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Conceptual Model of the Debarking Process of Large Wood in Rivers



Key Points:

- The debarking process of large wood during fluvial transport was investigated using a novel rotating drum experiment
- Three debarking modes ranging abrasion-dominated, expansion-abrasion, and expansion-dominated were identified and characterized
- A conceptual model of physical wood debarking during fluvial transport integrating both expansion and abrasion processes was proposed

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Abstract When transported in rivers by short-term episodic events such as floods and debris flows, large wood interacts with the flow, sediment, and river boundaries, leading to physical degradation such as weathering, abrasion, and breakage. This degradation, manifested as mass loss and structural alteration, weakens wood stability, increases mobility, and diminishes its geomorphic and ecological functions. However, this process remains largely overlooked when assessing wood transport and accumulation. Here, we introduce laboratory tumbling experiments to investigate the physical degradation of fresh large wood, focusing on mechanical bark removal during fluvial transport. Fifteen tests were conducted under varying flow velocities and water volumes, with three White Willow samples in each test. Wood debarking causes changes in the volume of wood samples during the experiment. Therefore, Structure-from-Motion photogrammetry was employed to quantify changes in wood volume and thereby evaluate the debarking process. Results revealed that debarking involves two coupled processes: (a) expansion due to mechanical cell-wall breakdown, increased porosity, and hydration, and (b) abrasion caused by friction and repeated contact. Three debarking modes were identified under varying hydraulic conditions: abrasion-dominated, expansion-abrasion, and expansion-dominated. These modes correspond to distinct transport regimes: congested (sliding-rolling), semi-congested (sliding-rolling-floating), and uncongested (floating). The maximum expanded volume increased with water volume, while abraded volume first increased then decreased due to reduced wood-chamber interactions. Under different water-volume conditions, increasing flow velocity decreased the maximum expanded volume and increased the abraded volume, with minor variations in the mean values, but relatively large standard deviations. A conceptual model integrating both expansion and abrasion processes is further proposed to describe physical wood debarking during fluvial transport. This study provides first experimental evidence and conceptual framework for understanding large wood degradation in rivers.

1. Introduction

Large wood (also known as driftwood, in-channel wood, or in-stream wood in the fluvial environment), that is, wood elements with size >1 m in length and 0.1 m in diameter, is of great significance in river dynamics and fluvial ecosystems (Keller & Swanson, 1979). In the past decades, large wood in rivers and its relevance to river ecosystems, hydro-geomorphology, aquatic habitat, carbon and nitrogen budgets, energy sourcing, as well as the related flood risk, have been increasingly recognized by researchers and river engineers (Bayón et al., 2024; Franca et al., 2025; Follett & Wohl, 2024; Naiman et al., 2002; Piégay et al., 2005; Qatarneh, Dupont, Michel, et al., 2021; Qatarneh, Dupont, Ruiz-Villanueva, et al., 2021; Ruiz-Villanueva, Piégay, Gaertner, et al., 2016; Ruiz-Villanueva, Piégay, Gurnell, et al., 2016; Swanson et al., 2021; Wohl, 2011). After being introduced into rivers, large wood may undergo complex dynamics consisting of the following three co-existing and overlapping processes: fluvial transport; accumulation; and degradation (Comiti et al., 2016; E. Merten et al., 2010; E. C. Merten et al., 2011; Piégay et al., 2017; Wohl & Jaeger, 2009; Wohl et al., 2010). During these three processes, large wood interacts with one another and with flow, sediment, and river boundaries, modifying local hydro-morpho dynamics and environment. For example, when transported in a river and forming jams, natural structures of wood accumulations, large wood influences the flow velocity and changes the ability of the river flow to mobilize sediment, further resulting in the variation of the local morphology (Gurnell et al., 2002; Huang et al., 2025; Ruiz-Villanueva, Piégay, Gaertner, et al., 2016; Ruiz-Villanueva, Piégay, Gurnell, et al., 2016). These structures not only play a significant role in local hydro-morphodynamics, for example, the backwater effect in the upstream and the sediment degradation in the downstream (Schmocker & Hager, 2013; Schalko et al., 2018), but also provide an ideal aquatic habitat for fish and microorganisms (Chin et al., 2014; Collins

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et al., 2012; Gurnell et al., 2005; Wohl et al., 2019). Large wood can also block infrastructures such as dams and bridges (Franca et al., 2025), causing negative effects like decreasing the reservoir volume of the dam, damaging spillways and turbines, and influencing the stability of bridge piles and further leading to its failure (De Cicco et al., 2018; Finch et al., 2025; Okamoto et al., 2021; Piton & Recking, 2016; Vasil'ev et al., 2019; Yu et al., 2025). For instance, recent flash floods in Sant Llorenç des Cardassar, 2018, and the Francolí River, 2019, Spain, provide clear examples of large wood transport amplifying flood impacts, leading to casualties and severe damage to infrastructure and homes (Lorenzo-Lacruz et al., 2019; Martín-Vide et al., 2023). Considering the above-mentioned, it is of great importance to understand the role of large wood in rivers and its interactions with the flow, sediment, topography, aquatic habitat, and environment.

Extensive research on the transport and accumulation of large wood has advanced our understanding of the underlying mechanisms and their effects on local hydro-geomorphology and ecosystems. However, the degradation of large wood during transport and accumulation has often been overlooked (E. C. Merten et al., 2013). Wood degradation can result from biological, chemical, or physical processes (Hassan et al., 2005), such as the decomposition caused by fungi, bacteria, or other biota (i.e., decay), the chemical transformation of the wood cellulose, hemicellulose, and lignin into simpler substances (Abril et al., 2015; Aristi et al., 2012; Diez et al., 2002; dos Santos Fonseca et al., 2013; Iroumé et al., 2017; Spänhoff et al., 2007; Zare-Maivan & Shearer, 1988), and the mechanical and structural failure and erosion of its structure (i.e., breakage and abrasion) (Cadot & Wohl, 2010; Hortobágyi et al., 2024; E. C. Merten et al., 2013). The degradation of wood alters the hydro-morpho-dynamics in two primary ways: (a) through the release of nitrogen and other nutrients that interact with local fauna and microorganisms, and (b) and through changes in wood structure and density that alter wood-sediment-flow interactions. In particular, the weakening of wood structure and the reduction in size that occur during degradation increase wood mobility and shorten its residence time in river systems, thereby reducing its hydraulic influence. This, in turn, leads to smoother flows, lower sediment retention, and simpler channel morphology, ultimately diminishing both the geomorphic and ecological functions of wood in fluvial environments (Gurnell et al., 2002; Hyatt & Naiman, 2001; E. C. Merten et al., 2013; Wohl & Goode, 2008). Investigating wood degradation may therefore provide valuable insights for researchers and river engineers seeking to better understand wood transport, accumulation, and their environmental relevance.

The time scales of bio-chemical and physical degradation of wood in rivers can differ significantly, depending on environmental conditions and wood characteristics (Cornwell et al., 2009; E. C. Merten et al., 2013; Weedon et al., 2009). While the first can range from months to decades (under particular circumstances wood can remain relatively intact for centuries), physical degradation in rivers starts in the very moment when the wood reaches the river channel and lasts hours to months. Moreover, physical degradation is often episodic, many often associated to high flows, whereas bio-chemical degradation is continuous and slower. Consequently, kinetics of wood degradation caused by bio-chemical and physical effects are not correlated and can be investigated independently.

Typically, bio-chemically or physically weathered decayed wood can be qualitatively classified into four categories, ranging from freshly recruited to fully decomposed wood, based on field observations or tests such as the knife test and acoustic techniques (Larjavaara & Muller-Landau, 2010; Machek et al., 2001; Müller-Using & Bartsch, 2009). A quantitative parameter, the decay coefficient k , has been proposed to describe the rate of wood decay and can be expressed as follow (Harmon, 2001):

$$k = \frac{\ln(X_0) - \ln(X_t)}{t} \quad (1)$$

where X_0 and X_t are parameters associated with wood mass, volume or density at initial state and at time t . However, most of these studies have focused on the in situ decay of small branches, twigs, and leaves, or on the degradation of large wood within forest environments exposed to physical factors such as sunlight and wind (Harmon, 2001; E. C. Merten et al., 2013), while overlooking the physical processes that occur simultaneously in large wood during fluvial transport (Spänhoff & Meyer, 2004).

Physical degradation of large wood during fluvial transport can be further divided into the fragmentation/breakage and debarking processes. The fragmentation/breakage, contributing to the debranching of large wood and the breakage of the main trunk (Hortobágyi et al., 2024; E. C. Merten et al., 2013), is usually observed during the early stage when trees are recruited into the river (Hortobágyi et al., 2024). This kind of wood degradation can

be characterized by the decrease in branch complexity (e.g., Horton-Strahler branch order) during the transport process of large wood in rivers (Cadol & Wohl, 2010; Hortobágyi et al., 2024; E. C. Merten et al., 2013). On the other hand, the debarking process refers to the detachment of bark from the main trunk, contributing to the mass or volume loss of large wood. Although this is a process widely observed in the field and mentioned in some studies, as far as we know, no studies have specifically investigated the debarking process of large (green) wood during its transport in rivers or even the abrasion process once the bark is removed. Considering that the debarked material from large wood is an important resource in river eco-system, and also the changes in volume and surface characteristics impact the transport and accumulation of large wood, understanding large wood debarking helps us to better explore the wood regime in rivers, aiding to better manage river ecology and environment (Wohl & Iskin, 2022; Wohl et al., 2024).

Advanced techniques, such as image processing, RFID tracking, SmartWood, etc., have been developed to track large wood transport in rivers (MacVicar et al., 2009; Spreitzer et al., 2019). However, these methods are primarily used to estimate wood budgets and analyze transport trajectories, often overlooking the detection of impacts and rotational motions resulted from the interactions among wood, flow, sediment, and river boundaries. In addition, field investigations aimed at tracking and monitoring individual wood pieces, and particularly observing their continuous degradation over time, remain highly challenging. Therefore, this paper focuses on experimentally investigating the debarking of large wood in rivers and aims at answering the following two questions: (a) Which factors control the debarking process of large wood in rivers? (b) Is it possible to establish a model for large wood debarking during its transport in rivers? To answer these two questions, wood samples from the same species and with the same decay stage were obtained from the field, and a novel laboratory experiment was designed to conduct wood debarking experiments. Results about wood debarking characteristics and modes under varying environmental conditions are presented and discussed considering non-dimensional parameters. A conceptual model describing the debarking process of large wood is proposed. This paper provides the first insight into the debarking of large wood in rivers, further contributing to understanding the role of large wood in river systems.

