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RFID TRACKING FOR MONITORING IN-STREAM WOOD MOBILITY IN A SMALL COASTAL MEDITERRANEAN MOUNTAINOUS RIVER: IMPLEMENTATION AND PRELIMINARY RESULTS

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ABSTRACT.- Rivers transport a wide variety of materials, ranging from submillimeter-sized sediment particles to entire trees. The transported wood, constituting a vital component of wooded river ecosystems, constantly alters the morphology of watercourses and influences river flow. Given the inherently complex and varied nature of river systems, a thorough exploration of their diversity is justified to identify recurring trends in the dynamics of wood transport. This need becomes imperative in regions already facing prolonged episodes of drought, frequent heatwaves, and an increase in extreme precipitation events. In the specific context of the Massane River, a small Mediterranean mountain river, our study aimed to lay the groundwork for a long-term monitoring of in-stream wood transport by the watercourse. We began by inventorying the wood present in the riverbed in the upper part of the watercourse. This inventory involved measuring, identifying the species, assessing the state of degradation, and geolocating all the pieces of wood present. To estimate the transport, we introduced pieces of wood representative of the fraction of the stock that was potentially mobilizable, marked with RFID tags. The results indicate that wood was present almost throughout the considered section of the watercourse. About one-third of the total volume of the wood stock could be transported during a bankfull flood. RFID tracking revealed that a moderate rise in water level could move such pieces nearly 4 kilometers downstream. This work marks the initiation of a long-term monitoring effort to trace the movement of in-stream wood from the river's source to its estuary and examine the relationship between flood event types and the extent of wood transport.

KEY WORDS: RIVERS, WATER RISE, LARGE WOODY DEBRIS, RADIO TELEMETRY, TRACKING, DISPLACEMENT LENGTH

INTRODUCTION

Wood plays a key role in the functioning of habitats along the land-sea continuum (Maser & Sedell 1994, Naiman *et al.* 1999). Fallen branches and trees from riparian forests create structurally rich banks (Naiman & Décamps 1997) , providing habitats for various animals, including insects (Parisi *et al.* 2021), amphibians (Herbeck & Larsen 1999), mammals (Radu 2006), and birds (Mikusinski & Angelstam 1997). Wood also plays an important role once it enters the riverbed. It provides essential shelters, spawning areas, and foraging opportunities for aquatic life (Anderson *et al.* 1984, Angermeier & Karr 1984). Additionally, it releases organic substances that contribute to biogeochemical cycles, enriching the water with essential nutrients (Bilby & Likens 1980). Downstream, wood maintains its ecological role (Sleeter & Coull 1973) and serves as a long-term carbon sink (Canuel & Hardison 2016), aiding in climate change mitigation (Mcleod *et al.* 2011, Russell *et al.* 2015, Zeng 2008).

Rivers naturally transport large wood debris (Harmon *et al.* 1986). Understanding this process helps identify debris accumulation zones, which is crucial in the perspective of flood mitigation and management of extreme flood events (Comiti *et al.* 2016, Mazzorana *et al.* 2018, Nicholson *et al.* 2012). Characterizing the spatial distribution of wood in river systems also provides information on the natural processes that shape riparian environments (Pedroli *et al.* 2002), guiding initiatives related to river restoration and biodiversity conservation (Roni *et al.* 2015, Wohl *et al.* 2015).

Field survey methods are essential for studying wood dynamics and storage by rivers (Gurnell *et al.* 2002). Repeated wood inventories allow for the identification of wood inputs, movements, and outputs, thus capturing temporal changes in river ecosystems (Wohl & Goode 2008). These inventories are conducted by collecting detailed and precise data, including direct measurements of the volume, size, and position of wood pieces (Abbe & Montgomery 2003). The mobility of individual wood pieces is primarily controlled by their characteristics, such as length, diameter, and type (Wohl & Goode 2008). Recently, remote sensing tools, such as aerial photography (Johnson *et al.* 2000, Piégay *et al.* 1999) or lidar (Marcus & Fonstad 2008), have enhanced field inventories, enabling the study of interactions between wood and floodplains, particularly in the context of large rivers (Wohl 2013).

Quantifying temporal wood dynamics in rivers can be achieved using aggregate or individual inventory techniques (MacVicar *et al.*2009, Schenk *et al.* 2014). Among these, individual tracking techniques offer precise assessments of wood mobilization, deposition, and transport distance. Visual methods, such as recognizing individual pieces based on their shape, location, and the presence of distinctive features (Lienkaemper & Swanson 1987), as well as tagging with waterproof acrylic paints (Jacobson *et al.* 1999) or using vinyl plastic tags for identification (Haga *et al.* 2002), have provided valuable information on the individual movement of wood. However, these visual methods are limited in precision and durability.

In contrast, radio-frequency identification (RFID)-based telemetry facilitates real-time data collection and allows for the precise tracking of the location of multiple pieces of wood simultaneously (Schenk *et al.* 2014), without the need for frequent replacements or maintenance efforts. Originally designed to improve military radar systems (Hanbury Brown 1994), RFID has become a practical identification tool widely used in various fields, including logistics, supply chain management, and ecological conservation. RFID technology has played an important role in tracking animal movements, migration patterns, and behaviors, providing information for habitat preservation and species conservation (Harrison & Kelly 2022, Kissling *et al.* 2014, Skov *et al.* 2008). More recently, its use in tracking wood movement (MacVicar *et al.*2009, Ravazzolo *et al.*2015, Schenk *et al.*2014) and pebbles (Cassel *et al.* 2020, 2017) has expanded its range of applications to the study of processes in fluvial environments.

