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RESEARCH ARTICLE

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Inter-basin comparison of wood flux using random forest modelling and repeated wood extractions in unmonitored catchments

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Abstract

Predicting wood flux (i.e., wood piece number per time interval) or discharge (metre cubes of wood per second) in rivers is crucial for adequate integrated river management that balances risk assessment and ecological improvement. To enhance our understanding of the transport mechanisms of wood and assess their effects in various geographical contexts, it is necessary to conduct inter-basin comparative studies and preliminary modelling. The wood flux of two river basins was analysed using video monitoring and random forest predictions based on hydrological drivers. The wood flux dynamics of the Ain and Allier rivers were both compared and contrasted. Although there was shared wood transport hysteresis, hourly wood flux, relative critical flow discharges of wood transport and certain hydrological factors exhibited differences between the two river basins. As a next step, the two random forest models, which were trained previously, were applied to predict wood flux and then wood discharge in a third river (the Rhône), in order to estimate a wood volume export, which can be compared with the wood volumes extracted over a series of a few monthly periods in the Génissiat reservoir. By using the random forest modelling, it is possible to estimate the volume of wood on the Rhône river. Despite the absence of any training data, there is a noticeable correlation, however, the estimated volumes were significantly overestimated. To resolve this issue, a correction factor was applied, accounting for disparities in wood recruitment dynamics between the Rhône basin and the training river basins. It was found that high flow events are underestimated, emphasizing the importance of incorporating local annotations and additional parameters in training the random forest model. Accurately predicting wood flux is important for integrated watershed management, but field observations are still lacking for validation and process-based understanding.

KEYWORDS

inter-basin comparison, large wood in river, random forest model, video monitoring, wood flux prediction

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1 | INTRODUCTION

Wood within rivers plays a crucial role in the riverine ecosystem (Benke & Wallace, 2010; Jones et al., 2014) and contributes to valuable landscape heterogeneity (Gurnell et al., 2002; Piégay & Gurnell, 1997). Wood provides organic matter (Beckman & Wohl, 2014; Harmon et al., 1986) to river ecosystems and serves as a source of carbon, contributing to carbon storage (Wohl et al., 2012). However, transported wood can sometimes damage human infrastructures and obstruct river channels, leading to local scouring processes and an increase in upstream water levels that can cause flooding (Comiti et al., 2008; De Cicco et al., 2018; Le Lay et al., 2013). Accurately quantifying wood recruitment, transport and deposition is essential for managing the risks associated with wood in river environments. Enhancing current river management necessitates precise understanding of wood spatio-temporal dynamics and access to appropriate tools for their evaluation, considering both the benefits and potential risks involved.

Video monitoring (Boivin et al., 2017; Ghaffarian et al., 2020; Lyn et al., 2003; MacVicar & Piégay, 2012; Zhang et al., 2021) and time-lapse photography (Kramer & Wohl, 2014) have been identified as useful tools for measuring wood flux (the amount of wood pieces in a specific amount of time). However, these methods have the limitation of being unable to capture information during night-time due to insufficient lighting. Initial research into monitoring wood flux has revealed a group of hydrological factors (namely discharge, rate of discharge increase and flow history) that regulate the amount and timing of floating wood. Consequently, the first model predictions have been made. Zhang et al. (2021) installed a video monitoring device in a channel cross-section and established a random forest (RF) model that can predict wood flux at night, when quantification is not possible. In this manner, it is feasible to calculate the wood flux for both short and extended periods (e.g., monthly or yearly). Currently, the goal is to observe and simulate new catchments to gain a better comprehension of the factors responsible for regulating wood transportation, mobilization and retention concerning the variety of hydrological (peak flow conditions and flow energy) and catchment parameters (woodland coverage, hillslope processes, catchment physiography and bank erosion rates).

Till date, wood flux has only been estimated in a limited number of rivers, typically over brief intervals. These include the Saint Jean river, Canada (Boivin et al., 2017), Isère river, France (Ghaffarian et al., 2020), Slave river, Canada (Kramer & Wohl, 2014) and North Yuba river, USA (Senter et al., 2017). However, the Ain river boasts the lengthiest record, with eight floods monitored between 2007 and 2022 (Zhang et al., 2021). Additionally, dams can serve as valuable locations to observe and measure wood export when they are not transparent to wood (Máčka et al., 2020; Senter et al., 2017; Seo et al., 2008). It is important to note that measurements for wood export in these contexts are typically evaluated over a period of several days or, in some cases, several months. The Génissiat reservoir, located on the Rhône river, has undergone wood storage monitoring using extractions at various time resolutions ranging from monthly to annual frequency. Additionally, field observations with weekly frequency for a month and a half were conducted on an exceptional

basis (Moulin & Piégay, 2004). Moreover, using time-lapse camera monitoring, a frequency of 1/10 min was recorded over 4.5 years (Benacchio et al., 2017).

Currently, there is still a limited understanding of wood flux, and comparisons between stations remain complex due to the short duration of temporal series. Furthermore, it is necessary to evaluate wood dynamics in diverse geographical conditions using the same technique.

The objectives of this paper are to:

- i. Compare wood flux on two 'gauged', monitored and modelled rivers using RF.
- ii. Compare the monitored wood flux to those of a third river that is 'ungauged' using the previous models, and validate the predicted wood flux with wood budget estimates observed over a series of few monthly periods.
- iii. Predict the respective contributions of the sub-catchments to the wood flux within this third 'ungauged' catchment, assuming that it is only related to their hydrological regime.

The wood fluxes of the Ain and Allier rivers in France are both measured using continuous video monitoring, whereas on the upper Rhône, we only have multi-monthly periodical wood volume estimates within the Génissiat dam. Although there is no video monitoring station upstream of the Génissiat dam that can be used as a training data series for modelling, the accumulated wood raft is regularly removed from the dam (at a frequency between monthly and annually). The extracted volume of wood is estimated and provides valuable information for (in)validating the potential application of existing models of wood flux. Studies of wood flux quantification provide an initial comparative understanding of the extent of transport processes and related hydrological conditions. They open a potential avenue for estimating the respective contributions of different sub-catchments to the total wood flux from their hydrological signature.

2 | MATERIALS AND METHODS

2.1 | Study sites

2.1.1 | Ain river

The Ain river, a tributary of the Rhône river, drains a basin of 3762 km². It features an actively shifting meandering planform within its lower forested valley, which introduces a significant amount of wood into the river. At the Chazey-sur-Ain gauging station (Figure 1), the characteristic discharge of a 2-year return period (Q_2) is 891 m³/s, with a mean annual discharge of 119 m³/s, corresponding to a drainage surface area of 3630 km². The hydrograph shows a strong seasonal pattern, with low flows in summer and most of the floods occurring between October and April. The mean active channel width is 65 m along the study reach. Wood recruitment has been estimated over several decades through the analysis of aerial photographs at a rate of 18–38 m³/km/year (Lassetre et al., 2008). Floating wood has been monitored since 2007 at this point on the river.

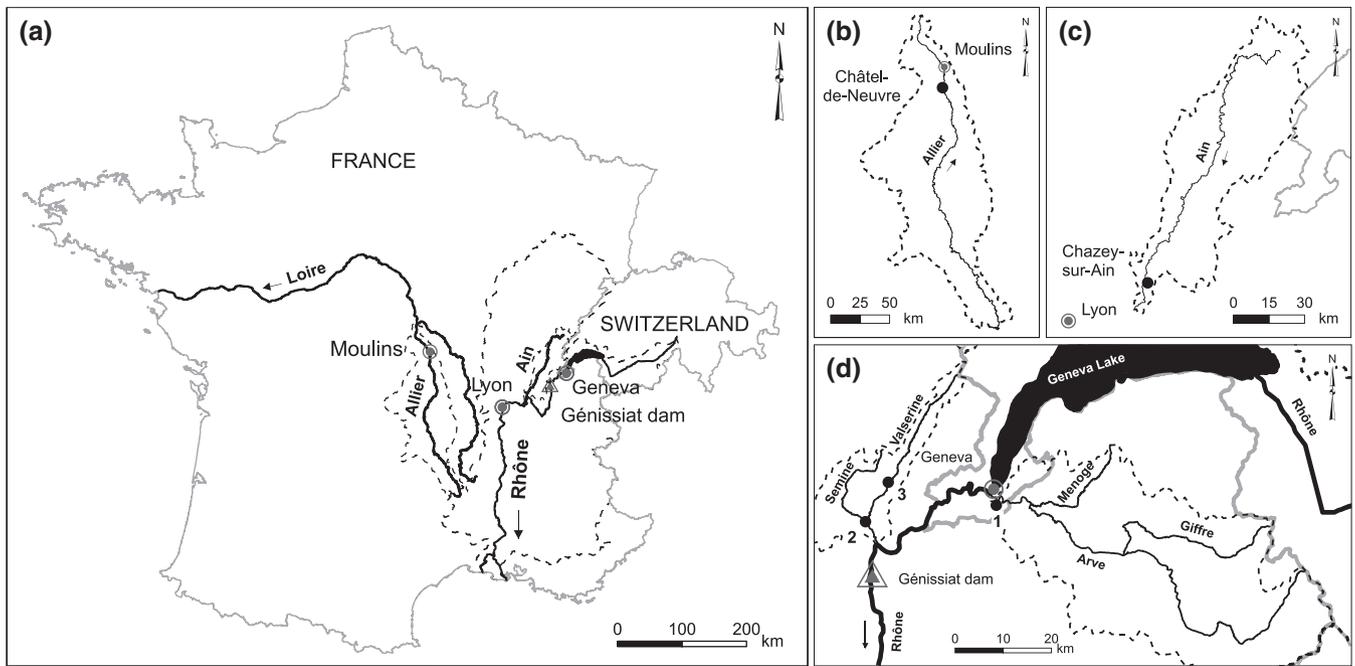


FIGURE 1 Study site of the Allier, Ain and Rhône rivers: (a) location of the Allier, Ain and Rhône river courses in France and Switzerland and their basins (dotted line), (b) camera position on the Allier River at Châtel-de-Neuvre bridge (solid dot), (c) camera position on the Ain river at Chazey-sur-Ain (solid dot). (d) The upper Rhône and its main tributaries and the location of the three gauging stations (solid dot): 1—Bout du Monde (Arve); 2—Châtillon-en-Michaille (Semine); 3—Chézery-Forens (Valserine). The arrow corresponds to the flow direction.

2.1.2 | Allier river

The Allier river, a tributary of the Loire river, encompasses a drainage basin of 14 400 km². This meandering river is also characterized in its lower valley by a mean active channel width of 60 m (SD = 15) and an active shifting and lateral erosion, which can locally reach up to 15 m/year (Petit, 2006), similar to the Ain. The study area is situated within the Val d'Allier Natural National Reserve and has experienced moderate anthropogenic impacts. Large alluvial bars offer space for wood storage. Landforms and vegetation succession undergo high turnover, leading to a spatially and temporally diverse landscape mosaic characterized by a heterogeneous distribution of vegetation patches varying in size and age (Geerling et al., 2006). The river hydrograph displays a highly seasonal pattern. At the Châtel-de-Neuvre bridge (Figure 1), the mean annual discharge is 114 m³/s, with Q_2 being 550 m³/s, where it drains an area of 12 430 km². At the study reach, wood recruitment has been estimated over two decades through the analysis of aerial photographs at a rate of 43–103 m³/km/year. Floating wood has been monitored since 2019 at the bridge.