2. Materials and Methods

2.1. Experimental Equipment

To replicate the physical debarking of large wood during relatively long-distance fluvial transport at an experimental scale, the laboratory model should meet the following three criteria: (a) ability to equivalent long-distance motion; (b) capacity to provide sufficient energy for wood debarking; and (c) easy operation. Similarly to previous research on the motion characteristics of debris flow (Kaitna & Rickenmann, 2007), cement degradation (Vogel, 2016), pebble attrition during transport (Attal & Lavé, 2009; Bray et al., 2024; Cassel et al., 2021) where a perpendicular circular flume or a rotating drum was employed to mimic the motion characteristics during wood transport and interactions with other environmental elements (e.g., water, sediment, river bed and banks), we adopted a rotating drum setup to generate collision and abrasion processes between the wood, the water and the equipment to mimic the large wood debarking process. Although the rotating drum adopted in this study cannot reproduce the stochastic stopping and jam formation processes observed in natural rivers, as well as the exact flow characteristics such as acceleration and turbulence in real rivers, it enables us to focus on the continuous and repeated impacts and rotational motions that resemble interactions among wood–wood, wood–flow, and wood–river channel boundaries.

Experiments were conducted at the Theodor Rehbock Hydraulic Engineering Laboratory, Karlsruhe Institute of Technology (KIT), Germany. Figure 1 shows the rotating drum used in the large wood debarking experiments. The drum was modified from a cement mixer and consists of two main parts: the cell chamber, where wood samples and water are placed for debarking analysis (Figures 1c and 1d), and the control system that regulates the frequency of the motor and thereby adjusts the rotation speed of the drum (Figure 1c). The drum is made of steel with a maximum radius of 0.4 m (Figure 1a). Its maximum and minimum widths, measured perpendicular to the axis of rotation, are 0.53 and 0.25 m, respectively (Figure 1b). To prevent water leakage during the experiment, the drum is sealed with planks (Figure 1b). A circular outlet with a diameter of 0.25 m is then used to insert and remove water and wood samples before and after the experiment. Additionally, a longitudinal iron vane with a negligible height of 0.01 m was installed in the cell chamber to inhibit sliding and jamming of the wood samples. The motor frequency can be adjusted by the control system from 12 to 60 Hz, corresponding to a tangential

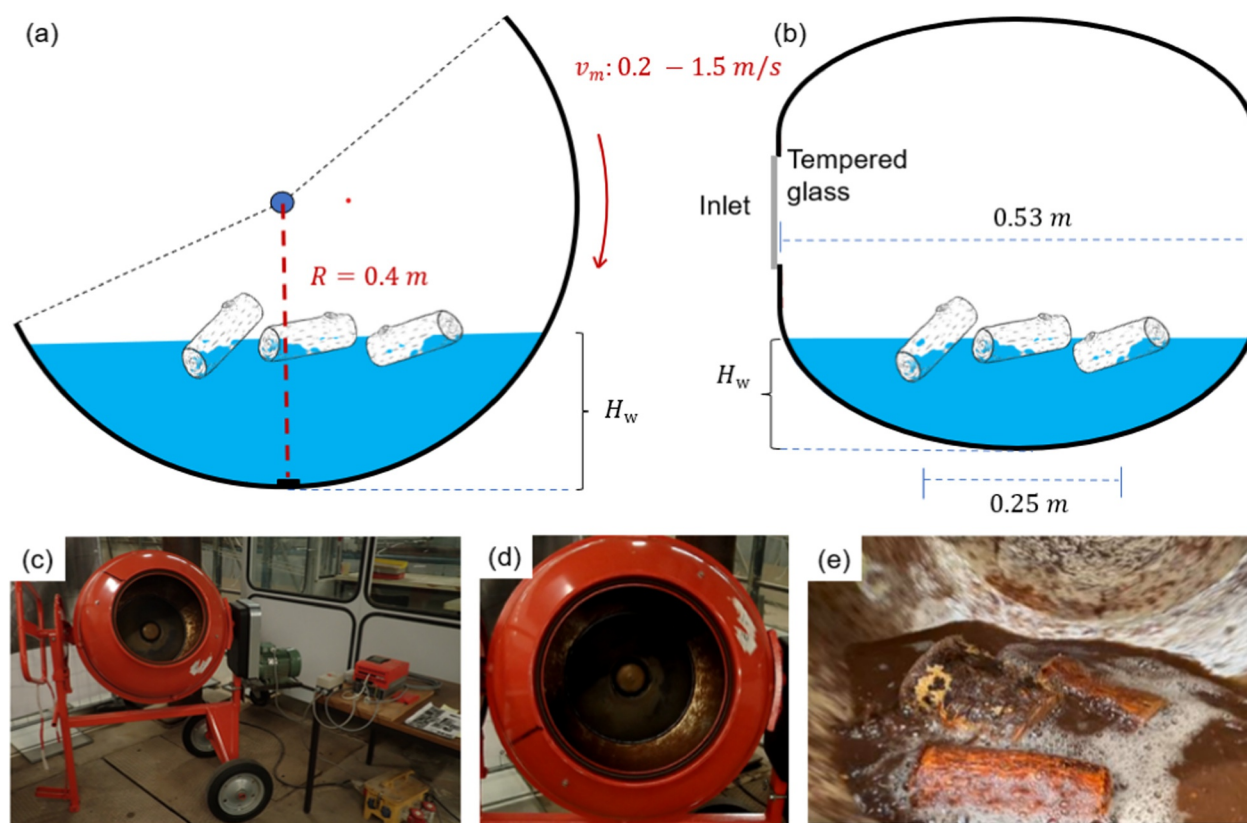


Figure 1. Experimental sketch and equipment: (a) sketch view perpendicular to the rotation; (b) sketch view alongside the rotation; (c) the equipment system; (d) the drum chamber; and (e) water and wood samples inside the chamber.

velocity of 0.2–1.5 m/s in the cell chamber. During the experiment, the motor frequency remained constant, and the outlet of the cell chamber was covered with tempered glass to both prevent leakage and allow visual observation (cf. Figure 1a).

2.2. Experimental Material

Two White Willows (*Salix Alba*) with gray-brown, fissured bark were felled alongside the Alb River (a first tributary of the Rhein River) in Karlsruhe, Germany, in January 2025 to conduct the wood debarking experiments (Figure 2a). In order to have a similar cylindrical shape and properties for all the wood samples, the lower part, which is close to the root, and the upper part, with abundant small branches, were removed. The selected parts of the two trunks have an average diameter ranging from 0.11 to 0.18 m, with a median value of 0.13 m (Figure 2b). The trunks were then cut into smaller samples with a ratio of 1:1.5 between their diameter and length (Figure 2c), with samples' length ranging from 0.165 to 0.27 m. It should be noted that the length of our samples is far below the length criterion that is used to define large wood (>1 m) in rivers. However, Wohl (2011) mentioned that the wood length mainly dominates the interactions between wood-wood and wood-riverbed during large wood transport, and can be scaled by using the ratio between the length of the wood and the bankfull channel width ($W = L_w/W_c$; Gurnell et al., 2002). Considering the maximum width (0.53 m) of the rotating drum, the parameter W ranges from 0.3 to 0.5 for wood samples in our experiment, which is very close to 0.28–0.40, value that was obtained from field observation of seven stream segments in the Colorado Front Range, USA (Wohl, 2011). The diameter of wood samples, which is largely determined by tree age, influences bark characteristics and the impacts arising from the interactions among wood pieces and between wood and the rotating drum. Therefore, the diameter of wood samples is selected in accordance with the definition of large wood, without considering any diameter scaling; all samples had a diameter larger than 0.1 m. Although the length of the wood samples was substantially shorter than those defined for large wood, leading to a smaller slenderness compared to the wood logs in natural rivers, their reduced length was necessary to allow free movement within the



Figure 2. The trees and wood samples for experiment: (a) white willow alongside the Alb River in Karlsruhe; (b) wood samples; and (c) the size and bark of the wood samples.

experimental device. Nevertheless, the samples are representative of freely transported large wood in rivers and provide valuable insights into its degradation processes.

A total number of 124 wood samples were obtained. Among them, the mass and volume of 111 wood samples were determined using scale and water displacement tests, respectively, to calculate their density. The bark volume (V_{bark}) was also determined using the water displacement test by comparing the wood volumes measured before and after bark removal, revealing that bark accounted for an average of 12% of the total wood sample volume. Additionally, 13 wood samples from upper (six), middle (five), and lower (two) part of the two trunks were selected and dried for 72 hr under 105°C to estimate the water content of the wood samples (Aristi et al., 2012). It should be noted that natural wood logs exhibit varying moisture contents and bark characteristics. The drying process can therefore be used to control bark properties by adjusting the drying duration or applying repeated wet–dry cycles. At the same time, it provides an efficient means of ensuring that all wood samples are in a uniform initial condition prior to experimentation, as was done in the present study. The basic characteristics, including the diameter (d), mass (M), volume (V), density (ρ) and water content (ω) of the wood samples were statistically analyzed (Figure 3). A linear relationship exists between the mass and volume of the wood samples. The density of the wood samples ranged from 840.7 to 966.1 kg/m³, with an average value of 903.7 kg/m³ (Figure 3b). In addition, a general decrease in the density and water content was observed with increasing diameter of wood samples. However, no statistically significant relationship was observed among water content, wood density, and the diameter of the wood samples. In order to minimize the influence of wood density on the experiment, 45 wood samples were further selected, taking into account the bark type, branch distribution, diameter of the wood samples. In addition, all the samples are totally dried for 72 hr under 105°C before the experiment to avoid the influence of water content of the wood samples.

