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Titolo tesi: **Valutazione del bilancio di legname in due diversi fiumi situati in ambiente alpino e andino**

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"Have you also learned that secret from the river,
that there is no such thing as time?
That the river is everywhere at the same time,
at the source and at the mouth,
at the waterfall, at the ferry, at the current,
in the ocean and in the mountains,
everywhere and that the present only exists for it,
not the shadow of the past nor the shadow of the future."
Hermann Hesse

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Abstract

In forested river basins, Large Wood (LW) is a key component responsible for the geomorphological and ecological aspect of fluvial systems but, at the same time, is a source of hazard for sensitive places. Given its dual role, the analysis and quantification of LW in rivers, as well as understanding its mobilization and deposition, are crucial steps in order to ensure an appropriate management of riverine areas. This study attempts to increase knowledge in the main LW-related processes, such as the lateral recruitment from bank erosion, fluvial transport and the presence of buried LW, assessing the LW budget in two rivers. The study was conducted in two different fluvial environments. A 3.7 km-long reach was selected along the middle course of the Italian Piave River, a human impacted gravel-bed river typified by wandering and island-braided morphologies. In addition, three 80 m-long reaches were selected along the lower course of the Chilean Blanco River, a natural river with a morphology that drastically changed because of a recent volcanic eruption. The three considered items of the budget were analyzed by field activities conducted during the three years of the PhD. The lateral recruitment of LW was analyzed only in the Piave River for an over-bankfull flood (RI~7yr) by measuring, positioning and tagging all standing trees (D≥ 0.1m) within a 20 m buffer wide along the floodplain banks and island perimeters. A similar methodology was used to investigate, in both rivers, the fluvial transport of LW by considering all woody elements (D≥0.1m and L≥1m) within the active channel. In this way, during post-event surveys it was possible to identify the input (deposition) and output (mobilization) elements. Because the sediments from the volcanic eruption caused the burial of several standing trees and LW, the presence of buried LW was explored only in the Blanco River by Ground Penetrating Radar (GPR) testing. In the Piave River, the LW budget was assessed for very low floods (RI<1yr), whereas in the Blanco River ordinary (RI~1yr) and not-ordinary floods (RI 10-25yr) were considered. The results highlighted that, in the Piave River, the recruitment from bank erosion is a common process for the supply of LW. Volumes of recruited LW were found to vary according to the extension of the eroded surface, type of eroded morphological unit and riparian vegetation characteristics. Larger volumes (25.1 $m^3 \cdot km^{-1}$) are recruited from both the floodplain and fluvial islands during not-ordinary floods (RI~7yr), whereas for ordinary events (RI<1yr) small amounts of LW (0.21 $m^3 \cdot km^{-1}$) are recruited just from the floodplain. Furthermore, flood magnitude was found to be an important factor controlling the temporal fluctuations of LW storage, resulting in decreases and increases of LW abundance during ordinary and not-ordinary events, respectively. The increase in wetted area results in a greater inundation of fluvial bars that allows, at the same time, the mobilization and deposition of LW. In addition to the role of flood magnitude, the local-scale morphology of the river appeared to be another factor influencing the

changes in LW abundance, with greater variations in multi-thread than single-thread channels, where the larger and faster increase in the inundated area increases the amount of in-transport LW. In particular, the budget for the Piave River featured negligible variations in LW storage (-9.7%) and a very low mobility rate (1.43%) reflecting the low magnitude of occurred events. By contrast, a higher dynamicity of LW was found in the Blanco River also during ordinary events, with mobility rates ranging from 41 to 94% and LW storage increasing up to 179%, because of the considerable input volumes (highest input of 285.35 $m^3 \cdot ha^{-1}$). The complexity of LW dynamics in the Blanco River is also due to the presence of buried LW (1.65 $m^3 \cdot ha^{-1}$) that can be easily exhumed and, thus, increase the amount of in-transport LW. This volume was obtained as a first approach with the GPR that proved to be a valid and non-destructive method to bridge this gap. The results obtained in this study can be considered useful advances in understanding the three main LW-related processes (recruitment, mobilization, deposition), knowledge of which is essential in order to ensure the positive contributions of wood to river ecosystems, and minimize potential hazards adopting correct management plans.

Riassunto

Titolo tesi: Valutazione del bilancio di legname in due diversi fiumi situati in ambiente alpino e andino

In bacini fluviali boschivi, il materiale legnoso è considerato un elemento chiave responsabile dell'aspetto geomorfologico ed ecologico dei sistemi fluviali ma, allo stesso tempo, anche un elemento di pericolo per alcune strutture sensibili. A causa di questo duplice ruolo, l'analisi e la quantificazione del legname nei corsi d'acqua, così come la comprensione dei processi di mobilizzazione e deposizione, sono step cruciali per assicurare una corretta gestione delle zone fluviali. Questo studio valuta il bilancio del materiale legnoso in due corsi d'acqua, al fine di incrementare le conoscenze riguardanti i principali processi in cui il legname è coinvolto, come il reclutamento laterale dovuto ad erosione spondale, il trasporto fluviale e la presenza di legname sepolto. Lo studio è stato condotto in due diversi ambienti fluviali. Un tratto fluviale di 3.7 km è stato selezionato lungo il corso mediano del fiume Piave (Italia), un fiume antropizzato a fondo ghiaioso con morfologie principali wandering e a canali intrecciati con presenza di isole fluviali. Inoltre, tre tratti fluviali con lunghezza di 80 m sono stati selezionati lungo il corso finale del fiume Blanco (Cile), un fiume naturale che ha subìto un drastico cambiamento nella morfologia a causa di una recente eruzione vulcanica. Le tre componenti del budget che sono state considerate, sono state analizzate attraverso attività di campo condotte durante i tre anni di dottorato. Il reclutamento laterale è stato analizzato solamente nel fiume Piave a seguito di una piena superiore alla bankfull (TR~7anni) misurando, geo riferendo ed identificando tutti gli alberi ($D \geq 0.1$m) posizionati all'interno di un buffer di 20 m di larghezza lungo le sponde della floodplain e lungo il perimetro delle isole. Una metodologia simile è stata applicata per analizzare, in entrambi i fiumi, il trasporto fluviale del legname considerando tutti gli elementi legnosi ($D \geq 0.1$m e $L \geq 1$m) presenti all'interno dell'alveo. In questo modo, durante i rilievi post-evento è stato possibile identificare gli elementi di input (deposizione) e quelli di output (mobilizzazione). Dal momento che i sedimenti vulcanici causarono la sepoltura di numerosi alberi e materiale legnoso, la presenza di legname sepolto è stata analizzata solamente nel fiume Blanco, testando l'efficacia di un georadar. Il bilancio del legname è stato analizzato, nel caso del fiume Piave, per piene ordinarie ($TR<1$anno), mentre per il fiume Blanco sono state considerate sia piene ordinarie (TR~1anno) che non ordinarie (TR 10-25anni). I risultati hanno evidenziato come, nel fiume Piave, il reclutamento per erosione spondale sia un processo importante per la fornitura del legname in alveo. I volumi di legname reclutato variano a seconda dell'estensione delle superfici erose, della tipologia di unità morfologica erosa e a seconda delle caratteristiche della vegetazione ripariale. Durante piene non ordinarie (TR~7anni) sono stati reclutati volumi maggiori (25.1 $m^3 \cdot km^{-1}$) per erosione della floodplain e delle isole fluviali, mentre

durante piene ordinarie (TR<1anno) il reclutamento di legname (0.21 $m^3 \cdot km^{-1}$) è avvenuto solo per erosione della floodplain. Inoltre, la magnitudo degli eventi di piena è risultata essere un fattore importante per il controllo delle fluttuazioni temporali dello storage di legname causando una riduzione ed un aumento della quantità di legname in alveo a seguito, rispettivamente, di piene ordinarie e non ordinarie. Per piene non ordinarie, l'aumento dell'area bagnata determina una maggiore inondazione delle barre fluviali e questo permette, allo stesso tempo, la mobilizzazione e deposizione del legname. Oltre alla magnitudo delle piene, un altro fattore responsabile delle variazioni del legname in alveo è riconducibile alla diversa morfologia locale dei tratti analizzati. Maggiori variazioni sono state riscontrate in corrispondenza di morfologie a canali multipli, dove, rispetto alle morfologie a canali singoli, il rapido e maggiore aumento dell'area bagnata aumenta la quantità di legname potenzialmente trasportabile. In particolare, il budget del legname nel fiume Piave si caratterizza per variazioni quasi trascurabili (-9.7%) ed un tasso di mobilità molto basso (1.43%) che rispecchiano la bassa magnitudo degli eventi verificatisi. Diversamente, il fiume Blanco presenta una maggiore dinamicità del legname anche durante eventi di piena ordinari, con tassi di mobilità variabili tra 41 e 94% ed un aumento nello storage di legname fino al 179% dovuto ai notevoli volumi di input (volumi massimi 285.35 $m^3 \cdot ha^{-1}$). La complessità delle dinamiche del legname del fiume Blanco è avvalorata anche dalla presenza di legname sepolto (1.65 $m^3 \cdot ha^{-1}$) che può essere facilmente riesumato ed aumentare la quantità di legname in transito. Tale analisi ha permesso di dimostrare l'utilità del georadar come un metodo valido e non distruttivo che potrebbe essere utilizzato per colmare questa lacuna inerente il legname sepolto. I risultati ottenuti in questo studio possono essere considerati come dei progressi utili per la comprensione dei tre principali processi legati al legname (reclutamento, mobilizzazione, deposizione) le cui conoscenze sono essenziali al fine di mantenere i benefici del legname per il sistema fluviale e minimizzare i potenziali rischi attraverso l'adozione di corretti piani di gestione.

Section One - Background

1.1. Large wood in river systems, definition, types and sizes

The term Large Wood (LW) is used to define woody elements of specific sizes, dead or alive, within a fluvial system, both in the active channel and on the floodplain (Gurnell, 2003; Piégay, 2003; Wohl, 2013). Until the 2000s, the term most commonly used to define this type of wood was Large Woody Debris (LWD) (Gippel, 1995; Abbe and Montgomery, 1996; Piégay et al., 1999). However, during the First International Conference on Wood in World Rivers, which took place in Oregon in 2000, many researchers suggested changing this term to Large Wood (LW), as the word "debris" was recognized to convey a negative connotation to the presence of in-channel wood. In particular, there was a tendency to underestimate all its ecological benefits.

Concerning the minimum wood sizes to be defined LW, the threshold often tends to vary according to the aspects considered (Seo et al., 2010). For example, Comiti et al., (2006) used the thresholds of 0.05 m in diameter and 0.3 m in length to study the hydrological and geomorphological consequences of woody material in mountain basins of the Dolomites, while May and Gresswell (2003) analyzed the recruitment and distribution of LW taking into consideration only elements with diameter and length equal to or greater than 0.2 m and 2 m, respectively. Recently, the call for common metrics of Wohl et al., (2010) highlighted the importance of adopting standard thresholds in LW monitoring that allows comparison of LW processes between different river systems. Overall, the minimum sizes most used in scientific classification is 0.1 m in diameter and 1 m in length (Gurnell et al., 2000; Jackson and Sturm, 2002; Marcus et al., 2002; Warren et al., 2007; Wohl and Jaeger, 2009).

Large wood, as well as sediments and water fluxes, is a crucial component of fluvial systems in forested basins and is responsible for its geomorphological and ecological aspect. Provided by riparian vegetation, LW supports river biodiversity and the ecosystem functioning (Daniels, 2006; Beckman and Wohl, 2014; Pilotto et al., 2016), affects the geomorphic processes (Gregory and Davis, 1992; Buffington and Montgomery, 1999) and river morphology (Montgomery et al., 1995; Abbe and Montgomery, 1996; Rosenfeld and Huato, 2003). Effects of in-channel LW will be described in more detail in the following section.

Commonly, LW can be distinguished in four categories (Fig. 1):

- Trees, are elements having both branches and roots;
- Logs, called also trunks, are elements composed just of the structure of plants without branches (roots can also be present);
- Shrubs, are medium-sized woody plants with multiple stems and shorter height;
- Roots, are elements composed just of the rootwads of a tree or shrub.

An additional category of LW can be found in human impacted rivers, where with the presence of villages nearby and accessibility to the riverine area there is a constant harvest of LW by local residents. In these rivers, LW can also be found as a residue of harvesting.

Figure 1: example of four LW categories detectable in a river. Clockwise from upper left: tree, log, root, shrub.

Large wood is not stable within a fluvial environment, but is usually involved in downstream transport during flood events (Abbe and Montgomery, 1996; Braudrick and Grant, 2000; Abbe and Montgomery, 2003). Because of this movement, woody pieces can be found as single elements or as wood jams (WJ), where a WJ is usually defined by the presence of at least two logs deposited together (Comiti et al., 2006).

Single elements composing a WJ can be divided into three categories depending on their function within the jam: key, racked and loose elements. The first, also called primary elements, are pieces that for their size and deposition pattern are responsible for the jam formation; the second are elements that, although they are not the cause of jam formation, are strongly linked with key elements and increase the accumulation volume; and lastly loose elements are smaller ones that are usually trapped in the empty spaces of a jam and determine an increase of the volume and structural complexity (Abbe and Montgomery, 2003).

According to the origin of key elements and the degree of displacement after entering the channel, WJ can be further divided into (Abbe and Montgomery, 2003):

- In situ wood jams, are called also autochthonous jams because they are accumulations formed by elements that remain in the place where they have been introduced. They are commonly formed by logs and trees with branches and roots having a sufficient size and mass to resist the hydrodynamic forces of ordinary flood events. An example of this category is the bank input jam, an accumulation composed of trees fallen into the channel due to bank erosion, windthrow or mass movements;
- Transported wood jams, or allochthonous jams are formed by elements that have been moved along the water course and, during transportation, can have recruited additional woody material;
- Combined wood jams is an intermediate category between the two end-types.

1.2. Physical and biological effects of large wood

The presence of LW within fluvial systems can be positive or negative according to the analysis perspective (i.e. ecology *vs* hydraulic safety). Owing to its influences on the river geomorphology, it is defined as a structural element of the fluvial system (Keller and Swanson, 1979). In fact, it has physical and biological benefits affecting morphological, sedimentological and ecological processes. The physical benefits of LW result from its interactions with water and sediments (Wohl et al., 2016). The magnitude of these physical effects depends on orientation, stability and volume of wood in respect to the cross-sectional area of the channel (Klaar et al., 2011; Collins et al., 2012). Due to the particular deposition way with the trunk oriented downstream and the rootwad upstream, a scour commonly occurs upstream of the roots, with deposition of coarse and organic materials (Francis et al., 2008) (Fig. 2).

