent flood, however, the threshold

of wood motion was approximately $0.2Q_{bf}$ (95 m^3/s), which is significantly less than the threshold at $0.6Q_{bf}$ for the other flood events (Table 3). Note that in some cases the thresholds occurred during the night, in which case the presented values are the modelled results.

Table 3 Wood volume and threshold of wood motion, modelled (M) or observed (O).

Event	F1	F2	F3	F4	F5	F6	W1	F7
Modelled wood volume* (m^3)	218.69	84.95	680.68	347.08	412.54	52.81	1.88	77.11
Observed wood volume (m^3)	88.75	32.41	120.01	118.29	235.05	26.12	0.03	29.36
Threshold (m^3/s)	275	300	300	300	350	356	<95	95
Modelled/Observed	M	O	O	M	M	M	O	O

* Modeled wood volume includes volume during both day and night time.

4.3. Validation optimal wood flux estimate from sampling

The temporal resolution of video monitoring plays a significant role on the quantity of monitored data. By introducing the passing time PT and the frame rate $1/\Delta t$ (as shown in Figure 4, section 3.7), Figure 9 shows the link between the fraction of detected wood fluxes as a function of the dimensionless parameter $PT/\Delta t$. As a note, this figure shows the numerical link between frame rate, passing time, and the fraction of detected objects, while in practice other sources of uncertainty may be important as discussed in section 5. From the Figure 9, it is nevertheless clear that frame rates less than the passing time are necessary for a full census monitoring of transported wood.

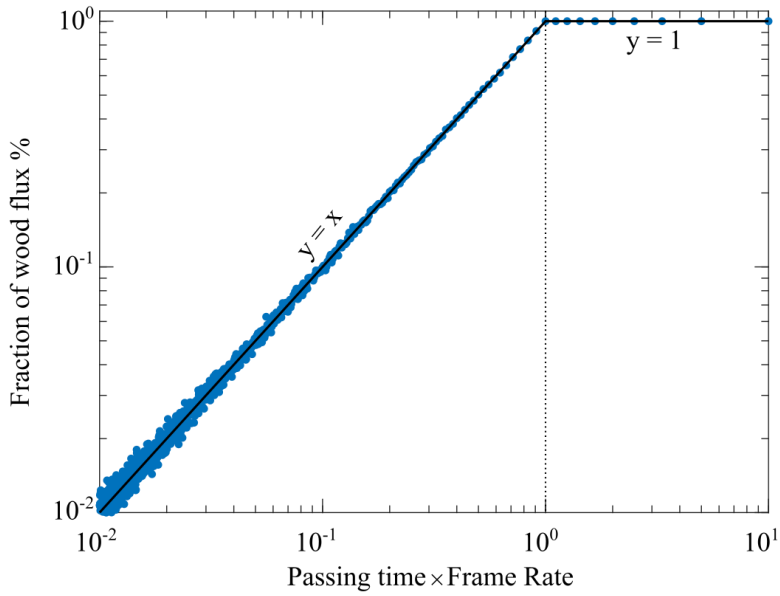

Figure 9. Effect of frame rate and passing time on the fraction of detected wood pieces.

In addition to the fraction of detected wood pieces, the time interval can affect the detection of some short events like wood pulses, defined qualitatively as the delivery of large amount of wood in a short time period (on the order of minutes). Figure 10.a is an example of detected pulses in the event F4 where the wood flux is presented on 1 min intervals. As shown, short term pulses with fluxes much higher than the hourly average are common. To check the quality of detection for such short events, Figure 10.b shows one day detection of wood with one pulse at 10am 3th Jan 2012. As it is seen, the possibility to detect wood pulse decreases by decreasing frame rate (from red to blue) when considering the flow conditions observed on the Ain River station.