2.3. Measurements

The main objective of the experiment was to analyze the debarking characteristics, which can be characterized by the volume change of wood samples during the experiment. Structure from Motion (SfM) photogrammetry technique was used to estimate wood volume with high resolution during the experiments. This technique is a close-range photogrammetry method, in which a series of photos are used to generate a point cloud data and a 3D model of the object's surface (Lane et al., 2001; Slama et al., 1980). Due to its high efficiency and low standard deviations, SfM photogrammetry technique has been widely used in experiments in association with hydraulics and morpho-dynamics in recent years (Ebrahimi et al., 2025; Kannen et al., 2024; Westoby et al., 2012; Zhang et al., 2022). The equipment for the SfM analysis in our experiment consisted of a 1 m × 1 m rectangular rotating table with eight markers targeted at the edge of the table, a digital camera with a resolution of 3,840 × 2,160 and a

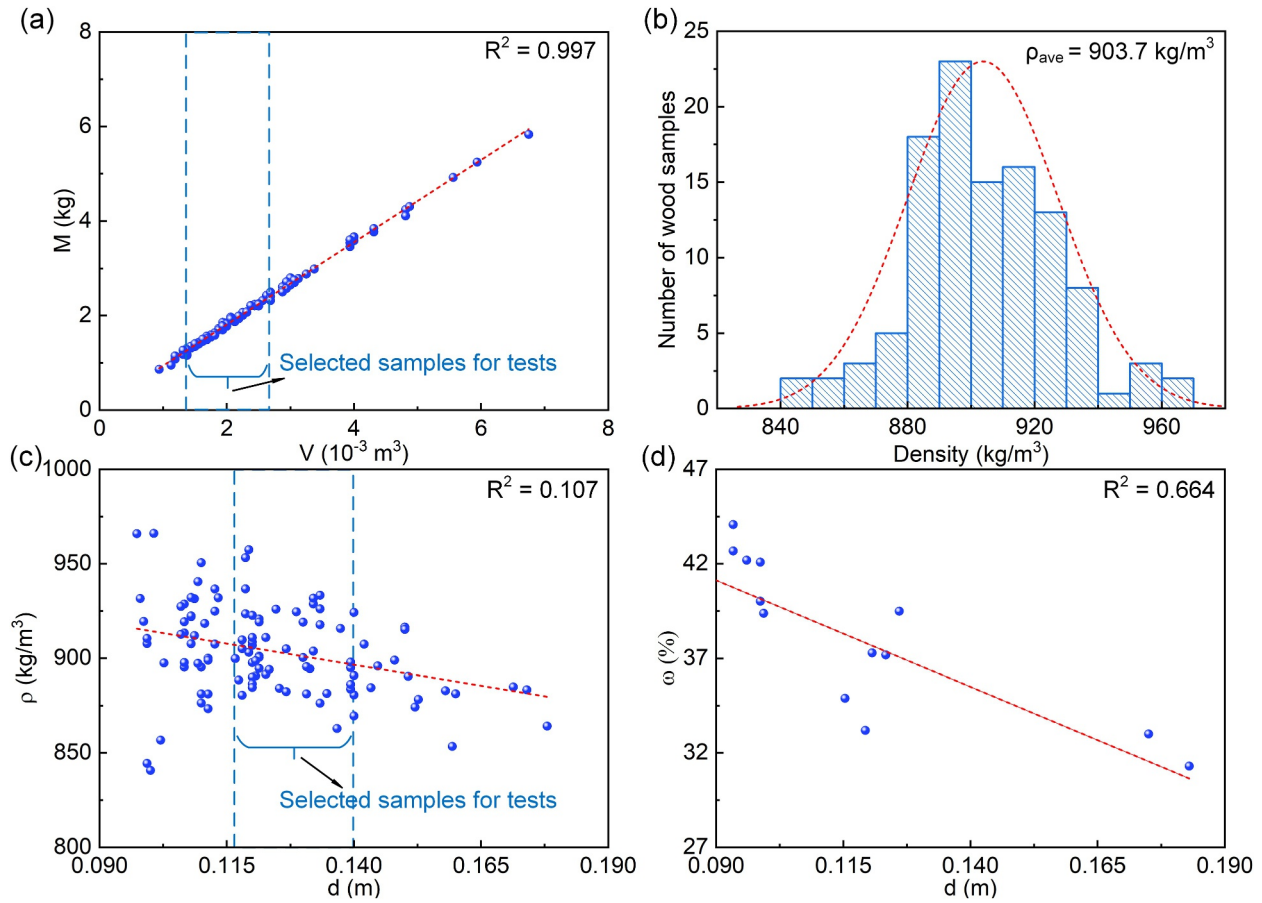


Figure 3. Basic characteristics of the wood samples: (a) mass (M) and volume (V); (b) distribution of wood samples' density (ρ); (c) relationship between wood diameter and density (ρ) and (d) relationship between wood diameter (d) and water content (ω).

lighting system for illumination (Figures 4a and 4b). The workflow for the SfM reconstruction of the wood samples is illustrated in Figure 4. First, each wood sample was fixed at the center of a rotating table (Figures 4a and 4b), and a 1-min video was recorded while rotating the table to capture the wood sample from different angles. At least 200 photos were then extracted from the video (Figure 4c) and processed in Agisoft Metashape (Agisoft LLC, 2022) to reconstruct the surface characteristics of the wood sample, including controlling points that were used to generate the point cloud of wood samples' surface (Figure 4d), dense cloud data (Figure 4e) and the 3D model (Figure 4f). It should be noted that both edges of the wood samples under frequent collision were highly abraded during the experiment, resulting in inaccurate data in these areas when using SfM method to generate the point cloud data, further leading to the inaccurate estimation of the volume of the wood samples. Based on the point cloud data and 3D model, five data sets for each wood sample, with segment lengths ranging from 0.04 to 0.12 m, were reconstructed using CloudCompare (Figure 4g). These segments, which allowed us to avoid the edge effects of the wood samples and to verify the accuracy of the point cloud data, were finally used in Agisoft Metashape to calculate the volume variations of all wood samples during the experiment. The variation of wood samples' volume is then calculated as the average value of the five segments from the vertical center of the wood with varying lengths ranging from 0.04 to 0.12 m (Figure 4g), and can be described as follow:

$$\frac{V_t}{V_0} = \frac{1}{5} \sum_{n=1}^5 \frac{V_{t,n}}{V_{0,n}} \quad (2)$$

where $\frac{V_t}{V_0}$ is the average ratio between volumes of wood sample at time t and before the test. $V_{t,n}$ and $V_{0,n}$ are the volumes of the five segments with length varying from 0.04 to 0.12 m.

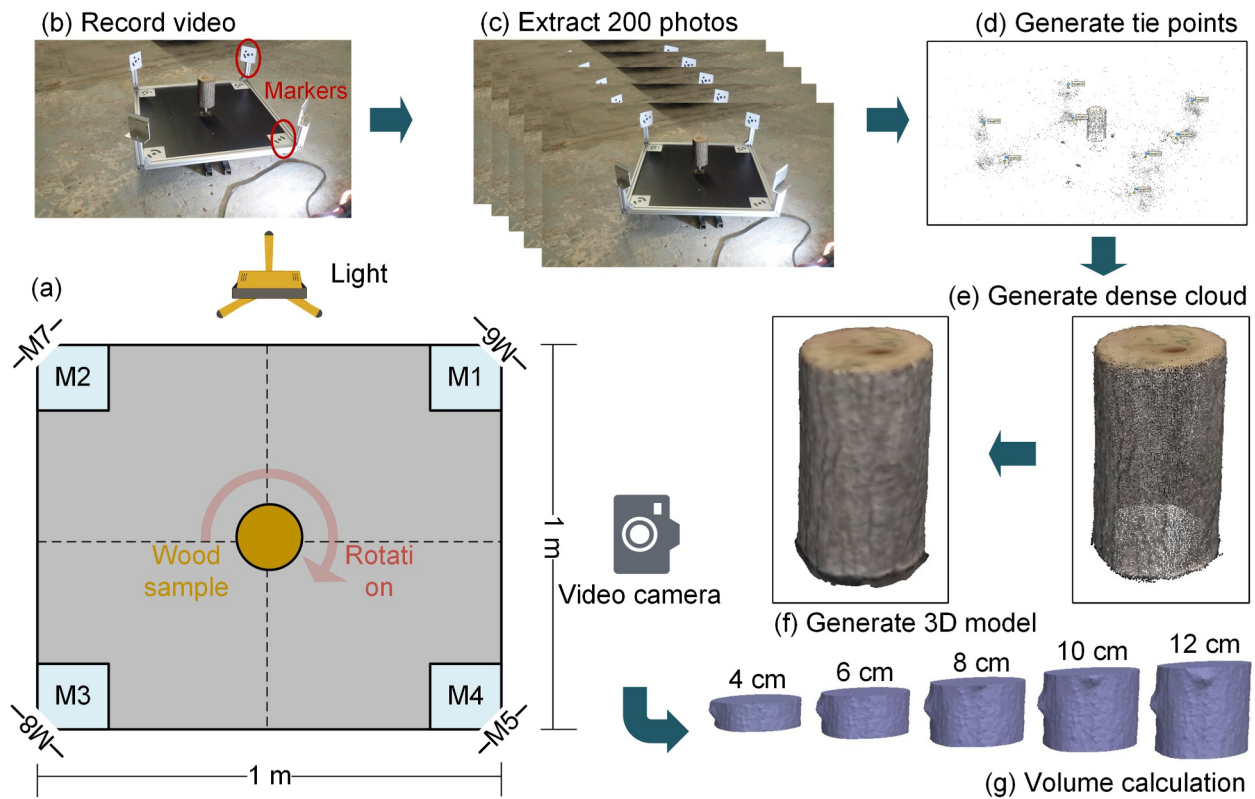


Figure 4. Equipment and procedures for Structure from Motion (SfM) photogrammetry analysis: (a) schematic of the SfM photogrammetry setup; (b) video recording using the rotating table, camera, and light system; (c) extraction of photos from video for SfM analysis; (d) generation of tie points of wood samples' surface; (e) generation of dense cloud data; (f) generation of 3D model of wood samples and (g) reconstruction of point cloud data sets with different lengths and the corresponding 3D model for volume calculation. Note: M1–M8 are the eight markers that are used to target the wood samples.

2.4. Experimental Scenarios and Procedures

Wood physical debarking is mainly controlled by its transport process, in other words, factors that affect wood transport also contribute to the physical debarking of large wood in rivers and these are summarized in Table 1. Among these factors, flow characteristics play a significant role in wood transport. Therefore, the experiment focused on the influence of flow characteristics, in particular, water depth and flow velocity, on the debarking process of large wood.