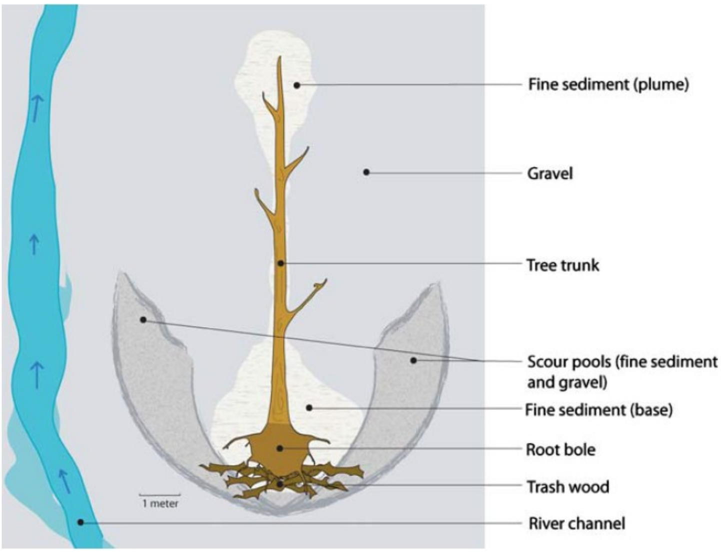


Figure 2: typical spatial patterning of a tree deposited along the Tagliamento River (Italy) (after Francis et al., 2008).

As reported by Wohl (2011), the channel width is an important variable for the spatial scale at which LW is able to produce effects. Isolated pieces in large rivers are more likely to create only local effects, whereas big jams that span a channel can have influences along an entire reach (Wohl, 2011). Large wood affects river morphology (Montgomery and Buffington, 1997), especially when it is jammed. In fact, WJ have the capacity to deflect flow and, in the case of big jams, create a multiple channel pattern (Harwood and Brown, 1993). The type and dimensions of bedforms within the river can also be affected by the presence of wood (Curran and Wohl, 2003), as well as location and dimension of pools (Robinson and Beschta, 1990; Rosenfeld and Huato, 2003) and cross-sectional channel geometry (Wallerstein and Thorne, 2004).

Woody material can also change sediment retention and transport (Mosley, 1981; Marston, 1982; Gregory and Davis, 1992), influence the processes of floodplain development (Wohl, 2013) and protect riverbanks from erosion by decreasing lateral shifts (Brookes, 1988). The interactions between wood and sediments vary depending on LW types and in-channel distribution and also according to river features such as morphology, slope and size (Montgomery et al., 1996). In mountain streams with high slopes, larger grain sizes and numerous sources for wood recruitment, the wood-sediments interactions are higher than in piedmont and lowland rivers. In fact, narrower sections can be critical points for LW, where it usually becomes trapped and tends to obstruct the flow. In mountain torrents LW deposits act as “trapping structures”, intercepting other floating material, both sediments and wood pieces and this can lead, in time, to the formation of fluvial bars and wood jams (Montgomery et al., 1996). Large wood can intercept up to 50% of total sediment transport (Keller and Tally, 1979; Megahan, 1982). Moreover, obstructions can substantially increase the frictional resistance to flow (Curran and Wohl, 2003; Mutz, 2003) and reduce flow velocity (Daniels and Rhoads, 2004; Davidson and Eaton, 2013), that in turn can promote deposition and storage of sediments and organic material around wood (Faustini and Jones, 2003; Beckman and Wohl, 2014). In correspondence to obstructions that span the entire channel width, backwater areas commonly occur upstream with lower velocity and higher water depth (Brummer et al., 2006).

Biological effects are strongly linked to physical ones (Wohl et al., 2016). The ecological benefits of in-channel LW are important for a series of aquatic and terrestrial organisms (i.e. fishes, small mammals, birds, reptiles, amphibians, insects) that use wood for feeding or nesting sites (Harmon et al., 1986; Roni, 2003; Pilotto et al., 2016). The influences of LW on flow velocity and depth, erosion and deposition along the channel bed and banks and on grain size distribution enhance habitat heterogeneity, increasing habitat abundance and diversity (Chen et al., 2008). Pools, runs and riffle mesohabitats created by wood (Fausch et al., 2002) are environments needed by different biota to complete their life cycles. Wood jams that act as obstructions increase the storage of fine organic matter and nutrients (Anderson and Sedell, 1979; Daniels, 2006; Beckman and Wohl, 2014), which can be an essential food source for micro and macro invertebrate communities that extract nutrients from it (Bilby, 1981; Steel et al., 2003). In addition, the habitat complexity commonly created around wood jams (i.e. pools) (Fig. 3), provides suitable sites for organisms for feeding, resting and protection from predators, as well as for surviving during cold winter periods, low summer flows and high current velocities during floods (Sedell and Froggatt, 1984; Fausch, 1993; Nagayama et al., 2012). Increased habitats lead to greater biomass and biodiversity (Nagayama et al., 2012), for example an increase of about 50% in trout biomass has been found in Colorado mountain streams in correspondence to pools formed by LW (Gowan and Fausch, 1996).

Figure 3: wood jams deposited on the head of a pioneer island with an adjacent scour and pool. (Piave River, Italy.)

In addition to the above-described biological effects which occur in all fluvial systems having in-channel wood, the ecological importance of wood in rivers is more evident in large rivers confined by riparian vegetation and with active erosion processes (Gurnell et al., 2005; Picco et al., 2015b). Studies conducted in large gravel-bed braided rivers, such as Tagliamento River in the North East of Italy and Queets River in the U.S.A., have led to the development of a conceptual model for islands formation downstream from an initial deposited wood (Abbe and Montgomery, 1996; Abbe and Montgomery, 2003; Gurnell et al., 2005) (Fig. 4). The authors highlighted that the presence of vegetation and deposited wood capable of regrowth, such as Salicaceae spp. (Karrenberg et al., 2002), strongly accelerates the process of fluvial islands formation and this allows the development of different linked habitat types.

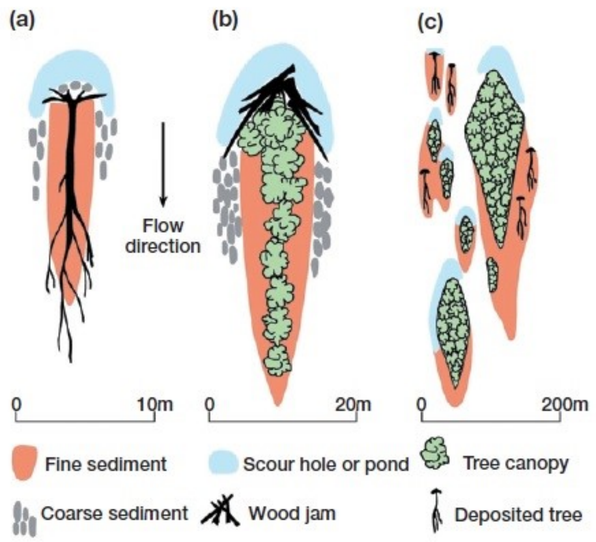


Figure 4: conceptual model for fluvial island development starting from a single piece of deposited living wood (after Gurnell et al., 2005).

1.3. Hydraulic hazards related to large wood

Despite the series of benefits, in-channel wood is well known to represent a problem to some anthropic structures and, in general, to human security. Large wood, and especially those pieces transported during major floods, can create hazards in river corridors due to its capacity to form dangerous obstructions along the channel network (Mazzorana et al., 2011; Comiti et al., 2016), disrupt navigation on large rivers (Gurnell et al., 2002; Piégay, 2003), damage human infrastructures (i.e. bridges or weirs) when it accumulates on or near them (Diehl, 1997; Comiti et al., 2008; Mao and Comiti, 2010; Rigon et al., 2012) and block culverts with overbank flooding hazards (Mazzorana et al., 2009) (Fig. 5). Large wood can also cause hydraulic problems, as it commonly induces localized erosion, increases the roughness and increases the peaks of floods (Abbe and Montgomery, 1996). Wood can also be a problem for recreational users in those reaches where in-stream (i.e. kayaking) and floodplain (i.e. trekking) activities usually take place (Wohl et al., 2016).

However, as happens with benefits, the magnitude of LW-related hazards depends on the volume storage in-channel and the tendency to be mobilized during high discharges (Wohl et al., 2016), which, in turn, depends on piece size relative to channel dimensions (Lienkaemper and Swanson, 1987; Braudrick and Grant, 2000). Moreover, the hazards associated to LW transport vary according to the size and construction type of bridges potentially blocking wood (Comiti et al., 2012).

Because of its potential dangerousness, several approaches have been proposed for hazard reduction. A series of risk assessment tools based on LW and infrastructure characteristics have been developed to predict hazards at individual human structures (Schmocker and Hager, 2011), while numerical models simulating wood recruitment and transport have been constructed in order to develop hazard maps along river corridors (Mazzorana et al., 2009, 2011, 2013; Ruiz-Villanueva et al., 2014a, 2014b, 2014c; Gschnitzer et al., 2015; Lucia et al., 2015).

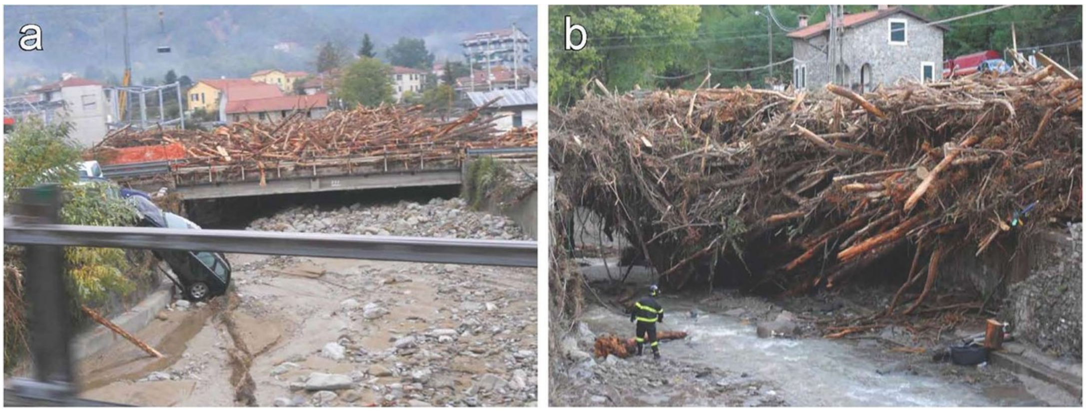


Figure 5: LW clogging in the Magra river catchment (Italy) after the 2011 flash flood (after Lucia et al., 2015).

1.4. Large wood modeling attempts

In the light of what described up to now, the interest of researchers in the study of wood material led to the development of some numerical models to simulate LW dynamics, mainly concerning recruitment, transport and clogging processes. The development of these models is quite recent, but several advances have been made. For instance, a conceptual GIS-based model has been developed by Rigon et al. (2012) predicting LW recruitment at a basin scale from hillslope instabilities, whereas Mazzorana et al. (2011) simulated wood transport through the design of a 2-D model using computational fluid dynamics (CFD). A more complex model was proposed by Ruiz-Villanueva et al. (2014a) in which wood transport is simulated coupling together with hydrodynamic conditions, taking account also interactions between logs and the channel configuration and among logs themselves. Since the complexity of LW dynamics, they are difficult to reproduce with only single models. So probably, one of the future step in LW modeling is the development of quantitative models able to couple both in-channel and riparian processes, linking fluvial morphodynamics with riparian vegetation (Camporeale et al., 2013). Although field data are usually used to validate and interpret model's results providing good correspondence between simulations and reality, these models are usually developed adopting a series of simplifications. Commonly, models consider LW only as cylinders without roots and crown, and ignoring variations in shape. Another simplification is represented by the adopted steady flow conditions when simulating different floods, without considering the effects of fluid dynamics and sediment transport. These simplifications might generate uncertainties in the model's results, especially for multiple thread channels and for extreme floods, during which geomorphic changes are expected to occur (Ruiz-Villanueva et al., 2015). Therefore, to allow the application of a model in real rivers it is important that all the aspects inherent to LW dynamics are taking account, and this can be achieved increasing the empirical or field information from which models can be developed.

1.5. Principles of large wood budget

Because of its hydraulic, geomorphic and ecological effects, the presence of wood in rivers has become an important topic for the management of forest basins, environmental assessments and for the ecological restoration of rivers and streams.

There are several studies in the literature concerning LW dynamics, however, for the most part, they are empirical studies, or strongly dependent on the spatial and temporal scale adopted. The need to understand spatial and temporal variables on the abundance and distribution of LW has motivated several studies analyzing the dynamics of wood in terms of budget. Although previous researches on full or partial budget had been conducted since the 1980s (Keller and Swanson, 1979; Likens and Bilby, 1982; Murphy and Kosky, 1989), the term "budget" associated to LW studies was adopted for the first time by Martin and Benda (2001). They proposed a volumetric quantitative framework (Eq. 1), similar to the well-established approach of sediment budgeting (Reid and Dunne, 1996, 2003), for evaluating wood abundance and distribution as a consequence of input, in-stream and output processes (Fig. 6a).

The proposed equation is the following:

$$\Delta S = [I\Delta x - O\Delta x + (Q_i - Q_0) - D]\Delta t \qquad \text{(Eq. 1)}$$

where:

- ΔS is the change in wood storage
- I is the lateral input (or recruitment)
- O is the lateral output over the floodplain
- Q_i, Q_0 is the fluvial transport into and out of the river segment
- D is the decay of wood

The term ΔS is usually expressed as volume of wood per surface area of the channel ($m^3 \cdot ha^{-1}$) or per length of channel ($m^3 \cdot m^{-1}$, $m^3 \cdot km^{-1}$). The terms Δx and Δt represent the length of study reach (x) and the time (t) of study period. Commonly, the length of segment should extend for at least several times average bankfull width but typically lies within the range of 10^1-10^3 m, whereas the time period should be in the order of at least one year (Wohl, 2016). Lateral input (I) and output (O) are expressed as volume of wood per channel length and time ($m^3 \cdot m^{-1} \cdot yr^{-1}$) and the remaining terms (Q_i, Q_0, D) are expressed as volume per unit of time ($m^3 \cdot yr^{-1}$).

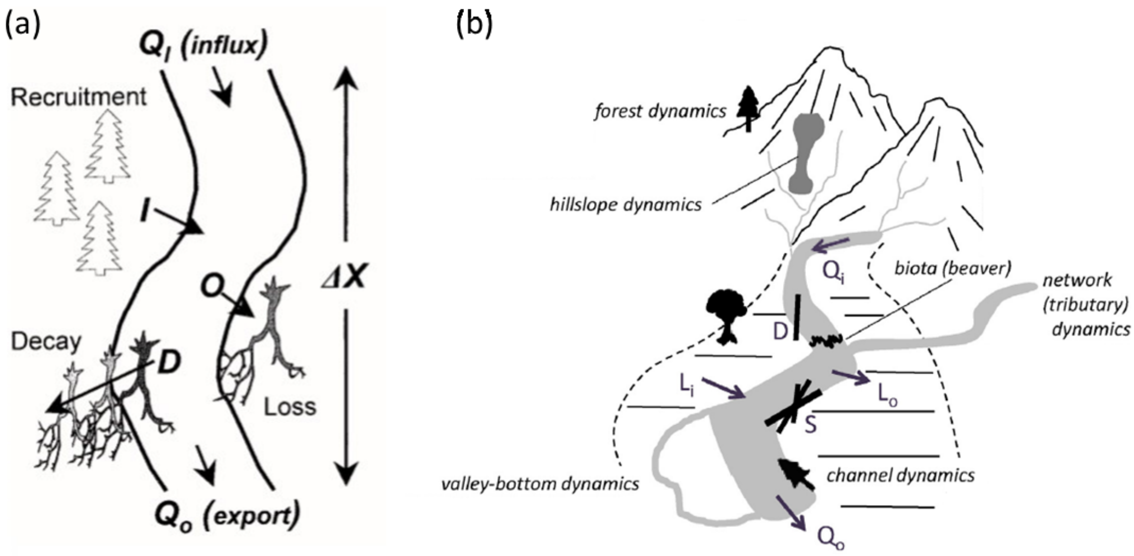


Figure 6: (a) variables used in the equation of LW budget (after Martin and Benda, 2001); (b) physical and biotic factors influencing variables in a wood budget (after Wohl, 2016).

