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A probabilistic multidimensional approach to quantify large wood recruitment from hillslopes in mountainous-forested catchments

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ABSTRACT

Large wood (LW) plays a key role in physical, chemical, environmental, and biological processes in most natural and seminatural streams. However, it is also a source of hydraulic hazard in anthropised territories. Recruitment from fluvial processes has been the subject of many studies, whereas less attention has been given to hillslope recruitment, which is linked to episodic and spatially distributed events and requires a reliable and accurate slope stability model and a hillslope-channel transfer model.

The purpose of this study is to develop an innovative LW hillslope-recruitment estimation approach that combines forest stand characteristics in a spatially distributed form, a probabilistic multidimensional slope stability model able to include the reinforcement exerted by roots, and a hillslope-channel transfer procedure. The approach was tested on a small mountain headwater catchment in the eastern Italian Alps that is prone to shallow landslide and debris flow phenomena. The slope stability model (that had not been calibrated) provided accurate performances, in terms of unstable areas identification according to the landslide inventory (AUC = 0.832) and of LW volume estimation in comparison with LW volume produced by inventoried landslides (7702 m^3 corresponding to a recurrence time of about 30 years in the susceptibility curve). The results showed that most LW potentially mobilised by landslides does not reach the channel network (only about 16%), in agreement with the few data reported by other studies, as well as the data normalized for unit length of channel and unit length of channel per year (0–116 m^3/km and 0–4 m^3/km y^{-1}).

This study represents an important contribution to LW research. A rigorous and site-specific estimation of LW hillslope recruitment should, in fact, be an integral part of more general studies on LW dynamics, for forest planning and management, and positioning in-channel wood retention structures.

1. Introduction

Large wood (LW) is a key factor in a woodland fluvial ecosystem as in-channel LW elements directly influence physical, environmental, chemical and biological aspects of aquatic life (Anderson et al. 1978; Abbe and Montgomery 1996; Gregory et al. 2003; Montgomery and Piégay 2003; Tockner et al. 2003; Seo et al. 2008; Beckman and Wohl 2014; Wohl 2017). However, floating and deposited LW also affects river morphology and sediment dynamics (Montgomery et al. 2003; Wohl and Scott 2016), causing obstructions of narrow channel cross sections, especially bridges and hydraulic structures, with hazardous clogging phenomena (Gippel et al. 1996; Mazzorana et al. 2011, 2011, 2017; Comiti et al. 2016; Wohl et al. 2016; Wohl 2017). Such phenomena usually occur during low-frequency and high-magnitude flood events (Mao et al. 2013) and induce a significant potential hazard for human populations and infrastructure (Ruiz-Villanueva et al. 2014; Badoux et al. 2015; Comiti et al. 2016; Lucía et al. 2015). Although the removal of LW storage is common practice in the hydraulic management of watercourses (Wohl 2014), recent restoration projects have included a reintroduction of woody material into fluvial systems in order to recover pristine conditions by improving their hydrological, morphological, and ecological status (Kail et al. 2007; Abbe and Brooks 2011; Antón et al. 2011).

In recent years, several authors have studied LW dynamics and budget, making a significant effort especially in the understanding of LW recruitment mechanisms and transport (see Wohl 2017). LW recruitment processes vary widely in terms of space and time within watersheds (Piégay et al. 1999; Gurnell et al. 2002; Benda and Sias 2003). According to the literature (e.g., Keller and Swanson 1979; Kaplan and Garrick 1981; Harmon et al. 1986; Bragg 2000; Benda

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et al. 2002, 2003, 2003; Benda and Sias 2003; Miller et al. 2003; Ruiz-Villanueva et al. 2014), identifying the following relevant recruitment processes is possible:

- mass wasting processes from hillslope to channel (e.g., landslides, debris flows, deep-seated failures, snow avalanches);
- streambank erosion (e.g., shallow slides, slab failures, cantilever failures, bank undercutting, basal cleanout, windthrow along streamside);
- forest mortality (tree-killing processes including blowdown, insects, fungal diseases, pathogens and waterlogging, and chronic mortality such as suppression and stem exclusion);
- stand-replacing events (e.g., wildfires, snowstorms, windstorms);
- fluvial transport during floods; and
- human activities (e.g., harvesting, arson, logging restorations).

Bank erosion is the primary source of LW recruitment in high-order lowland rivers, whereas colluvial processes such as landslides and debris flows are the dominant mechanisms for delivering woody material from hillslopes and small headwater channels to valley-bottom streams in low-order mountain streams (Keller and Swanson 1979; Nakamura and Swanson 1993; Comiti et al. 2008; Cadol et al. 2009; Iroumé et al. 2010; Rigon et al. 2012).

In this context, investigating the LW dynamics in a reach of a watercourse requires a quantification of the LW budget, accounting for inputs, storage, and outputs (e.g., Martin and Benda 2001; Benda and Sias 2003; Comiti et al. 2016):

$$\Delta S = \left(L_i - L_d + \frac{Q_i}{\Delta x} - \frac{Q_0}{\Delta x} - D \right) \ \Delta t \tag{1}$$

where ΔS is the change in LW storage, L_i is lateral recruitment per unit of channel length and unit of time, L_d is lateral deposition on the floodplain, Q_i and Q_0 are the fluvial transport into and out of the stretch, D is LW decay caused by degradation processes, Δx is channel length, and Δt the time interval considered.