2.1.3 | Upper Rhône basin

The Génissiat dam is situated on the upper Rhône river in France, downstream at a distance of 7 km from Valserine and 50 km from the Arve river, the two primary upstream tributaries, located on the right and left banks, respectively (Figure 1). At Surjoux, downstream of the dam, the Rhône river drains a catchment area of 10 950 km², with a mean annual discharge of 365 m³/s (HydroPortail, <https://hydro.>

[eaufrance.fr](https://hydro.)). The hydrological regime is complex and the glacial character is partly smoothed by Lake Geneva, through which, the Rhône flows. The lake also strains out all the wood material carried from upstream, meaning that the main sources of wood are tributaries downstream of Lake Geneva. Consequently, the wood-contributing catchment is no larger than 2500 km². The dam produces a reservoir of approximately 23 km in length and retains all the wood, which is mechanically extracted by the dam's management company, the 'Compagnie Nationale du Rhône'. The extractions take place three to four times a year, typically after high flow events, and the estimated volume is documented (Moulin & Piégay, 2004).

The Arve river is characterized by a glacio-nivo-pluvial hydrological regime. At the gauging station of Bout du Monde in Geneva, the mean annual discharge stands at 78.2 m³/s, where the river drains a basin area of 1976 km² (Federal Office for the Environment, <https://www.bafu.admin.ch>). While bank protections restrict lateral mobility and associated wood recruitment in specific regions, certain parts of the Arve and its tributaries, such as Giffre and Menogé, remain mobile, providing wood through bank erosion. Braided river pattern is partially present (Peiry, 1988). Additionally, hillslope processes also contribute to wood supply (Benacchio et al., 2017).

The Valserine basin covers an area of 390 km² at Lancrans, situated 2 km upstream from its confluence with the Rhône river. The mean annual discharge corresponds to 16 m³/s with a nival hydrological regime. This single-thread river has a greater forest cover than the Arve river at catchment scale (Moulin & Piégay, 2004).

For ease of writing, in this paper, we will refer to the combined Arve and Valserine rivers as the Rhône river, although it is noted that the obtained discharge only partially reflects the real Rhône river

discharge. Benacchio et al. (2017) assumed that the total discharge of the two rivers corresponds to the hydrological signal of the upper Rhône river downstream of Lake Geneva for the catchment area that generates the wood flux. The hourly flow discharge during the analysed wood extraction period varied between 8 and 1013 m³/s.

2.2 | Materials and methods

2.2.1 | Ain and Allier training data sets

Since 2007, a stream-side network camera has been continuously capturing day-time video footage on the Ain river. The footage has proved beneficial for numerous wood monitoring studies (Ghaffarian et al., 2020; MacVicar et al., 2009; MacVicar & Piégay, 2012; Zhang et al., 2021), providing a comprehensive description of the equipment. In this specific study, we have implemented wood annotation for six flood events of the Ain river, which correspond to six of the seven flood events analysed by Zhang et al. (2021). In our study, the last flood event has been excluded as it occurred after an exceptional wind event that significantly modifies the wood motion threshold. We employed the operator-based (continuous and sampled) visual floating wood detection method to generate a database that integrates the time of occurrence for each piece of wood. The cameras installed on the Ain and Allier rivers enable the measurement of the number of pieces of wood per unit of time. The discharge of the river falls within a range of 184 and 1020 m³/s during the flood events that have been annotated (Figure 2a). It is worth noting that each of the six events surpassed the biannual flow level (Table 1).

The camera positioned on the bridge at the gauging station in the Allier river, facing downstream, was calibrated using a database comprising four flood events. Operator-based detection was conducted, with continuous annotation for the first three events and sampling selected videos for the last one. During the annotated flood events on the Allier river, river discharge varied between 77 and 631 m³/s (Figure 2b). The maximum discharge of all four occurrences surpassed the Q_{1.5} flood level (463 m³/s) (Table 1). The third event reached the biannual flow level (550 m³/s), and the fourth event slightly exceeded it.

The camera on the Ain river was an AXIS P221 Day/Night™ fixed network model and recorded continuously at a resolution of 640 × 480 pixels from 2007 to 2011 and 768 × 576 pixels from 2011 to 2023. The camera was placed at an elevation of 9.84 m above the base flow surface on the side of the river closest to the thalweg to ensure a view of the entire river width under most flow conditions and a maximum resolution where the majority of wood pieces are observed. The monitoring of wood pieces on the Allier river involved the use of a Hikvision DS-2CD2T42WD-I8 fixed network camera. Videos were continuously recorded at a resolution of 1920 × 1080 pixels. Positioned near the thalweg at a height of 11 m above the baseflow surface, the camera on the Allier, similar to the setup on the Ain river, is affixed to a bridge, facing downstream.

To distinguish between large wood and smaller wood pieces, a widely adopted criterion in the literature involves defining a

truncation length. Typically, a minimum length of 1 m has been utilized globally to classify wood as large wood (Wohl et al., 2010). In line with previous similar studies (MacVicar & Piégay, 2012), a 1-m truncation length was applied in this research for consistency. Additionally, this truncation helps to minimize missing rates for both cameras. While in term of wood flux, we may miss significant number of smaller pieces, for the volume, which is crucial for risk management, we will only miss approximately 5% (Ghaffarian et al., 2023).

2.2.2 | Wood extractions at Génissiat dam and hydrological conditions

Between 2011 and 2019, the study analysed 20 extraction periods, during which, the extracted volumes (V_{obs}) (Table 2) ranged from 117 to 3800 m³ as shown in Figure 3. In contrast to the wood flux measurement with the cameras, at Génissiat, it is the volume of wood removed from the dam per unit of time that is recorded. The time-lapse between two extractions varied from 34 to 531 days. The maximum hourly discharges per extraction period were between 40 and 189 m³/s on the Valserine and 168 and 902 m³/s on the Arve as depicted in Figures 3 and 4a. On the Arve, the highest discharge reached in 2015 (before extraction 14) is estimated to have a return period surpassing 100 years (HydroPortail, <https://hydro.eaufrance.fr>). On the Valserine, the greatest event has a return period of 20 years and occurred at the same time as on the Arve. The maximum discharge during each period is consistently lower on the Valserine and attains its proportional maximum (in comparison to the Arve's maximum discharge) between the second and third extraction (Figure 4b).

The discharge data from the Arve and Valserine rivers were utilized to predict the wood flux, rather than relying on a gauging station from the Rhône river. This decision was made because the primarily wood supply originates from the Arve and Valserine river basins (Moulin & Piégay, 2004), while the latter contributes the majority of the water discharge. Due to the closure of the nearest measuring station to the Rhône river, a series of hourly discharge data was compiled to predict wood flux series of the Valserine river. This involved combining the discharge readings recorded at Chézery-Forens on the Valserine river and at Châtillon-en-Michaille on the Sémine river (Figure 1d). The Sémine river is the principal right bank tributary of the Valserine. Hourly discharge data from the Bout du Monde station on the Arve river were utilized for predicting wood flux (Figure 1d).

In order to compare the predictions, which generate the wood flux, with the volume of wood extracted at the dam reservoir for a given period, the wood flux has to be converted into wood volume. The initial step involves redistributing the predicted wood volume of each extraction period into length classes using the length distribution of the Ain and Allier rivers. To obtain the volume of wood for a given length, the relationship between wood length and diameter must be established. MacVicar and Piégay (2012) conducted measurements on both variables for 8465 floating pieces of wood visible on video recordings and calculated the volumes by fitting the wood shape to a cylinder. The database was augmented with 213 field measurements from the Allier river, which also included wood pieces of greater

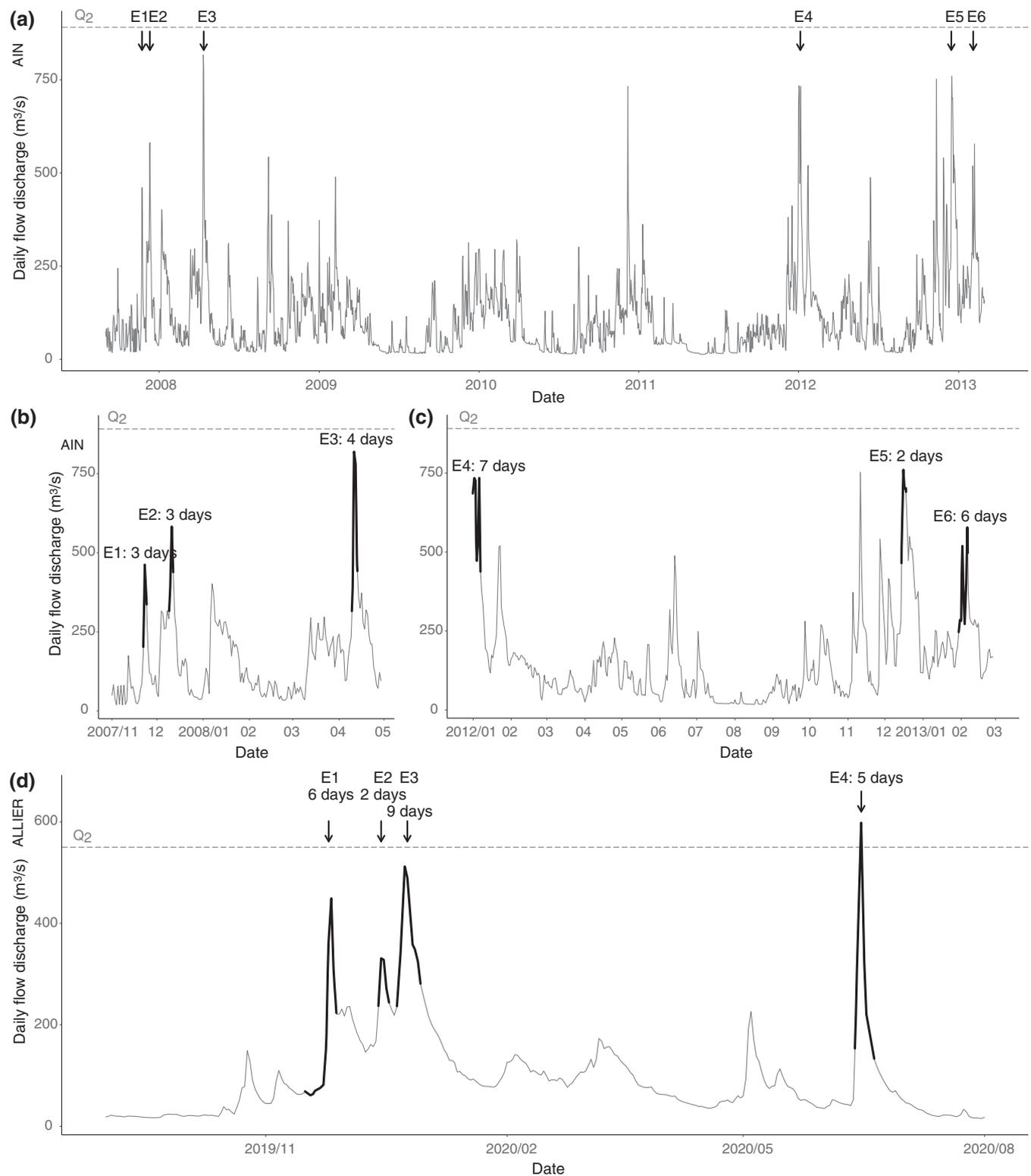


FIGURE 2 Daily mean discharge of the (a) Ain and (d) Allier rivers. Panels (b) and (c) provide close-up views of the events on the Ain river. Annotated high-flow events are indicated by arrows and black lines, with their duration displayed in days.

length (Figure 5). The database was segmented into size classes, and the corresponding mean volume was computed. The same length classes were used as for the predictive redistribution. Finally, the relationship established between length classes and volumes was applied to

derive predicted volumes. Since volume is computed on a large number of specimens, the error in volume estimates (assuming no bias in the length-volume model) is negligible compared with volume estimates. We estimate the variance in the volume estimate for each

TABLE 1 Wood annotation method and flow conditions of the 10 analysed events.