The budget variables are influenced by several physical (forest, hillslope, network, valley-bottom and channel dynamics) and biotic (beavers and vegetation) factors (Wohl., 2016) (Fig. 6b). Forest dynamics able to induce variations in LW budget are related to the characteristics of riparian vegetation such as density, age, size, species composition and mortality (Latterall and Naiman, 2007; Wohl and Goode, 2008; Kasprak et al., 2012; Welber et al., 2013; Beckman and Wohl, 2014; Costigan et al., 2015). Hillslope dynamics refer to mass wasting events that can introduce wood locally into channels such as debris flows, snow avalanches, landslides (these processes are described in more detail in sections 1.4.1.3). Network dynamics refer to the wood budget contribution from tributaries while valley-bottom dynamics include interactions between channel and floodplain areas and between main and secondary channels (Wohl et al., 2011). Channel dynamics (described in the following sections) include the transport of LW, bank erosion process and water fluxes while the last factor important for budget refers to the biotic component of the river system. Biota include living riparian vegetation that can alter hydraulic forces and transport or deposition of woody pieces (Johnson et al., 2000; Mikus et al., 2013), and the activity of animals, notably beavers, that can retain and stabilize LW locally (John and Klein, 2004; Polvi and Wohl, 2013; Picco et al., 2015b).

1.5.1. Lateral recruitment of large wood

The variable I of Eq. 1 can be further split into five different terms (Eq. 2) resulting from several types of supply related to hillslope events, in-channel processes and natural events (Martin and Benda, 2001; Benda and Sias, 2003; Benda et al., 2003):

$$I = I_m + I_f + I_{be} + I_{ms} + I_e \qquad \text{(Eq. 2)}$$

where:

- I_m is the input from natural tree mortality
- I_f is the input from catastrophic events
- I_{be} is the input from bank erosion
- I_{ms} is the input from mass wasting events and hillslope instability
- I_e is the input from exhumation of buried wood via floodplain and bars erosion

Recruitment processes tend to vary along the channel network according to the interactions between hillslope processes and floodplain dynamics (Reeves et al., 2003; Seo and Nakamura, 2009). In mountain basins with steeper slopes, LW is recruited mainly from natural mortality and mass wasting events (Keller and Swanson, 1979; Swanson et al., 1998; Rigon et al., 2008). With increase of the active channel the amount of LW recruited from the adjacent floodplain increases and the portion recruited from slopes decreases (Nakamura and Kikuchi, 1996; Seo et al., 2008) (Fig. 7). Consequently, LW in a medium to large river basin is mainly supplied from bank erosion, which represents one of the main recruitment processes in large low-gradient rivers (Moulin et al., 2011). An example has been reported by Moulin et al., (2011) for the wandering Roanoke River (U.S.A.) where 73% of all woody pieces stored in-channel derive from lateral erosion.

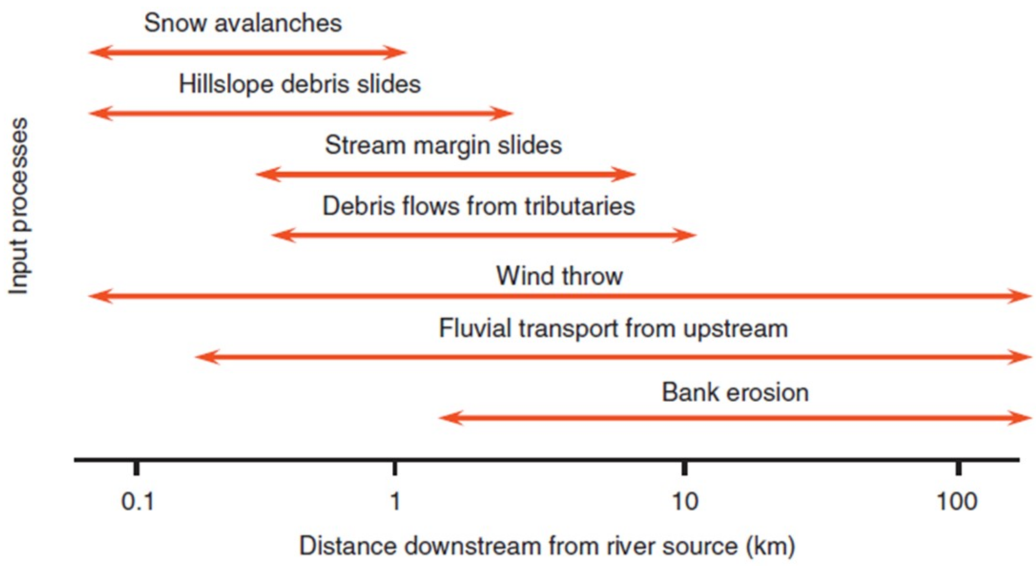


Figure 7: variations in wood input processes according the distance from river source (modified from Gurnell., 2013).

1.5.1.1. Forest mortality

Natural tree mortality (I_m) has been widely explored in the forest ecology literature (Mast and Veblen, 1994; Lester et al., 2003; Van Mantgem et al., 2009). According to Benda et al. (2003) the forest mortality rates depend on stand age, tree species, climate and topography. Tree mortality is commonly estimated on long-term spatial scales (up to several decades) using information on volume and sizes of standing trees (Benda et al., 2003).

1.5.1.2. Catastrophic natural events

Other recruitment processes are related to catastrophic natural events such as windstorms (Bahuguna et al., 2010), forest fires (Harmon et al., 1986; Agee, 1993; Benda and Sias, 2003), volcanic eruptions (Lisle, 1995; Nakamura and Swanson, 2003; Iroumé et al., 2012; Ulloa et al., 2015a,b), ice storms (Kraft et al., 2002), pathogens and other diseases (Costigan et al., 2015).
Toppling of trees by windstorms varies depending on topographic position, wind direction, soil moisture and the type of forest species (May and Gresswell, 2003; Nakamura and Swanson, 2003). It can be a dominant mechanism of LW recruitment that can occur over decades or be concentrated during single catastrophic events, such as tornadoes (Peterson, 2007), hurricanes or cyclones

(Hilton et al., 2008; Philips and Park, 2009) that can induce formation of wood rafts and jams by introducing huge quantities of LW almost instantaneously (Wohl, 2016).

The importance of forest fires in the recruitment of wood depends on the frequency, extent and severity of fires, as well as other variables that change according to climatic gradients (Harmon et al., 1986; Benda and Sias, 2003). However, the effect of fires on wood input are usually concentrated only in a period of years to decades (Bendix and Cowell, 2010; King et al., 2013), because a period of recruitment decrease then occurs as trees regrow (Jones and Daniels, 2008; Wohl, 2011). The fall of trees is not directly caused by fires because, in most cases, fires affect just the epigean part of trees leaving the trunk and roots still alive (Agee, 1993). For this reason, trees that do not die during the passage of fire become weaker and therefore more easily attacked by insects and/or pathogens, facilitating death and a fall into the river bed (Agee and Huff, 1987).

In volcanically active regions, volcanic eruptions may represent an important process of LW supply. As highlighted by Lisle (1995) and Ulloa et al. (2015a), eruptions severely increase the recruitment and abundance of in-channel wood. Pyroclastic density currents (PDCs) produced during an eruption usually damage standing vegetation, which can be partially or totally killed (Major et al., 2013; Swanson et al., 2013). As for forest fires, also in this case damaged trees are weak and more likely to be recruited, increasing input rates.

1.5.1.3. Bank erosion and mass wasting events

Bank erosion, usually occurring during floods, causes a punctuated supply of LW to channels (Keller and Swanson, 1979; Murphy and Koski, 1989; Benda and Sias, 2003) (Fig. 8). It is a process that tends to increase downstream (Hooke, 1980), even if its dynamics are not uniform along the channel network. In mountainous regions subject to hillslope instability, bank erosion can recruit at least a third to half of the LW (Benda and Bigelow, 2014), whereas it can be the dominant source of LW recruitment in piedmont rivers where flow energy remains high and banks are susceptible to erosion (Latterell and Naiman, 2007; Lassettre et al., 2008; Moulin et al., 2011; Boivin et al., 2015). With increase of drainage area, recruitment of LW increases because of associated decreased particle size of bank sediment and greater lateral channel mobility (Hooke, 1980; Martin and Benda, 2001; O'Connor et al., 2003).

Erosion rates also depend on the magnitude and frequency of floods (Golladay et al., 2007; Picco et al., 2016b). Large floods can erode considerable areas of floodplain with the subsequent recruitment of a considerable volume of wood (Bertoldi et al., 2013; Picco et al., 2016b). Characteristics of riparian vegetation and erodibility of riverbanks also influence rates of wood recruitment (Benda and Sias, 2003). The resistance of banks to erosion depends, in turn, on the particle size of bank material and the presence of tree roots able to reinforce the soil (Hooke, 1980). However, also the river morphology also plays an important role in the supply of LW via bank erosion. For example, a study conducted on French rivers showed that wandering rivers have higher erosion (0.24 ha·yr^{-1}·km^{-1}) and recruitment (39 ton·yr^{-1}·km^{-1}) rates than braided rivers where erosion occurs at a mean rate of 0.15 ha·yr^{-1}·km^{-1} and gives rise to LW supply of about 12 ton·yr^{-1}·km^{-1} (Piégay, 2003).

To estimate wood recruitment from bank erosion knowledge on stand density and size and bank erosion rates is usually essential. Bank erosion rates can be predicted using numerical models (Simon et al., 2000; Lai et al., 2015) or calculated using remote imagery (Kasprak et al., 2012; Picco et al., 2016b), whereas riparian forest information can be collected through field measurements (Picco et al., 2016b) or remotely sensed surveys (Bertoldi et al., 2013; Comiti et al., 2016).

Recruitment of LW from hillslope instability commonly occurs in mountain streams (Rigon et al., 2012). Mass wasting events can occur in the form of landslides, debris flows or snow avalanches that transport a considerable volume of LW almost instantaneously (Wohl, 2016). According to Benda and Sias (2003), the input of LW by mass wasting depends on the type and frequency of landslides (or debris flows, avalanches), the size of affected area, the age of recruited trees, the number of potential landslide sources intersecting the channel length and the fraction of recruited wood that is deposited within the channel. As for bank erosion, also for mass wasting events it is also possible to estimate the probability of slope failure using GIS software and combine this information with data on forest stand volume (Lancaster et al., 2001; Ruiz-Villanueva et al., 2014a).

Figure 8: views of trees recruited from bank erosion along the Piave River (Italy).

1.5.1.4. Exhumation of buried wood

The last process by which LW can influence the budget is the recruitment of buried and downed wood via floodplain and bars erosion. As highlighted by Wohl (2016), the importance of this recruitment process is more relevant in those environments where the floodplain stores significant amounts of wood and when it is subjected to frequent overbankfull floods and lateral channel erosion. These woody pieces can be thousands of years old and buried beneath floodplain and bars sediments (Howard et al., 1999; Latterell and Naiman, 2007; Guyette et al., 2008) or be on the actual floodplain and more recent in age (Wohl, 2016). Additionally, the importance of buried wood may be significant in specific environments such as fluvial systems affected by volcanic eruptions, where the river valley is commonly filled with volcanic material (Major et al., 2013; Pierson et al., 2013; Swanson et al., 2013) and wood pieces become buried under ashes.

Although in some cases this process can play an important role in LW recruitment, estimating the proportion of wood delivered from floodplain/bars erosion remains a challenge. Indeed, as recently pointed out by Wohl (2016), very little information on recruitment from buried wood is available because distinguishing between LW that has remained in the channel from LW that has been exhumed from the floodplain is very difficult and, moreover, there are few studies that have quantified the age of in-stream LW and identified old wood that is likely to have been buried.

For example, Brooks and Brierley (2002) estimated that wood composed 32%, by volume, of the bed sediments in the sand-bed Thurra River (Australia), whereas in a fire-prone forested river system in northern Quebec Arsenault et al. (2007) found that burial may have a greater importance in wood removal than decay.

Despite buried wood being rarely investigated and little knowledge being available, it can form an important component of the wood budget and have a widespread significance for the form and stability of forested rivers and floodplains (Gurnell, 2013) especially in migrating or incising reaches (Arsenault et al., 2007).

1.5.2. Fluvial transport of large wood

Transport of LW in a fluvial environment usually occurs downstream (Abbe and Montgomery, 1996) and can be divided, according to the way in which logs move, into three types: flotation, rolling or sliding. These types of transport vary depending on the relative density, expressed as the ratio between density of wood and water, and the relative submergence, expressed as the ratio between water depth and diameter of wood pieces. In low submergence conditions wood is mainly transported by dragging or rolling on the bottom, whereas for water depth greater than wood diameter and for wood density similar to water density, LW is mainly transported in suspension. Flotation of wood occurs when wood has a lower density than water and water depth is equal to or greater than wood diameter (Degetto, 2000).

Another classification of wood transport can be made according to the degree of interaction between pieces. Braudrick et al. (1997) identified three wood transport regimes:

- Uncongested: when logs move without piece-to piece interactions and occupy less than 10% of the channel area;
- Congested: when logs move together as a single mass and occupy more than 33% of the channel area;
- Semi-congested: is intermediate between the two end-regimes.

On the basis of flume experiments, they found that transport regimes are influenced by a dimensionless input rate, defined as the ratio between wood volume delivered to the channel (Q_{log}) and water discharge (Q_w). For uncongested transport this value is in the order of 0.015 and 0.20 for congested transport (Braudrick et al., 1997).

Factors controlling wood transport in rivers are primarily related to the properties of wood (sizes) and fluvial processes (Gurnell et al., 2002; Merten et al., 2010). Numerous studies have highlighted how the mobility of logs could be predicted adopting two dimensionless parameters: the ratio between wood length and channel bankfull width (LW_{length}/W_{bf}) and the ratio between wood diameter and water depth ($LW_{diameter}/W_{depth}$) (Lienkaemper and Swanson, 1987; Bilby and Ward, 1989; Gurnell et al., 2002; Warren and Kraft, 2008; Cadol and Wohl, 2010; Wohl, 2011; Iroumé et al., 2015; Ruiz-Villanueva et al., 2015).

According to the river width, LW appears to be more likely to move when the ratio between LW_{length}/W_{bf} is < 0.5 and < 1.0 for large and small rivers, respectively (Lienkaemper and Swanson, 1987; Abbe et al., 1993), whereas for the ratio $LW_{diameter}/W_{depth}$ a threshold value ranging from 0.6 and 1.0 was found (Mazzorana et al., 2009). In turn, the influence of wood properties on wood mobility also depends on the morphological configuration of the river, in multithread channels wood diameter appears to have the greater importance whereas in single-thread channels it seems to be wood length that exerts more control on wood transport (Ruiz-Villanueva et al., 2015). Wood diameter also plays a key role for LW deposition, when it is about half the water depth LW tends to stop its movement downstream (Abbe and Montgomery, 1996).