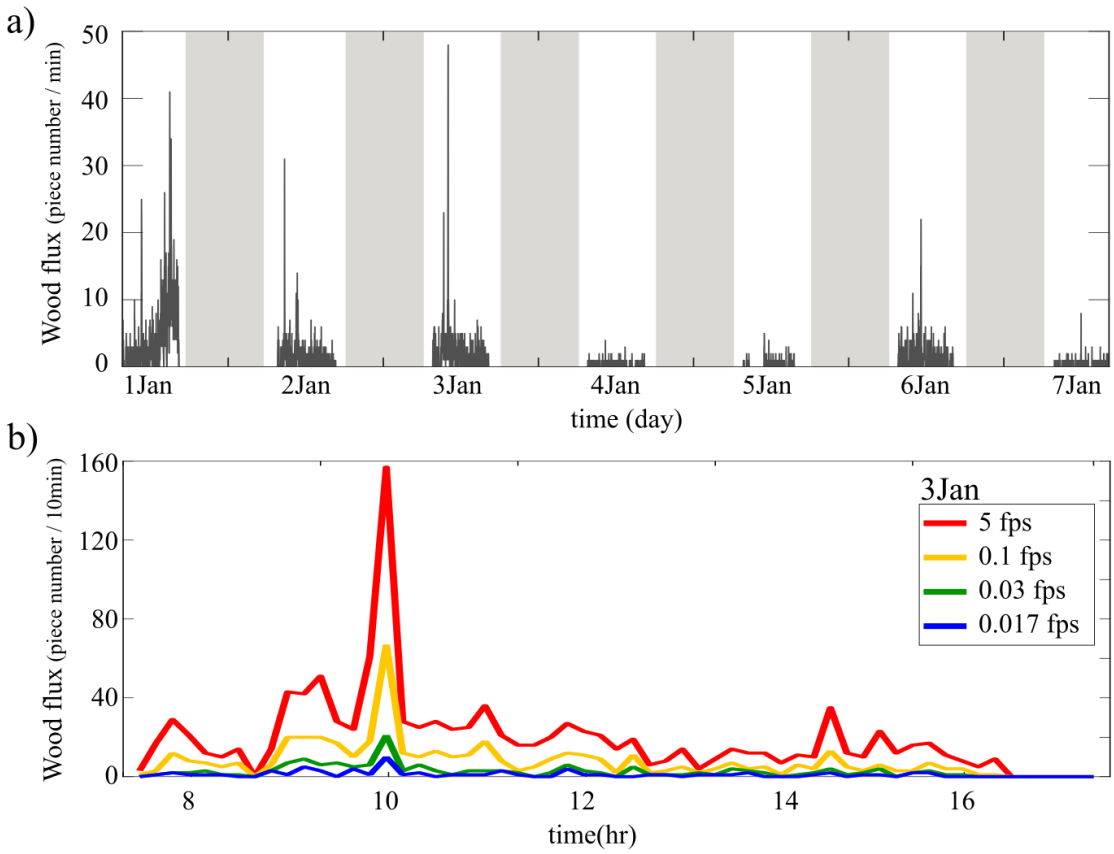

Figure 10. a) Wood fluxes as observed in 1-minute intervals. Beside short fluctuations of wood flux, pulses of wood can be defined qualitatively as the delivery of large amount of wood in a short period of time. The gray boxes show the night time when video monitoring was impossible. b) Effect of the temporal resolution on detecting short time events (a wood pulse).

5. Discussions and conclusions

5.1. The link between flow hydrographs and wood fluxes

Our observations confirm that most of the wood pieces are mobilized on the rising limb of the hydrograph than the falling limb following MacVicar and Piégay, (2012), Kramer and Wohl, (2014) and Ghaffarian et al. (2020a). The peak in wood flux is generally reached before the flood peak. These observations

demonstrate some hysteresis of water discharge that agrees with MacVicar and Piégay (2012) and Ghaffarian et al. (2020a), who state that the peak discharge and the peak of wood flux do not occur simultaneously and normally wood transport rate decreased before the peak of hydrograph. This result has also been confirmed by the model of Ruiz-Villanueva et al. (2016a). They show that wood flux increases with discharge until it attains an upper threshold or tipping point and then decreases or increases much more slowly.