River	Event	Annotation period	Annotation method	Discharge conditions						RF predictors	
				Q _{1.5}	Q ₂	Q _{min} (instantaneous)	Q _{max} (instantaneous)	Q _{max} / Q _{1.5}	Q _{max} / Q ₂	Max. dQ/dT	Max. T _Q
Allier	1	23–28 November 2019	Continuous	463	550	77	497	1.1	0.9	1.0	688.0
	2	15–16 December 2019	Continuous			315	352	0.8	0.6	0.8	19.0
	3	22–30 December 2019	Continuous			228	530	1.1	1.0	1.7	716.0
	4	13–17 June 2020	Sampled			139	631	1.4	1.1	1.5	2598.0
Ain	1	22–24 November 2007	Sampled	782	891	184	578	0.7	0.6	2.4	189
	2	10–12 December 2007	Sampled			297	616	0.8	0.7	2.3	207
	3	10–13 April 2008	Sampled			276	1020	1.3	1.1	3.1	1965
	4	1–7 January 2012	Continuous			427	814	1.0	0.9	2.9	390
	5	15–16 December 2012	Continuous			473	914	1.2	1.0	3.2	1709
	6	1–6 February 2013	Continuous			244	694	0.9	0.8	3.9	46

Abbreviation: RF, random forest.

TABLE 2 Frequent abbreviations.

Abbreviation	Definition
Q	Represents the discharge at time <i>t</i> . It is not continuously recorded but rather gauged at discrete, irregular intervals. Therefore, the values of <i>Q(t)</i> are interpolated to correspond to instantaneous estimates that align with the times of wood occurrences
T _Q	Time elapsed since the last time that <i>Q</i> was higher or equal to <i>Q(t)</i>
dQ/dT	Gradient of discharge over a time lag (5 min)
F _{obs}	Observed wood flux
F _{pred}	Predicted wood flux
F _{predR}	Predicted wood flux of the Rhône river using merged hydrological data series of the Arve and Valserine rivers
F _{predA}	Predicted wood flux of the Arve river
F _{predV}	Predicted wood flux of the Valserine river
V _{obs}	Extracted wood volume at Génissiat dam
V _{pred}	Predicted wood volume
V _{predR}	Predicted wood volume of the Rhône river using merged hydrological data series of the Arve and Valserine rivers
V _{predA}	Predicted wood volume of the Arve river
V _{predV}	Predicted wood volume of the Valserine river
V _{predAV}	Predicted wood volume of the Rhône River reconstructed by merging the individually predicted volumes of the Arve and the Valserine rivers
RF	Random forest
RMSE	Root mean square error

wood piece according to wood length classes. It varies between 0.00016 and 10.97 m³. Taking into account the number of pieces predicted in each wood length class, and assuming the individual volume

estimate is unbiased, we calculate the error in the total estimate of volume. It varies between 0.11 and 0.7 m³, which represents less than 0.5% of the total volume estimates for each extraction.

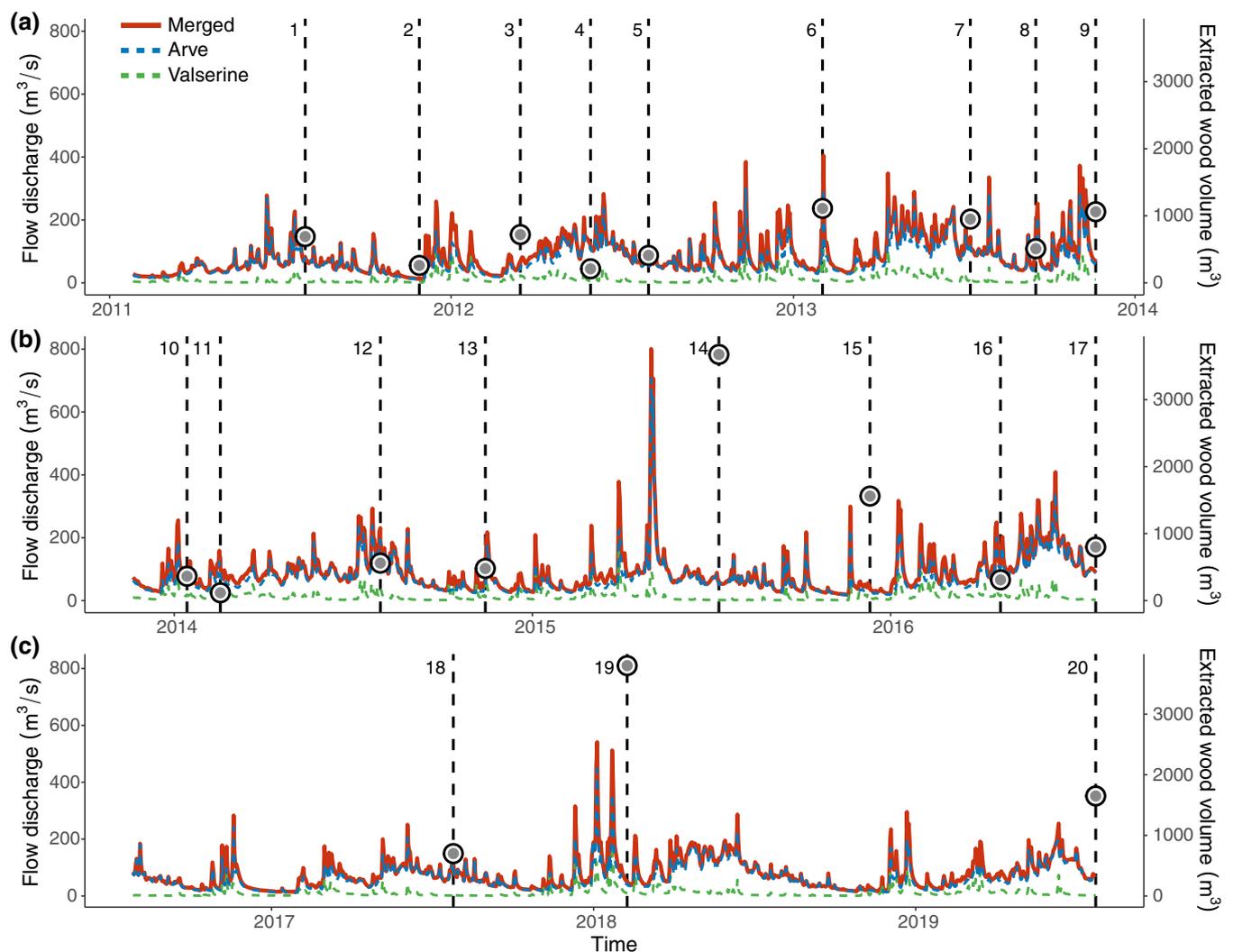


FIGURE 3 Mean daily discharge of Valsérine and Arve rivers, along with the combined discharge of both rivers. Dots represent the extracted volume at Génissiat dam, with numbers indicating wood extraction periods.

2.2.3 | RF model

The data analysis was conducted entirely within the R software package (R Core Team, 2022), using the woody package (Vaudor, 2022), which was specifically developed for modelling and predicting wood fluxes based on hydrological drivers. This package builds on the RF model described by Zhang et al. (2021), which predicted wood flux based on hydrological drivers. A RF is an ensemble learning method that fits multiple decision tree regressors on random subsets of the data and averages their predictions to provide a robust and accurate non-linear regression model. Precisely, the response variable is $1/T$ where T is the time lag between a certain wood piece occurrence and the previous one, and the predictors are instantaneous hydrological drivers calculated based on discharge. The package improves the reusability of this method to other sites and dates by automating the complex and computational steps of formatting and merging the discharge and wood occurrence datasets (in particular by calculating the instantaneous hydrological drivers). It also makes easier to run the RF regression model, to predict instantaneous wood flux, and to estimate

hourly or total fluxes based on instantaneous frequency. We then utilized the package to produce the RF non-linear regression algorithm that models the relationship between wood flux and flow discharge. Two data sources are necessary: wood piece occurrences (response variable, obtained here from video monitoring) and the corresponding instantaneous flow discharge. The three predictors are derived from the flow time series and are as follows: (i) $Q(t)$, representing the discharge at time t , is not continuously recorded but rather gauged at discrete, irregular intervals. Therefore, the values of $Q(t)$ are interpolated to correspond to instantaneous estimates that align with the times of wood occurrences; (ii) the time elapsed since the most recent occasion when Q was equal to or greater than $Q(t)$, known as T_Q ; and (iii) the discharge gradient over a time lag (5 min) dQ/dt .

The performance of the Ain and Allier RF models is assessed by comparing the hourly predicted and annotated wood flux (nb/time), calculated as follows:

$$R^2 = 1 - \frac{\sum (F_{\text{pred}} - F_{\text{obs}})^2}{\sum (F_{\text{obs}} - \bar{F}_{\text{obs}})^2},$$

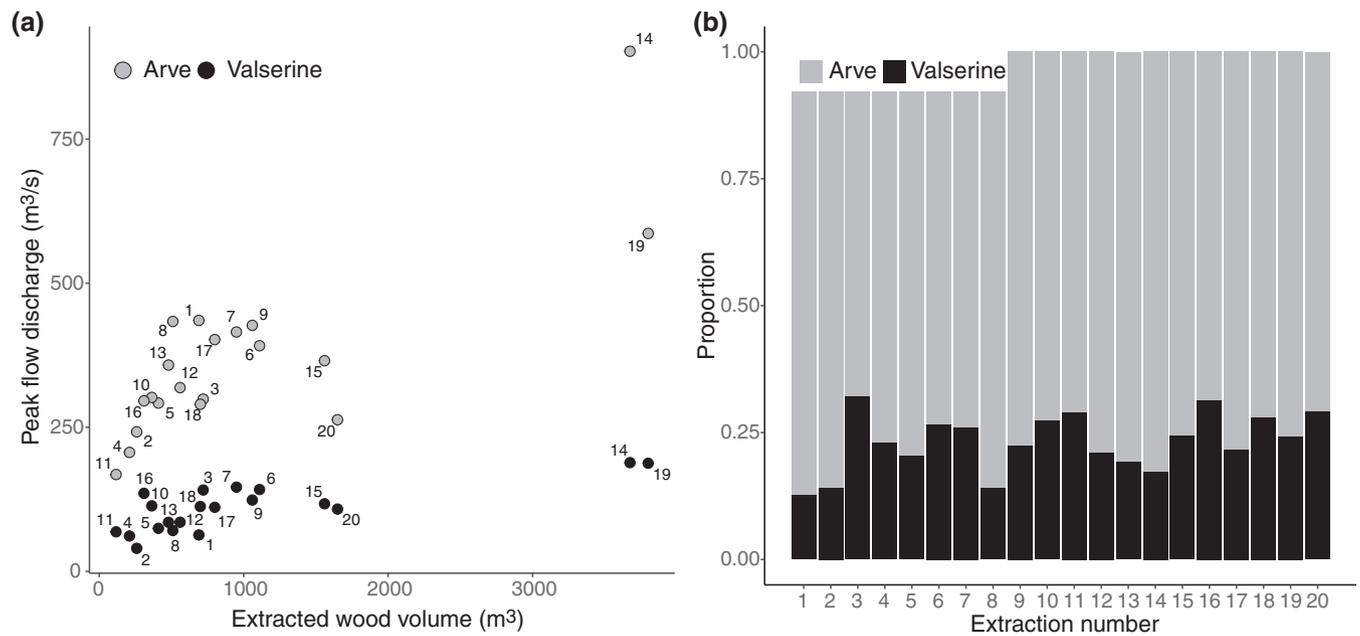


FIGURE 4 (a) Relationship between hourly peak flow discharge during the inter-extraction periods and the extracted wood volume at the end of each period at Génissiat. (b) Relative importance of observed peak discharge between the Arve and the Valserine during the inter-extraction periods following each extraction.