According to Ruiz-Villanueva et al. (2019), wood transport can be characterized by a parameter H_w/kd that describes the ratio of water depth (H_w), layers of wood (k), and wood diameter (d). Based on this parameter, wood transport can be categorized into uncongested, congested and hyper-congested transport regime, and the motion behavior changes from floating dominated to rolling-sliding dominated transport with decreasing water depth. Here, considering $k = 1$, this parameter was then used to determine the water volume that was considered in the

Table 1
Potential Factors That Affect Physical Wood Debarking Process During Fluvial Transport

Object	Interaction	Factors	References
Wood	Wood	Wood density per cubic meter (ρ_{LW}), Diameter (d), Length (L_w), Density (ρ), water content (ω), decay class (DI)	Wohl (2011)
	Water	Water depth (H_w), Flow velocity (v)	Schalko et al. (2018)
	Sediment	Sediment transport rate (q_s), Grain size distribution (GSD), Median diameter (d_{50})	Ruiz-Villanueva, Piégay, Gaertner, et al. (2016); Ruiz-Villanueva, Piégay, Gurnell, et al. (2016)
	River topography	Channel slope (S), Roughness (n), bed composition (BI), Channel width (W_r)	Yu et al. (2025)

Table 2
Experimental Scenarios and Parameters Under Varying Flow Velocities and Water Volumes

Test	v_m (m/s)	V_w (10 ⁻³ m ³)	Wood samples									Duration (hr)
			Sample 1			Sample 2			Sample 3			
			L (m)	M (g)	V (10 ⁻³ m ³)	L (m)	M (g)	V (10 ⁻³ m ³)	L (m)	M (g)	V (10 ⁻³ m ³)	
T1	0.5	0	0.162	1,383	1.500	0.170	1,398	1.500	0.195	2,251	2.500	8
T2	1.0	6.25	0.167	1,575	1.750	0.179	1,637	1.813	0.198	2,316	2.563	8
T3		12.5	0.153	1,178	1.375	0.179	1,855	1.938	0.197	2,404	2.688	8
T4		0	0.162	1,340	1.438	0.184	1,783	2.000	0.195	2,068	2.250	8
T5	1.5	6.25	0.167	1,542	1.750	0.182	1,781	1.938	0.196	2,203	2.500	8
T6		12.5	0.162	1,475	1.625	0.182	2,069	2.313	0.202	2,534	2.875	8
T7		0	0.166	1,435	1.563	0.181	2,004	2.250	0.20	2,574	2.938	8
T8	1.0	6.25	0.165	1,487	1.688	0.180	2,020	2.250	0.193	2,427	2.625	8
T9		12.5	0.167	1,583	1.813	0.180	1,947	2.188	0.209	2,750	3.063	8
T10		0	0.167	1,517	1.688	0.177	1,697	1.875	0.209	2,741	3.063	8
T11	1.5	9.375	0.169	1,503	1.625	0.180	1,822	2.000	0.209	2,880	3.250	8
T12	1.5	12.5	0.160	1,379	1.500	0.180	1,935	2.188	0.190	2,206	2.438	8
T13	0.5	6.25	0.159	1,369	1.500	0.187	1,794	1.938	0.210	2,697	3.063	12
T14	1.0	6.25	0.159	1,565	1.688	0.185	1,900	2.125	0.210	2,715	2.938	12
T15	1.5	6.25	0.160	1,515	1.688	0.188	1,934	2.188	0.215	2,985	3.375	12

rotating drum. Three water volume values of 0, 0.00625 and 0.0125 m³, which correspond to sliding-rolling transport without water ($H_w/d = 0$), sliding-rolling-floating transport ($H_w/d = 0.5$) and floating transport ($H_w/d = 1$), has been selected. Regarding flow velocity, the tangential velocity of the rotating drum, v_m , was considered as a proxy for relative motion intensity, v , and three values of 0.5, 1.0, and 1.5 m/s were selected. These three values were controlled with motor frequencies of 24, 42, and 60 Hz, corresponding to low, medium and intense flow regimes, respectively. This simplification allows us to focus on the dominant wood debarking processes and investigate large wood debarking under controlled conditions. Details of the experimental scenarios, including the tangential velocity of the tumbler machine (v_m), water volume in the tumbler (V_w), the mass (M), length (L), and the volume (V) of each wood sample, are summarized in Table 2. In total, 15 tests were performed, including nine isolated scenarios under varying water volumes and flow velocities, one additional test considering a water volume of 0.009375 m³, and five repeat tests. In each test, three wood samples, corresponding to small ($d = 0.115$ – 0.125 m), medium ($d = 0.125$ – 0.135 m), and large ($d = 0.135$ – 0.145 m) samples, were put in the rotating drum. The first nine tests (T1–T9) and the tests with water volumes of 0, 0.009375 and 0.0125 m³ (T10, T11, and T12) last 8 hr, while a duration of 12 hr was considered for the three repeat tests, considering a water volume of 0.00625 m³ (T13, T14, T15). The end of the test was determined by the visual observation of complete debarking of the wood samples.

In summary, and focusing on the physical debarking process of large wood during its transport, the experimental procedures are summarized as follows: first, three wood samples were prepared and oven-dried at 105°C for 72 hr prior to testing. The mass of each sample was measured, and Structure-from-Motion (SfM) was applied to reconstruct the initial point cloud data. Next, the desired volume of water was poured into the rotating drum, and the three wood samples were placed in parallel inside the machine. Finally, after sealing the drum chamber, the rotating drum was operated under specified velocities by adjusting the motor frequency. Each test lasted 8 hr for the nine primary tests and 12 hr for the repeat test. Throughout the process, SfM was used to capture the point cloud data of the wood samples every hour after the test, resulting in seven data sets at different stages for each of the nine primary tests, and nine data sets for the repeat test. After the experiment, the samples were oven-dried again, and the masses of both the samples and the remaining bark were measured.

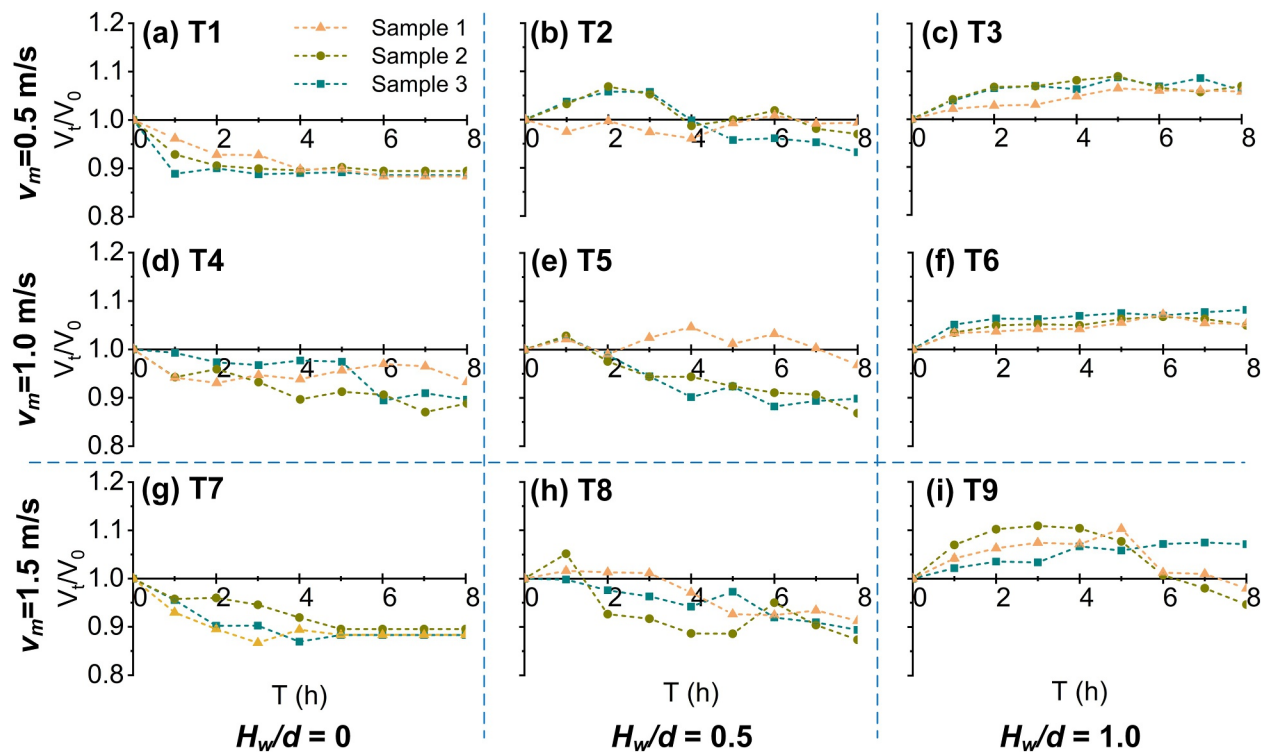


Figure 5. Physical debarking process of wood samples under varying flow velocities and water volumes: (a) T1; (b) T2; (c) T3; (d) T4; (e) T5; (f) T6; (g) T7; (h) T8; and (i) T9. Note: T refers to time, V_t and V_0 are the volume of wood samples at time t and before the test, respectively.

3. Results

3.1. Physical Debarking Processes of Wood Samples

Figure 5 depicts the variation of wood samples' volume under variable flow velocities and water volumes in the rotating drum. Three distinct physical debarking modes of wood samples can be summarized under varying water volumes and flow velocities. The first one, corresponding to the tests with no water content (T1, T4, and T7), can be described as the result from friction and repeated contact among the wood and between the wood and the tumbler, causing abrasion or erosion as the main debarking mode. In this mode, wood samples slide, roll and collide with the drum or with each other inside the rotating drum without or with negligible water volume involved. These kinds of motion characteristics and interactions abrade the surface of the wood samples gradually (Figure 6a), leading to a monotonic decrease in the volume of the wood samples. During the whole process, the debarking rate decreased gradually until the wood samples were totally debarked, and a final volume loss of around 12% was observed in all wood samples.

When water was present in the experiment, wood became more hygroscopic, increasing moisture absorption, leading to a first expansion of the wood samples that can be explained by the dilatation of the bark under hydration effect. Therefore, two different debarking modes were observed: the expansion-abrasion debarking (Figure 6b) and expansion-debarking (Figure 6c) modes. These two modes can be further distinguished as a function of the ratio between water depth and the diameter of wood samples (H_w/d).

The expansion-abrasion debarking mode (Figure 6b), corresponding to T2, T5, and T8 with mid water content and mid tangential velocity, refers to $H_w/d < 1$. In this mode, interaction between water and wood leads to the expansion of the samples, but abrasion induced by rolling, sliding and collision between the wood samples and within the rotating drum still dominated the debarking process of large wood. Under these circumstances, the debarking process was more complex; initially, the wood volume expanded, followed by a volume decrease due to abrasion (Figures 5b, 5e, and 5h).



Figure 6. Debarking modes under varying flow velocities for the same water content (take sample 3 in tests T4, T5, and T6 as examples): (a) T4; (b) T5; and (c) T6.

When the water content was higher, $H_w/d \geq 1$, wood samples mainly floated above the water during the experiment with little contact with the tumbler, leading to the expansion debarking mode (Figure 6c). In this scenario, the water depth in the rotating drum was large enough that the rolling, sliding and collision behaviors caused by the interaction between wood samples and the rotating drum were negligible. The water-induced expansion of wood samples dominated the debarking process compared to wood abrasion, leading to an increase in wood volume to its maximum value (Figures 5c, 5f, and 5i corresponding to the tests with the highest water content T3, T6, and T9). When the current in the drum became sufficiently strong to break down the wood surface (e.g., the highest velocity in T9 as shown in Figure 5i), abrasion dominated the debarking process, resulting in a decrease in wood volume.