A flood hydrograph can be characterized by several peaks. We observed that the second or the third peaks, even when more intense, carry lower amounts of wood (Table 2). This result agrees with Moulin and Piégay (2004) who indicate that the deposited wood on channel edges from the last event (such as: flood, wind and ice (Boivin et al., 2015)) is transmitted by the first rising of water depth. In addition, Kramer et al. (2017) showed that the sequence of peaks, flow discharge and the shape of hydrograph can influence the amount of wood during a flood. As it is seen in the Table 2, more than 60% of wood pieces are carried out on the first peak and then, only 30~40% of wood pieces are observed. This decrease in wood flux by increasing the peaks of the flood can be related to the rate of bank erosion and by the initial conditions of the channel in term of wood delivery by external drivers such as wind, ice and tree mortality. The first peak of hydrograph washes most of the wood available

within the channel and its edges and prepared over the previous no-flood period, only depositing few wood pieces on channel edges as new recruited material from bank erosion. There is also less green wood which is recruited by a new bank erosion process in the next peaks of hydrograph because the shear stress is not as high as the one observed during the first peak along the eroded bank because channel is now wider and not yet adjusted through vegetation encroachment on the accretion area on the other side of the channel.

Moulin and Piégay (2004) show that the wood flux during flood events is not independent from previous floods. For comparison we can look at events F5 and F6, which occur one year and two months after a big flood event respectively. F5 has 5 times the wood flux of F6, which indicates that more wood was available for F5, likely from smaller events and external drivers within the inter-flood period that introduced wood pieces that are then flushed by F5. Therefore, wood flux can be a combination of fresh material as well as in-channel stored and newly recruited material. These internal mechanisms are fairly important as shown by the RF results which showed T_Q is the most important predictor. This agrees with Ruiz-Villanueva et al. (2016a) which shows that a lot of wood material stored upstream of a dam spent some time as deposited wood in the river before being delivered to the reservoir.

This is also potentially confirmed by observations done during and after the

exceptional wind event which played a critical role on wood delivery. In the current study, for example, some of the wood transported in event F7 was likely provided by W1. This result indicates that during a windy period, pieces of wood are recruited into the river, but there is not enough flow velocity and depth for moving these wood pieces further downstream. Later, when water depth and the wetted area of the river increases, the river flow is able to begin to move these wood pieces relatively easily, i.e. at thresholds less than the threshold of wood motion where exceptional wind events did not occur ($0.6Q_{bf}$). Therefore, while the wind is not directly related to the mobility of wood, it can decrease the threshold of motion and prepare wood material to be exported during the next flood playing a significant role to explain the T_Q contribution. This result is the first example in which we were able to detect an effective role of a potential driver within the upper catchment.

A practical recommendation that derives from this improved understanding of wood mobilization is that recording can largely be initiated strictly as a result of flow discharge, for example by setting the camera to record only when Q exceeds $0.6Q_{bf}$, which would minimize the storage needs for videos while capturing by far the largest contributions to the annual wood flux. However, the effect of wind that causes wood transport at lower discharges needs to be more deeply explored using longer time series to explain wood flux differences

between floods. This factor could be then added in the RF model if applied on a longer time series with more flood events.

5.2. Continuous modeling of wood fluxes

As it is described in section 3.5, a Random Forest model was used to model wood pieces during the night, when no wood is visible in relation to three predictors derived from a continuous flow hydrograph. Figure 6 shows that these three predictors and wood flux are correlated. Regarding the first predictor $Q(t)$, MacVicar & Piégay, (2012) and Ghaffarian et al. (2020a), both showed that the wood flux is expected to have a non-linear positive relationship with flow discharge, which was reflected in Figure 6.a. Also, dQ/dt, as the second predictor, captures the effect of variations in water discharge on wood recruitment during rising (positive values) vs falling (negative values) limb. The direct link between dQ/dt and wood flux on the rising limb in Figure 6.b suggests that increasing the water level during the rising limb of the flow hydrograph can be considered as one of the key parameters on wood delivery in rivers.