As wood mobility is controlled by the sizes of wood in respect to the size of the river channel, Gurnell et al. (2002) proposed a classification of rivers according their sizes:

- Small rivers: channels whose width is less than the majority of wood pieces length;
- Medium rivers: channels having widths greater than the length of most wood pieces;
- Large rivers: channels wider than the length of all the wood pieces delivered.

In small mountain rivers, where wood pieces are larger in respect to the channel width, LW is less mobile and tends to be deposited close to where it is delivered and retained on the river bed (Naiman et al., 1987; Piegay et al., 1999; Gurnell et al., 2002; Marcus et al., 2002) whereas in larger rivers the retention of wood is reduced by the increase of transport capacity (Bilby, 1985; Lienkaemper and Swanson, 1987; Bilby and Ward, 1989, 1991).

Others variables able to control the stability of LW were recognized as being wood density, state of decay, presence of branches and rootwads, degree of anchoring, orientation to the flow and sprouting capacity (Abbe and Montgomery, 1996; Braudrick and Grant, 2001; Bocchiola et al., 2006; Merten et al., 2010).

Because wood movement is affected by several variables, the dynamics governing transport, velocity and travel distance during floods are not easy to understand. However, several studies of wood movement in small (Jochner et al., 2015), medium (Ruiz-Villanueva et al., 2015a) and large (MacVicar and Piégay, 2012; Schenk et al., 2014; Ravazzolo et al., 2015a) rivers have found that the movement of LW occurs above a threshold discharge that can be expressed as a proportion of bankfull stage or a recurrence interval (R.I.) (Wohl, 2016). Moreover, as wood is commonly transported during floods, direct observations of LW in transport are very limited, so many studies investigate wood movement in an indirect way based on transport capacity and mobility rate using information on recruitment and variations in wood storage (Wohl, 2016). A series of innovative technologies have been implemented in large gravel bed rivers to study the dynamics of wood in transport. For example, a video camera installed in the wandering Ain River (France) has spotlighted that the higher rate of transported wood occurs during the rising limb of the hydrograph (MacVicar & Piegay, 2012); or the use of GPS tracker systems in the Tagliamento River (Italy) has pointed out that LW deposition mainly occurs at peak flow (Ravazzolo et al., 2015a).

1.5.3. Large wood decay

Large wood deposited within the active channel or on the floodplain can decay, which reduces its size, density and internal strength with a consequent alteration of the stability (Wohl, 2016).

The decomposition processes, induced by weathering and microorganisms activity, occur with different times and ways depending on fluvial system conditions, characteristics of wood and its residence times.

The oxygen content was found to be the main factor affecting the rate of LW decomposition (Harmon et al., 1986; Webster and Benfield, 1986; Bisson and Bilby, 1998; Hassan et al., 2005). The oxygen level, responsible for the biological activities of microorganisms, depends on the LW submergence conditions (Harmon et al., 1986; Keller and Swanson, 1979; Hyatt and Naiman, 2001). An increasing size of the active channel usually corresponds to an increase in the flow with a greater likelihood of LW submergence. Therefore, in the presence of submerged wood the decomposition rates are longer due to the prevalence of anaerobic conditions (Harmon et al., 1986; Keller and Swanson, 1979; Richardson et al., 2005). The rate of degradation for submerged wood is about 2-3% per year, depending on the forest cover type (Bilby et al., 1999). Similar anaerobic conditions occur when wood is buried by sediments, both in the channel and on the alluvial plain (Harmon et al., 1986; Abbe and Montgomery, 2003), with consequent longer decomposition time.

The rate of decomposition is also influenced by environmental conditions, mainly temperature and humidity. Significant and repeated changes in moisture conditions cause wood to contract and expand, resulting in cracks that facilitate the colonization of microorganisms (Harmon et al., 1986). The temperature affects the activity of microorganisms; for example, the optimum temperature for degradation by organisms belonging to *Fungi* (*L.*) is between 25 °C and 30 °C (Kaarik, 1974), so in lowland rivers with a higher air and water temperature, the biological activity of microorganisms can increase, as well as the rate of respiration of invertebrates (Harmon et al., 1986), influencing the LW decomposition speed. The loss of LW can also occur through physical fragmentation during fluvial transport or the fall of trees (i.e. bank erosion or mass movements). Also in this case, the breakup of LW by physical factors is strongly influenced not only by the species and stage of decomposition, but also by the energy of the current (Harmon et al., 1986) and by the presence of bedload sediment transport that contributes to the abrasive action (Warren et al., 2009).

Although there are still few studies concerning LW decay, the decomposition rates are, in general, 50 to 100 years for forests of dry climates (O'Connell, 1997; Ellis et al., 1999), 10 to 100 years in humid temperate climates (Boyce, 1961; Harmon, 1982) and < 10 years in the tropics (Lang and Knight, 1979; Delaney et al., 1998; Clark et al., 2002; Lewis et al., 2004).

1.6. Previous studies on large wood budget

The conceptual framework for constructing a wood budget proposed by Martin and Benda (2001) has been applied in different riverine environments adopting different methodologies and focusing on specific components. Table 1 summarizes the main studies on LW budget available to date (2016) in the literature.

Table 1: definition of piece sizes, analyzed components and river type in previous studies documenting LW budget.

LW sizes	Main components analyzed	River type	References
Channel width < 5m: D > 0.10 m L > 1.5 m Channel width > 5m: D > 0.10 m L ≥ 3 m	Transport, recruitment	Gravel-bed	Martin and Benda (2001)
D > 0.08 m L > 1.8 m	Recruitment	Gravel-bed	Benda et al., (2002)
D > 0.10 m L > 1 m	Transport	Gravel-bed	MacVicar and Piégay (2012)
D > 0.2 m	Transport	Sand-bed	Schenk et al., (2014)
D ≥ 0.10 m L ≥ 1.5 m	Recruitment	Gravel-bed	Benda and Bigelow (2014)
D > 0.10 m	Transport, recruitment	-	Lucía et al., (2015)
D ≥ 0.10 m	Transport, recruitment, decay	Gravel-bed	Hassan et al., (2016)

Among the first studies, Martin and Benda (2001) assessed the budget at a basin scale analyzing the spatial-temporal influences on the abundance and distribution of LW. They adopted different thresholds of piece sizes according to the active channel width. On the basis of field surveys they found bank erosion, natural mortality and mass wasting events to be the dominant processes in LW recruitment, and how they vary according the drainage area. For example, erosion rates tend to increase with the discharge area, from 1 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in a small river basin to 16 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in a drainage basin > 60 km^2. The transport of wood, analyzed on the basis of inter-jam spacing and mean transport distance, also varies with the basin sizes, increasing up to 50% in fluvial basins of 50 km^2. Innovative devices were used by MacVicar and Piégay (2012) in a wandering gravel-bed river (Ain River, France) in order to better understand the transport dynamics of LW during high floods and relationships with the discharge. By using a stream video camera, the authors detected 90% of pieces transported during floods, highlighting how higher transport rates occur in correspondence to the rising limb of the hydrograph. However, they pointed out that the resolution of images captured with the camera is a crucial factor for identification of in transport pieces. More specifically, woody pieces less than 0.2 m in diameter appeared to be difficult to identify.

Remote devices to analyze transport dynamics were also tested in Schenk et al., (2014), one of the most comprehensive studies on wood budget (Fig. 9). The combined use of Radio Frequency Identification Devices (RFID), metal tags and colored paints permitted the transport of LW and its variations with increasing floods to be quantified in a wandering sand-bed river (Low Roanoke River, North Carolina). The authors found that about 41% of deposited LW is mobilized again during floods with mean and maximum traveled distances of 11.9 $km \cdot yr^{-1}$ and 101.1 $km \cdot yr^{-1}$. The wood budget assessed by Schenk et al., (2014) highlighted that the annual turnover of LW is equal to 5% of stored LW with 16% involved in the internal displacement.

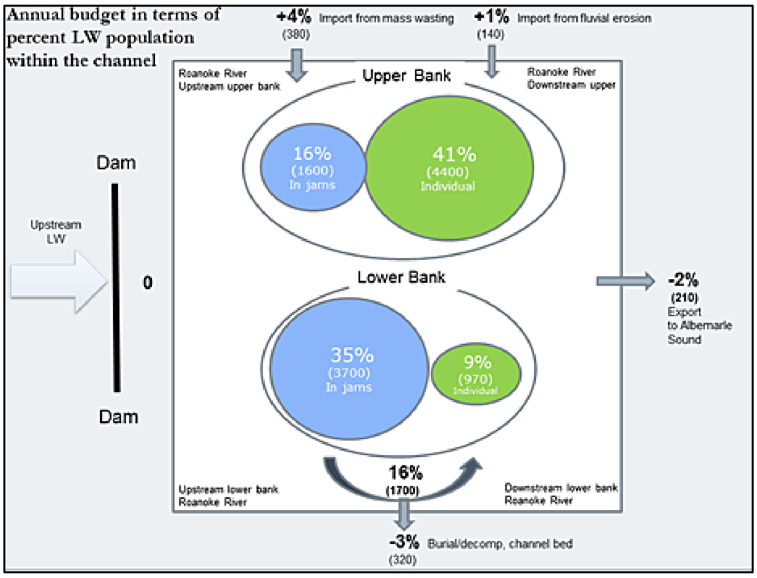


Figure 9: summary scheme of LW budget for the Lower Roanoke River, North Carolina (after Schenk et al., 2014).

According to the processes involved in the wood dynamics, there is a different importance in the evaluation of single items of the budget. For example, studies aimed to quantify the budget in mountain streams usually focused attention on lateral recruitment rather than fluvial transport. In this environment, in fact, the lower channel width and steep slopes lead to a greater importance of recruitment and deposition processes rather than transport processes (Rigon et al., 2012).

Among the main studies on LW recruitment, Benda et al., (2002) and Benda and Bigelow (2014) identified the variables that affect the lateral recruitment of LW. Differently from the river of piedmont areas where recruitment is mainly from bank erosion, in mountain streams having a drainage area < 50 km^2 LW delivery through natural mortality (50%), erosion (43%) and mass wasting events (7%) (Benda and Bigelow, 2014). Moreover, recruitment from natural mortality is influenced by the riparian vegetation characteristics; fluvial systems with old-growth forests have lower recruitment rates (2.5 $m^3 \cdot km^{-1} \cdot year^{-1}$) than systems with second-growth vegetation (4 $m^3 \cdot km^{-1} \cdot year^{-1}$) (Benda et al., 2002).

Among the recent developments on wood budget, a model was proposed by Hassan et al. (2016) to simulate a reach-scale budget for two mountain streams of British Columbia, analyzing the recruitment from mortality, mass movement and bank erosion and the output by decay, transport and depletion. Modeled over a century, the budget identified bank erosion and mass movement as the dominant LW input processes and fluvial transport to be an important component of budget, particularly downstream of reaches with wider channels. As recruitment is mainly governed by natural processes, LW storage showed fluctuations over time related to the magnitude of the LW input events and local rate of LW decay, with a time to equilibrium estimated in the range of 50-120 years (Hassan et al., 2016).

Section Two – Motivations and objectives

2.1. Main problem analysis: gaps in the large wood budget assessment

Differently from sediments dynamics, for which pioneer studies can be dated to the first half of the twentieth century (Shields A., 1936; Einstein H.A., 1937; Meyer-Peter and Muller, 1948), the presence of LW in rivers and its related effects became a research topic just over the last nearly 40-50 years (Keller and Swanson, 1979; Marston, 1982; Murphy and Koski, 1989).

Several studies, based on field data, numerical models or flume experiments, provided information on LW dynamics, especially exploring how LW abundance varies according to the river type (Wyzga and Zawiejska, 2005; Wyzga et al., 2015), how LW can enter into rivers (Moulin at al., 2011; Bertoldi et al., 2013; Picco et al., 2016b), how it decays (Murphy and Koski, 1989; Hyatt and Naiman, 2001), how it can be transported downstream (Ravazzolo et al., 2015a; Ruiz-Villanueva et al., 2015) and how it can influence channel geometry, sediments, water fluxes, organic matter and the ecological status of river (Piégay et al., 1999; Gurnell et al., 2002; Pilotto et al., 2016).

Nonetheless, some important gaps remain in specific LW processes that could help in the quantifying LW budgeting. Considering the ratio between LW sizes and channel width, the vast majority of LW studies were conducted on small-to medium sized rivers (Robison and Beschta, 1990; May and Gresswell, 2003; Mao et al., 2008; Wohl, 2011; Rigon et al., 2012), whereas wood dynamics in large rivers remain less understood. With respect to wood recruitment, we lack evidences on the amount of LW volume that could enter into rivers during bank erosion caused not only during large floods but also during low-ordinary events. Moreover, additional information on how the LW transport at a scale event can change the abundance of LW storage can be useful to better predict the fluctuations also over short-term period. Another significant knowledge gap is represented by the exhumation of buried LW. Floodplain erosion, as well as the remodeling of fluvial bars, have the capacity to recruit these woody elements and, in this way, can have important implications in the budget computation. However, because of the difficulties to detect and measure the buried LW, to date there are low studies dealing with this topic.

2.2. Objectives

On the base of knowledge gaps highlighted in the previous section, the main objective of this thesis consists in the assessment of large wood budget in two rivers located in a different environment and suffering different impacts. The first river (Piaver River, Italy) is an anthropic gravel bed river that was subject to intense human disturbances over time. A reach along its middle course was chosen because of the multiple thread morphology with fluvial bars allowing deposition of LW and because it is easily accessible to be monitored through time by repeated surveys. The second one (Blanco River, Chile) is a natural river recently impacted by a volcanic eruption that completely changed its morphology. Because of the rarity of this disturbance and the presence of LW data already available, it was selected as a second study area in which analyze the dynamics of LW in a naturally altered system.
The attention will be focused on three main items of the budget: the lateral recruitment from riverbank erosion, the fluvial transport of LW and the exhumation of buried wood.

Specific objectives of this study are the following:

- Evaluate the amount of LW potentially available from riparian areas (i.e. floodplain and fluvial islands) and the recruitment rates for an over bankfull flood;
- Expand knowledge on the temporal variations in the abundance of in-channel large wood due to fluvial transport during ordinary and not-ordinary floods, considering mobility and retention rates;
- Identify which may be the main factors controlling large wood mobilization and deposition;
- Propose a method to analyze the presence and calculate the volume of LW buried in volcanic sediments.

Section Three – Study areas and methodology

3.1. Study areas

The research was conducted in two study areas, the Italian Piave River and the Chilean Blanco River. The following sections summarize the geomorphic and hydrologic features of the rivers, and characteristics of the study reaches.

3.1.1. The Piave River

3.1.1.1. General settings of the basin

The Piave River rises from Peralba Mount in the Dolomites, at an altitude of 2037 m a.s.l.. Flowing south through the provinces of Belluno, Treviso and Venice, the river has a length of 220 km until its mouth into the Adriatic Sea, near the Venice lagoon (Fig. 10).