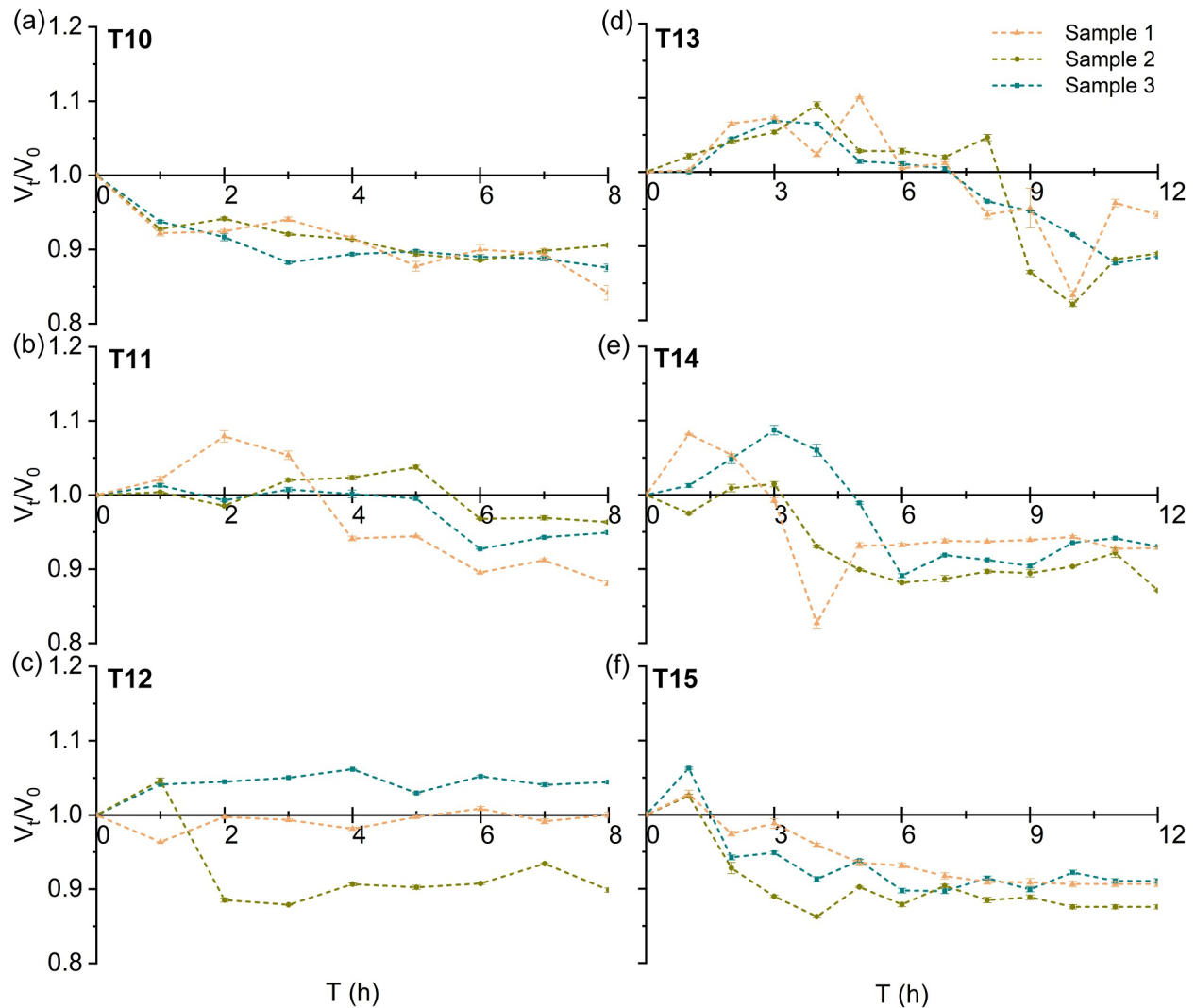


Figure 7. Physical debarking process of wood samples of additional tests: (a) T10; (b) T11; (c) T12; (d) T13; (e) T14; and (f) T15. Note: T refers to time, V_t and V_i are the volume of wood samples at time t and before the test, respectively.

To ensure reproducibility and verify the three physical wood debarking modes, six additional tests were conducted, including five repeat experiments and one test considering a water volume of 0.009375 m^3 , corresponding to $H_w/d = 0.7$, were carried out. Among these tests, three of them with $H_w/d = 0.5$ were conducted for 12 hr to totally debark the wood samples. The variation of wood samples' volume during their debarking process is shown in Figure 7. Although the dimensionless volume was different compared to those in Figure 5 due to the differences in basic properties of wood samples (e.g., density), the three debarking modes are well reproduced. For instance, the wood samples' volume decreased gradually without water getting involved (As T10 shown in Figure 7a), while the volume first increased and then decreased under specific conditions when water was added in the rotating drum (T11 and T12 in Figures 7b and 7c). The difference between tests with the same conditions, that is, the varied volume change in each time step, was attributed to the natural variation of physical properties (bark, density, diameter, etc.) of wood samples. However, this difference does not change the debarking pattern, but the abrasion rate during large debarking. Regarding the three tests with longer duration, a clear first increase and then decrease in volume until wood sample has been totally debarked were observed (T13, T14, and T15 shown in Figures 7d–7f), which is similar to what can be observed in Figures 5b, 5e, and 5h. Additionally, with the same water volume ($H_w/d = 0.5$), both the duration for wood expansion and the expected maximum volume of wood samples during their debarking process decreased with increasing the flow velocity.

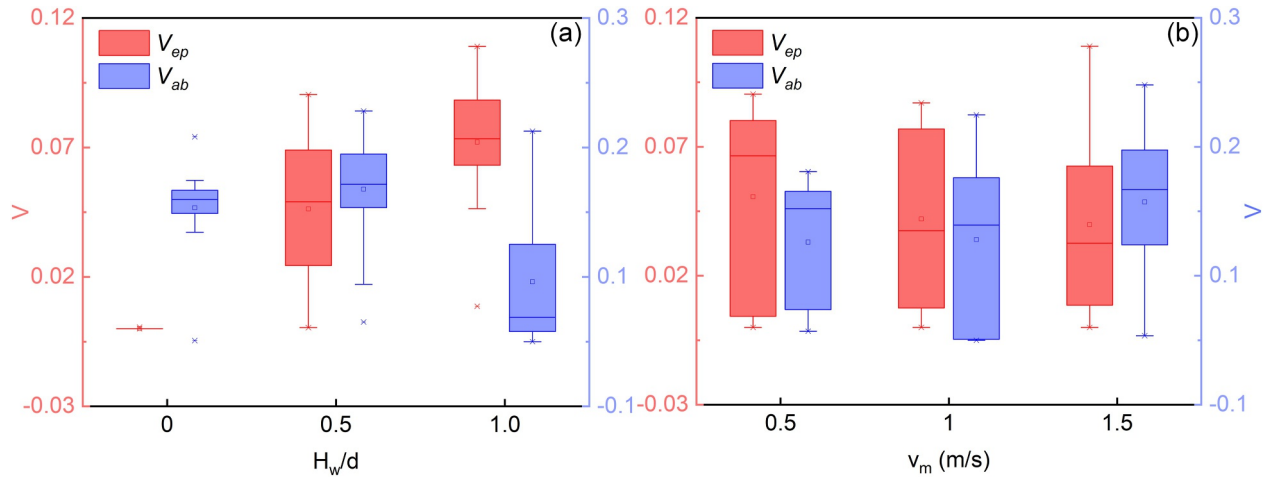


Figure 8. Influence of flow velocity and water volume on wood debarking process: relationship between the expanded and abraded volumes (V_{ep} and V_{ab}) during debarking process with the (a) water volume (represented by H_w/d) and the (b) tangential drum velocity (v_m) which is a surrogate of the flow velocity.

3.2. The Effect of Water Volume and Flow Velocity on Physical Wood Debarking

The physical wood debarking process under varying water volumes and flow velocities can be summarized as the combination of an expansion process and an abrasion process. Water in the rotating drum contributes to wood expansion. Simultaneously, the motion behavior of wood samples changes gradually from rolling, sliding, and collision to floating with increasing water volume inside the drum, further influencing the abrasion process. Flow velocity determines the frequency and intensity of wood–rotating drum and wood–wood interactions, thus, influencing the abrasion during wood debarking process. In order to quantify the expansion and abrasion of wood samples during the experiment, we define two non-dimensional variables, the relatively expanded volume (V_{ep}) and the relatively abraded volume (V_{ab}), to analyze the influence of water volume and flow velocity on wood debarking. The two parameters can then be calculated as follows:

$$V_{ep} = \frac{1}{5} \sum_{n=1}^5 \frac{V_{exp,n} - V_{0,n}}{V_{0,n}} \quad (3)$$

$$V_{ab} = \frac{1}{5} \sum_{n=1}^5 \frac{V_{exp,n} - V_{abr,n}}{V_{0,n}} \quad (4)$$

where $V_{exp,n}$ and $V_{abr,n}$ are the maximum and final volumes of corresponding to the five segments with length varying from 0.04 to 0.12 m of each wood sample.

In Figure 8, V_{ep} and V_{ab} are represented against the variation of water volume characterized by H_w/d and flow velocity v_m . In general, the relatively expanded volume, V_{ep} , increases, while the relatively abraded volume, V_{ab} , first increases and then decreases with increasing water content, H_w/d , from 0 to 1.0. Statistical analysis using ANOVA indicated that the observed trends were statistically significant, with both p -values smaller than 0.05. This proves that the increase in water volume in the rotating drum facilitates the expansion but attenuates the abrasion of wood samples in the initial steps of the experiment. There is no statistically significant relationship between the relatively expanded (V_{ep}), the relative abraded (V_{ab}) volume, and tangential velocity (v_m), with $p = 0.171$ and $p = 0.509$, respectively. In order to analyze the potential relationships between the abovementioned parameters, their relationships are further plotted considering the same conditions in Figure 9. In particular, the relationships of the relative expanded and abraded volumes, V_{ep} and V_{ab} , versus the ratio between water content, H_w/d , under varying flow velocities are shown in Figures 9a–9c, while Figures 9d–9f show the relationships of the relative expanded and abraded volumes, V_{ep} and V_{ab} , versus the tangential velocity, v_m , under varying water volumes.

