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Wood density and moisture sorption and its influence on large wood mobility in rivers

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ABSTRACT

Dynamics of large wood in aquatic systems significantly influence physical and ecological processes in rivers. Wood mobility is notably becoming a critical issue, not only in the context of restoration, but also in terms of flooding and hazard potential. Although the number of studies focusing on instream wood has increased substantially over the last few years, physical properties of wood have rarely been measured in aquatic systems. Instead, forest industry-based standards are often used. In this study, we quantitatively assess properties of instream wood density using decayed samples from the Rhône River stored within the Génissiat Reservoir and green samples from the Ain River floodplain (France). Using *in-situ* and laboratory experiments, we demonstrate how wood density varies between species, how density changes with moisture sorption and decay, and how density affects buoyancy. Results illustrate that both green (e.g., 800 ± 170 $\text{kg}\cdot\text{m}^{-3}$) and instream woods (e.g., 660 ± 200 $\text{kg}\cdot\text{m}^{-3}$) have much greater densities than standard values used in the literature (500 $\text{kg}\cdot\text{m}^{-3}$). Sorption processes differ in green versus instream wood; moisture desorption of green wood is faster than absorption, whereas for instream wood, absorption is faster than desorption. These findings and the related changes in density affect wood buoyancy and mobility and therefore influence wood dynamics in rivers. Finally, two case studies illustrate how more accurate density values can be used to improve wood transport modeling and wood budget estimates based on numerical simulation and ground video-imagery-based monitoring.

1. Introduction

The number of publications focused on large wood (LW) in fluvial ecosystems has significantly increased in the scientific and technical literature over the past two decades (Gurnell et al., 2002; Wohl, 2013; Ruiz-Villanueva et al., 2016). These studies demonstrated that the spatial distribution of wood shows significant variations depending on climate, hydrology, geological, and geomorphological setting and human interactions (Piégay et al., 1999; Wyzga and Zawiejska, 2005; Comiti et al., 2006; Andreoli et al., 2007; Wohl and Goode, 2008). However, wood properties (in terms of mechanical and physical properties) are still not commonly quantified in aquatic environments (Le Lay et al., 2013). Studies that address temporal variability are much less abundant in general due to the difficulties in estimating changes in wood storage (i.e., wood budget). Wood budgets have been estimated based on recruitment volumes, changes in storage, and then back-calculation of wood export or flux (i.e., wood in transport over a certain time or area; Benda and Sias (2003)). However quantifying wood flux is challenging and requires direct observations during different hydrological conditions (MacVicar et al., 2009; Kramer and Wohl, 2014). Usually, volume of wood, rather than mass, is required for budgeting or flux estimations. Wood volume (V_{wood}) is often estimated based on the geometrical shape of the wood (Thévenet et al., 1998). To directly quantify wood volume and compute wood budgets, different techniques have been used, such as repeat estimates of the amount of wood deposited along a given reach, or direct counts of wood pieces at a given location. One of the first attempts to compute wood fluxes was using a video camera recording wood transported during different flood events in the Ain River in France (MacVicar et al., 2009). Aside from some technical issues due to camera resolution and the possible distortion of the images, an important limitation using this technique is the accurate estimation of the detailed wood shape. For cylindrical and simple-shaped logs, length may be more easily observed, but in the images from the camera only the emergent (or above-water) part of the woody piece is observed, not its entire diameter. Therefore, an uncertainty exists when wood volume is estimated using this monitoring technique. For floating wood, the proportion of unsubmerged log depends basically on its buoyancy, and that depends on the density of the wood. Wood density is also one of the main parameters in

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controlling the initial motion and the transport mechanism of wood (i.e., floating or sliding/rolling). The incipient motion of wood pieces, assuming logs are cylinders and avoiding any influence of root wads or branches, can be described as a balance of forces (Braudrick and Grant, 2001): (i) the driving forces, including the gravitational force acting on the log, equal to the effective weight of the log in a downstream direction, and the drag force, also acting in the flow direction, which is the downstream drag exerted on the log by the water in motion; (ii) and the resisting forces, including the friction force acting in the direction opposite to flow, which is equal to the normal force acting on the log times the coefficient of friction between the wood and the river bed. Wood entrainment is therefore mainly a function of four characteristics: length, diameter, orientation, and wood density, plus three hydraulic characteristics: slope, water velocity, and depth. Once a log is put in motion, two possible transport mechanisms are possible: one analogous to bedload movement along the river bed and the second, floating. These transport mechanisms depend on the hydraulics and morphology of the river and the wood piece characteristics (i.e., density).

Finally, there is also a growing interest in estimating wood biomass and carbon storage in rivers, as large wood can contribute significantly to the carbon flux in stream ecosystems (Wohl et al., 2012). Usually direct measurements of biomass during wood inventories are not possible. Instead, the volume of individual woody pieces is estimated and biomass is calculated by multiplying this volume by an estimate of wood density (Flores and Coomes, 2011). Therefore, wood density has to be accurately estimated in order to calculate biomass accurately.