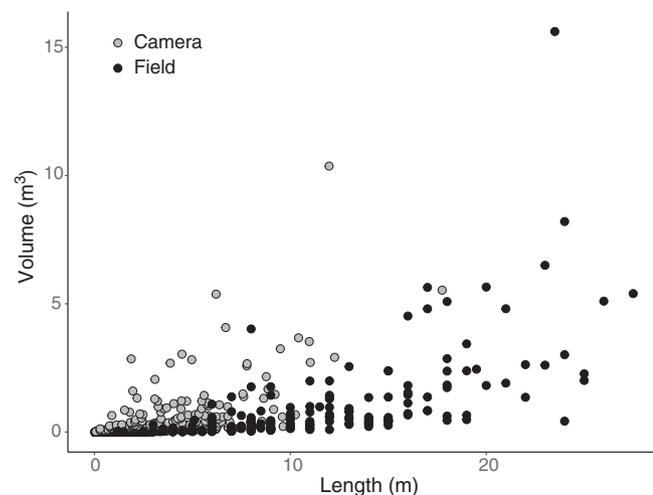


FIGURE 5 Relationship between wood length and volume calculated using diameter measurements from video recordings of the Ain river and field sampling from the Allier river.

where F_{obs} is the hourly observed wood flux and F_{pred} is the hourly predicted wood flux.

2.2.4 | Wood volume prediction at the Génissiat dam

Two calibration datasets (Ain and Allier) were utilized to develop two RF models, resulting in two wood flux predictions ($F_{\text{pred Ain}}$, $F_{\text{pred Allier}}$)

for each extraction period of the Génissiat dam. Initially, to predict the wood flux of Génissiat dam (V_{obs}), the reconstructed hourly flow discharge of the Rhône river ($V_{\text{predR Ain}}$, $V_{\text{predR Allier}}$) was used. The entire workflow is illustrated in Figure 6. In a subsequent phase, we analysed the predictions of the Arve and Valserine rivers separately, without merging the flow discharge ($V_{\text{predAV Ain}}$, $V_{\text{predAV Allier}}$), to determine the respective contribution of each sub-catchment.

Pearson's correlation coefficient and root mean square error (RMSE) were calculated to measure the association between the model predictions (V_{pred}) and the volumes extracted at the dam (V_{obs}).

Two factors influencing wood flux were employed to adjust predicted wood flux: (i) the size of the basin at gauging stations and (ii) wood recruitment dynamics through lateral erosion. Correction factors are determined by calculating simple ratios between the calibration basins (Ain and Allier) and prediction basins (Arve, Valserine and the sum considered as Rhône river) to appropriately adjust the predicted volumes. The amount of wood recruited (supplied) is equivalent to the amount of vegetated surface eroded between 2008 and 2022 relative to the length of the river (area per unit length of channel). However, the use of wood recruitment as a comparison is limited due to its reliance on data sources with low spatial resolution (5 m being the lowest). Nevertheless, it still enables its application for a relative comparison between river basins. Data on the river channel and vegetation are sourced from BD TOPO® of the National Institute of Geographic and Forest Information (IGN, <https://geoservices.ign.fr/>). However, the information obtained is rather incomplete for the Valserine basin, as the cartographic data on river channels used is incomplete for the earlier year. Additionally, observing lateral erosion in the Valserine basin is challenging due to the very small channel width. To

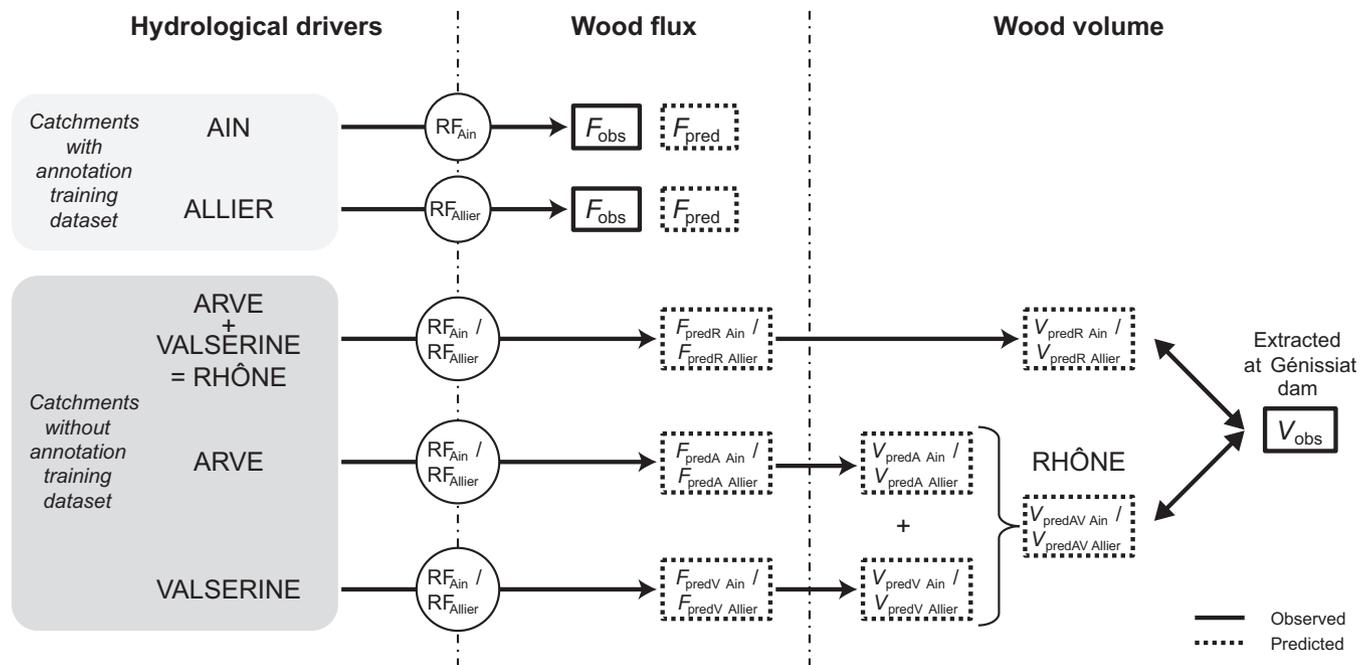


FIGURE 6 Global workflow indicating data sources and steps to obtain wood volume using random forest (RF) model.

ensure a more thorough analysis, a visual comparison of the aerial photographs from 2008 to 2022 was conducted on the Valserine basin and no additional vegetated surface erosion was identified beyond what was already mapped.

3 | RESULTS

3.1 | Observations of critical flows on the Ain and Allier rivers

On the Ain river, the maximum hourly F_{obs} was equal to 597 pieces/h and 69 pieces/min (truncated at 1 m), with an estimated maximum volume of 41 m³/h (Figure 7) and 3.5 m³/min. The RF model utilized three predictors to estimate the wood flux, as described above. Figure 8 illustrates the link between wood flux and three hydrological variables: (i) flow discharge during the rising limb ($Q(t)$) (Figure 8a), (ii) discharge gradient over a 5-min time lag (dQ/dT) (Figure 8b), and (iii) time elapsed since the last instance of Q equalling or surpassing Q (T_Q) (Figure 8c). Predictions are presented for annotated periods and when the flow discharge falls within the same range as the annotated events. The threshold for critical wood motion discharge is 300 m³/s, which corresponds to 38% of $Q_{1.5}$ and 34% of the Q_2 discharge. MacVicar and Piégay (2012) observed this threshold during two flood events on the Ain river. Zhang et al. (2021) identified the critical discharge at 450 m³/s, which corresponds to the second wave of wood flux increase following a slight decrease between 400 and 450 m³/s. Wood flux above this discharge increases and peaks at a rate of approximately 870 m³/s, conforming to 1.1 $Q_{1.5}$ and 0.98 Q_2 .

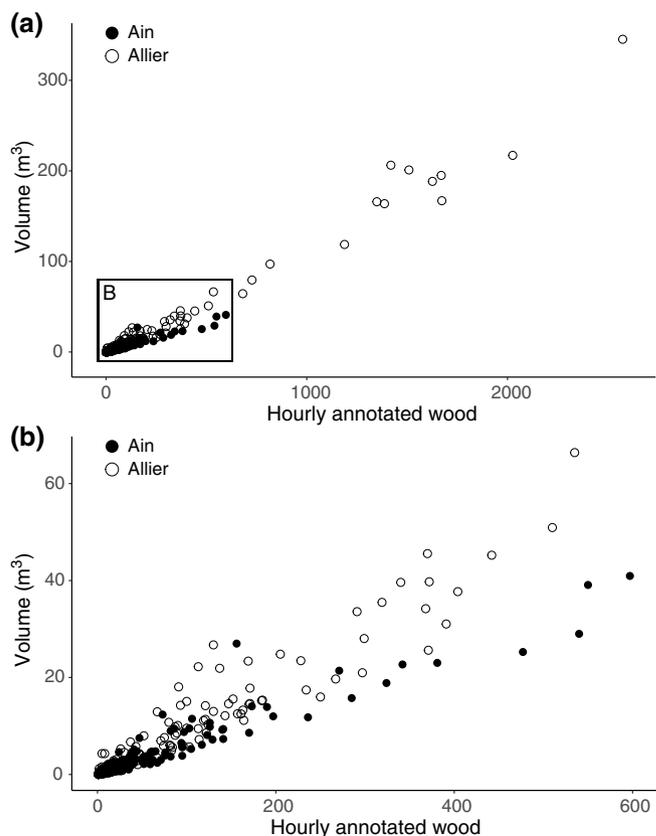


FIGURE 7 Relationship between hourly annotated wood quantity (piece nr/hour) and the corresponding wood volume. Figure (b) is a zoom of the figure (a), focusing on the maximum annotated hourly wood range of the Ain for enhanced visibility.