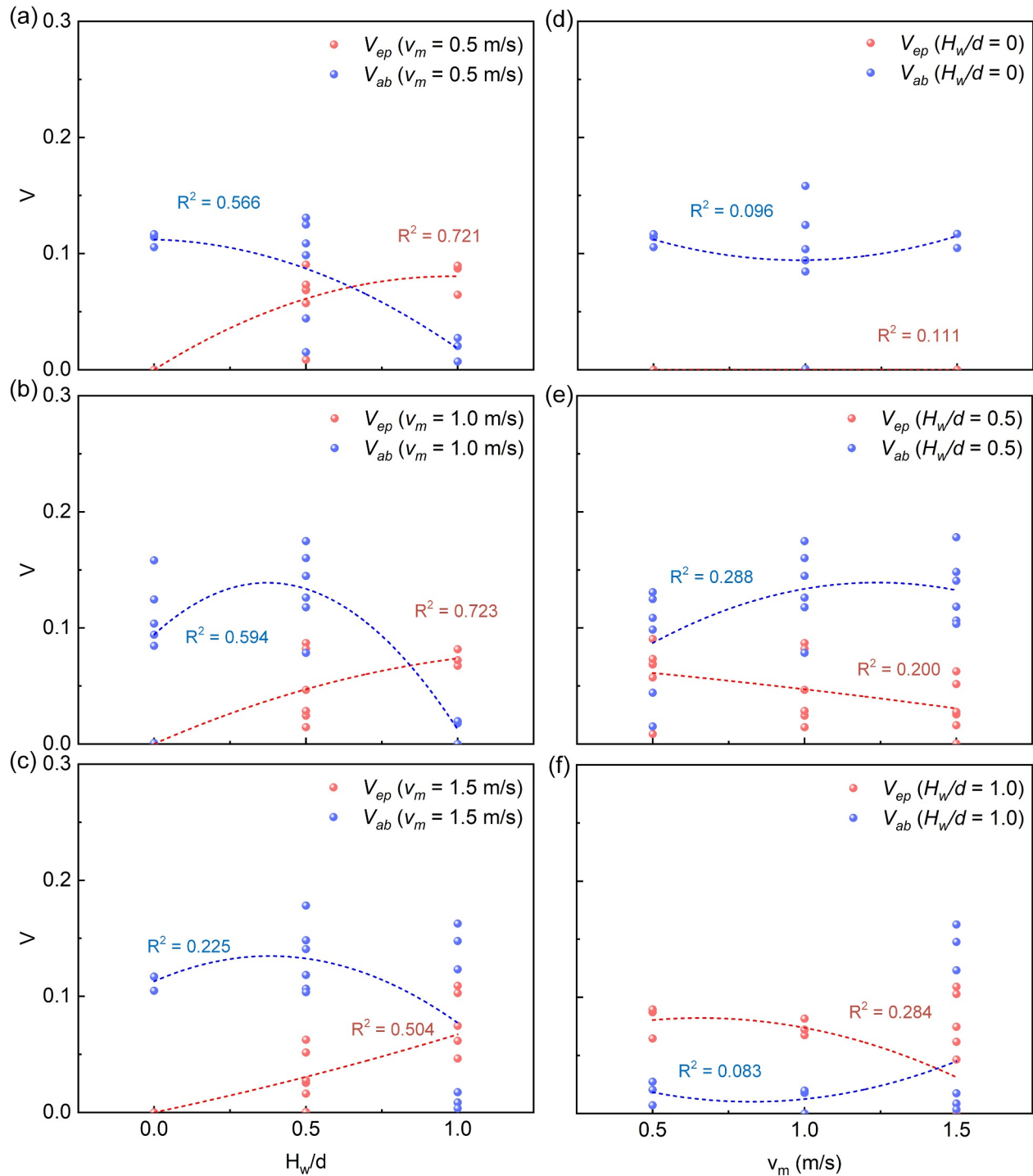


Figure 9. Variation of relative expanded (V_{ep}) and abraded (V_{ab}) volumes under varying flow velocities and water volumes: (a–c) represented against H_w/d for several flow velocities; (d–f) represented against v_m for several water volumes.

Under varying flow velocities, similar variations of the relative expanded and abraded volumes, V_{ep} and V_{ab} , with increasing water content, H_w/d , can be observed (Figures 9a–9c) that compare with the relationships shown in Figure 8a. However, the variations of V_{ep} and V_{ab} with increasing flow velocity differ from each other under varying H_w/d . Specifically, when water is not considered in the test ($H_w/d = 0$), there is no expansion of wood samples during the experiment (Figure 9d). While the abraded volume, V_{ab} , is totally determined by the bark

volume of each wood sample, because wood samples in these scenarios are totally debarked. Therefore, both V_{ep} and V_{ab} remain constant under varying tangential velocity (v_m). When water is considered in the test ($H_w/d = 0.5$ and 1.0), an opposite relationship compared to that in Figures 9a–9c can be observed. Here, the relatively expanded volume, V_{ep} , decreases, while the relatively abraded, V_{ab} , increases with increasing the tangential velocity (v_m). This indicates that the increase in the flow velocity attenuates the expansion process while promoting the abrasion process during the physical wood debarking.

4. Discussion

4.1. Physical Wood Debarking During Fluvial Transport

Wood in natural environments exhibits heterogeneous properties along its radial direction, including variations in composition, density, and water content (Longuetaud et al., 2017). Generally, the bark is less dense, more fibrous and porous, and has a higher initial moisture content when alive, although it can dry out rapidly after detachment or exposure. Consequently, the bark can be more easily removed or abraded than the cambium. Under these conditions, wood debarking plays an important role in the overall process of physical wood degradation. This study was then designed to improve our understanding of physical degradation of large wood during fluvial transport. In particular, we aimed to explain how wood debarks and what factors that influence the debarking process of large wood during fluvial transport. Unlike the degradation of inorganic sediment in rivers, such as pebbles and gravels, in which a direct decrease in mass and volume can be observed during transport (Attal & Lavé, 2009; Bray et al., 2024), our results highlight an expansion phase during the debarking process of large wood. This expansion not only modifies the bark properties of large wood but also influences the abrasion process, thereby affecting the rate and magnitude of mass and volume loss. This volume expansion in wood samples can be attributed to mechanical cell wall breakdown, increased porosity, and moisture reabsorption or hydration, and influenced by several parameters. It enhances the abrasion rate, accelerating the abrasion process by weakening the bark of large wood, eventually leading to a distinct debarking process of large wood during fluvial transport. While the abrasion process, or surface wear and erosion, is induced by friction and repeated contact, eventually leading the bark loss of wood samples. In particular, our experiments show that the relative volume variation during the debarking process for all the samples always ranges between 88% and 110% of the initial volume of wood samples (Figure 10a). The maximum and minimum values which define an envelope of observed variation of volume can change depending on wood type, age (biochemical decay stage) and environmental forcing conditions. Therefore, it is of great importance to take into account the volume expansion of large wood in its debarking process during fluvial transport.

Meanwhile, in our experiments, the debarking process of wood samples under varying water volumes and flow velocities follows three different transport modes that are defined by Ruiz-Villanueva et al. (2019): the floating regime ($H_w/d \geq 1$, Uncongested/Semi-congested regime), the rolling-sliding-floating regime ($H_w/d < 1$, Congested regime) and the rolling-sliding regime ($H_w/d = 0$, Hyper-congested regime). Depending on the interaction between volume expansion and abrasion of wood samples during fluvial transport, which in turn depends on the abovementioned transport regimes, the wood samples may, either reach a maximum expansion followed by a reduction due to abrasion (expansion dominated, Figure 10b and expansion-abrasion combined, Figure 10c), or immediate reduction due to abrasion with no initial period of expansion (abrasion dominated, as shown in Figure 10d).

4.2. A Conceptual Model for Wood Physical Debarking During River Transport

4.2.1. Model Development

A conceptual model is further introduced for White Willow (*Salix Alba*) based on the experimental results, as shown in Figure 11. The physical-based envelope defined by pure expansion and pure abrasion is first illustrated in Figure 11a. The pure expansion constraint corresponds to the maximum expanded volume ($(V_{exp})^{max}$) of a sample during its transport process. The pure abrasion constraint, on the other hand, corresponds to the maximum abraded volume ($(V_{abr})^{min}$), which is equivalent to the initial bark volume of the wood sample. Corresponding to these two volumes, the times to $(V_{exp})^{max}$ and $(V_{abr})^{min}$ are also defined as t_{exp} and t_{abr} . Based on these four parameters, the enveloped area for the debarking process of White Willow can be identified (Figure 10a). Furthermore, the expansion and abrasion processes interact throughout the debarking process. Expansion

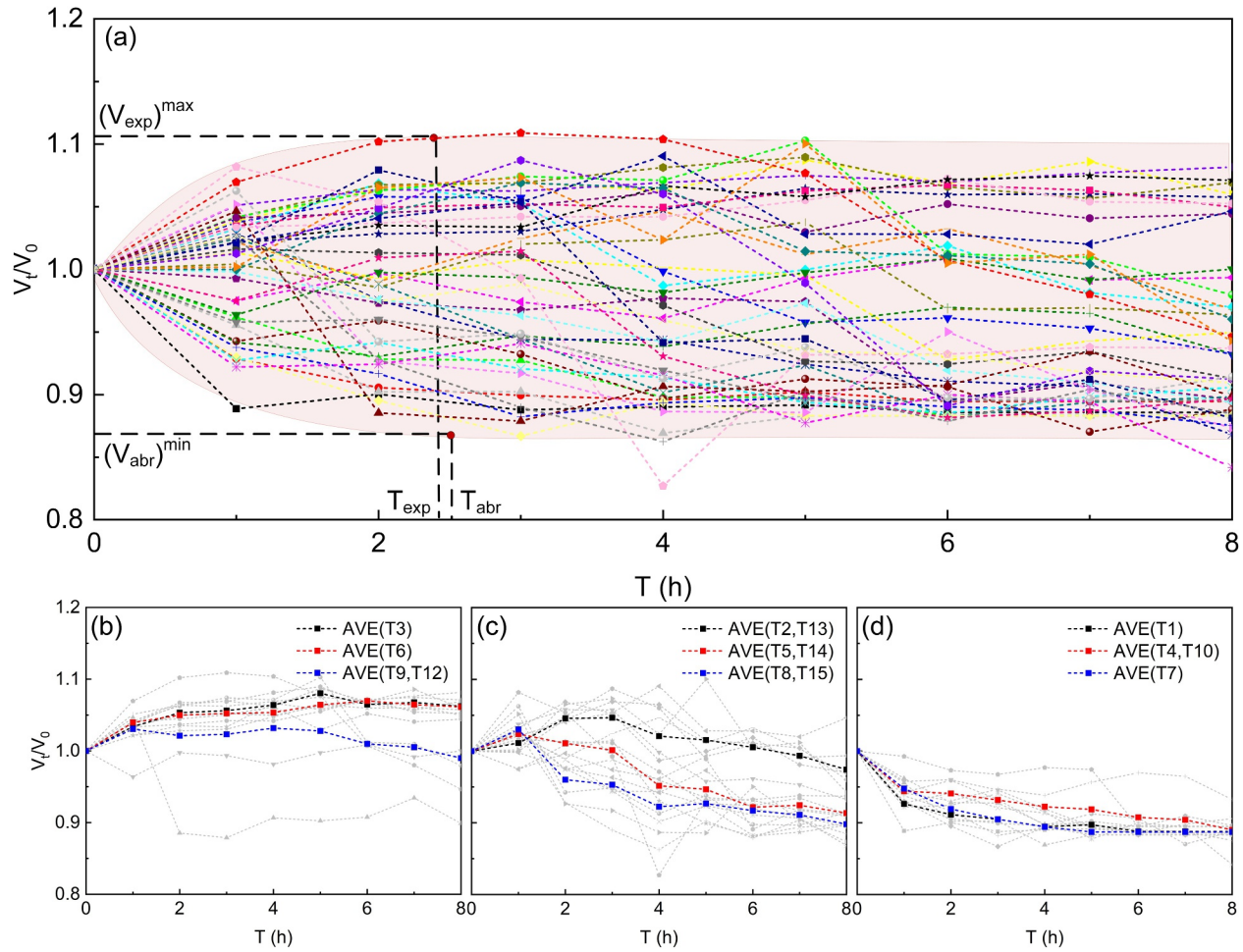


Figure 10. Characteristics of physical wood debarking: (a) range of volume change during wood debarking; (b–d) are averaged volume change of three debarking modes, respectively. Note: s, m, and l are wood samples in small, medium, and large sizes, respectively.

weakens the bark structure and thereby accelerates abrasion, whereas abrasion removes bark material and limits further expansion, resulting in a reduction of the maximum attainable expanded volume. The three debarking modes are therefore summarized and the main descriptive parameters are analyzed within the enveloped area, as shown in Figures 11b–11d.