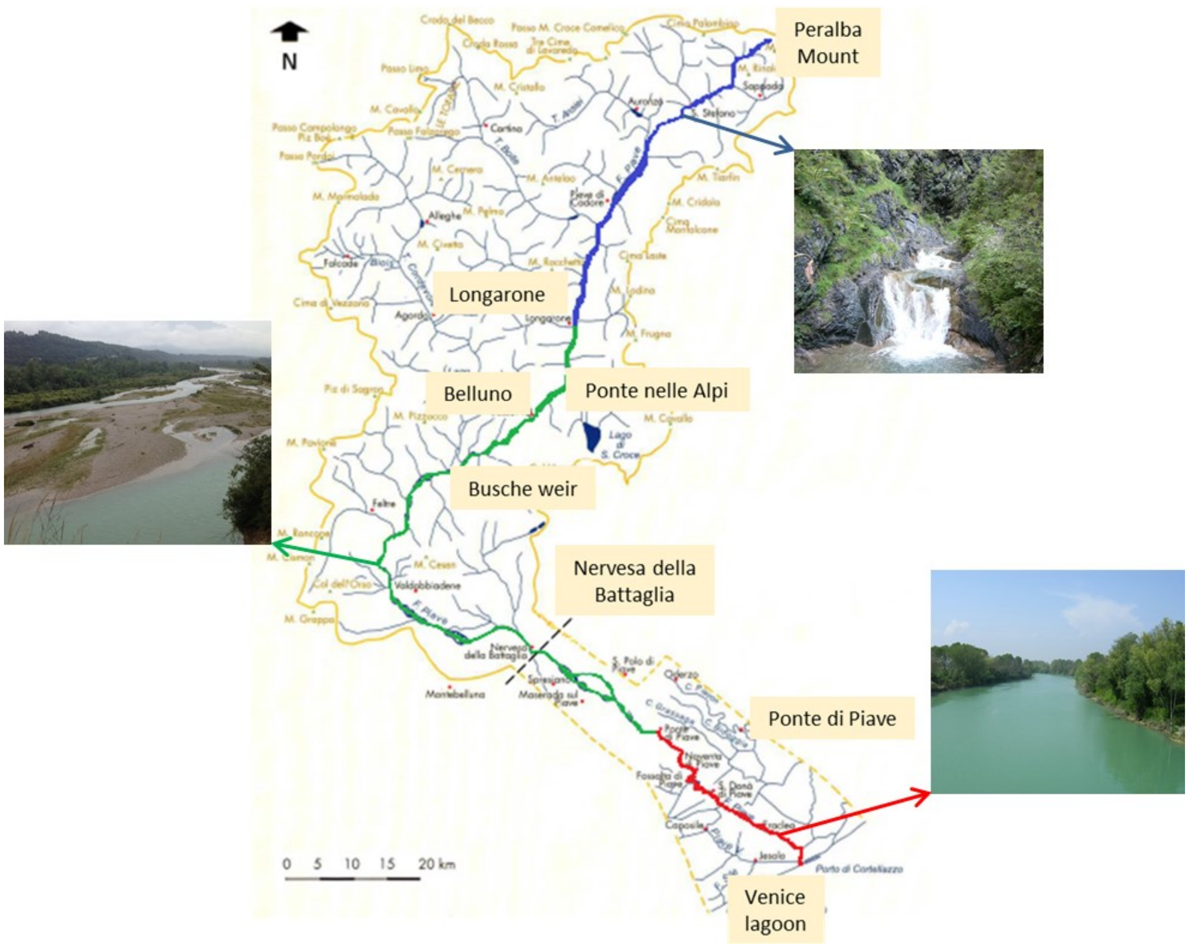


Figure 10: drainage basin of the Piave River with the three main reaches highlighted, upstream (blue), intermediate (green) and downstream (red) one. The black dashed line indicates the division between the mountainous and lowland part (modified from Bondesan, 2000).

The river basin covers an area of 3899 km^2 and is mainly composed of sedimentary rocks (i.e. limestone, dolomite) (Surian, 1996). From a geomorphological point of view, the basin is divided in two main parts, the mountainous and lowland parts (Fig. 10). The first one extends from the source to Nervesa della Battaglia (Treviso Province) and features a drainage system with several contributing streams (Da Canal, 2006), whereas the lowland part, which extends until the mouth, is characterized by only few resurgent channels along the final stretch.

The Piave River has five main tributaries in the mountain part of the basin (Belluno Province): the Cordevole River draining water from the western area, the Boite River located near Perarolo di Cadore, the Maè River near Longarone, the Ansiei River placed near Auronzo di Cadore and lastly the Sonna River that rises near the town of Feltre. Table 2 summarizes the main characteristics of these tributaries.

Table 2: characteristics of the main tributaries of the Piave River.

	Bank side	Basin area (km^2)	Basin area (%)*	River length (km)
Ansiei	right	240.7	6.7	37.3
Boite	right	395.9	11.2	45.0
Maè	right	232.0	6.7	33.4
Cordevole	right	866.8	24.0	78.9
Sonna	right	136.9	3.8	7.5

*percentage of the tributary basin with respect to the whole basin of the Piave River basin.

The river features a complex morphology reflecting the variety of downstream geographical areas, i.e. mountain areas, foothills, lowland areas and coastal areas. A morphological classification (Surian, 1999) divides the main river channel into three reaches, the first from the headwater to Longarone (Belluno Province), the second from Longarone to Ponte di Piave (Belluno and Treviso provinces) and the third from Ponte di Piave to the mouth (Venice Province) (Fig. 10).

Within the first reach (~70 km), the Piave River features the typical characteristics of a mountain torrent with steep gradients and confined narrowed bedrock. The river widens from a few meters at the source to 400 m at the end of the first reach. The bed slope also varies downstream, from higher values of 8.8% along the first 7 km to 1% and 3.2% in the following reach until Perarolo, and lower values of 0.5% and 0.6% at the end of the stretch near Longarone (Vollo, 1942). As regards grain size, the upstream part of the reach features a high concentration of blocks, boulders and gravel, whereas in the downstream part the bed sediments are mainly composed of gravel.

Along the second reach (~110 km), the river valley widens from a few hundred meters to 2-3 km (maximum values are found on the plain of Ciano del Montello and Papadopoli, Treviso Province) and it is characterized by a well-established alluvial plain. Here, the river has high energy and shows a multithreaded channel pattern with braided and wandering morphologies. As typified by these morphologies, the river is formed by channels, bars and islands that are unstable and tend to be constantly reformed and modified due to the high erosion and transport capacity (Fig. 11). The bed gradient, between 0.7% and 0.2%, remains constant along the whole stretch as does grain size, which is quite homogeneous and has a mean diameter of between 20 and 50 mm (Surian, 1998).

Figure 11: aerial view of the Piave River upstream of the Vidor bridge (Treviso province).

Finally, in the third reach (~ 40 km), the Piave River flows on a sand-bed featuring a meandering morphology of high sinuosity alternating with straight stretches confined by artificial embankments. River width and slope decrease significantly (0.1‰ at the mouth) causing a gradual decrease in flow velocity.

The entire Piave River basin lies in a humid and temperate-continental zone. The least rainy period corresponds to the winter season, whereas the rainiest ones usually occur during spring and autumn. According to the orography, slopes, elevation and proximity to the sea, the rainfall in the basin is subject to marked differences from place to place. Considering a 60-years period (1928-1987), the average annual rainfall on the whole basin is 1350 mm. However, areas with different amounts of rainfall can be identified. Mean annual precipitation ranges from about 1000 mm in the north-west part of the basin (high valley of Pettorina Stream) to 1500-2000 mm in the east-central area (Cansiglio Plateau, Alpago valley, Vajont basin).

3.1.1.2. The study reach

The analyses were conducted in a 3.7 km-long study reach located in the intermediate course of the Piave River, between the village of Ponte nelle Alpi and Belluno (Fig. 12). The study reach features a morphology that alternates wandering and braided patterns with the presence of some pioneer and building islands (Picco et al., 2014). With a present (measured in 2016) minimum, maximum and mean active channel width of 138 m, 512 m and 320 m respectively, the total study reach area is about 97 ha. The actual braiding index is equal to 1.87 and the majority of the study reach features only two channels, except in the downstream part where the number of channels rises to 6 (Fig. 13). The average gradient is 0.0033 $m \cdot m^{-1}$ (Picco et al., 2016a) and the mean grain size is 31.15 mm (Rainato et al., 2015). Table 3 summarizes the main characteristics of the study reach.

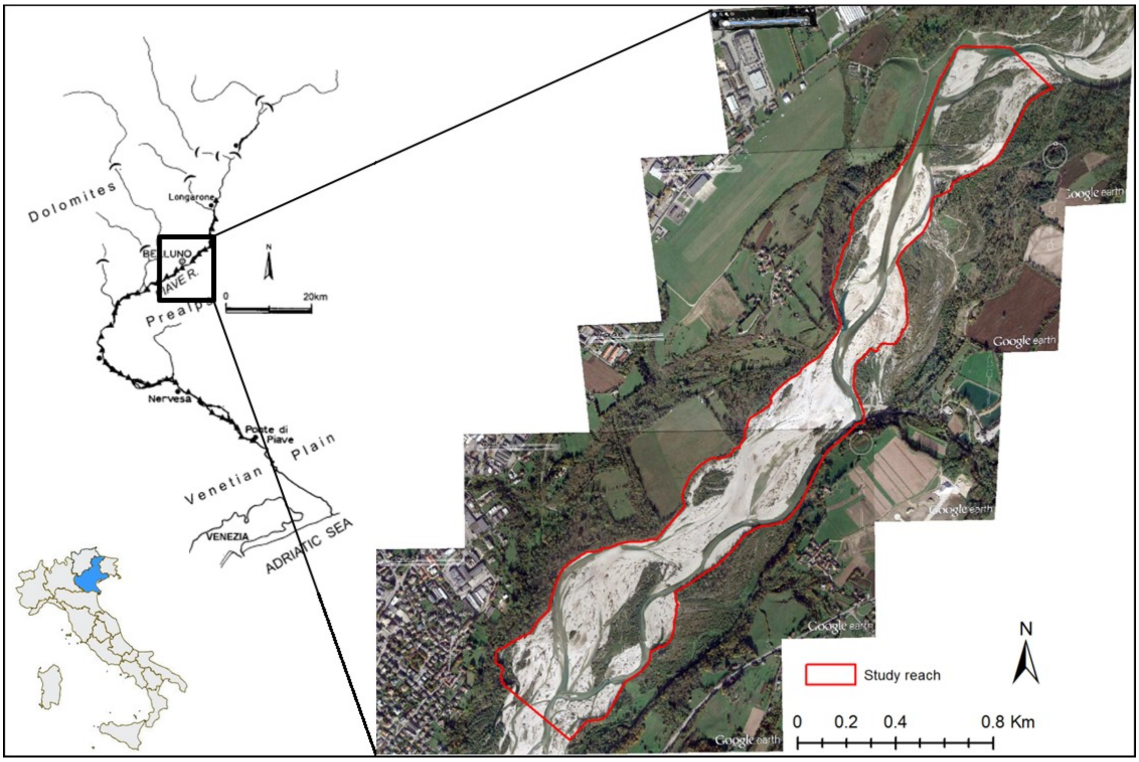


Figure 12: location of the Belluno reach and view of the study reach (aerial photos of 2016 from Google Earth).

Table 3: main characteristics of the Piave River study reach.

	Study reach
River length (km)	3.7
Range and (mean) active channel width (m)	138-512 (320)
Area (ha)	97
Braiding index	1.87
Mean slope ($m \cdot m^{-1}$)	0.0033
Mean grain size (mm)	31.15

The study reach is characterized by high human impact. Indeed, the active channel is affected by the presence of groynes and bank protections on both riverbanks, covering almost a third of the total reach length, and gravel mining started again during the past year. On 1951 a dam was constructed 7 km upstream of the reach, blocking the input of LW and sediments from the upstream river course. In this way, the selected study reach represents a good opportunity to study the local delivery of LW. Differently from the right bank where there is a wide, mature vegetated area, along the left bank the active channel is in proximity to a high, post-glacial terrace (Picco et al., 2016a).

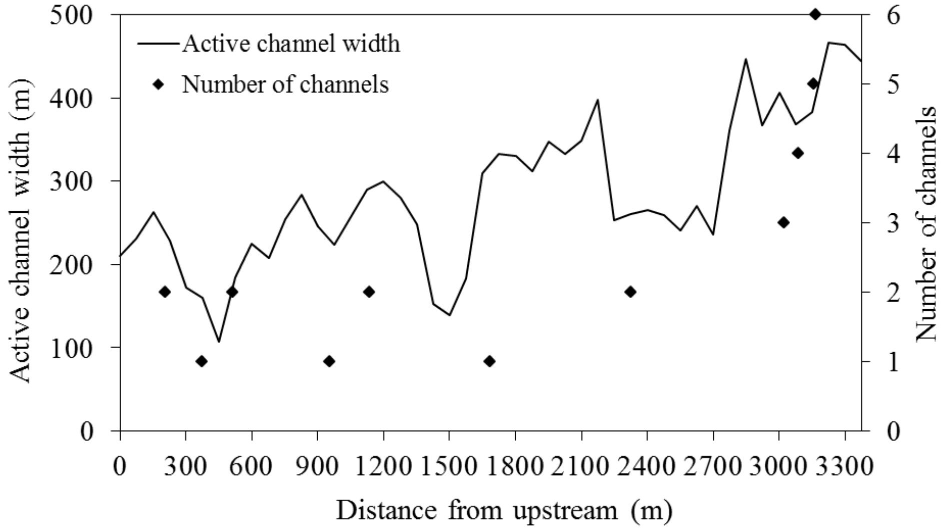


Figure 13: variation of active channel width and number of channels along the study reach.

Within the analyzed study reach, the Piave River features a complex pattern of vegetation distribution (Picco et al., 2012). The strong narrowing and incision of the active channel that occurred during the twentieth century (Comiti et al., 2011) has allowed the colonization of large areas by riparian forests (Picco et al., 2012). Furthermore, the widening tendency shown during the last 20 years has led to the creation of pioneer and young islands through the recruitment of LW from bank erosion (Picco et al., 2012). Fluvial islands within the study reach are of different ages and sizes, but there are no established islands. The riparian woody vegetation differs substantially from those characterizing near-equilibrium systems (Picco et al., 2016a). The riparian vegetation of floodplain and fluvial islands is composed of typical riparian species (i.e Alnus, Fraxinus, Populus, Salix), whereas in some areas, notably in the upper part of the study site and near the bank protections, there is a high presence of conifers, i.e *Pinus sylvestris* and *Picea abies*, as a result of reforestation after the Second World War. The non-native species *Robinia pseudoacacia* is common along the whole study reach.