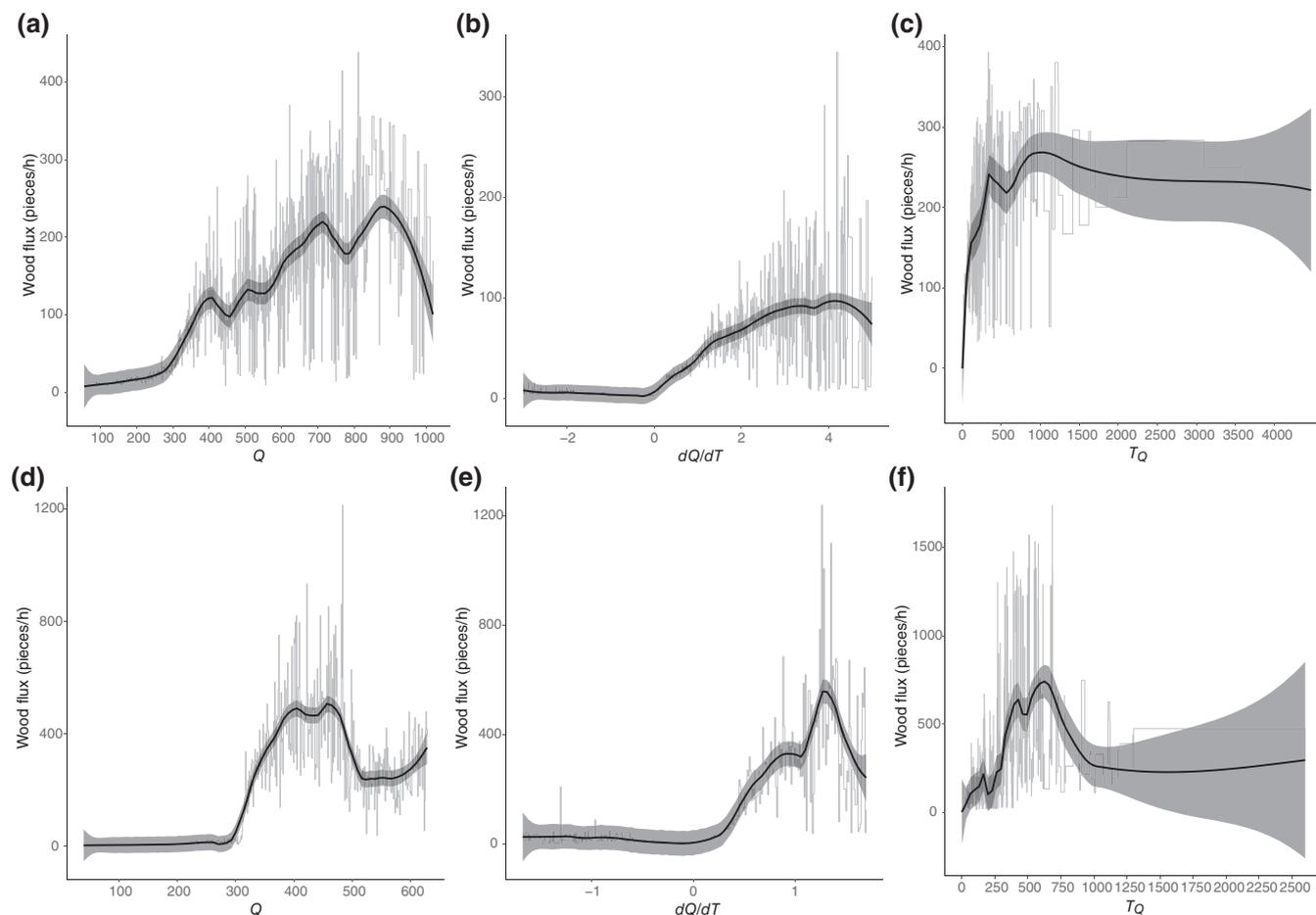


FIGURE 8 Predicted values of wood flux (in grey line) on the Ain (a–c) and the Allier (d–f) Rivers as a function of (a, d) flow discharge of the rising limb, Q (m^3/s , resolution of $1 \text{ m}^3/\text{s}$), (b, e) discharge gradient, dQ/dT ($\text{m}^3/\text{s}/\text{h}$, resolution of 2 decimals) and (c, f) the time elapsed since the last time that Q was higher or equal to $Q(t)$, T_Q (days). The black line represents the Loess model (span 0.2) and the grey shading area indicates the 95% confidence interval.

A reduction in the gradual increase is noticeable when flow discharge ranges from 770 to $790 \text{ m}^3/\text{s}$. During the rising limb, a clear gradient effect in flow discharge can be observed, with positive values of dQ/dT exhibiting a rate of up to $3.2 \text{ m}^3/\text{s}/\text{h}$, contrasting with the falling limb (negative values) (Figure 8b). At least, 83% of the wood flux is predicted during the rising limb (Figure 9). The rise of wood flux halts just before the flow discharge reaches its maximum. According to Figure 8c, the wood flux increases rapidly as the inter-flood time increases up to 300 days, peaks at about 900 days, and then becomes relatively constant.

When considering each event individually, it becomes evident that implementing an RF model rather than a linear model with a single variable is necessary. The critical discharge varies between events (Figure 10), with events 2, 4 and 5 delivering wood at a significantly higher flow discharge than events 1, 3 and 6. Furthermore, it is apparent that the connection between discharge gradient and wood flux or T_Q and wood flux is not linear.

On the Allier river, the maximum hourly F_{obs} recorded is 2574 pieces/h, 84 pieces/min (truncated at 1 m) with an estimated maximum volume of $345 \text{ m}^3/\text{h}$ (Figure 7) and $14.8 \text{ m}^3/\text{min}$. This

greatly exceeds that of the Ain river. The threshold for wood motion is observed at $320 \text{ m}^3/\text{s}$, which corresponds to 70% of the $Q_{1.5}$ discharge and 58% of the Q_2 discharge (Figure 8d). The wood flux culminates first at $400 \text{ m}^3/\text{s}$ corresponding to $0.87Q_{1.5}$ and $0.72Q_2$, then remains relatively stable with a slight increase until $480 \text{ m}^3/\text{s}$ ($1.0Q_{1.5}$ and $0.87Q_2$), before decreasing. The wood flux drops earlier during the rising limb compared with the Ain river. The variable dQ/dt reaches its maximum at about $1.3 \text{ m}^3/\text{s}/\text{h}$ and then decreases (Figure 8e). At least, 86% of the wood flux is predicted on the rising limb (Figure 9). Wood flux increases with T_Q until just above 600 days and then drops rapidly (Figure 8f).

The critical discharge also varied between the events on the Allier river (Figure 10). Wood transport initiation occurred earlier during event 4 (~ 206 – $270 \text{ m}^3/\text{s}$), but the sudden increase in wood flux coincided with event 1 (around 320 – $330 \text{ m}^3/\text{s}$). Wood flux started to increase at the same discharge during events 2 and 3, but much more smoothly compared with events 1 and 4. Event 4 delivered wood up to a greater discharge than event 3 (500 vs. $420 \text{ m}^3/\text{s}$). Event 3 behaves differently, having attained a relatively high wood flux at the end of the rising limb. Event 4 was characterized by the highest

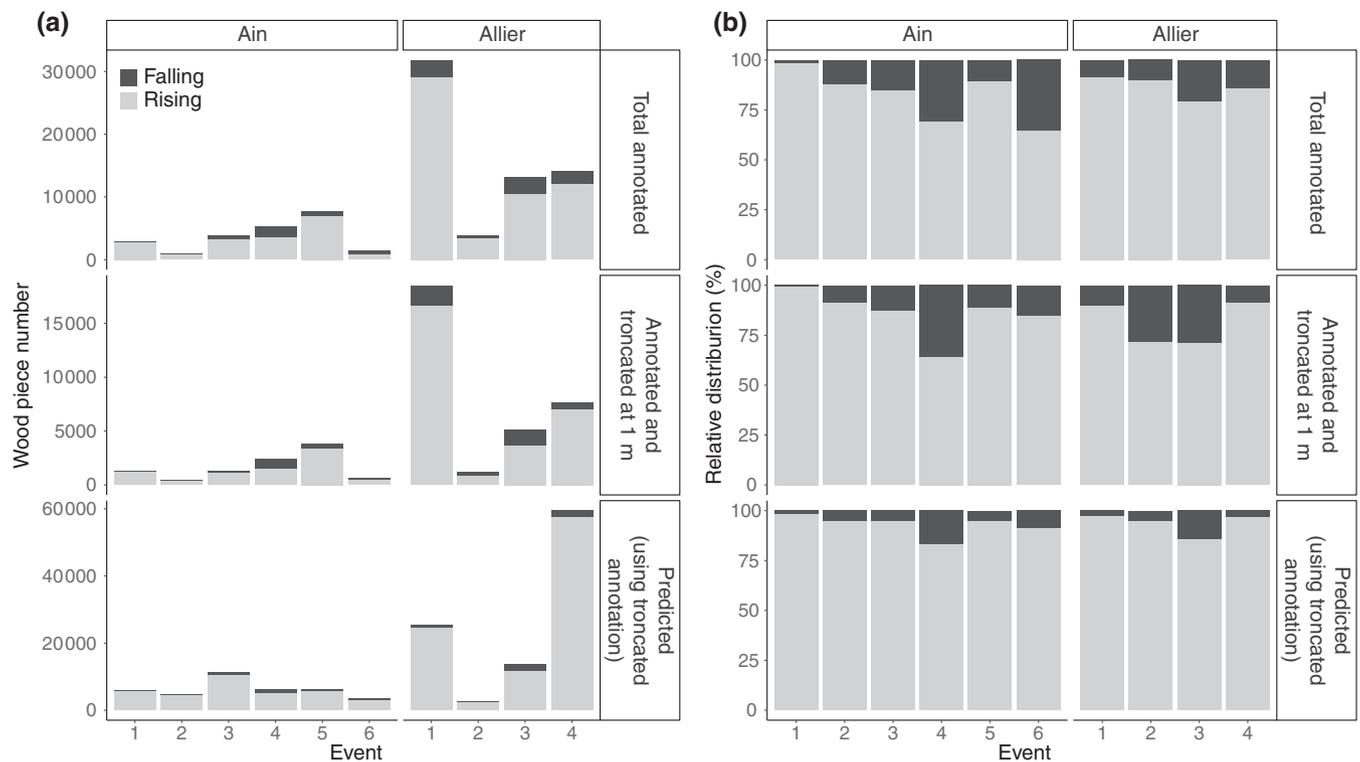


FIGURE 9 Wood annotation statistics from video recordings and random forest predictions by high flow events represented as (a) absolute wood piece number and (b) relative distribution (%).

dQ/dt , which may potentially account for why high wood flux is reached with low T_Q characteristics.

3.2 | Model performance

The average R^2 value, computed between the hourly annotations of wood flux (F_{obs}) and predicted values (F_{pred}), is 0.68 for the Ain and 0.56 for the Allier river (Table 3). The F_{pred} for day and night-time is overlaid with the hourly F_{obs} shown in Figures 11 and 12. Certain events are better predicted than others. Notably, events 1, 3, 5 and the initial peak of event 4 are accurately predicted on the Ain. However, the RF model overestimates the wood flux during the peaks of events 2, 6 and the second peak of event 4. Conversely, there is an underestimation of peak wood flux during events 1 and 4 on the Allier. On the Allier, T_Q is the primary predictor, accounting for 45% of the total increase in node purity, followed by Q (28%) and dQ/dT (27%). On the Ain river, the importance of T_Q is 43%, dQ/dT 38% and Q 18%.