While most research on wood transport and its ecological impacts has focused on large rivers, the approaches and conclusions do not necessarily apply to smaller streams that drain most watershed areas. Studies on large rivers often emphasize large-scale processes and often overlook the distinct dynamics and ecological significance of small streams (Benda *et al.* 2005, Gregory *et al.* 2004). The physical characteristics, flow regimes, and wood transport dynamics in small streams differ significantly from those in larger rivers (Gurnell *et al.* 2002), necessitating tailored research approaches (Wohl *et al.* 2016). Therefore, investigating wood dynamics in small streams is essential for a comprehensive understanding of fluvial processes and for informing effective management and conservation strategies. This study addresses this gap by focusing on a small forested Mediterranean mountain river. Mediterranean forests, despite covering a small part of the world's forests, harbor a remarkable diversity of woody species (Gauquelin *et al.* 2018). In the meantime, climate change poses challenges to this region with changes in precipitation patterns, leading to decreased rainfall and increased extreme rainfall events (Zittis *et al.* 2019). River flow and discharge are expected to decrease significantly, leading to water shortages, more frequent droughts, and severe flood events (Tramblay & Somot 2018). These changes are expected to influence wood inputs, transport, and deposition dynamics within river systems.

The general objective of this study is to initiate RFID tracking to monitor wood mobility in the Massane River, a small mountain river originating in the foothills of the French Pyrenees and flowing into the Mediterranean Sea. The study aims to achieve three specific objectives: to quantify the distribution of wood in the riverbed, to develop an RFID tracking protocol for individual pieces of wood in a forested and rugged environment, and to obtain information from the first significant flood event that displaced RFID-tagged wood pieces.

MATERIAL AND METHODS

Study site

The Massane River, depicted in Fig. 1, originates at an elevation of 970 meters in the foothills of the French Eastern Pyrenees and flows for 22 kilometers before reaching the Mediterranean Sea at Argelès-sur-Mer. The watershed covers an area of 17.2 km². From its source to its confluence with the 'Source des Alemanys' at an elevation of 610 meters, the river traverses 5.2 km through the 336 hectares of the National Nature Reserve of the Massane Forest. In this section, the riverbed covers an area of 4.9 hectares (Magdalou *et al.* 2009). The river's geomorphology corresponds to 'Type A' according to Rosgen's (1994) classification. The channel is entrenched with a frequently steep slope (> 4 %) and is bordered by 18.4 hectares of riparian forest. The river features cascades, steps, and zones of accelerated flow due to constrictions in the rocky channel. In the narrowest sections, the distance between the rocky walls that frame the watercourse is only 2.5 meters. The water level is variable but generally low; thus, the zero elevation at the Mas d'en Tourens gauging station is 80.7 mm (Fig. 1). In this upper reach of the river, the dominant tree species are beech (F*agus sylvatica*)

Fig. 1.- Study Site – Topography of the Massane River watershed, river course, and gauge station location. The boundaries of the Massane Forest National Nature Reserve are delineated by the orange line. The position of the reserve's rain gauge station is indicated.

and alder (*Alnus glutinosa*). Beech trees are present throughout this section, while alder trees are only found at altitudes below 800 meters. In this section of the watercourse, wood pieces were inventoried, and pieces equipped with RFID tags were installed to track their movement during water level rises.

Wood stock in the upstream section of the river

In June 2021, the quantity and distribution of in-stream wood were assessed in the upstream section of the river that crosses through the National Nature Reserve of the Massane Forest (Fig. 1). In-stream pieces were defined as any elements located at an elevation lower than the bankfull height. The portion of the riverbed where flow occurs outside of periods of bankfull flooding was used as the base surface for quantifying wood, expressed as cubic meters per hectare (m^3 ha^{-1}) and pieces per hectare (pieces ha^{-1}). Data collection involved measuring the length, average diameter, tree species, degradation state, and geographical position of each piece of wood. Length and diameter measurements were then used to calculate volumes using a cylinder equation. Given that wood pieces shorter than the typical size used for large rivers (i.e., diameter > 0.1 m and/or length > 1 m; Ruiz-Villanueva *et al.*2016) alter hydraulics and habitat in small streams (Jackson & Sturm 2002, Comiti *et al.* 2006), large wood in the present study was defined as any piece longer than 0.4 m with a diameter greater than 0.1 m. To assess the degradation process, a 4-class decay scale was used to characterize the decay stage of the wood pieces. Membership in a class was assessed based on criteria similar to those used by MacVicar *et al.* (2009) :

• Class 1: Recently recruited pieces of dense wood with intact bark, leaves, or buds at the ends of branches.

• Class 2: Dense wood with more than 70 % of its bark intact and no signs of abrasion from river scouring.

• Class 3: Pieces of wood that are still dense, have spent several months in the riverbed, lost more than 70 % of their bark, and show clear signs of abrasion.

• Class 4: Completely rotten wood that decomposes upon contact or under weak pressure.

Stages 1 and 2 capture recent recruitment of wood into the river. Stages 1, 2, and 3 represent wood that can be mobilized during floods, while Stage 4 represents wood that can no longer be transported.

RFID tracking in the field

RFID system description

RFID technology, originally developed for managing inventory, logistics, and various applications like microchipping domestic animals, gates, and access points, is typically employed in scenarios where the tagged object is mobile, while the reader, connected to a powered main PC, remains stationary. Although embedded solutions exist, they often require carrying a laptop or tablet, which can be cumbersome, power-consuming, and fragile. Due to the absence of an off-the-shelf solution, we undertook the development of a lightweight and compact reading device designed for pedestrian use over long distances in rugged natural environments (Fig. 2). All RFID equipment used in this study

Fig. 2.- RFID System. The detection system is mounted on a carrying rack for traversing the river to locate tagged logs; RFID tags are embedded within the wood pieces. Upon detection, the system displays the tag's identification code, signal reception strength indication (RSSI), and geographic coordinates on a liquid crystal display. All data is stored on a micro SD card.

was designed by ELA Innovation, France. The tags employed were PUCK IDs® tags, the receiver was the SCIEL READER lite® reader, and the antenna was the semi-directional SLENDER III® antenna. Detailed technical specifications can be found on the manufacturer's website at https://elainnovation.com/. We used active RFID tags equipped with onboard batteries, enabling signal exchanges at a frequency of 433.92 MHz over distances of up to 100 meters, as specified by the manufacturer. To capture, read, and record the information received by the receiver, we employed an Arduino AT Mega 2560 microcontroller board. The RS232 PC serial port signals from the RFID reader were converted into logic-level data using a serial adapter RS232/TTL module connected to the universal asynchronous reception and transmission serial port 1 (UART 1) of the board. The identification number and received signal strength indicator (RSSI) level of the detected tag were displayed in real-time via the Integrated Circuit Interface (I2C) port of the microcontroller on an LCD I2C 20x40 module (Fig. 2). Data was further stored on a micro SD card as a text file using a micro-SD reader/writer module connected to the serial peripheral interface (SPI) port of the microcontroller. The recording frequency matched the emission rate of the tags, which transmitted one signal every 2 seconds. Each acquisition was timestamped and included latitude and longitude data collected from a GPS module (Adafruit Ultimate GPS Breakout) connected to the UART 2 port of the AT Mega board. A 12V 6800 mA rechargeable li-ion battery provided power for the system, enabling operation for more than 8 hours. The complete detection system, including the protective casing, had a weight of 550 grams and dimensions of 13x12x12 cm (Fig. 2).