The hydrological data used in this study are derived from a gauging station located 2 km downstream of the end of the surveyed area, corresponding to a drainage basin of 1827 km^2. The gauging station is operated by Agenzia Regionale per la Protezione Ambientale del Veneto (ARPAV) and provides data concerning the hydrometric level and water discharge. There is a small tributary (Ardo Stream) between the study reach and the gauging station; however, given its low contribution (Q=1.2 $m^3\ s^{-1}$), the discharge values recorded by the station are assumed to be valid all along the whole stretch. The main floods are usually recorded in spring and autumn as the result of snowmelt and the rainiest period, respectively; whereas the mean annual minimum discharge is between 3 and 4 $m^3 \cdot s^{-1}$ (E.N.E.L. C.R.I.S., 1996). As documented in a previous study (Comiti et al., 2011), the bankfull discharge Q_2 (Recurrence Interval = 2 years) was calculated at about 700 $m^3 \cdot s^{-1}$ corresponding to an average bankfull stage of 3.10 m. Figure 14 reports the annual maximum peak discharge measured during the last 76 years, from 1940 until 2016. The highest recorded flood (RI = 200 years) occurred in November of 1966 with a peak of almost 4000 $m^3 \cdot s^{-1}$, and the last over bankfull flood took place in November 2014 when a 7-years R.I. flood was recorded with a maximum peak of 1329 $m^3 \cdot s^{-1}$. After this, only ordinary floods took place, with peaks of about 100 $m^3 \cdot s^{-1}$. The maximum discharge measured during 2015 (145 $m^3 \cdot s^{-1}$) was found to be the lowest value recorded during the last 51 years.

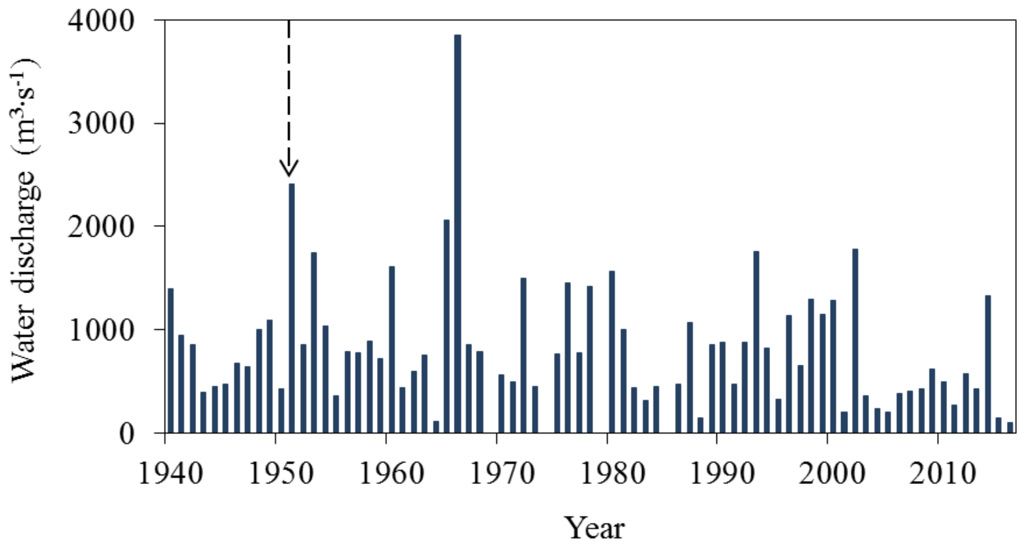


Figure 14: maximum annual peak discharge in the last 76 years (1940-2016) measured at the downstream end of the study reach (modified from Comiti et al., 2011). The arrow indicates the time of dam construction.

3.1.2. The Blanco River

3.1.2.1. General settings of the basin

The Blanco River, also called Chaitén River by local residents, is a fourth-order river located in southern Chile, about 254 km south of Puerto Montt city, in the Los Lagos Region. The river flows for about 18 km from the southwest of the Michinmahuida volcanic complex until its mouth into the Pacific Ocean, crossing the small village of Chaitén. Through its main tributary called Caldera Creek (Major and Lara, 2013; Pierson et al., 2013), the drainage area of Blanco basin is also directly connected to the southern slope of Chaitén volcano (Fig. 15).

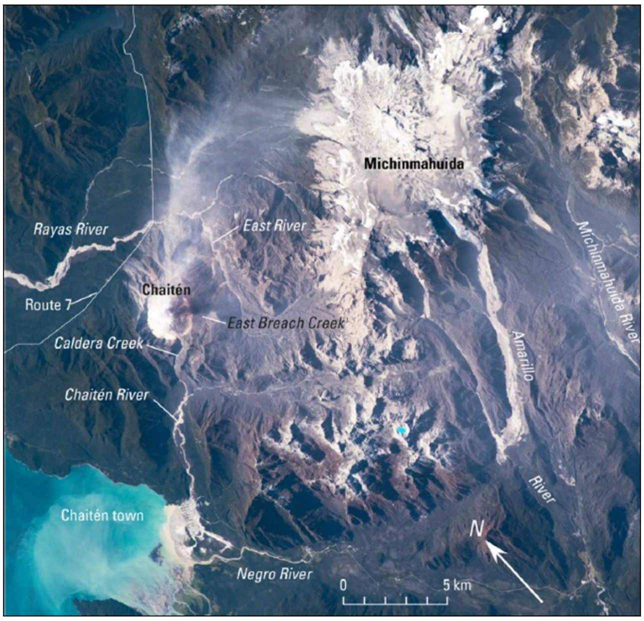


Figure 15: satellite view of Blanco (or Chaitén) River and the two nearest volcanoes of Chaitén and Michinmahuida (after Major and Lara, 2013).

Upstream of Chaitén village, the study catchment of Blanco River covers an area of about 70 km^2 and lies in an altitude ranging between 7 and 1545 m a.s.l. with an average gradient of about 50%. Mainly composed of bedrock, the basin is characterized by a Pleistocene volcanic cover overlying a basement formed by both Miocene granitoids and Paleozoic schists and gneisses (Piña-Gauthier et al., 2013). The bedrock geology of the basin, reflecting the presence of the nearby volcano, is mainly composed of volcanic sediments that feature a high instability favoring creeping and landslides phenomena (Peralta, 1980). Fluvial deposits can be found just in the lowland area of the basin.

The Blanco basin is dominated by the typically wet climate of the Andean Patagonia region. Precipitation increases with altitude by a factor of about 2-3 from the coast to the western front of the Andes (Garreaud et al., 2013) and near Chaitén Volcano there is heavy winter rainfall exceeding 3000 $mm \cdot yr^{-1}$. During the six year period 2004-2009, annual precipitation varied from ~2500 to

~7000 mm·yr^{-1} (Direccion General de Aguas, unpublished data). The largest floods usually occur during the autumn-winter season (March-August). Forty-three percent of the basin area is covered by old growth forests with evergreen tree species, 40% by shrub formations and the remaining 16% corresponds to snowy and glacial areas located in the upper part of the basin (CONAF, 1997). The evergreen forest type, as described by Donoso (1981), is mainly represented by the native *Nothofagus* spp. such as *N. dombeyi* (Coihue), *N. nitida* (Coihue de Chiloé) and *N. betuloides* (Coihue blanco).

3.1.2.2. Effects of Chaitén volcanic eruption on the basin

The Blanco River basin was highly altered by the unexpected eruption of the Chaitén Volcano that occurred between 2008 and 2009.

The Chaitén volcano (1122 m height) is located about 10 km northeast of Chaitén town on the Gulf of Corcovado and about 17 km west-southwest of the much larger and glaciated complex of Michinmahuida volcano (2400 m height) (Fig. 15). The Chaitén Volcano is surrounded by steep, dissected, high-relief, volcanic and glaciated terrain that is densely covered with temperate rainforest vegetation (Major and Lara, 2013). In respect to other Chilean volcanoes, it is a relatively small, remote rhyolitic volcano with a 3-km-wide caldera (Carn et al., 2009) produced during the last known major eruption that occurred about 9400 years ago (Naranjo and Stern, 2004). Owing to its lengthy lack of activity, the volcano was perceived as being inactive and was not considered a threat so was not monitored, but in 2008 a large eruption began unexpectedly.

The eruption was preceded by minor ash emissions and a 3-5 magnitude earthquake (Basualto et al., 2008) recorded at about 15 km north of Chaitén town. The eruption started on 2 May 2008 (Carn et al., 2009; Lara, 2009) with a first brief Plinian explosive phase (~2 weeks) followed by a more prolonged effusive phase (~18-20 months) (Pallister et al., 2013). According to Pallister et al. (2013), the eruption can be divided into different phases according to the type and characteristics of emitted material. From the point of view of the volcanic impacts, the most dangerous phase occurred from 1 to 9 May during which the heavy rainfall recorded after the first explosion mobilized the tephra fall deposits inducing lahars and floods (Pierson et al., 2013) that devastated the nearby Chaitén village (Fig. 16).

Figure 16: a, oblique aerial view looking downstream along Chaitén river valley from the caldera rim (after Major and Lara, 2013); b-c, houses buried by deposition of volcanic sediments; d, new channel cutting through the village following avulsion (photos from SERNAGEOMIN).

The eruption effects on Blanco River have also been documented on bed morphology (Pierson et al., 2013), forest vegetation (Major et al., 2013; Swanson et al., 2013) and LW dynamics (Ulloa et al., 2015a). Comparing the active channel width between the pre and post eruption conditions, the active channel widened 3.5 times up to a maximum of nine times (Ulloa et al., 2015a) (Fig. 17a).
The heavy rainfall (up to 600-900 mm in twelve days), recorded soon after the first eruption, caused pyroclastic sediments remobilization downstream of the Chaitén river valley triggering lahar floods that resulted in a 7 m aggradation along the river channel (Pierson et al., 2013). Several km^2 of the lowland forested floodplain were greatly affected by the fluvial deposition of remobilized tephra (Fig. 17b). However, given the moderate temperature of Pyroclastic Density Currents (PDCs) (< 300 °C) (Major et al., 2013), trees were not completely charred (Swanson et al., 2013). Another disturbance reported by Swanson et al. (2013) was induced by the fine tephra accumulating on the tree crowns that led to breakage and bowing of old and young trees, respectively. Destruction of the riparian forest increased the recruitment rate of trees resulting in a dramatic variation of LW abundance, Ulloa et al. (2015a) reported an increase of LW pieces from 16 to 736 during the period 2005-2009 (Fig. 17c-d).

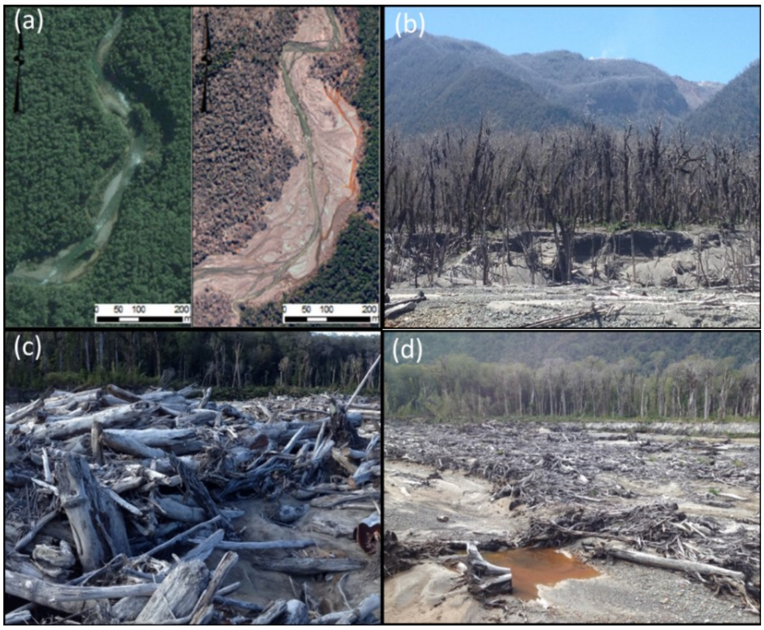


Figure 17: images of volcanic effects on Blanco River. a, example of active channel widening due to sediment loading along the middle course of the river (after Ulloa et al., 2015a); b, damaged riparian forest; c-d, large wood deposited within the active channel.

3.1.2.3. The study reaches

Three study reaches, within an area located in the lower part of the river course, were chosen to analyze the temporal variations of LW. Reaches are identified in an upstream order as reach 1, reach 2 and reach 3 (r_1, r_2 and r_3, respectively) (Fig. 18). Because of the considerable amount of in-channel LW and the extension of the active channel width, the selected reach length was reduced to 80 m, extending 40 m upstream and 40 m downstream of a cross section (as previously done, i.e, by Gurnell et al., 2000 and Ravazzolo et al., 2015a). Study sites were selected to represent different morphology of the reaches. The upstream reach 3 is a single-thread channel characterized by the main channel flowing forming a well-pronounced bend, while reach 2 features a single-thread pattern with the main channel bordered by a high bar. In the downstream reach 1 the morphology appears to be similar to the multiple-thread channel pattern because of the presence of two dry channels. From upstream, the mean bed relative elevation of the selected reaches decreases from 1.9 to 1.04 and 0.78 m of reach 3, 2 and 1, respectively.

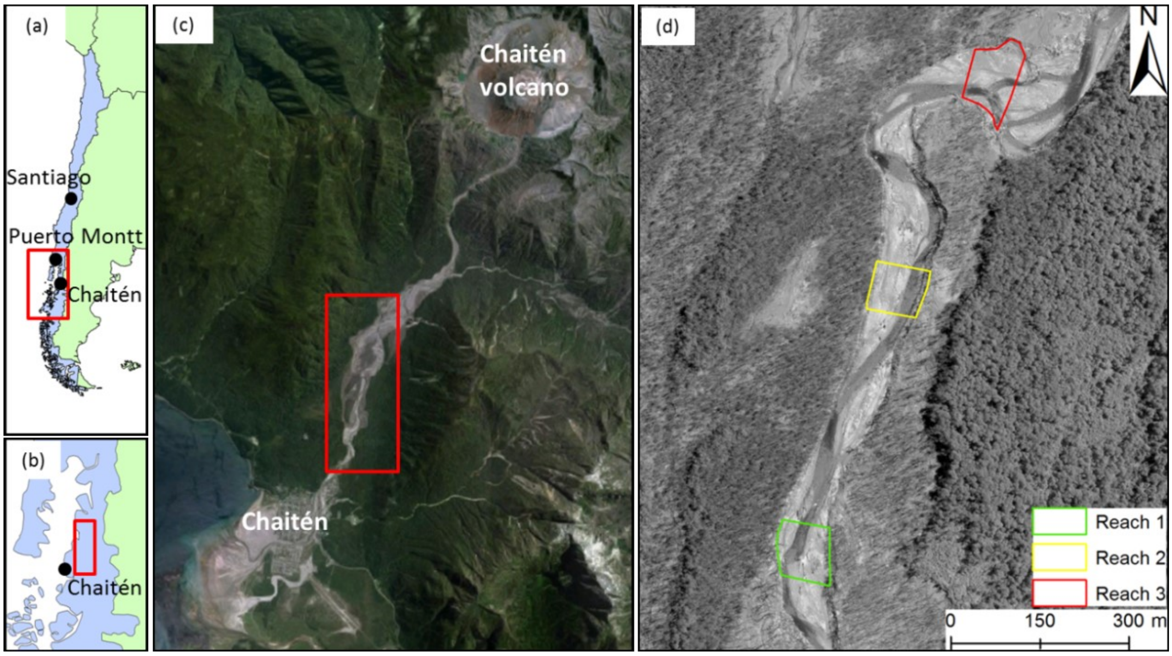


Figure 18: location of the study area (a, b), overview of the Blanco River course (c) and location of the three study reaches (d).