The third predictor, T_Q was introduced to account for wood input processes between floods. The RF modelling showed that this parameter was the most important predictor of wood flux for this data set, which is surprising given the

primary focus on water level and rate of increase in previous work. Kramer et al. (2017) do show the strong effect of time between floods on the pulses of wood exported from the Slave River, Canada. Ghaffarian et al. (2020a) also show that time between floods has a logarithmic relation with wood flux, which is confirmed in Figure 6.c. The wood input processes are not modelled explicitly, however, and greater understanding at the process scale may help to develop models that are more readily adapted for different catchments. In conclusion, the good performance of the three predictors (Q, T_Q and dQ/dt) RF model shows that it can be used to predict the wood fluxes on the Ain River given a flow hydrograph. Similar models could be developed in other catchments for comparison and a more general result.

5.3. Selecting an optimized frame rate

A reduced frame rate may reduce wood detection rates so that considering frame rate and passing time is critical to optimize the wood detection. Because reducing the frame rate is a rational strategy to reduce recording costs, there is always a trade-off between the temporal resolution of video (and computer storage capacity) and the recording and post-processing costs to carefully consider. For example, at a frame rate of twice the passing time, only about 50% of the passing wood pieces are detectable (Figure 9). Figure 11, (solid

lines) shows the fraction of detected fluxes as a function of passing time PT based on the model presented in Figure 9 for the frame rates used by three different studies: (i) Kramer and Wohl, (2014) on the Slave River, Canada with 0.033 fps, (ii) Ghaffarian et al. (2020a) on the Isère River, France with 1 fps and (iii) MacVicar and Piégay (2012) and this study on the Ain River, France with 5 fps. The link between PT and the fraction of detected fluxes is a function of camera frame rate on each river. This function which is presented as solid lines in Figure 11, is compared with the estimated passing time on each river (dashed lines). For all cases an increase of PT results in an exponential increase of the fraction of detected wood pieces, which is governed by Δt (Figure 9). This exponential relation is a strength for the model because the fraction of detected wood pieces is not so sensitive to the PT, so we do not need to select an exact Δt and it can be varied in the same order of magnitude.

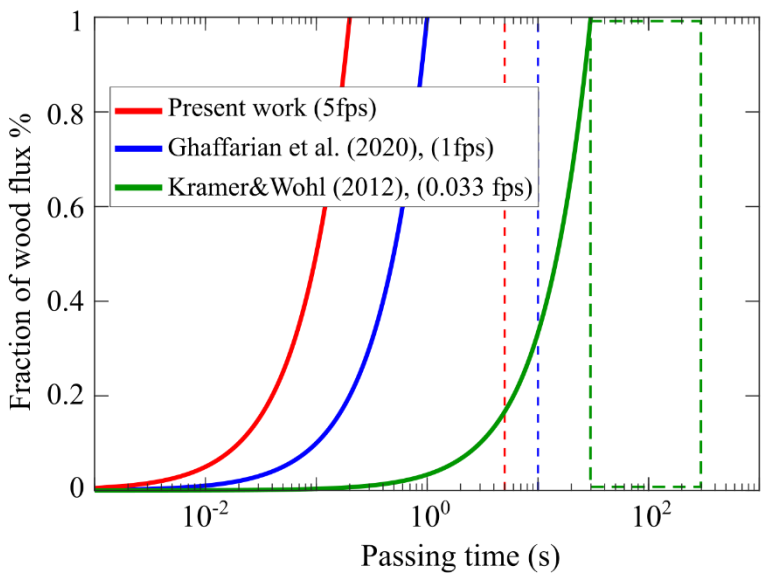

Figure 11. Fraction of detected woods based on passing time in different rivers.

Dashed lines show the estimated passing time on each river, green the Slave, blue, the Isère and red the Ain rivers respectively.

The three studies vary in the fraction of detected wood due to differences in passing time and frame rate. As shown by Ghaffarian et al. (2020a), the passing wood in the monitored sections in both the Ain and Isère Rivers was highly concentrated within a relatively narrow band of the wetted width. As a result, PT was relatively consistent, with a mode of ~ 5 and 10 s in the respective channels (Figure 11, red and blue dashed lines respectively). In contrast, wood on the Slave River was laterally dispersed across the channel from 20 to 100 m (Kramer and Wohl, 2014) and the flow velocity on the Slave River was relatively low (~1/10th the velocity in Ain and Isère Rivers). Large variation in transport distance and low flow velocity both result in huge variation of PT on this river, roughly from $30s$ to 120s (Figure 11, green dashed line). As a result, all wood on the Isère and Ain Rivers using the parameters as described by Ghaffarian et al. (2020a), MacVicar and Piégay (2012) and this work. In contrast, on the Slave River the frame rate is $0.033\ fps$ ($\Delta t = 30s$) and $30s < PT < 120s$, as shown in Figure 11 (green dashed line), which indicates that not all the wood was detectable.