Experimental setup

The tagged wood used in the experiment consisted of 50 freshly cut beech logs measuring 0.6 m in length and ranging in diameter from 0.11 to 0.15 m. The RFID tags, 57 mm in width and 20 mm in height, were inserted into pre-drilled slots (Fig. 2), and securely affixed using silicone glue. On May 17, 2021, starting from the source of the river, the tagged wood logs were placed at 100-meter intervals along the riverbed. Upon installation of the tagged wood pieces, we conducted several measurement campaigns to establish the signal propagation model under natural conditions. Knowing the precise locations of the tagged wood pieces at installation, we traversed the river to collect received signal strength indicator (RSSI) levels and GPS coordinates of the RFID reader at signal reception. This data enabled calculation of distances between tags and the detector using the Haversine equation, and subsequent correlation with RSSI measurements. These measurement campaigns ensured the reliable operation of the tags until they were relocated by the river.

To characterize the attenuation of RSSI as the radio signal propagates, we used a simplified equation based on the Free Space Path Loss (FSPL) model, as shown below:

$$RSSI = RSSI_0 - 10 \times n \times \log_{10}(d) \quad (1)$$

where: RSSI represents the received signal strength indicator level. RSSI0 is the received signal strength level at a reference distance of 1 meter. n is the attenuation parameter, which is a parameter that determines the rate of power decrease of the signal with distance. The parameter can vary depending on the environment, obstacles, and propagation path characteristics. In a free space environment, without obstacles or reflections, the typical value of n is generally close to 2. d represents the distance, in meters, between the tag's position and the receiver's position at the time of the tag's detection.

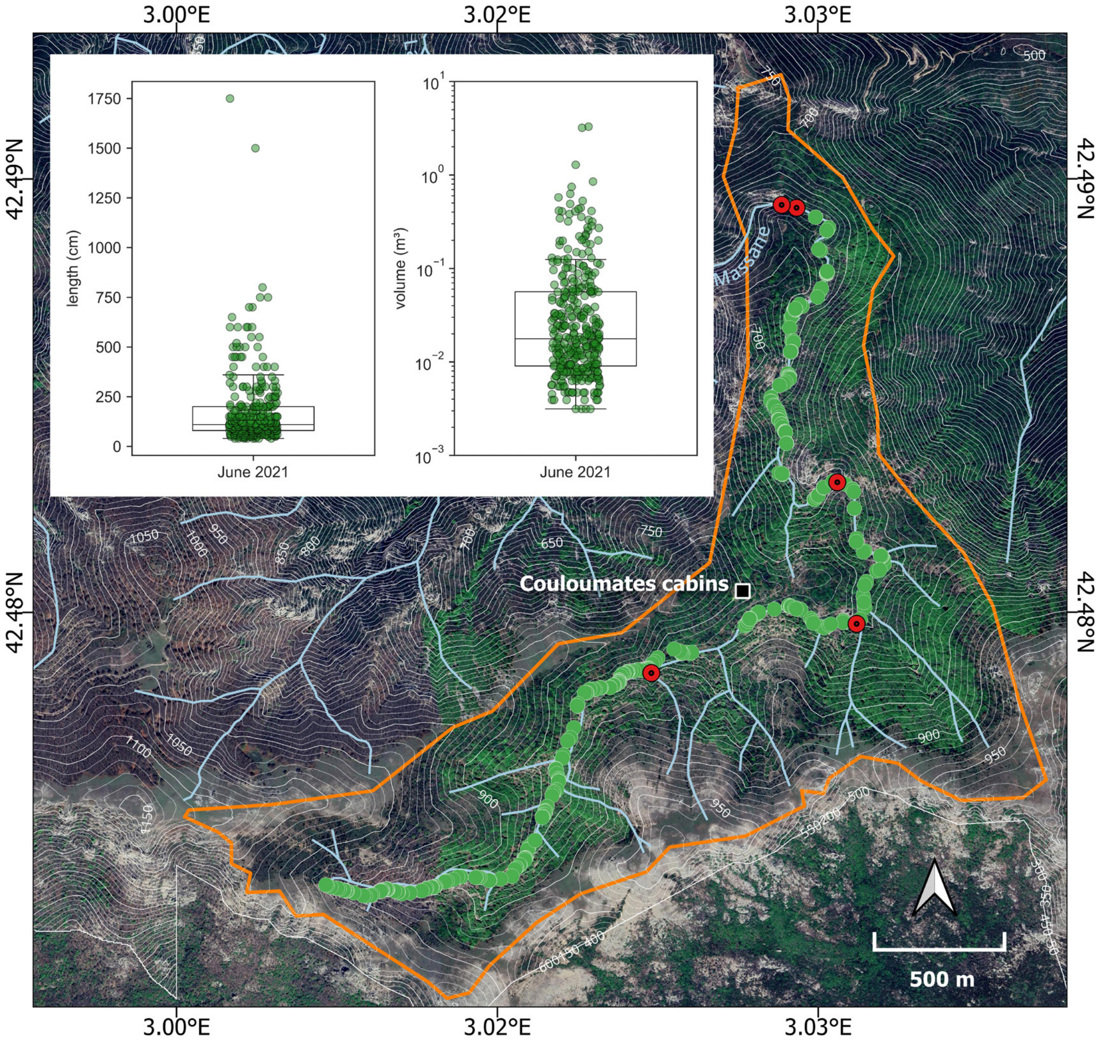

Fig. 3.- Wood in the upstream section of the Massane River – Mapping of wood locations (green dots) and main natural constrictions (gorges and waterfalls, indicated by red dots) along the riverbed within the Massane Forest National Nature Reserve. Boxplots illustrate the distributions of length and volume of individual wood pieces.