Due to the effects of the eruption, the whole study area features a 6-7 m difference in height between the bed level and the top of the riverbanks. Indeed, the deposition of volcanic material has led to the formation of a complex river system where the active channel is now well confined by these non-natural "slopes". However, in some locations where almost all volcanic sediments have been removed the original vegetated floodplain is now starting to reappear (Fig. 19).

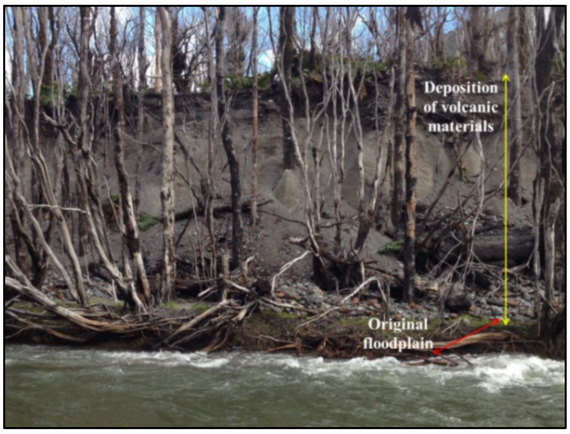


Figure 19: field evidence on the position of the original vegetated floodplain.

The three reaches were surveyed in different periods from January 2015 until March 2016. Reach 1 and reach 2 were first surveyed in January 2015 (Survey 1) and then resurveyed after the summer in March 2015 (Survey 2) and after a winter season in January 2016 (Survey 3). The reach 3 was first monitored during March 2015 and then after a year in March 2016 (Survey 4). The main characteristics of the three reaches related to each survey are reported in table 4.

Table 4: date of field surveys and characteristics of the reaches at each survey.

	Reach 1 (r_1)			Reach 2 (r_2)			Reach 3 (r_3)	
Survey	January 2015	March 2015	January 2016	January 2015	March 2015	January 2016	March 2015	March 2016
Width (m)	94	94	94	80	80	137	108	108
Area (m^2)	7940	7940	7940	7500	7500	12685	8941	8941

Figure 20 depicts the longitudinal profile of the study area and position of the study reaches.

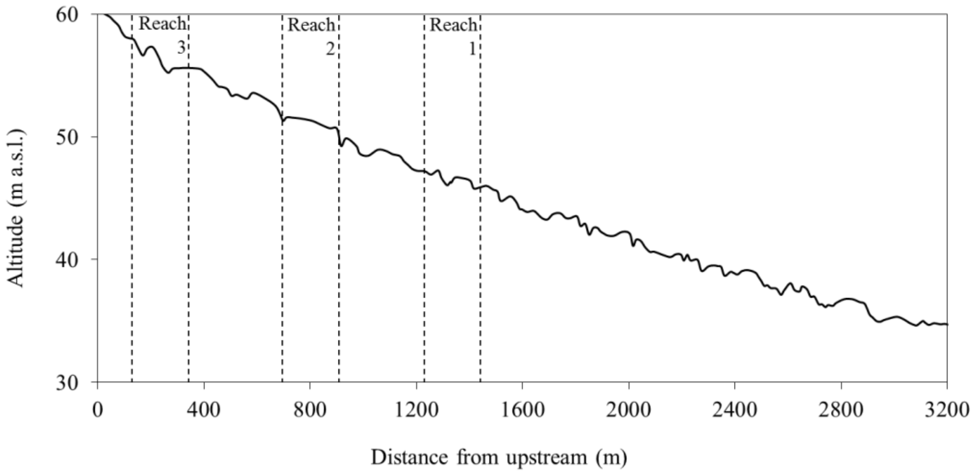


Figure 20: longitudinal profile of the Blanco River (corresponding to the area marked in figure 19c) and location of the three study reaches.

3.2. Methodology

The large wood budget developed in this study followed the quantitative frameworks (Eq. 1, 2) proposed by Martin and Benda (2001). Two different frameworks were applied according to the study area. For both rivers, as the balance was calculated for short time periods, the in situ decay (D) and input from chronic tree mortality (I_m) were omitted; whereas, as there were no floods exceeding the bankfull level during the study period, the loss of LW due to overbank deposition (O) was not considered.

In the case of Piave River, the LW budget was computed considering, in addition to the fluvial transport into and out the study reach ($Q_i - Q_0$), the lateral recruitment due to bank erosion (I_{be}). In fact, because of the morphological aspect of the study reach where no steep slopes are present, the input from mass wasting events (I_{ms}) was not considered and, as no catastrophic events occurred, the toppling of trees for natural events (I_m) was not taken into account. From field evidences, we also considered that the input from exhumation (I_e) is negligible, so the LW budget equation applied in the Piave River study reach reduces on (Eq. 3):

$$\Delta S = [I_{be}\Delta x + (Q_i - Q_0)]\Delta t \qquad \text{(Eq. 3)}$$

Differently, in the case of Blanco River the budget was assessed only for variations due to fluvial transport ($Q_i - Q_0$) and the input from exhumation of buried LW (I_e). Also in this case inputs from catastrophic events (I_m) and from mass wasting (I_{ms}) were assumed to be insignificant. However, the budget of Blanco River considered only partially the variations occurred in the LW storage as the supply of LW due to bank erosion was not considered. Despite bank erosion was measured, the lack of data concerning riparian vegetation did not allow to estimate the recruitment of LW. The equation used for the Blanco River is the following (Eq. 4):

$$\Delta S = [I_e\Delta x + (Q_i - Q_0)]\Delta t \qquad \text{(Eq. 4)}$$

To assess the LW balance a series of different activities were carried out in the two study areas. The analysis of each component of the budget required the application of different methods. This section describes the field activities and materials used during this study (Table 5).

Table 5: analysis methods, materials used and their application sites.

Components of budget analyzed	Field activities	Materials	Piave River	Blanco River
I_{be}	Monitoring of lateral LW recruitment	DGPS, caliper, metal tags, field sheets	✓	-
	Monitoring of riverbanks	DGPS, aerial images	✓	✓
Q_i-Q_o	Monitoring of LW deposited within the active channel	DGPS, caliper, tape, metal tags, colored paint, field sheets	✓	✓
I_e	Monitoring of buried LW	GPR	-	✓

3.2.1. Assessment of bank erosion and large wood recruitment

As already described in section 1.4.1, the lateral inputs of LW can occur through different recruitment mechanisms (i.e. tree mortality, hillslope instability, bank erosion).

In piedmont environments, where flow energy remains high and banks can be more susceptible to erosion than in lowland environments (Latterell and Naiman, 2007; Lassettre et al., 2008; Moulin et al, 2011; Boivin et al., 2015), bank erosion can be the main source of wood to rivers. Recruitment of wood from riverbank erosion can be predicted using numerical models of bank erosion (Simon et al., 2000; Lai et al., 2015) or quantified by knowing the riparian vegetation characteristics (i.e. spatial density and tree size).

In this study bank erosion and large wood recruitment was assessed only in the Italian Piave River through a detailed characterization of riparian vegetation in order to quantify the wood volume available for input during bank erosion events. Recruitment of LW from bank erosion was analyzed for a 7-yr R.I. flood that occurred in November 2014. During the flood the water discharge remained over the bankfull level for 1.58 days (38 h), and the maximum peak recorded was 1329 $m^3 \cdot s^{-1}$ (Fig. 21).

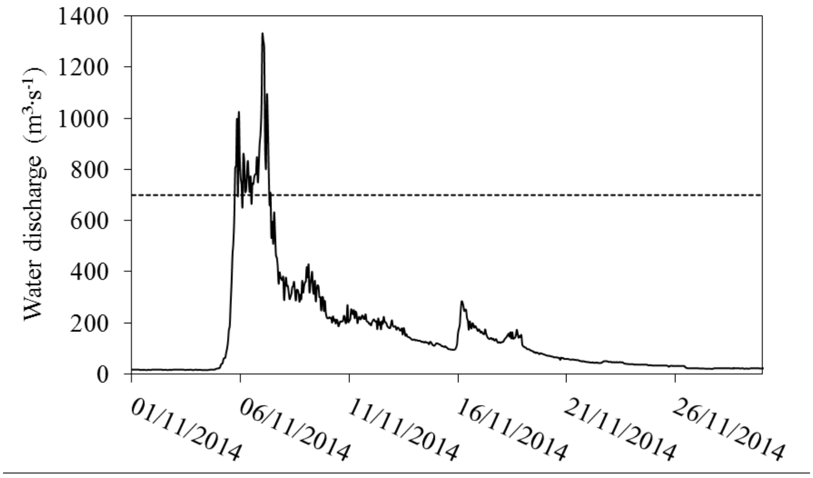


Figure 21: maximum hourly discharge on the Piave River as measured at Belluno gauging station during the over bankfull flood of November 2014. Dashed line indicates the level of bankfull discharge.

One of the main open questions about the study of lateral LW recruitment regards the delineation of a buffer zone in which riparian vegetation is more likely to be recruited during erosion events. In a previous study (MacVicar and Piégay, 2012) conducted on a river with similar morphology and dynamics (Ain River, France), a 5 m wide strip on both riverbanks proved to be not sufficient because bank retreat exceeded 5 m in some locations. Thus, as suggested by MacVicar and Piégay (2012) and according to mean bank erosion width detected during the period 2006-2014 along the Piave River (unpublished data), a reasonable buffer zone was found in a 20 m wide strip on both, floodplain and fluvial islands.

Within this buffer, every standing tree (n=3320) with a diameter ≥ 0.10 m was measured in its diameter at breast height (DBH) and height. The species was also noted in order to assign a wood density value according to Hellrigl (2006). Others characteristics related to the state of health (i.e. alive, dead, broken), presence of branches and leaves were recorded and a numbered tag was attached in order to uniquely identify each tree and simplify the post-event recovery. Lastly, the spatial density of riparian vegetation was obtained georeferencing each tree using a Differential Global Positioning System (DGPS) (average accuracy ± 0.025 m) (Fig. 22, 23).

Figure 22: images of field data collection along the Piave River study reach. Measuring (a), tagging (b) and positioning (b) of riparian vegetation.

Wood volume of standing trees was calculated according to the methodology already followed by Piégay et al. (1999) and MacVicar and Piégay (2012) using the Algan-Monnin formula (Rondeux, 1993) (Eq. 5, Eq. 6):

$$V_{st1} = 0.4 * d^2 * (h + 5) \quad \text{(Eq. 5)}$$

$$V_{st2} = 0.5 * d^2 * (h + 2) \quad \text{(Eq. 6)}$$

where:

V_{st} = volume of standing tree (m^3) (V_{st1} with h > 10 m; V_{st2} with h < 10 m)
d = DBH (m)
h = height (m)

For all tagged trees the morphological unit of provenance was noted in order to discriminate between the contribution of LW input from different morphological units. Overall, considering all the vegetated areas along the Piave study reach, two morphological units were found, floodplain and islands.

Fluvial islands were distinguished following Picco et al., (2014), into:

- Pioneer islands (P), vegetation height ranging between 3 m and 5 m;
- Building islands (B), vegetation height ranging between 5 m and 15 m;
- Established islands (E), vegetation higher than 15 m (not found in the study reach).

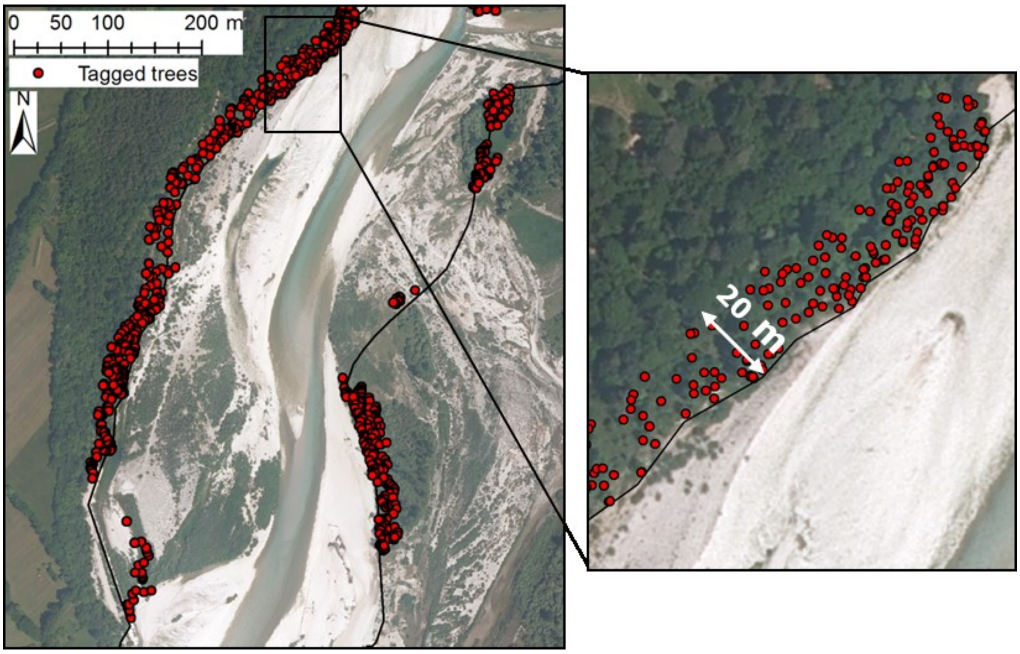


Figure 23: example of riparian trees surveyed in the 20 m-wide strip along floodplain and islands.

Bank erosion was evaluated using a DGPS device (average accuracy ± 0.025 m) surveying floodplain bank and island perimeters before and after the flood. Eroded areas on the floodplain and islands were defined comparing the pre and post-flood conditions using ArcGIS 10.1 (Environmental Systems Research Institute - Esri, Inc., Redlands, CA, USA). Figure 24 illustrates an example of how it is possible to study bank erosion through a DGPS survey.

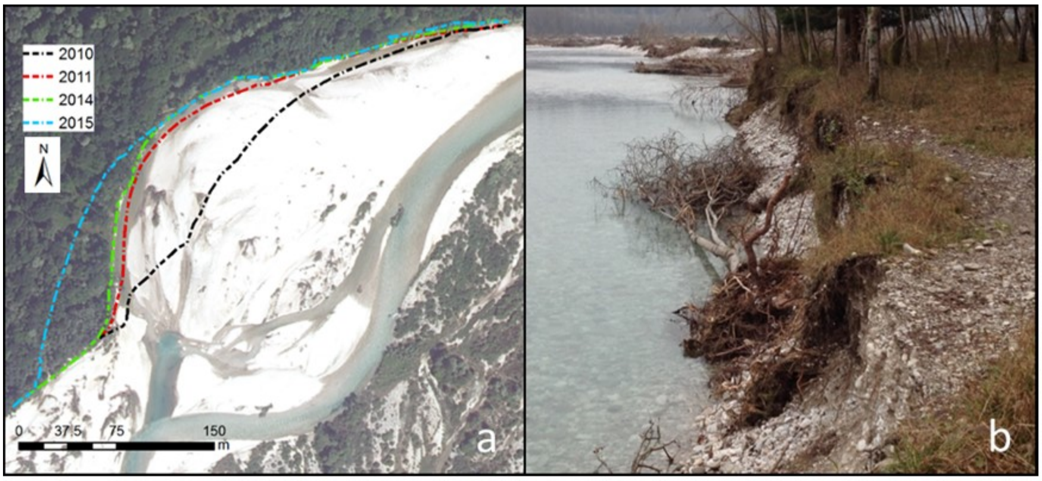


Figure 24: images showing an erosion area located along the right bank of the Piave study reach. The different dashed lines represent the position of riverbank monitored with a DGPS in 2010, 2011, 2014 and 2015 (a); an example of the same riverbanks after the 2014 flood (b).