We are interested on a descriptive model for the abrasion process considering as initial boundary value (V_{ini}): the highest volume expansion achieved ($V_{ini} = V_{exp}$), for mode 1 and 2, at instants $(t_{exp})^1$ and $(t_{exp})^2$, respectively; and the volume at the beginning of the experiments for mode 3 ($V_{ini} = V_0$), corresponding to $t = 0$, at instant $(t_{exp})^3$. Considering the compound average of all the results conditioned to the period after the initial boundary value (Figures 10b–10d), we can establish a model for the relative volume of the wood samples during the abrasion period (identified with *):

$$V^*(t^*) = a + ke^{-\lambda t^*} \quad (5)$$

where $V^*(t^*)$ is the relative volume of wood sample at time t^* , which origin is defined at the moment of the initial boundary value (V_{ini}) (* indicates local coordinates for the model window). When $t^* \rightarrow \infty$, $V^*(t^*)$ refers to the lower boundary of debarking, $(V_{abr})^{min}$ (cf. Figures 10a and 11). This boundary refers to the final volume of each wood sample after wood debarking. If we assume that (green) wood in rivers will eventually be fully debarked during the studied event, we have:

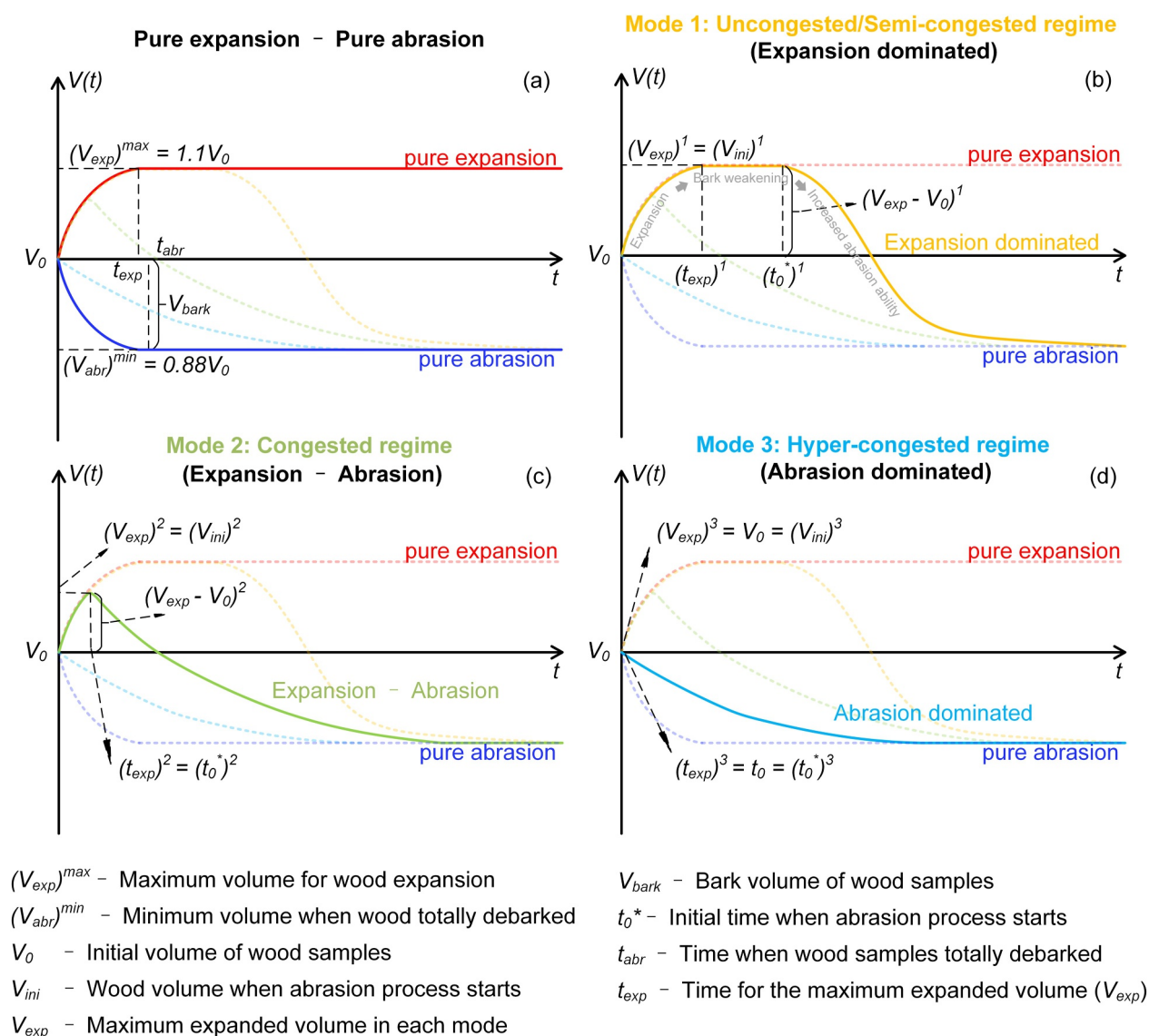


Figure 11. Conceptual models for physical wood debarking of White Willow during river transport.

$$a = (V_{\text{abr}})^{\text{min}} = V_0 - V_{\text{bark}} \quad (6)$$

note that V_{bark} represents the bark volume in the wood sample.

When $t^* = 0$, is $V^*(t^*) = V_{ini}$ and $V^*(t^*) = a + k$, therefore, k in Equation 5 can be expressed as:

$$k = V_{\text{ini}} - (V_{\text{abr}})^{\text{min}} = V_{\text{ini}} - V_0 + V_{\text{bark}} \quad (7)$$

Replacing Equations 6 and 7 into Equation 5, and normalizing by V_0 , we then obtain:

$$\frac{V^*(t^*)}{V_0} = 1 - \frac{V_{\text{bark}}}{V_0} + \left(\frac{V_{\text{ini}} - V_0}{V_0} + \frac{V_{\text{bark}}}{V_0} \right) e^{-\lambda t^*} \quad (8)$$

Note that $\frac{V_{mi} - V_0}{V_0}$ in Equation 8 is exactly the same as V_{ep} defined in Equation 3. Therefore, Equation 8 can be further expressed as follow:

$$\frac{V^*(t^*)}{V_0} = 1 - \frac{V_{\text{bark}}}{V_0} + \left(V_{\text{ep}} + \frac{V_{\text{bark}}}{V_0} \right) e^{-\lambda t^*} \quad (9)$$

Equation 9 is then the final expression which can be used to describe physical wood debarking process considering both the expansion process and the abrasion process. The three parameters V_{bark} , V_{ep} , and λ , meaning bark volume, relative non-dimensional expanded volume and abrasion rate respectively, can be obtained empirically and depend on the wood type, age (biochemical decay stage) and environmental forcing conditions. It should be noted that in V_{ep} , the expansion process during wood debarking is considered. Moreover, the abrasion rate λ implicitly aggregates the effects of both the expansion and abrasion processes, and assumes constant abrasion efficiency once abrasion begins.

4.2.2. Model Application

Our tests show that the bark volume (V_{bark}) equals to roughly 12% of the initial volume of each wood sample (V_0). In this case, Equation 9 can then be further simplified as:

$$\frac{V^*(t^*)}{V_0} = 0.88 + (V_{\text{ep}} + 0.12) e^{-\lambda t^*} \quad (10)$$

In our experiments, the maximum expanded volume of wood samples increases with increasing water volume but decreases with increasing flow velocities (cf. Figure 9). As shown in Figures 9a–9c, V_{ep} increases linearly with increasing $\frac{H_w}{d}$ under varying flow velocities. Additionally, the maximum volume that wood can expand during river transport ($(V_{\text{ep}})^{\text{max}}$, as the upper boundary in Figure 10a) is estimated to be 1.1 V_0 . We assume a linear model to explain V_{ep} as follow:

$$V_{\text{ep}} = \frac{(V_{\text{ep}})^{\text{max}}}{V_0} f\left(\frac{H_w}{d}, F\right) = 1.1 f\left(\frac{H_w}{d}, F\right) \quad (11)$$

where $F = \frac{v}{\sqrt{gd}}$ is non-dimensional flow velocity following the form of Froude number. $f\left(\frac{H_w}{d}, F\right)$ is then a function that describe the maximum expansion volume variation as a function of the relative water content and flow velocity. $f\left(\frac{H_w}{d}, F\right)$ can be expressed through a multiple linear regression analysis:

$$V_{\text{ep}} = 1.1 \times \left(0.0677 \frac{H_w}{d} - 0.023F + 0.0208 \right), R^2 = 0.620 \quad (12)$$

To obtain the abrasion rate in Equation 10, λ , the experimental data is fitted with an exponential model, then, the same approach can be used to obtain the relationship between λ , $\frac{H_w}{d}$, and F , and it can be expressed as follow:

$$\lambda = -0.548 \frac{H_w}{d} + 0.0735F + 0.503, R^2 = 0.893 \quad (13)$$

Substituting Equations 11 and 12 into Equation 9, the concept model for wood debarking, under our specific test conditions of wood type, age (biochemical decay stage) and environmental forcing, can finally be expressed as:

$$\frac{V^*(t^*)}{V_0} = 0.88 + \left(1.1 \times \left(0.0677 \frac{H_w}{d} - 0.023F + 0.0208 \right) + 0.12 \right) e^{(0.548 \frac{H_w}{d} - 0.0735F - 0.503)t^*} \quad (14)$$