Analysis of tag travel distances and transport outcomes

After rainfall events that occurred following the installation of the tags, we conducted surveys along the river to relocate the tagged wood logs. Using the data collected by the RFID reading system, we retrieved the GPS coordinates corresponding to the reader's position that corresponded to the best-recorded RSSI level for each tag. To determine the distances covered by the tags, we obtained the geo-referenced course of the river from the repository maintained by the French national administration service for water data (http://www.sandre.eaufrance.fr/geo/CoursEau/Y0110540). We then applied the Haversine formula to calculate the distances between consecutive points on this route. By summing the lengths of these consecutive intervals, we could calculate the distance between each geo-referenced point on the river and the position of the river's source. Knowing the distance between the source and the tag's position at the time of installation, and the distance between the source and the tag's position after its displacement, we calculated the distance traveled by the tag by subtraction. We recorded whether the wood logs ended up isolated or caught in a logjam after their transport, either within or outside the main channel of the river.

RESULTS

In-stream wood

The inventory conducted in June 2021 revealed that wood was consistently present throughout the upper stretch of the watercourse as shown in Fig. 3. Only a few areas, notably near the Couloumates

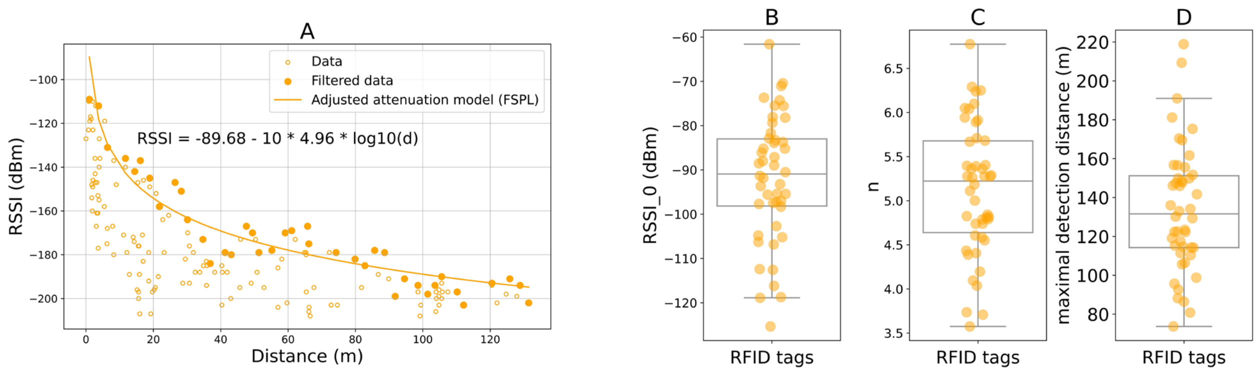

Fig. 4.- RFID wood tagging. (A) Example of received signal strength indication (RSSI) levels vs. distance between the RFID tag and the reader system. Each point represents an individual measurement; solid points indicate values used for the free space path loss (FSPL) signal model calibration. Boxplots of (B) RSSI_0 levels, (C) signal attenuation parameter, and (D) maximum detection distance of RFID tags under field conditions.

per hectare (ha^{-1}), representing a total volume of 32.9 m^3 (7.7 m^3 ha^{-1}). Most of the wood originated cabins showed a scarcity of wood. In total, 368 pieces of wood were recorded, equivalent to 75 pieces from beech trees, making up 82 % of the total number of trees and 78 % of the entire stock volume, followed by alder trees, which accounted for 12 % of the total number of trees and 13 % of the entire stock volume. The lengths of the wood pieces varied considerably, ranging from a minimum of 0.4 m to a maximum of 17.5 m (Fig. 3). The median length was 1.1 m. This disparity was also observed in terms of volumes, with values ranging from 0.003 m^3 to 3.290 m^3. The median volume was 0.018 m^3 (Fig. 3). Wood pieces with a length smaller than the width of the river at its narrowest points (Fig. 3), including rock walls and waterfalls, constituted 74 % of the counts and 34 % of the total wood volume. The most common state of degradation observed was stage 3, characterized by wood pieces that had spent some time in the riverbed, shedding over 70 % of their bark, and displaying evident signs of abrasion. This stage accounted for 85 % of the overall wood volume. Stage 4, indicative of completely rotten wood, comprised 6 % of the total wood volume.

Testing RFID tracking methodology

Fig. 4 depicts the relationship between received signal strength indicator (RSSI) levels and the distance of the RFID reader from the tags. It shows that short distances between the tag and the reading system can lead to both low and high RSSI levels (Fig. 4A). In natural environments, where the operator's movement is not always in a straight line, the alignment of the antenna with the tag's position can vary. To address this variability, the data were filtered to retain only the highest RSSI values within a 5-meter range. The path loss model (FSPL), adjusted based on these data collected with the semi-directional RFID antenna oriented towards the tag, illustrates the attenuation of RSSI as the radio signal propagates.