Lateral input is, in turn, the result of several different processes (Wohl 2017), although most LW volume recruitment can be assumed to originate from the fluvial corridor because of bank and floodplain erosion and from hillslopes owing to landslides and debris flow processes (Comiti et al. 2016).

In the scientific literature, a variety of models have been proposed to evaluate LW recruitment, including deterministic (e.g., Wallerstein et al. 1997; Downs and Simon 2001; Welty et al. 2002; Benda and Sias 2003; Hassan et al. 2016) and stochastic models (e.g., Van Sickle and Gregory 1990; Meleason et al. 2002, 2003; Lancaster et al. 2003). Detailed models have also been proposed for large-scale analyses to identify the potential source area of LW. Czarnomski et al. (2008) developed a statistical and simple mass balance analysis to assess the impact of natural processes and forest management on wood input to streams. Mazzorana et al. (2009) introduced a series of empirical indicators to determine the relative propensity of mountain streams to recruit woody material. Rigon et al. (2012) presented a GIS-based model focusing on LW recruitment from hillslope instabilities, combining a bivariate geostatistical analysis (WofE) for slope stability and a slope decay function for connectivity. Kasprak et al. (2012) developed a spatially extensive method for localizing the sources of large wood and for identifying the recruitment mechanisms using LiDAR data in a coastal watershed of Maine (U.S.A.). Eaton and Hassan (2013) proposed a stochastic model to investigate the geomorphic function of wood changes as a consequence of tree mortality at the catchment scale. Ruiz-Villanueva et al. (2014) developed a procedure based on multicriteria and multiobjective assessment analysis using fuzzy logic principles in a spatially distributed way. Lucía et al. (2015) predicted LW recruited from river corridors and unstable slopes connected to the stream network combining SHALSTAB (Dietrich et al. 1995), a coupled steady-state runoff and two-dimensional slope stability model, and a GIS-based connectivity index (Cavalli et al. 2013). Recently, Hassan et al. (2016) explored the long-term implications of woody dynamics and evaluated LW budget comparing two frameworks, one based on the decay and downstream transport and the other on the depletion of LW. More detailed reviews on this subject are given in Gregory et al. (2003) and Ruiz-Villanueva et al. (2016).

Despite all this, the assessment of LW recruitment volumes is still challenging and subject to considerable uncertainty, especially in cases where hillslope instability is a concern (Comiti et al. 2016) and, where a spatially distributed numerical simulation of LW recruitment is considered a gap that needs to be filled (Wohl 2017).

Indeed, the extreme complexity and spatial and temporal variability of LW recruitment processes from hillslopes is a considerable challenge for most conceptual models and needs a spatially distributed implementation. In addition, forest characteristics (e.g., tree sizes and density) strongly affect slope stability (e.g., Cislaghi et al. 2017; Cohen and Schwarz 2017) and the potential LW quantity and size (e.g., Comiti et al. 2016). The identification of potential LW sources and the quantification of LW amount from hillslopes would, therefore, require the use of spatially distributed, physically based models able to relate forest characteristics to slope stability.

Given this background, this study aims to investigate the relationship between low-order forested mountain catchments prone to soil instabilities and potential LW volume, providing a new method to evaluate LW recruitment from forested hillslopes. The proposed approach is able to produce a more precise estimation of LW input from different sectors of the catchment and to evaluate the effects of different forest management strategies.

A probabilistic multidimensional approach has then been adopted to model shallow landslide susceptibility and the related recruitable LW.

2. Materials and methods

2.1. Slope stability analysis and potential LW recruitment from hillslopes

A reliable method to evaluate the potential LW recruitment volume from a hillslope starts from the prediction of potentially unstable areas over the entire catchment with particular reference to forested ones. To achieve this, we adopted a two-step procedure. The first step involves a slope stability analysis to identify the potential source areas of LW recruitment, and the second estimates the related potential LW volume based on forest maps.

2.1.1. Slope stability model

Evaluating the potential areas of slope instability, and as a consequence the sources of LW recruitment, requires the temporal and spatial variability of each input parameter. The adopted method is the PRobabilistIc MUltidimensional shallow Landslide Analysis, PRIMULA, recently developed by Cislaghi et al. (2017) consisting of the combination between a three-dimensional limit equilibrium model and a Monte Carlo Simulation, MCS. It is based on several assumptions: (i) the force balance is applied to the centre of a potential landsliding block; (ii) groundwater level is steady and parallel to the slope surface; (iii) infiltration, suction, and capillary rise are not taken into consideration; and (iv) the single block is divided into saturated and unsaturated zones. PRIMULA also takes into account earth pressure lateral forces, soil cohesion, and the reinforcing effects provided by root systems acting on potential landslide boundaries.

The factor of safety FS for each potential landsliding block can be evaluated as the ratio between resisting and driving forces as follows:

$$FS = \frac{F_{rb} + 2 F_{rl} + F_{rd} + F_{ru} - F_{du}}{F_{dc}} \tag{2}$$

where the driving forces consist of the downslope component of the central block mass F_{dc} and the force on the central block acting from