Figure 12 shows the model application, namely the comparison of V_{ep} measured and predicted using Equation 11, and the comparison of measured and predicted sample relative volume at the end of the tests using Equation 13. The proposed wood debarking model considers only the following two test conditions: the ratio between water depth and wood diameter and the velocity. Therefore, values for the maximum expanded volume (V_{ep}) and the abrasion rate (λ) in Equation 14 are only determined by $\frac{H_w}{d}$ and F , as shown in Equations 12 and 13. Under this circumstance, Figure 12 provides only the first insights of the model application. No volume expansion is

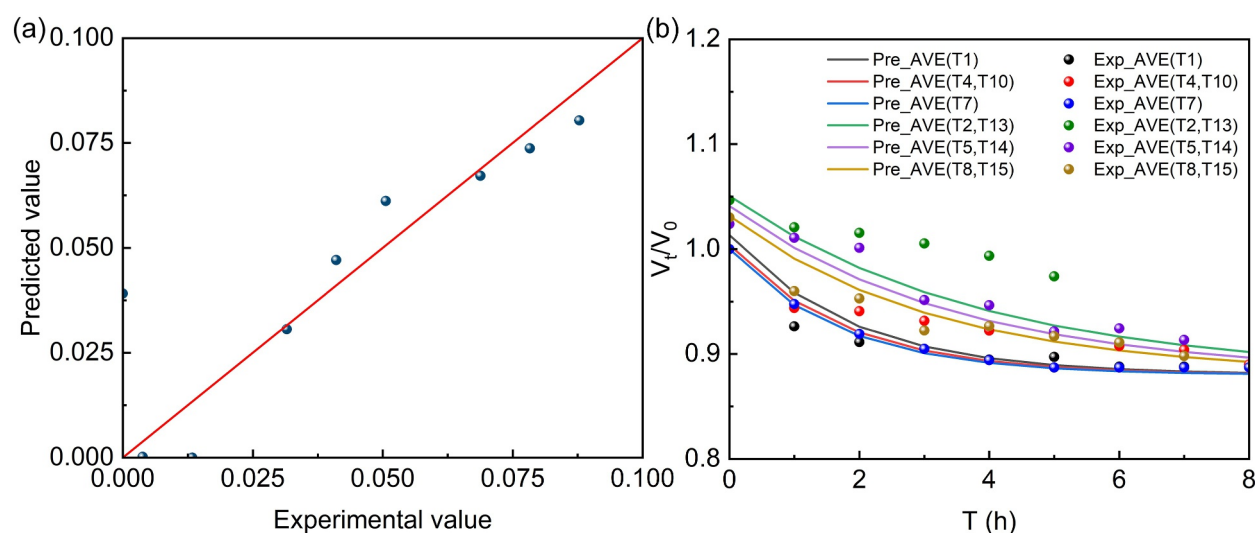


Figure 12. Comparisons between predicted and experimental results: (a) the maximum expanded volume; (b) the debarking process after reaching the maximum volume.

observed in the absence of water during the experiment, therefore, only the results with $\frac{H_w}{d} > 0$ are plotted in Figure 12a. Additionally, there is no debarking when $\frac{H_w}{d} = 1.5$, thus, only results from the six conditions with lower water content are shown in Figure 12b. It is indicated that the maximum expanded volume of different scenarios calculated using Equation 11 is in good agreement with the experimental value (Figure 12a). Regarding the simulation of the debarking process, the concept model can well represent the wood debarking process when the expanded volume is small. Yet, it seems to overestimate the debarking volume when larger expanded volume and longer expansion duration are involved during the wood debarking process (Figure 12b). Under these circumstances, wood samples go through repeated bark loss and volume expansion, leading to a more complex debarking mode of wood samples during fluvial transport. Therefore, the expansion process affects the abrasion process, and the maximum expanded volume should be integrated into λ to better estimate the wood debarking process. However, both the conceptual model and mathematical models assume a single expansion phase for simplification. Further refinement of the model through additional experiments, considering more complex interactions contributing to expansion–abrasion processes, will be conducted in the future.

4.3. Limitations, Perspectives, and Implications

Physical degradation of large wood in natural environment involves manifold interactions between wood–river boundaries, wood–wood, wood–sediment, and wood–infrastructures. These interactions lead to the frequently variation of the motion characteristics of large wood, further affecting its physical degradation during river transport. However, in our experiment, it should be noted that the constant simplified motion behavior generated by the rotating drum under varying conditions is unsimilar to what we observed in the field. This simplified motion behavior ignores the accumulation, the deposition of large wood during its transport process, as well as the variation of the river flow (e.g., acceleration, turbulence structure). In particular, large wood transport in natural rivers is episodic, with long stationary state or rest period between motion events. It may also undergo continuous shifting transport modes as flow changes. In this way, the continuous motion in the drum likely compresses time scales of debarking, thus leading to a shorter duration of the physical debarking process in our experiment. However, we explore effects of short time-scale event on green wood, and therefore, the stationary state or rest period during large wood transport can be ignored.

Our experiments consider only interactions between wood–wood and wood–boundary contacts, while neglecting interactions between wood and other constituents, particularly inorganic sediments. The presence of sediments may modify the bark damage pathways and, consequently, influence the expansion process, altering abrasion rates during wood debarking. Under such conditions, our results may underestimate abrasion rates in sediment-rich rivers or in bedload-active systems. Future work should incorporate the role of sediments in wood debarking processes.

Given the limitations of the present experimental design, the possible way to connect our experimental results to the physical debarking of large wood in natural environments is to monitor the motion characteristics of large wood during its transport in rivers. Nevertheless, two motion behaviors are hypothesized to contribute to the debarking of large wood, abrasion induced by rolling and sliding, and collisions among wood–wood and wood–other elements. These two motion behaviors dominate the duration for wood debarking and can be monitored in the field by a Lagrangian monitoring of wood logs in rivers through motion sensors (e.g., RFID from MacVicar et al. (2009) and SmartWood from Spreitzer et al. (2019)).

Another limitation is the conceptual model we use to describe the debarking process of large wood. Natural wood debarking is a more complicated process that involves both the physical and bio-chemical effects (Hortobágyi et al., 2024; E. C. Merten et al., 2013; Seibold et al., 2021). The three debarking modes identified in this study may also transition from one to another in response to changes in flow regimes. Nevertheless, given the different time scales of biochemical and physical processes, we believe that they can be investigated separately. The proposed debarking modes, therefore, provide a first conceptual framework for understanding the physical degradation of large wood in rivers. Additionally, the physical debarking process is influenced by several other parameters, as those listed in Table 1. Our model is sufficiently general to be extended to white willow and to include additional factors such as decay class and bark loss during wood accumulation, as well as the continued abrasion of large wood after the debarking process. Following Schalko et al. (2018, 2019a, 2019b) and Yu et al. (2025), the relationships between the physical degradation of large wood (e.g. wood volume V) and river parameters can be expressed as follow:

$$f(V) = f(\rho_w, v, H_w, g, L_w, d, \rho, N_w, q_s, d_{50}, W_r, S) \quad (15)$$

where ρ_w and ρ are density for water and wood, respectively. g is the acceleration due to gravity. L_w , d , and N_w are wood length, diameter and number, respectively. q_s and d_{50} are sediment transport rate and median diameter of sediment, respectively. W_r and S are channel width and gradient for the river. Based on Equation 15, the generalization of our conceptual model can be derived through calibration of V_{ep} and λ , with further experiments needed to explore these varying parameters, longer durations, and different tree species.

Despite of the abovementioned limitations, our results provide the first insight into the physical debarking process of large wood during fluvial transport. The results enhance our understanding of physical wood degradation and highlight the interaction between volume expansion and abrasion during wood debarking. In addition, the conceptual model, in which both the expansion and abrasion processes are considered, provide potential insights in predicting residence time, mobility and ecological functions of large wood dynamics in rivers. Furthermore, the experimental approach provides a framework for connecting physical wood degradation and transport behavior of wood under varying hydrodynamic conditions, further aiding river restoration and wood budget analysis. Future research will focus on interpretation of physical wood degradation in the aspect of wood transport and improvement of the conceptual model to better predict the evolution of large wood in river systems.

5. Conclusions

A laboratory rotating drum experiment was designed and used to investigate the physical debarking process of large wood during river transport. 15 tests with nine distinct scenarios and 45 wood samples from White Willow were conducted considering varying water volumes and flow velocities. Our results demonstrate that the physical debarking of large wood during river transport can be divided into the following two processes: the expansion process and the abrasion process. The debarking process can further be categorized into three modes under varying water volumes and flow velocities: the expansion mode, the expansion-abrasion mode and the abrasion mode. Our results suggest that these three debarking modes could be related to the sliding-rolling transport without water ($H_w/d = 0$), sliding-rolling-floating transport ($H_w/d = 0.5$) and floating transport ($H_w/d \geq 1$) regimes of large wood transport in rivers. Among these, the water volume contributes to the different debarking modes that can be observed during the physical wood debarking process, while, the flow velocity controls the frequency of interactions between wood–drum chamber and wood–wood, thus varying the maximum volume that the wood samples can expand and the time scale when abrasion occurs during the debarking process. We further analyzed the influence of water volume and flow velocity on wood debarking by quantifying the following two parameters: the relatively expanded volume (V_{ep}) and the relatively abraded volume (V_{ab}). Our results indicate

that the relatively expanded volume V_{ep} increases with increasing water volume but decreasing flow velocity. Regarding the relatively abrasion volume V_{ab} , it first increases and then decreases with increasing water volume. However, there is no clear relationship between V_{ab} and the flow velocity, since some of wood samples are totally debarked during the experiment. Furthermore, based on the three physical wood debarking modes and the two processes that get involved during wood debarking, a concept exponential model that considers both the expansion process and the abrasion process under limited conditions is proposed. In this model, the expansion and abrasion processes interact with each other, resulting in variations in the maximum expanded volume (V_{ep}) and abrasion rate (λ), thereby generating distinct debarking trajectories. The proposed model is able to well predict the expanded volume under varying flow velocities and water volumes and the abrasion process under limited conditions during physical wood debarking. This study represents a first attempt to develop a conceptual model of the debarking of large wood during fluvial transport and to identify the factors controlling this process, providing new insights into wood attrition in rivers and the effects of large wood on riverine ecosystems. However, limitations still exist in the current methods and the proposed model; future research including the relative motion of large wood and water, and experiments considering longer duration for wood degradation after debarking and more factors that affect wood debarking will be conducted to better understand the mechanisms of physical wood degradation in natural environment.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All the data described in this paper was produced by the authors (Yang, 2025) and is available online at <https://doi.org/10.5281/zenodo.17661521>. The volume of each wood log in the data set was obtained from SfM photogrammetry. Point cloud data of each wood log was generated by Agisoft Metashape software (Version 2.2.0, Agisoft LLC, 2022). CloudCompare (Version 2.12.4, CloudCompare Development Team, 2021) was used to process the cloud data and Agisoft Metashape was used for volume calculation.

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