This analysis, conducted on all the tags in place at the time of measurement, indicated that the

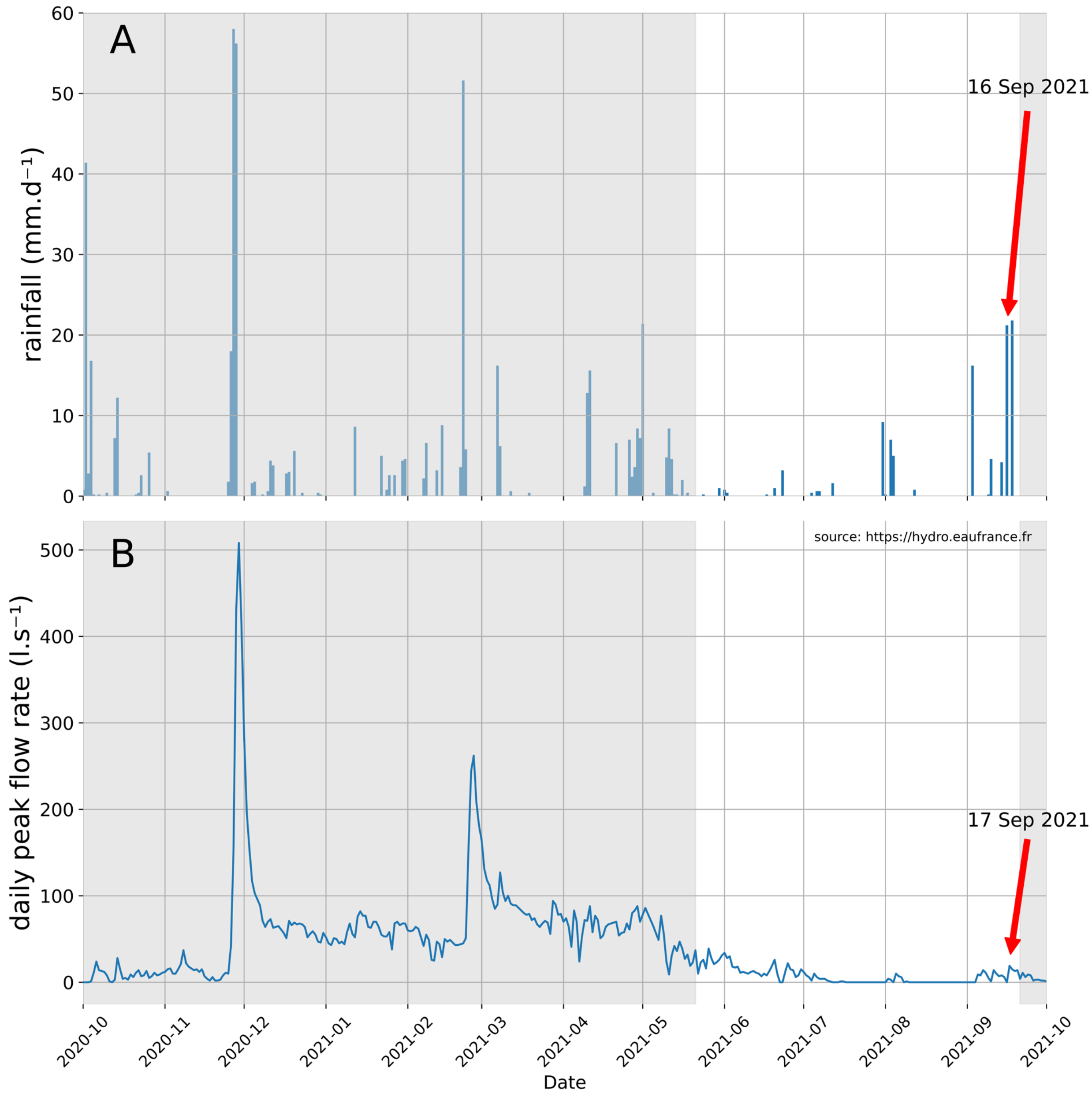

Fig. 5.- Recorded data for 2020-2021 from the reserve's meteorological station showing daily precipitation (A) and instantaneous flow rates from the Mas d'En Tourens hydrometric station (B). The unshaded area on the graphs indicates the time window during which the experiment was conducted.

best RSSI value was around -90 dB (Fig. 4B). The average value of the attenuation parameter, 'n,' was 5.1, with extreme values ranging from 3.5 to 6.7 (Fig. 4C), and a mean detection range of 134 meters, ranging between extremes of 73 and 220 meters (Fig. 4D). Given that RFID tag specifications suggest a range of approximately 100 meters, outliers are likely attributable to temporary inaccuracies in GPS positioning at the time of detection. This is a common and transient issue during sessions lasting several hours in natural environments, where the orientation of the GPS antenna relative to satellites can vary and may not always be optimal.

This monitoring, conducted between the installation of the tags and their relocation by the river, allowed us to detect that one tag went missing in the vicinity of the Couloumates cabins, and two others malfunctioned before the onset of the first river rise. We replaced the faulty tags, while the missing wood piece was not replaced.