3.3 | Inter-basin comparison of wood flux

Several general rules observed on the Allier and Ain rivers align with previous research. More wood is transported during the rising limb than the falling limb, a pattern observed in various climate regions, such as the Isère (France) (Ghaffarian et al., 2020), the Ain (France)

(Ghaffarian et al., 2020; MacVicar et al., 2009; MacVicar & Piégay, 2012; Zhang et al., 2021), the Tagliamento (Italy) (Ravazzolo et al., 2015) and the Slave rivers (Canada) (Kramer & Wohl, 2014). The RF model predicted more than 80% of the wood flux on the rising limbs for both the Allier and the Ain. Despite wood transport increases with rising flow discharge, wood flux is not perfectly synchronized with river flow dynamics. The peak wood flux generally occurs before the flow discharge reaches its maximum (Ruiz-Villanueva et al., 2016), typically around the estimated bankfull discharge ($0.7 Q_{1.5}$) on the Ain river (B. MacVicar & Piégay, 2012). The Allier and Ain rivers respond similarly to hydrological drivers, albeit with different thresholds and ranges of values. The highest annotated and predicted wood fluxes are reached for the Allier at $1.0 Q_{1.5}$ and $0.87 Q_2$. Meanwhile, Zhang et al. (2021) have documented slightly elevated values of $1.1 Q_{1.5}$ and $0.98 Q_2$ on the Ain. In comparison with the $Q_{1.5}$ and Q_2 discharges, the wood motion discharge is lower on the Ain than on the Allier river, that is, $0.38 Q_{1.5}$ versus $0.7 Q_{1.5}$ and $0.34 Q_2$ versus $0.58 Q_2$. MacVicar and Piégay (2012) reported a transport threshold of $2/3$ of the bankfull discharge ($0.67 \times 550 = 366 \text{ m}^3/\text{s}$; $300 \text{ m}^3/\text{s}$ for two events and between 220 and $390 \text{ m}^3/\text{s}$ for one event), Ghaffarian et al. (2020) $0.3Q_{1.5}$ ($0.3 \times 840 = 252 \text{ m}^3/\text{s}$) and Zhang et al. (2021) $0.6Q_{bf}$ ($0.6 \times 550 = 330 \text{ m}^3/\text{s}$) but indicated a critical discharge of $450 \text{ m}^3/\text{s}$ on the Ain river. Therefore, wood motion appears to initiate somewhere between 250 and $450 \text{ m}^3/\text{s}$ on the Ain river, corresponding to the $300 \text{ m}^3/\text{s}$ threshold, we identified using video monitoring and modelling methodologies. The estimated critical discharge of the Canadian Slave river is lower than $2/3$ of $Q_{1.5}$,

as reported by Kramer and Wohl (2014). The same applies to the Isère river, where it is equivalent to $0.5Q_{1.5}$ (Ghaffarian et al., 2020). While a higher threshold was observed on the Allier river compared with other rivers, it should be noted that wood motion began at $0.5Q_{1.5}$ in a singular observation (i.e., event 4). Intra-basin wood motion threshold variability can be related for example to wind events (Zhang et al., 2021), but wood loads also vary relative to their position in a succession of floods, resulting in different wood fluxes for the same river flow as noted on the Ain river (MacVicar & Piégay, 2012; Zhang et al., 2021). The impact of the first event on the Allier's wood load

was evident in the third event that occurred a month later. Wood flux did not increase suddenly at the critical flow discharge, but increased gradually and slowly, never reaching as high a level as the first event studied.

Overall, the Allier appears to transport wood within a smaller discharge range compared to the Ain, at least based on a model trained on four events. One possible reason may be the difference in geomorphology. Over the first 20 km upstream of the camera, the Allier river has over twice the quantity of alluvial bars (37 vs. 15 $m^2/1$ m river length). When considering the sum of bar and relatively open vegetated bar areas, the Allier again has more than twice the area (136 vs. 64 $m^2/1$ m of river length). This can cause differences in the time of wood release and filtering/deposition during a flood event. It is also possible that wood flux decreases in both rivers when the water level reaches bankfull discharge and the riparian forest provides a large filtering effect, but this hypothesis should be supported by additional analysis. Similarly, differences in the cohesion of the banks can impact erosion and wood recruitment, which may occur earlier or later depending on Q_2 or $Q_{1.5}$ discharge. Once wood is mobilized on the Allier, the wood flow increases more quickly. dQ/dt on the Allier does not spread as much as on the Ain, which means that the river discharge increases more slowly on the Allier. The conclusion drawn from these findings is that all three predictors (Q , T_Q and dQ/dt) of the RF model are needed and perform well on both rivers.

Up to four times higher wood flux per hour was quantified on the Allier, despite the truncation at 1 m length that could compensate for differences in camera resolution. Figure 9 indicates that predicted wood pieces from two equivalent floods ($Q_{max} = 1.1Q_2$), Allier event 4 and Ain event 1, are more than five times greater on the Allier. A possible reason for this is that more wood are being recruited by lateral erosion on the Allier (Hortobágyi et al., 2024), in addition to its larger catchment area (Allier: 14400 km^2 ; Ain: 2642 km^2 , when not including the area upstream from Vouglans dam). As a result, the maximum amount of wood per hour is also higher on the Allier (2574 pieces/h vs. 597 pieces/h and 84 pieces/min vs. 69 pieces/minute). Accordingly, the maximum hourly wood flux is also higher on the Allier (2574 pieces/h vs. 597 pieces/h and 84 pieces/min vs. 69 pieces/min). When comparing these results with the literature, the wood flux of both rivers appears to be relatively high, a phenomenon that could be attributed to lateral channel shifting within a

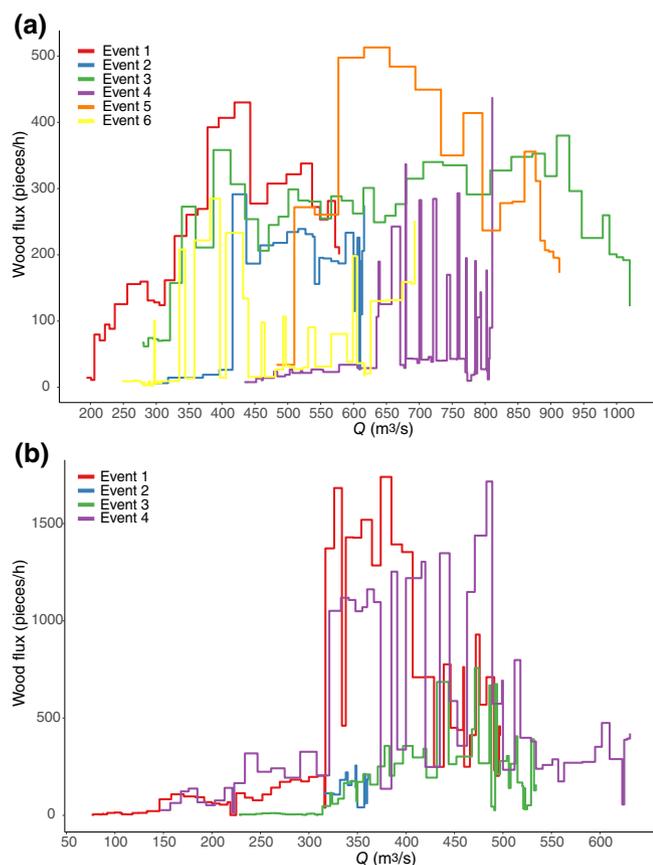


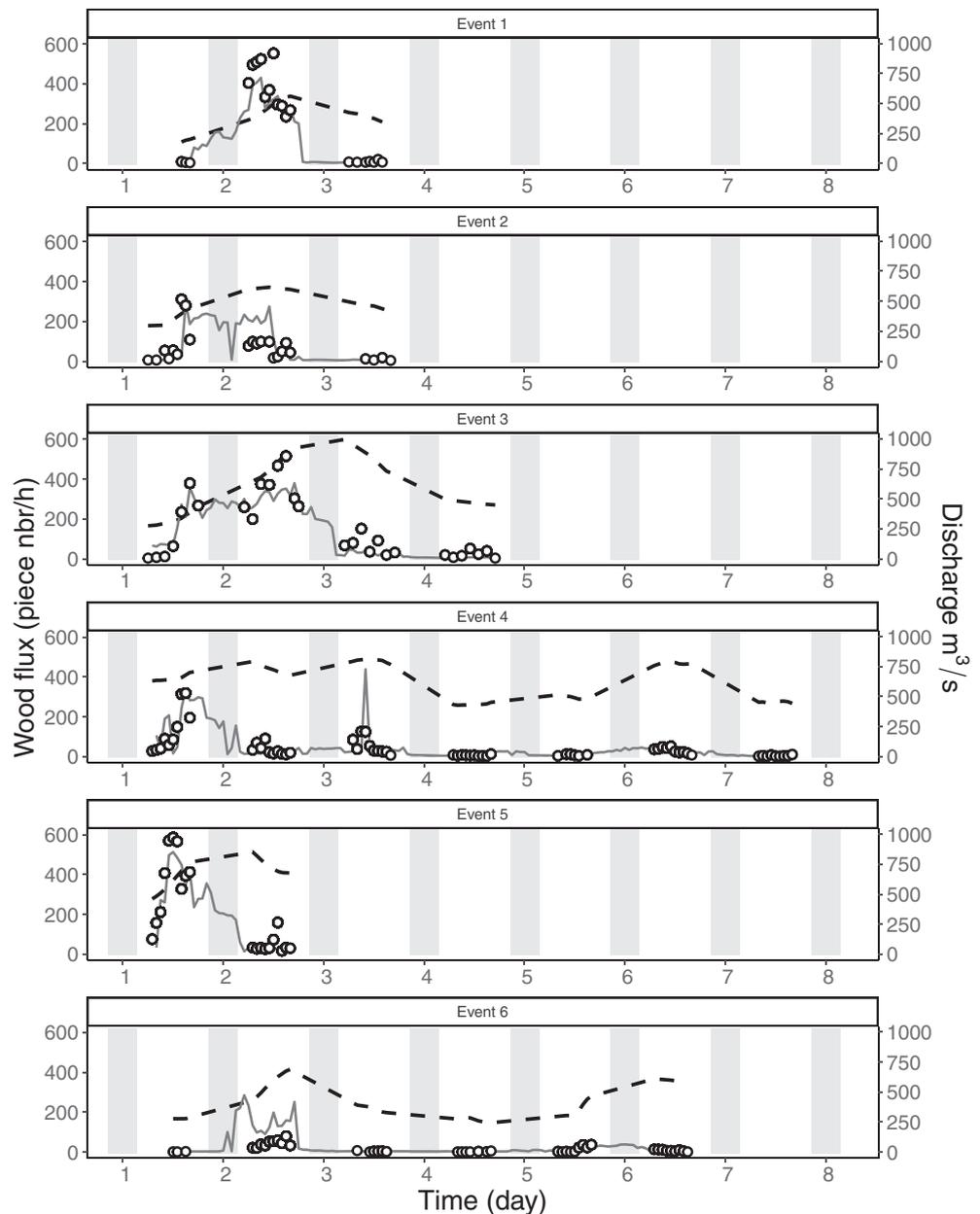
FIGURE 10 Wood flux evolution in relation to flow rate for (a) the six events of the Ain River and (b) the four events of the Allier River.

TABLE 3 Wood flux and wood volume prediction performance of random forest model.

River	RF model wood flux prediction performance		Wood volume prediction performance at Génissiat			Approximate proportional recruitment rhyme compared to the 'Rhône river'	
	Predicted versus annotated	R^2	Predicted versus extracted	Predicted and corrected by basin area size versus extracted	Predicted and corrected by recruitment rhythm versus extracted		
			R^2	RMSE	RMSE	RMSE	
Ain		0.68	0.53	1249.7	870.1	857.3	1.8
Allier		0.56	0.73	2294.0	923.3	825.8	4.3

Abbreviations: RF, random forest; RMSE, root mean square error.