To discuss the Slave River, it is necessary to distinguish between time-lapse photography and videography techniques. Although time-lapse

photography and video monitoring use the same approach (photos are taken per unit time), time-lapse photography is intended to subsample wood flux and there is no expectation that all of the wood is recorded. Missing data is expected and planned for. In contrast, video capture is a method to store and record the entire sample of wood flux and each piece of wood is expected to be captured in multiple frames. The condition near $PT \cong \Delta T$, however, represents a transition zone between time-lapse photography and video monitoring where errors may occur. For example, at this frame rate a given piece of wood may be seen once or maybe a few times within the series of captured frames. If it appears more than once the wood may be double-counted, particularly where visibility is poor, the wood changes in orientation or submergence, or changes in the surface reflections and lighting can fool the operator such that they flag the same piece of wood more than once. Higher frame rates will decrease the differences between frames and the likelihood of double-counting along with it. Lower frame rates will remove the possibility of double counting and ensure that the monitoring captures only a sub-set of the passing wood, which can then be corrected for missing data as is expected for this technique. The Slave River study is thus within the transition zone from time-lapse photography to video monitoring where double-counting remains a possibility.

As a further practical recommendation, it is important to select an

appropriate frame rate for the camera based on a good estimate of velocity conditions in space and in time. Moreover, if the pattern of pulses or the source of wood pieces is important, the frame rate should be large enough to continuously detect wood pieces, while if there is a limitation on storage or long-term data is needed it is recommended to decrease frame rate and adopt a time-lapse subsampling strategy but considering a continuous acquisition window of at least 30 minutes as shown by Ghaffarian et al. (2020a) to minimize uncertainties in wood frequency estimate due to short term pulses.

5.4. Wood pulses

During our observations, it is seen that in some cases the wood flux is mobilized in a sharp pulse, which is typically accompanied by some large pieces of wood that may be recent tree falls or a jam suddenly mobilized. The clarity of these pulses in the video monitoring technique directly relates to the temporal resolution of the camera (Figure 10.b). Moreover, such pulses are fully detectable only if continuous monitoring approach is applied. The difference between continuous monitoring and sampling is visible in Figure 5 where the blue scatters show more consistency through each day, which likely is due to the continuous sampling method (samples were the total per hour rather than 15 min multiplied by 4 as for the red scatters).

It can be hypothesized that wood pulses are the result of either localized or distant wood delivery. Presumably, in such cases of local mobilization, the source of wood could be close to the camera and so the wood would be tightly grouped in time. Such pulses are observed at the Ain River location, where large wood with visible leaves and root wads are followed by large numbers of smaller pieces of wood. In this case the pulse was attributed to local bank erosion or the sudden mobilization of a wood jam. In contrast, the source of wood could be far upstream from the camera, which dispersed wood in transport tending to agglomerate over longer distances. Such a process of ‘rafting’ or ‘clumping’ has been observed in the lab and field (Braudrick et al., 1997; Kramer et al., 2017). Therefore, due to the dissipation, the wood pulse spreads out during transport in long distances. The pulses at the camera location would therefore be very spread out and come more or less regularly, which could mean that the inputs are random or that the distribution has been randomized by dissipation during transport. On the falling limb, despite the bank erosion due to the decrease in the soil pore pressure, the flow might not be enough to transport this wood. Also, some wood pieces have already been deposited in the highest possible locations with other wood jams on the upstream floodplain (Ruiz-Villanueva et al., 2016b; Wohl et al., 2018). A careful analysis of wood flux pattern thus provides some potentially key insights about

the processes that prepare the stock of available wood within a reach and should by the subject of further investigation.

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Data availability statement

Research data not shared.

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