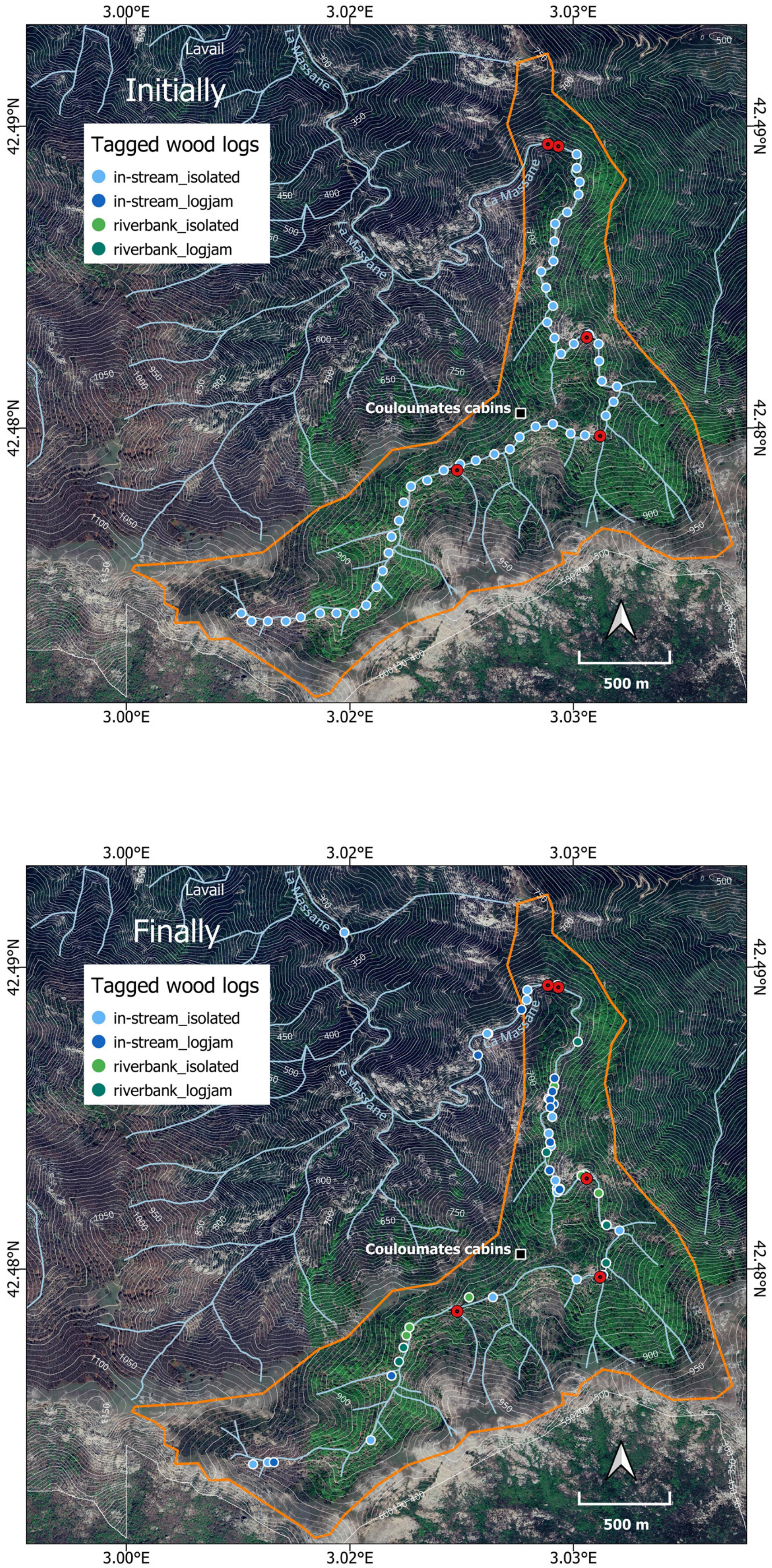

Fig. 6.- RFID-tagged wood log locations pre- and post-flood. The polygon outlines the boundaries of the Massane Forest National Nature Reserve. Dot color indicates whether a log was located inside (blue) or outside (green) the riverbed. Dot shade represents the log's context after displacement: light shade for isolated logs and dark shade for logs within a logjam. Main channel constriction points (gorges and waterfalls) are indicated by the red dots.

Tag travel distances

An episode of rainfall occurred on September 16th and 18th, 2021. During these days, the daily precipitation accumulations recorded at the meteorological station within the reserve did not exceed 22 mm (Fig. 5A), but they triggered the movement of wood. The stream gauging station at Mas d'en Tourens, 14 km from the source, recorded an instantaneous flow of 0.058 m^3/s on September 17th (Fig. 5B). The position of the tags after this event (Fig. 6) indicates that the majority of the marked logs were relocated over distances up to 3.8 kilometers. Three marked wood pieces exited the reserve boundaries.Upon analyzing individual travel distances, Fig. 7 illustrates that most of the marked logs shifted. Some logs moved over short distances, ranging from 0 to 170 meters (e.g., tags 2B3, 2BD, 2DB, 2E2), while others traveled distances from 2 to nearly 4 kilometers (e.g., tags 2B9, 2C3, 2D3, 2E1). The median travel distance was 790 meters. Fifty percent of the tagged wood traveled between 330 meters (Q1) and 1550 meters (Q3, Fig. 7). The tagged logs were mobilized by the rising water level, with no observable effect of the initial location of the wood piece on the distance traveled. Among the logs, half ended up isolated, while the other half became part of logjams. Location categorization revealed that 65 % remained within the river's channel (37 % isolated, 28 % in logjams), while 35 % were deposited overbank, either isolated (15 %) or in a logjam (20 %). Most of the tag relocations occurred in the lower part of the upstream river section, where the riverbed was wider.

DISCUSSION

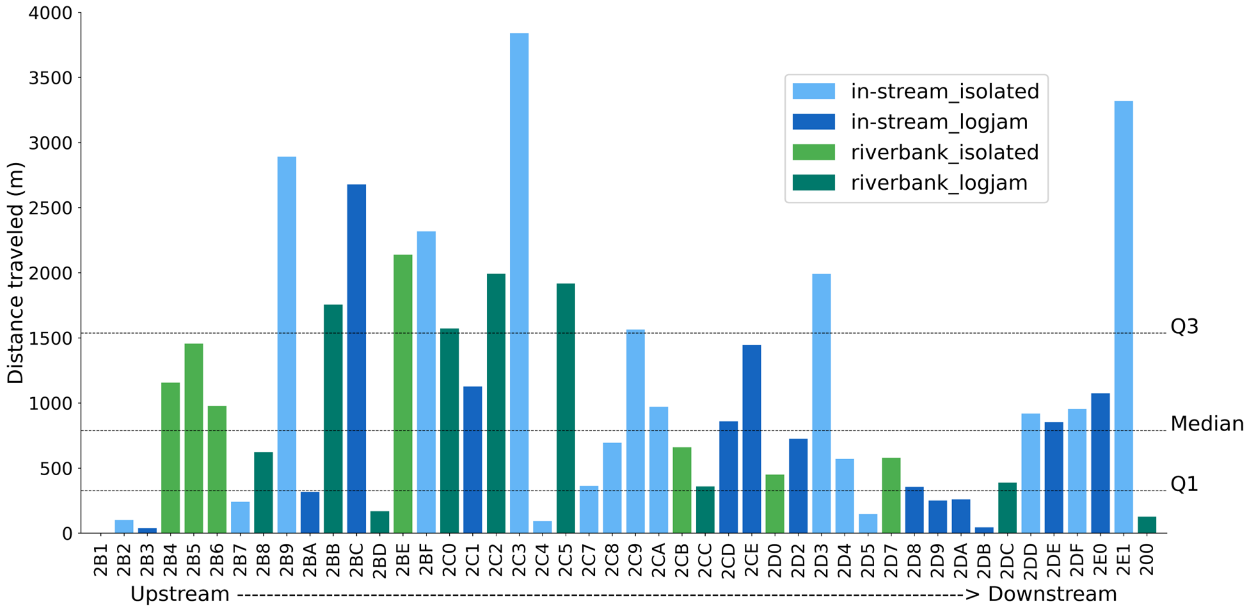

Fig. 7.- Travel distances of RFID-tagged wood logs. The x-axis labels indicate the initial tag positions relative to each other, from the river source to the river's exit from the Reserve. The color of the bars indicates whether a log was located inside (blue) or outside (green) the riverbed. The tone of the bars represents the log's context after displacement: light tone for isolated logs and dark tone for logs within a logjam. Q1 and Q3 represent the first (25th percentile) and third quartiles (75th percentile), respectively.