FIGURE 11 Predicted (grey continuous line) and observed (dot) hourly wood flux and hourly river discharge (black dashed line) on the Ain River for the six annotated flood events. The grey rectangles represent night-time, when wood annotation is unavailable.



forested alluvial corridor. For example, during a flood with ice breakup, the Canadian Saint-Jean river transported a maximum of 15 pieces per minute (Boivin et al., 2017). On the Isère, the highest wood flux recorded was only 40 pieces per hour (Ghaffarian Roohparvar, 2019). Furthermore, the hourly wood volume is also higher on the Allier, as depicted in Figure 7, suggesting a proportionally greater number of larger logs.

3.4 | Predictions at Génissiat dam

The V_{predR} values are satisfactory for both predictions ($R^2_{\text{Ain}} = 0.53$, $R^2_{\text{Allier}} = 0.73$) and are better for the Allier RF model (Table 3). The predicted volumes exceed the actual extraction volumes for both models (Figure 13a,b). However, the overestimation is more

prominent in the Allier model, as evidenced by the higher RMSEs of 1249.7 m³ (Ain) and 2294 m³ (Allier) (Table 3). Extraction numbers 14 and 19 denote the highest V_{obs} , while extraction numbers 20 and 18 or 14 correspond to the highest V_{predR} . Extractions 14 and 19 occurred after the highest floods of the studied period and have been underestimated by the models. Extraction numbers 20 and 18 correspond to the longest periods without wood extraction from the dam, lasting 531 and 363 days, respectively. Afterwards, extraction numbers 14 and 19 follow with 238 and 197 days each, ranking as the third and fourth longest periods. The wood volume during the first two longest extraction periods is significantly overestimated by the models.

Overall, volume overestimation may be linked to the distinct features of the training rivers, as well as those of the Arve and Valserine rivers, including basin size and wood recruitment rhythm. The basin

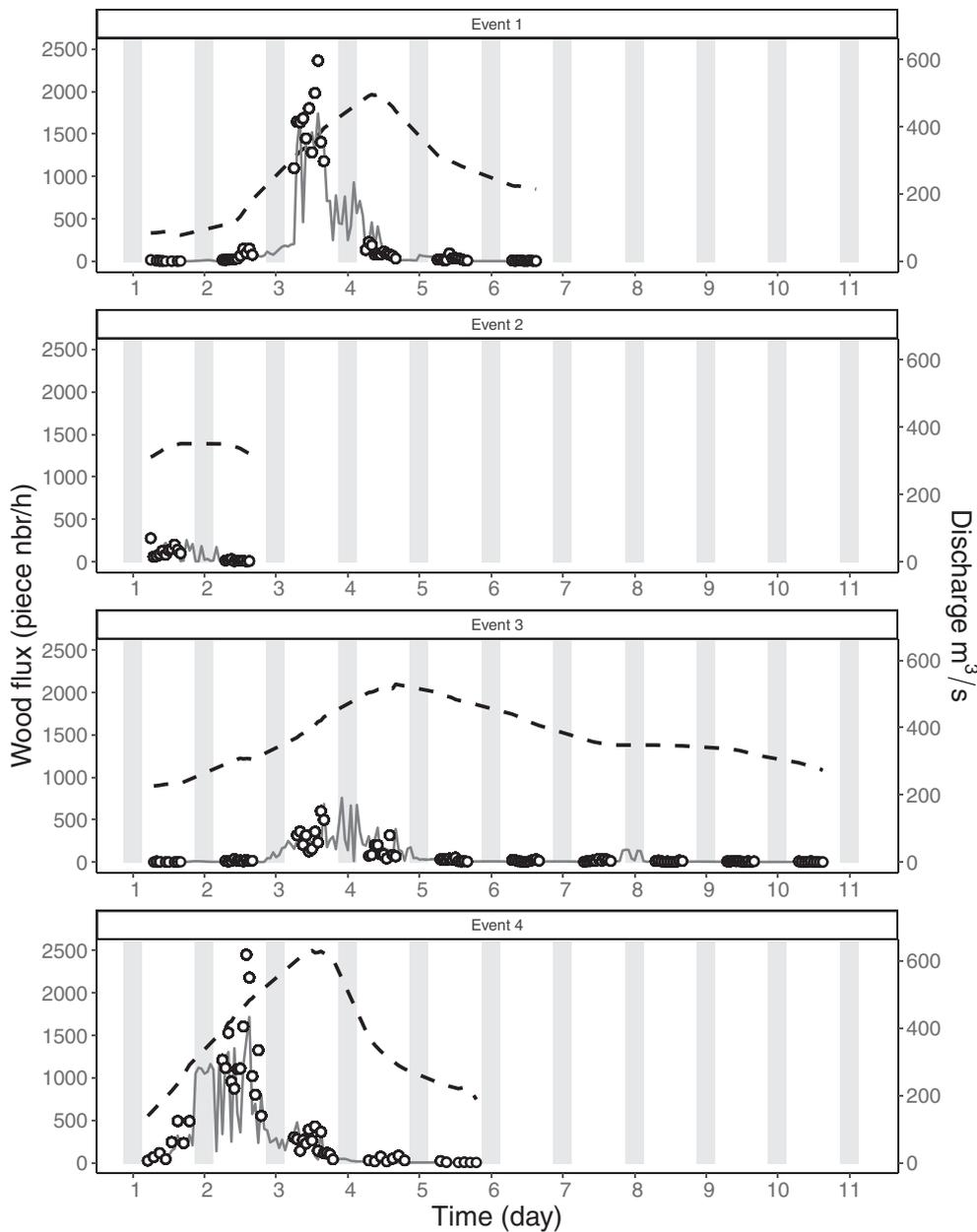


FIGURE 12 Predicted (grey continuous line) and observed (dot) hourly wood flux and hourly river discharge (black dashed line) on the Allier River for the four annotated flood events. The grey rectangles represent night-time, when wood annotation is unavailable.

size of the Ain river is 1.6, while that of the Allier is 5.5 times greater than that of the Rhône river. Additionally, they, respectively, recruit 1.8 and 4.3 times more wood via lateral erosion. This indicates lower wood production in the Rhône river, due to the smaller basin area and lower wood recruitment when compared with both calibration basins. These factors were utilized to proportionally correct the predictions based on the differences in basin area (Figure 13c,d) and wood recruitment (Figure 13e,f). After applying the correction factors, the predicted volume is reduced or even underestimated (see Figure 13 for the evolution of the 1:1 line). The RMSEs demonstrate a significant reduction after correction with the Ain RF model, 870.1 m³ after adjusting for basin area size and 857.3 m³ after accounting for differences in wood recruitment (Table 3). When using the Allier RF model, the corrected RMSEs are 923.3 and 825.8 m³, respectively. Extractions 14 and 19 exhibit the most significant prediction errors with

both models. Extraction 15, which experienced the highest flood event, was heavily underestimated by both models. After applying recruitment dynamic correction to the Ain model, the mean error in percentage compared with V_{obs} is 57% (SD: 53; median: 54). The Allier model shows a mean error of 34% (SD: 29; median: 25).

The correction for the wood recruitment rhythm due to bank erosion resulted in the closest association with V_{obs} . Although we cannot control the quality of each individual prediction, we additionally estimated the wood flux via the Ain and Allier RF models on the Arve (V_{predA}) and the Valserine (V_{predV}) rivers separately (Figure 14a, b). We then adjusted these results with the wood recruitment correction coefficient. The Allier model shows greater proportional variances than the Ain model. Notably, extractions 9, 13, 1, 14 and 8 demonstrate a significant production increase of the Arve, exceeding 7.5%. By summing the predictions of the two rivers (V_{predAV}) and

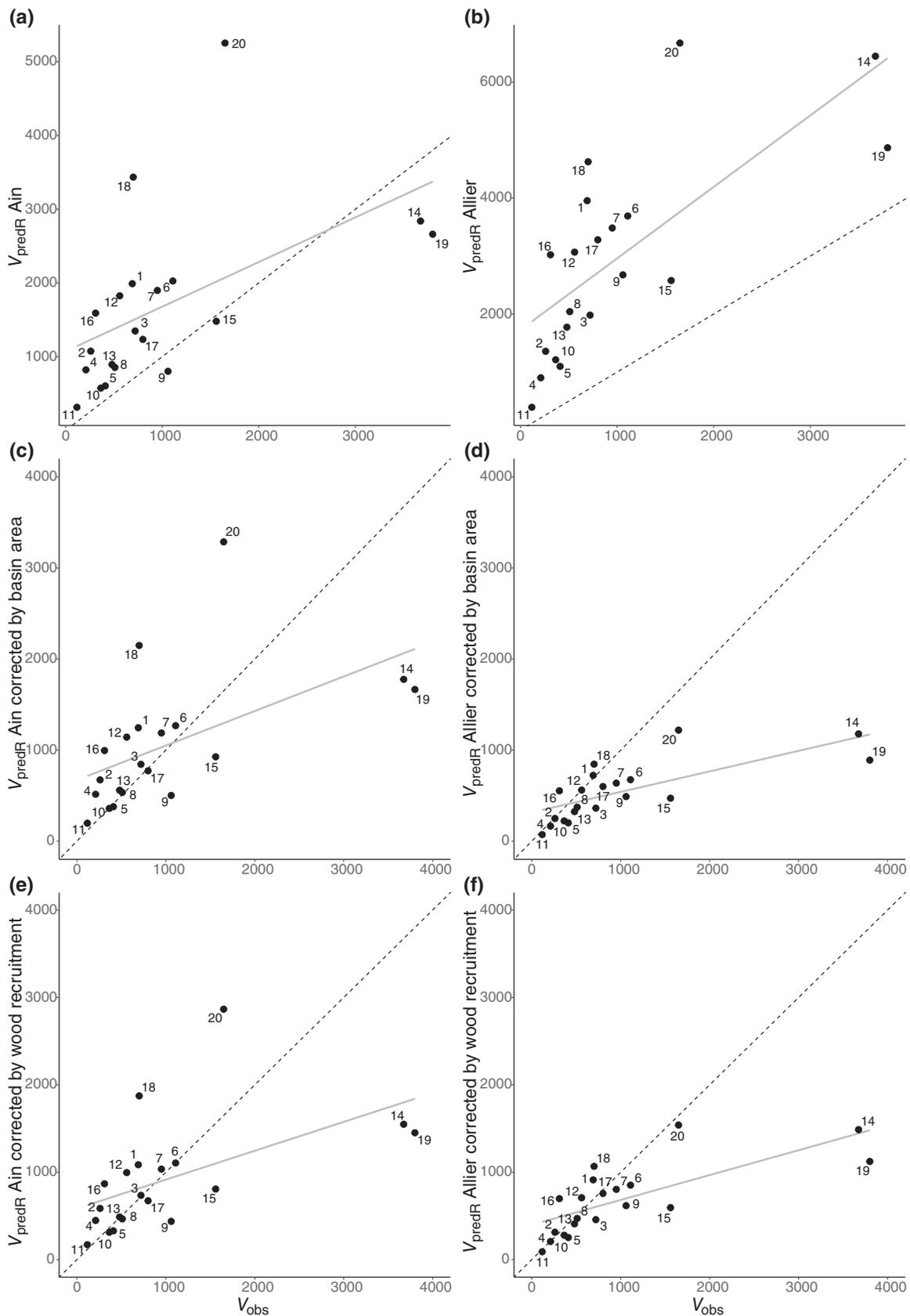


FIGURE 13 Relationship between the predicted wood volume of the RF model (V_{predR}) and the extracted volume at Génissiat dam (V_{obs}) using the Ain (a), (c), (e) and the Allier training data (b), (d), (f). (a) and (b) represent raw predictions of wood volume, (c) and (d) represent the predicted wood volume corrected by the basin area differences and (E) and (F) represent the predicted wood volume corrected by the wood recruitment. Grey lines indicate regression lines, while black dotted lines indicate the 1:1 line.