Surprisingly, for any of these calculations where wood density is required (i.e., wood budget, wood transport, or biomass estimates), a value of 500 $\text{kg} \cdot \text{m}^{-3}$ has been systematically used in the literature (Harmon et al., 1986). This is due to the fact that unlike in forestry research, wood density is infrequent assessed in aquatic studies. Wood density varies as a function of several factors including tree species, wood type (proportion of early to late wood), tree age (and proportion of heartwood to sapwood), decay status, and water sorption (Thévenet et al., 1998; Millington and Sear, 2007; MacVicar et al., 2009; Curran, 2010; Shmulsky and Jones, 2011). Environmental conditions and processes in rivers are very different than those in forests, where most of the data about wood density is obtained. For example, woody pieces in watercourses are usually exposed to wetting and drying cycles controlled by the hydrological regime (i.e., frequency, duration, and magnitude of flows). In addition, in aquatic systems, anaerobic conditions may affect decomposition rates and decay processes, significantly differing from terrestrial wood decay (Bataineh and Daniels, 2014). Therefore, using standard values or relationships extracted from inventories of wood in forests, such as the Global Wood database (density as oven-dried mass/fresh volume; Zanne et al. (2009)), or the database from the Forest Products Laboratory-USDA (2010), or those compiled by the United States Department of Agriculture (USDA; Harmon et al., 2008, 2011) may not be appropriate for large wood in rivers. Especially when wood transport is analyzed or if wood shape needs to be extracted from videos, it is more appropriate to use values of wood density that include water content, whereas for biomass or carbon stock estimations, dry wood density may be more accurate.

Despite the abundant literature on wood properties, especially for manufacturing processes (Forest Products Laboratory-USDA, 2010; Shmulsky and Jones, 2011), and studies of wood in forests (Harmon et al., 2008), few studies have been published regarding instream wood physical characteristics. As an example, Thévenet et al. (1998) analyzed wood slices from instream wood collected at the Ain River, to estimate the ability to absorb water and test how the age, decay stage, density or size of samples influence the sorption process. Díez et al. (2002) analyzed small branches of several species to quantify wood breakdown in a first order stream in the Iberian Peninsula. Macvicar et al. (2009) analyzed samples also collected from the Ain River (France) and calculated residence times using C^{14}, wood mechanical characteristics (i.e., wood resistance to penetration), decay status, and wood density to quantify temporal dynamics of wood in rivers. Cadol and Wohl (2010) analyzed wet and dry densities, decay and residence time of wood extracted from tropical streams in Costa Rica. Turowski et al. (2013) collected wood samples from a mountain stream in Switzerland, and for large wood, mass was calculated assuming a cylindrical shape and a dry density. Merten et al. (2013) analyzed the importance of breakage and decay (measuring density) of large wood in rivers, using samples extracted with increment cores from wood found within several low order streams in USA. In these studies, different types of samples were used, most of them were small samples of wood (e.g., slices, cores), making the generalization to larger pieces or comparison very difficult. Therefore, many gaps exist regarding instream wood properties, particularly in relation to wood density.

The aim of this study is to provide empirical data on instream wood density and its variability with regard to the most influential factors (i.e., species, decay and moisture content) using large samples extracted from rivers. Moreover, the goal is to better understand the differences between instream wood and green wood, and to compare measured instream wood density values with some reference values from terrestrial environments. To do this we used two different types of wood, freshly cut green wood samples and decayed instream wood samples. In addition, this study evaluates the importance of wood density in modeling wood transport in rivers and in estimating wood budgets based on tracked floating wood pieces using video records.

2. Material and methods

2.1. Study sites, sampling strategy, and laboratory experiments

We analyzed the characteristics of two series of wood pieces, one set of instream wood samples extracted from the Rhône River, stored in the Génissiat reservoir (decayed floating wood); and another set of samples collected from living trees (undecayed and never-dried, green or freshly cut wood) located in the riparian forest of the Ain River.

The Génissiat dam is located in France 50 km downstream from Geneva (Switzerland) and 160 km upstream from Lyon (Fig. 1A). The drainage area of the Rhône River at Génissiat is 10,910 km^2. With a mean annual flow of 356 $\text{m}^3\ \text{s}^{-1}$, it is characterized by summer high flows but its seasonal variations are more subdued than typical glacier-fed regimes. Lake Geneva (50 km upstream, altitude 371 m, surface area 585 km^2, volume 89 km^3) retards and attenuates the peak flows, and interrupts the transfer of wood and sediments. At Génissiat, the Rhône is supplied with driftwood from two tributaries, the Arve and the Valserine Rivers. The drainage area of the Arve is 1984 km^2, 6% being ice-covered and 50% located at an altitude of over 1360 m; it drains the massif of Mont Blanc (4807 m). In its upper reaches, it is particularly influenced by snowmelt, which occurs from the end of winter until June, and then by summer rains and storms, followed by cyclonic rain storms in the autumn. Where it merges with the Rhône, the Arve has a hydrologic regime influenced by rainfall, snow and ice-melt. The river drains an alluvial corridor for a large part of its course with a braided pattern for several kilometers. The Valserine, on the right bank of the Rhône, drains a watershed with a 374 km^2 surface area and flows through the Jura limestone massif, which reaches altitudes just in excess of 1500 m. Its hydrological regime has a very pronounced nival influence with a maximal flow in April and a secondary minimum in January, but it also has a pluvial influence with another flow maximum in the autumn. The geomorphic pattern of the Valserine is a single-thread river, flowing through a gorge and draining a more forested watershed than that of the Arve.

Génissiat dam has no overflow pathway, so all woods coming from upstream in the Rhône and from the Arve and Valserine Rivers are blocked and must be extracted mechanically, usually before they sink to the bottom of the reservoir such that significant wood accumulation against the dam wall could be avoided systematically and successfully