Study scope

Our study provides quantitative insights into the stock and condition of wood in a small coastal Mediterranean mountainous river, encompassing both decay stage and storage condition (i.e., jams, isolated pieces). It demonstrates the efficiency of RFID tracking in evaluating wood mobility. However, it is essential to consider these results within the context of the limitations stemming from methodological choices. These limitations encompass the in-stream wood assessment, the reliability of the RFID tracking equipment, and the methodology used to evaluate wood transport. The exclusion of wood pieces with a diameter less than 0.1 meters and a length shorter than 0.4 meters from the inventory aligned with the methodology used by Magdalou *et al.* (2009), to ensure consistency in evaluating in-stream wood since 2001. While this choice may lead to an underestimation of the wood stock in the riverbed, it does not affect the main findings of our study, which focused on 'large wood' significantly influencing fluvial dynamics. This size criterion resulted in minimal omission of wood present in the river. Regarding RFID tracking, malfunctions such as the lack of waterproofing of tags or unexpected battery depletion can impact data collection and interpretation. Signal loss may raise questions about the possibility of the tag ceasing to emit without movement, or having been transported and then ceasing to emit. Without visual confirmation of the presence of the wood piece, we assumed that the last flood event had caused its movement, and the tagged piece was excluded from further tracking. In our study, such incidents remained anecdotal, as only one piece out of fifty was lost. However, over the long term, this issue is likely to gradually increase due to the aging of the equipment and the environmental stresses it will endure. The last limitation pertains to the methodology used to assess wood transport. Introducing standardized marked wood pieces for tracking transport cannot accurately replicate the movement of the entire transportable wood stock. No method could capture the stock in its entirety and track its evolution over time. The method used is widely used in environmental studies to monitor material movement (Cassel *et al.*2020, 2017; Haga *et al.*2002; Millington and Sear, 2007). The marked wood pieces had the size, condition, and shape characteristics of a portion of the pieces comprising the natural stock. Their introduction as markers for wood transport allowed for comparison of the behavior of recently recruited wood pieces (i.e., in-stream isolated logs, Fig. 6) at different locations in the river where wood naturally occurred. Using standardized-sized pieces had the additional benefit of facilitating field research orientation and visual recognition.

In-stream wood stock

The inventory of wood pieces in the riverbed within the Massane Forest Reserve showed that wood is present throughout the river's course, with most pieces being small and shorter than the river's narrowest points. The river's width acts as a filter, primarily allowing wood pieces shorter than the bankfull width (here, < 2.5 meters) to be transported over long distances. This threshold effect indicates that the amount of in-stream wood transported by a bankfull flood could represent about one-third of the total stock volume. In this respect, the results of the inventory are consistent with those of Magdalou *et al.* (2009), who conducted similar inventories multiple times between 2001 and 2008. The quantities of wood and the location of wood aggregates in the form of logjams vary from year to year, reflecting the natural variability in annual wood inputs and river flows. This variability is likely amplified by climatic disturbances affecting tree mortality and the decline of the riparian forest stand (Allen *et al.*2010, Carnicer *et al.* 2011, Ruiz-Benito *et al.* 2013). The distribution of size frequency and the placement of naturally occurring wood pieces guided our choice to equip small beech wood pieces with RFID tags, as beech is the most commonly encountered species in the inventories. These wood pieces were regularly placed along the upper course of the river to initiate the monitoring of their transport. Standardizing the types of tagged wood pieces aimed to reduce sources of variability in the comparison of this process. We observed the absence of wood in the river section near the Couloumates cabins (Fig. 3A). Specifically, one tagged log disappeared in this area before any rise in the river's water level. This particular area serves as a bivouac site for hikers. Despite our efforts to locate the log, for which we knew the GPS installation location, we suspect that the log, along with its RFID tag, may have been removed from the river to be burned.

RFID reliability

The recovery rate of tagged logs reached 96 %. This high rate resulted from multiple pre-flood monitoring sessions of RFID tags to ensure their activity and from the river's geomorphology featuring

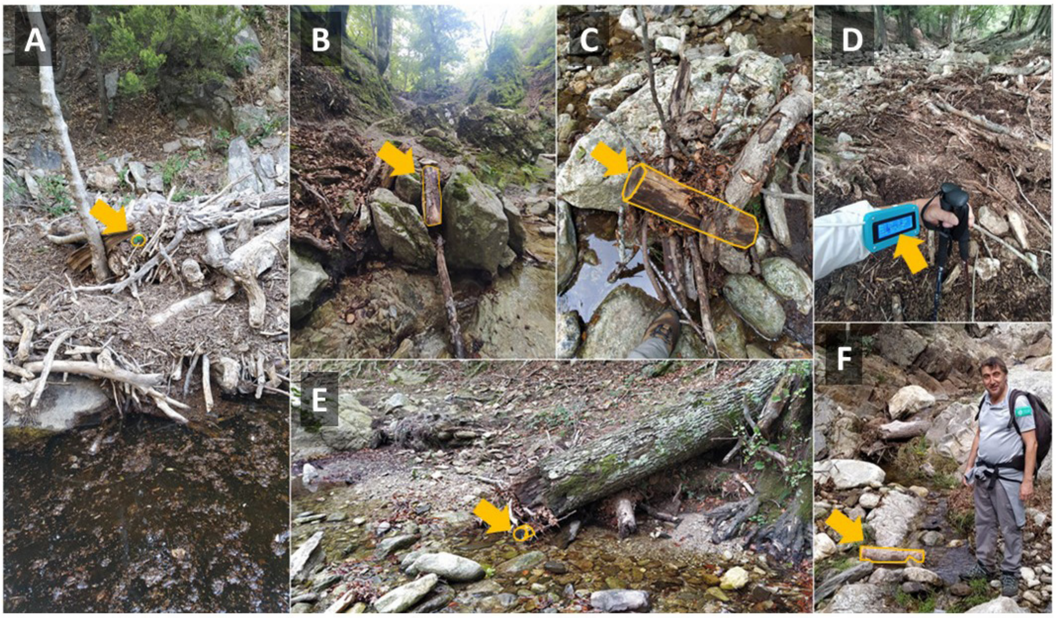

Fig. 8: Photographs of RFID-tagged wood pieces after transport. Wood logs are in large logjams (A, D), wedged between rocks (B), beneath large logs (E), or simply deposited directly in the riverbed (C and F).