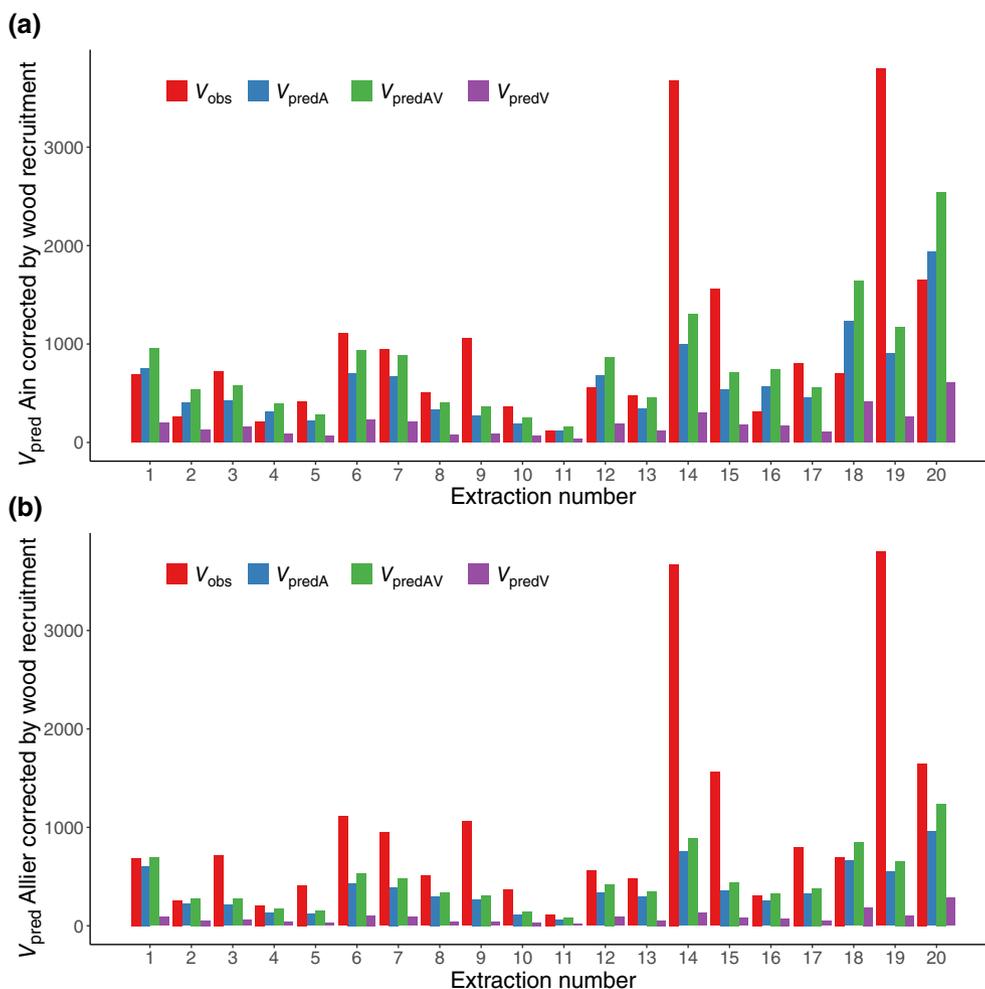


FIGURE 14 Predicted wood volume (V_{predAV}) reconstructed from the individual predictions of the Arve (V_{predA}) and the Valserine (V_{predV}) rivers after correction by recruitment dynamic predicted with (a) the Ain model and (b) the Allier model, compared to the extracted volumes at Génissiat (V_{obs}).

comparing it with V_{obs} , we obtain an RMSE of 896.3 m^3 and a correlation coefficient of 0.49 with V_{predAV} Ain and, respectively, 1018.5 m^3 and 0.60 with V_{predAV} Allier. Compared with V_{predR} , the results are slightly more deviated from V_{obs} . However, there is a slight improvement when combining the predictions of V_{predA} Ain, Allier and V_{predV} Ain, Allier. By adding V_{predV} Ain and V_{predA} Allier, the RMSE is 953.3 m^3 , and the correlation coefficient is 0.58. Conversely, the RMSE for the opposing scenario is 925.0 m^3 , and the correlation coefficient is 0.49. However, in both cases, the merged models demonstrate a lower correlation coefficient compared with the 100% Allier model. It is challenging to choose a model for the Valserine due to its negligible impact on the overall predicted volume, resulting in a minor role in the correlation.

3.5 | Short term versus long term use

Over the 8-year period, the total cumulative predicted volumes (V_{predR} Ain and V_{predR} Allier), corrected by the wood recruitment rhythm, were slightly lower than the cumulative observed volume (V_{obs}). When taking the cumulative sum of V_{obs} as 100% at the end of the 8-year period, the error accounted for 8.3% and 31.6% for V_{predR} Ain and V_{predR} Allier, respectively.

4 | DISCUSSION

4.1 | Wood prediction in ungagged basins

We achieved relatively high correlations between the predicted wood volumes on the Rhône and the extracted wood volumes at the Génissiat reservoir with both training datasets. The Génissiat volumes always correlate better with the Allier model predictions, and the relative errors are lower. The combination of predictions from the two models revealed that neither the Arve nor the Valserine wood flux can be predicted more accurately with the Ain model, as none of the combined models gave a higher correlation coefficient compared with the 100% Allier model. If we use the RF model trained with the Allier dataset to make predictions with either the merged or unmerged discharge series, we can expect to underestimate the wood flux when the Valserine discharge is higher. When training the RF model with the Ain dataset, we can expect an underestimation for the high flows of the Arve, but not for the lower flows, when the Arve and Valserine are predicted separately.

We found that the predictions for longer extraction periods tended to be overestimated, especially, with the Ain model (i. e., extractions 18 and 20) (Figure 13e). Overall, the predictions follow the expected trends, but some overestimations persist despite the

correction and accumulate over time when the extraction period is long. This error actually compensates for the underestimation caused by high flow events, as observed during the long-term performance evaluation (8 years) of the model. However, for the Ain model to perform well in the long term, it requires both long extraction periods with low and high flows to occur. On a larger time scale, the Allier model will only underestimate the volume if high flow events are predicted. These findings suggest that the Allier model is better adjusted for wood flux predictions, particularly for the Arve river which the predictions indicate has a higher amount of wood. The reason for the improved long-term volume estimation of the Ain model is that V_{predR} significantly exceeds V_{obs} for some extractions, thus compensating for the strong underestimation associated with high flow events. However, the Allier model does not exhibit such a period of overestimation to balance the underestimation of extractions 14, 15 and 19.

The differences in the size, discharge regime and wood production dynamics of the Ain, the Allier, the Arve and the Valserine rivers could lead to significant overestimations or underestimations of volume. The Ain has a discharge range of 180–995 m³/s, while the Allier has a range between 76 and 631 m³/s. Predictions are made within a range of 8–1013 m³/s. Accurate predictions have been achieved by implementing correction factors. As previously mentioned, the Allier produces a larger amount of floating wood and higher volume, which may result in the Allier model overestimating the Rhône data before correction.

Other factors could affect the accuracy of the RF model in predicting the volume of wood removed from the Génissiat reservoir. For instance, the distance of tributaries from the reservoir might impact the amount of wood accumulated in the reservoir. They could also slow down or hold the wood during transport to different degrees depending on their length, which could explain a time lag or discrepancy between input and output. This may partly explain why the estimated volume of event 15 is lower than actual. A prior extreme flood event, occurring before event 14, appears to have recruited a large amount of wood, which was not immediately evacuated from the Arve and Valserine systems and could have arrived later with successive flood events. Moulin and Piégay (2004) previously reported considerable wood input at Génissiat despite low water discharge during that period. Conversely, exceptionally high flow events can lead to a moderate accumulation of identical wood. The greatest flow discharge occurred during the extraction period 14 on the Arve (flood of >100 year period), and on the Valserine (flood of >20 years), resulting in the accumulation of 3674 m³ of wood in the reservoir. Meanwhile, the highest volume extraction at Génissiat (nr 19; 3800 m³) was preceded by a much lower ($\sim Q_3$ – Q_4) flood event on the Arve. However, during the extraction period 19, the Valserine reached the same discharge level as during period 14. This suggests that, whether a flood of Q_4 or a Q_{100} happens in the Arve basin, almost the same amount of wood is delivered to the reservoir. The question is whether the Valserine provided the rest of the wood. The Arve's contribution compared with the Valserine is still heavily debated. Our RF predictions suggest a higher wood flux on the Arve and a higher recruitment rate compared with the Valserine.

4.2 | Current RF model issues, limitations and future challenges

The woody R package (Vaudor, 2022) is a free and open solution for predicting wood fluxes that require easily accessible data, such as river discharge. This paper presents a first attempt to apply the model to a river for which no training data (wood pieces occurrence data) is available. Our RF models provide wood flux estimates for predictor values within the ranges that occur in the training data. Predictors values at the edges or beyond these ranges will have higher uncertainties or errors. This could be a reason for underestimating major flood events (Arve: >100 year flood, Valserine: >20 year flood). We also encountered a problem with missing data regarding the highest peak flow (period 14) in the past. One of the three parameters of the RF model is the time elapsed since the last occurrence of the same discharge (T_Q). Our information on the Arve river only extends back to 1990, and during the last 25 years, the flood level of 2015 was never reached. Nonetheless, our model provided a reasonable estimate between the training rivers (Ain, Allier) and the upper Rhône.

A further challenge will be to determine and integrate additional parameters besides hydrological data into the model to obtain coherent results without a training dataset. The two corrector parameters (basin size and wood recruitment by lateral erosion) proved to be necessary for integration. Other factors, such as weather conditions (e.g., wind, season), beaver and human activity (e.g., forest harvesting), can influence wood recruitment and flux (Moulin & Piégay, 2004; Zhang et al., 2021). Additionally, other hydrological variables, such as flood duration, may also be incorporated as they have been found to influence wood dynamics (Hortobágyi et al., 2024; Kramer & Wohl, 2017). Further case studies are needed to refine the parameters and enhance the potential of this RF model for estimating wood flux in other rivers using video monitoring techniques.

5 | CONCLUSIONS

The current research enhanced the capability and usefulness of video monitoring in examining the wood flux dynamics of two river basins, namely, the Ain and the Allier rivers. It also investigated and interpreted the differences in drivers. General patterns were observed, while disparities were identified between the Ain piedmont river and the lower Allier, providing novel insights. The RF model has demonstrated confident applicability for night-time prediction when a training dataset exists for the same river. However, the integration of additional parameters such as basin size or wood recruitment is necessary to calibrate the model for use without training data. Wood flux predictions and modelling are still in early stages, and inter-basin comparison studies and preliminary modelling are essential for advancing this field. With the growing use of video monitoring stations, there is potential for an ever-increasing number of training datasets for multiple river basins. Additionally, research on appropriate calibration parameters for non-monitored basins could enhance the RF model and our ability to comprehend the factors driving wood transport and

accumulation. This study highlights the importance of advancing modelling techniques to predict wood dynamics in rivers, providing insights into the intricate interactions between hydrological factors and wood transport. Through the refinement of predictive models and the exploration of new variables, this study improves our ability to forecast wood flux accurately. Consequently, it aids in making more informed decisions regarding river management and promotes ecosystem resilience in response to environmental challenges.

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DATA AVAILABILITY STATEMENT

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

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