a single narrow channel, which simplified the recovery process by reducing the width of possible search areas. The RFID tag reading system demonstrated remarkable robustness in traversing the river. Despite variations in the maximum detection range from one RFID tag to another due to natural obstacles and wave reflections disrupting the radio signal propagation locally, the system consistently performed well. The 'n' values for the attenuation parameter were consistently higher than the characteristic value for signal propagation in an obstacle-free open space. Typically, the recovered logs were visually confirmed. In all instances, a higher or near -120 dB RSSI value indicated the presence of the marked log within a distance of less than 10 meters. Alternative methods like GPS tracking were considered for monitoring wood transport over time (Ravazzolo *et al.* 2015), but these methods face challenges in remote areas with unreliable GPS and GSM geolocation, exemplified by the Massane River's GSM coverage gaps. Thus, RFID remains the most reliable method for tracking wood mobility in forested entrenched river system.

Wood mobility

RFID technology is widely utilized in river and stream studies, but few specifically investigate wood mobility in watercourses using this approach (Clark *et al.* 2022, MacVicar *et al.* 2009, Ravazzolo *et al.* 2015, Schenk *et al.* 2014; Aarnink *et al.* 2022). Consequently, data on the distances traveled by wood during flood events are limited. Studies vary in the types of rivers studied and tracking methods employed, from fixed RFID antennas (Aarnink *et al.* 2022, MacVicar *et al.* 2009, Schenk *et al.* 2014) to mobile antennas (Clark *et al.* 2022, Ravazzolo *et al.* 2015, Schenk *et al.* 2014). Some provide data on wood fluxes, while others report on the distances traveled. Comparing results across RFID studies remains challenging; however, all studies are valuable for documenting diverse scenarios. For instance, the tag recovery rate we recorded (96 %) was significantly higher than those reported by Ravazzolo *et al.* (2015), which ranged between 40 % and 43 % across different studies. Schenk *et al.* (2014) reported a recovery rate of 40 % but observed wood traveling tens of kilometers in the Lower Roanoke River, a large, low-gradient river. In this context, our study's results stand out, indicating a river type that is notably different. They provide insights into the maximum distances that logs can travel during rising water levels since short isolated logs are more responsive to changes in water flow and may travel longer distances compared to larger logs (Ruiz-Villanueva *et al.* 2016).

The rise in river water levels following the September rainfall prompted the relocation of almost all tagged pieces. Specifically, compared to previous studies on introduced wood in steep-gradient watercourses (Millington & Sear 2007), our experiment shows that wood shorter than bankfull width can travel considerable distances-up to 17 % of the river's total length—even with a minor rise in water levels (Steeb *et al.* 2017). Initial logs arrangement was disrupted. This first rise in river water level resulted in a natural relocation of the tagged wood logs before tracking their future movements (Fig. 8).

Aligned with findings from the in-stream wood inventory, the tagged wood pieces were also notably absent from river sections characterized by swift currents, such as around river width constrictions and waterfalls, where wood retention was less favorable. The wood log relocation underscored the influence of local geomorphological features on wood transport dynamics, emphasizing the propensity for deposition in river widened areas characterized by reduced flow velocities. Wood pieces isolated in the riverbed or trapped in logjams within the main channel remain more easily mobilized compared to wood pieces caught in logjams or isolated on the banks (Fig. 8). The latter can only be mobilized during intense floods, provided these events occur before the wood fully degrades, a process that can take up to a decade (Charles *et al.*2022). Future monitoring of the tagged wood pieces will help in assessing how contextual factors, such as isolation or trapping in a logjam, and their position inside or outside the riverbed, influence wood transport dynamics (Oettel *et al.*2022).

The daily precipitation accumulations that triggered wood movement were relatively low. Despite the flow at the stream gauging station being only 0.058 m^3/s—significantly lower than the typical 2-year return period flow of 25 m^3/s—the September rainfall, following a prolonged drought, caused a notable increase in water levels in the upper stream. Wood logs begin to move once a certain flow threshold is reached (Kramer & Wohl 2017). Although this threshold could not be directly measured at the gauging station, it was locally exceeded in the river section where the tagged logs were initially installed. These observations highlight the challenge of correlating wood movement with gauging station records due to localized precipitation effects, even within a small area like the Massane River watershed.

CONCLUSION

Understanding the storage, processes, and dynamics of wood transport is crucial for developing effective river management strategies, especially in the current context of climate change (Benda & Sias 2003). A study of a small river like the Massane River reveals that a significant portion of wood deposited between its upstream banks can be easily transported over long distances during minor water level rises. The narrowness of the river channel, combined with several constriction points such as gorges and waterfalls, acts as a filter, preventing very large pieces from descending the watercourse and reaching infrastructure. The entanglements and obstacles formed by the presence and transport of wood mitigate the effects of successive water level rises due to precipitation events in the watershed, thereby contributing to the natural regulation of river flow.

This study establishes the foundation for long-term monitoring aimed at linking the transport of tagged wood with variations in river water levels in an increasingly drought-prone region. Our findings reveal a lack of correlation between the local effects of upstream precipitation and readings from the main hydrometric station of the river. This underscores the challenge that flow measurements at gauge stations may not consistently or reliably reflect actual wood transport, even at the spatial scale of a small river watershed.

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