3.2.2. Assessment of large wood input and output from fluvial transport

The methodology applied to assess the temporal variations in the storage of LW is similar for both study areas. Within the considered reaches all woody pieces ≥ 0.1 m in diameter and ≥ 1 m in length (Morris et al., 2010) were measured, using a measuring tape and a tree caliper, respectively. According to Iroumé et al. (2010), measurement precision is 1 cm for diameter and 5 cm for length. The analysis concerned just those pieces lying in the active channel (defined as the area between riverbanks that can be flooded during events) and those located along the riverbanks. According to the type of aggregation each piece was classified as a single (normally called LW) or jammed element (normally called WJ). To define a wood jam a minimum number of two elements was considered (Comiti et al., 2006).

Woody elements were classified in five categories:

- trees, identified as plants with branches and roots completely of partially present;
- shrubs, identified as elements with multiple coarse branches;
- logs, identified as elements lacking in branches and roots;
- roots, identified as the rootwad of a tree;
- residues, identified as woody elements of any form that have been cut by local people.

As commonly done in other LW studies (Andreoli et al., 2007; Wyzga and Zawiejska,, 2010; Iroumè et al., 2010), the volume was calculated assuming a solid cylindrical shape from the mid-diameter and length (Huber's formula (Eq. 7)).

$$V_{lw} = \left[\pi * \left(\frac{D^2}{2}\right)\right] * l \quad \text{(Eq. 7)}$$

where:

V_{lw} = volume of LW ($m^3 \cdot ha^{-1}$)
D = mid-diameter (m)
l = length (m)

In the case of roots, the length was considered as the direct distance between the top of the log and the bottom of the roots. The volume of WJ was calculated by measuring all visible and accessible individual pieces within the jam and assuming that this represents a minimum volume of LW within the jam (Wohl and Cadol, 2011; Ravazzolo et al., 2015a). In this way, differently from the methodology of Thévenet et al. (1998), the air space in between was not considered.

For each LW a series of qualitative characteristics were collected during surveys such as orientation to the flow (parallel, orthogonal, oblique), morphological unit in which it was found, interactions with water (completely or partially submerged), and the delivery mechanism of recruitment (transport from upstream, lateral bank erosion, harvested residue).

The delivery mechanism was identified on the basis of field evidences. Woody pieces mainly having a rounded, smoothing shape and lacking in branches were identified as floating pieces. Identification of those elements recruited from bank erosion was possible, in the case of Piave River, thanks to the numbered tag installed on riparian trees whereas, in the case of Blanco River, it was done on the basis of field evidence (i.e. fallen trees but still anchored, logs partially lying in the active channel but still in part buried under bank sediment deposits). Lastly, elements whose shape were due to chainsaw cutting were classified as harvested residues.

To analyze the temporal variations in the LW storage between each survey, the GPS position of woody elements was recorded, and each element was marked with colored paint and a numbered metal tag attached using a steel nail (Fig. 25). The use of this field methodology permitted each element to be uniquely identified, and quickly detected during subsequent surveys. Similarly to what already done by Piégay et al., (2017), during each post-event survey wood elements that were not found in their previous position within the study reach were classified as an output, whereas elements without tags (or having a tag coming from riparian trees in the case of Piave River) were classified as an input. Every new input was measured, classified, GPS positioned, and tagged, whereas LW already present were just GPS positioned again to detect potential transport along the reach.

The numbered tags also made it possible to conduct a downstream search for both recruited trees and moved LW pieces. For each recovered element, the new position was recorded and traveled distance measured as a trajectory between starting and ending point, considering the thalweg line.

The LW mobility and retention rates, expressed in percentage, were calculated for Blanco and Piave rivers considering each study period. The mobility rate is defined as the ratio between the number of tagged elements repositioned or not found within the reach and the total number of tagged LW within the same reach, whereas the retention rate is expressed as the ratio between the number of tagged elements not transported and the total number of tagged LW (Iroumé et al., 2015; Ruiz-Villanueva et al., 2015).

Figure 25: examples of tagged and painted LW along the Piave River (a-b), and Blanco River (c) study reaches.

3.2.3. Buried large wood detection

The assessment of buried LW was performed based on the Ground Penetrating Radar (GPR) technique. This is a geophysical approach to analyze the subsoil using electromagnetic radiation in the microwave band of the radio spectrum. A GPR system is usually composed of surface antennas, a radar system to produce pulses, a computer to process data, a video monitor and a power source. Radar waves are propagated with distinct pulses from the surface antenna, reflected off buried obstacles and detected back at the source by a receiving antenna. Each time a radar pulse traverses a material with a different composition or water saturation, the velocity changes and a portion of the radar energy is reflected back to the surface and recorded by the receiving antenna. The remaining energy continues to pass into the ground to be further reflected, until being dissipated with depth (Conyers and Goodman, 1997). An example of the subsurface reflector configuration is given in figure 26.

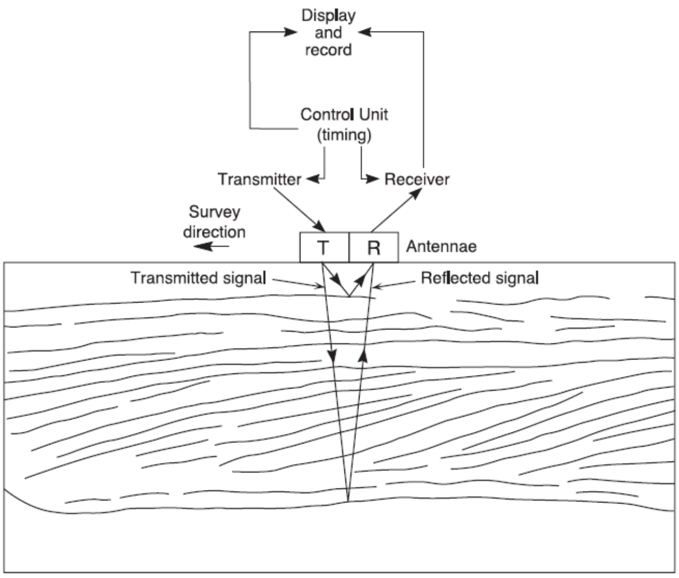


Figure 26: diagram of GPR data acquisition (after Neal, 2004).

Data recorded during surveying result in a radar reflection profile, commonly called a radargram, which shows the distance surveyed on the ground (horizontal axis), the time of reflected radar's waves propagation (primary vertical axis) and the estimated depth of the object reflecting waves (secondary vertical axis). The quality of obtained data, in terms of depth of penetration and resolution, differs depending also on the antenna frequencies. In fact, one of the most important variable in GPR surveys is the selection of a proper antenna according to the desired depth and resolution of buried objects. Commonly, there are three different antennas with low (f<100MHz), medium (1GHz>f>100MHz) and high (f>1GHz) frequency. Usually, the high is the necessary depth of investigation and lower is the antenna frequency needed.

The depth (D) of the object that induces radar reflections can be resolved following the equation of Daniels (1996) (Eq. 8):

$$D = \frac{v*t}{2} \quad \text{(Eq. 8)}$$

where:

v = waves velocity propagation (cm/µs)

t = two-way travel time (µs)

Waves velocity propagation (v) can be obtained from the following equation (Al Hagrey, 2007) (Eq. 9):

$$v = \frac{c}{\sqrt{\varepsilon r}} \quad \text{(Eq. 9)}$$

where:

c = speed of light in vacuum ($3 \cdot 10^8$ $m \cdot s^{-1}$)

ε_r = relative dieletric permittivity (according to the material)

As the waves velocity is a function of the relative dieletric permittivity (ε_r) that changes according to the properties of the reflecting object (Topp et al., 1980; Davis and Annan, 1989), it is clear how also the velocity of radar pulses varies according the physical and chemical properties of the soil (Conyers, 2004; Conyers and Goodman 1997). For this reason, the GPR needs an accurate calibration according to the type of soil in which it is used.

When the waves velocity propagation is known, it is possible to measure the distance, or depth in the ground, as (Eq. 10):

$$D = \frac{c*t}{2*\sqrt{\varepsilon r}} \quad \text{(Eq. 10)}$$

The only unknown parameter is the two-way travel time of propagation, which can be obtained converting the distance surface-object (D) into time (t) knowing the longitudinal length of the surveyed ground (L), which corresponds to a portion of the radargram (R), and the distance from the origin to the object (l) (Eq. 11):

$$t = l * \frac{R}{L} \quad \text{(Eq. 11)}$$

Combining equations 10 and 11, we obtain the depth in the ground where the reflecting objects are located.

Following these first analyses on the radargram, a series of specific tools are applied in order to extract the dimensions (length and diameter) of buried wood.

The device tested in this study, provided by the Department of Civil Engineering of the Universidad Austral de Chile, is a GPR MALA RAMAC X3M equipped with three shielded antennas of 250, 500 and 800 MHz (Fig. 27).

Figure 27: the GPR MALA RAMAC X3M used in this study.

Before conducting the geophysical analysis, a correct calibration of the instrument was required. In particular, we investigated on different antenna frequencies in order to evaluate which one yields the best resolution.

The analyses were conducted along the lower part of the Blanco River, 3 km upstream of the mouth, during the southern summers (January 2015 and 2016) when rainfall is low and soils are dry enough.

Calibration was done using wood pieces of different sizes and buried at different depths. As illustrated in figure 28, two groups of logs having diameter less and greater than 0.1 m were used. Woody pieces were artificially inserted at increasing depths of 0.5, 1.0 and 1.5 m and their location recorded with a DGPS. In this way, knowing the sizes, depth and position in which they were located, it was possible to adjust the waves velocity propagation. Moreover, from the resulting radargrams, the correspondence was verified between the spatial distribution of buried logs and the reflection hyperbolas recorded on the radargram.

Following the calibration phase, two study areas were chosen to conduct the geophysical analysis (Fig. 29). The first one (486 m^2) is located close to the main channel and was surveyed by 3 m-spaced profiles whereas the second one (2000 m^2) is on a high lateral bar and was surveyed by 5 m-spaced profiles. The different positions of the two study areas permitted the waves velocity propagation to be tested in volcanic soils with different water saturation, moist and dry for the first and second area, respectively.

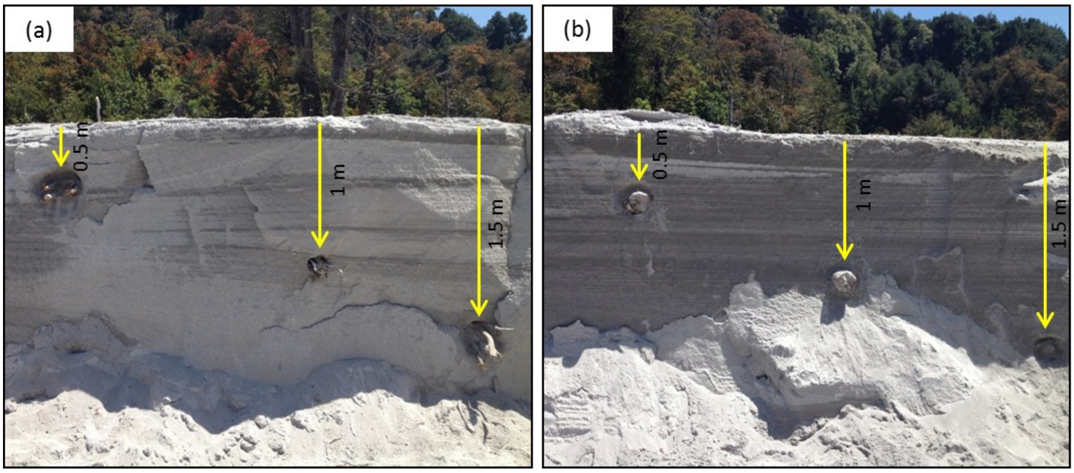


Figure 28: calibration of GPR for wood pieces with D < 0.1 m (a) and D > 0.1 m (b) placed at increasing depth.

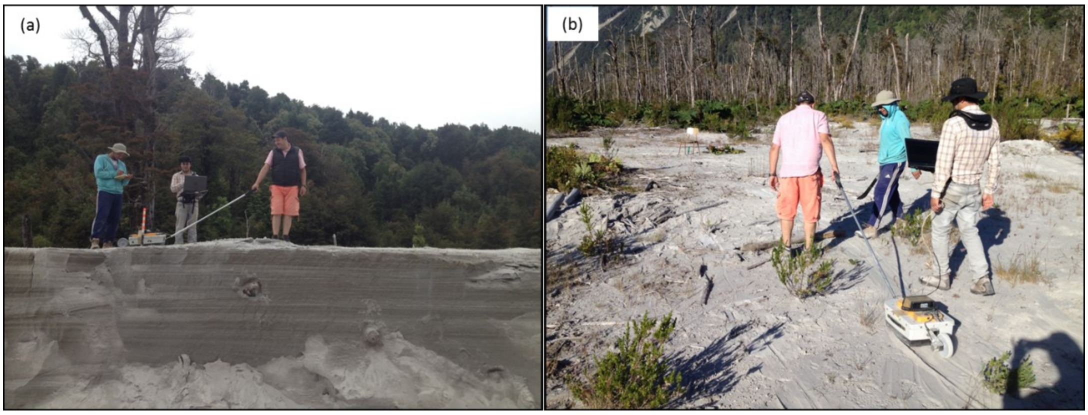


Figure 29: example of two applications of GPR, during the calibration phase (a) and a general survey on dry volcanic sediments (b).

A time schedule of field activities conducted along the Piave and Blanco rivers is reported in table 6.

Table 6: time schedule of the field activities carried out during the 3-years research in the Piave (P) and Blanco (B) rivers.

	2014				2015						2016			
Month(*)	06	07	08	09	01	03	06	07	08	09	01	03	05	06
Monitoring of riverbanks	P	-	-	-	P	-	-	-	-	-	-	-	-	P
Collection of riparian trees data	P	P	P	P	-	-	-	-	-	-	-	-	-	-
Collection of LW data	-	-	-	-	B	B	P	P	P	P	B	B	P	P
Monitoring of buried LW	-	-	-	-	B	-	-	-	-	-	B	-	-	-

(*) just the months in which activities were conducted are reported.

3.3. Topical and methodological limitations

The main objective of this research is the assessment of large wood budget along two differing gravel bed rivers. The budget is formed by a series of items that, depending on the study area characteristics (i.e. mountain torrent, piedmont rivers) and the temporal scale adopted, may be or not considered. For example, as the budget will be developed for short time periods, the role of decaying LW process will not be investigated and, as no catastrophic natural events occurred during the study period, the input due to this process will not be assessed.
However, this study presents two main topical limitations:

- Firstly, the assessment of lateral recruitment due to bank erosion in the Piave River will be made taking in account only the volume of standing tree, while the volume of LW deposited on the ground will not be considered.
- Secondly, the budget constructed for the Blanco reaches will be characterized by an underestimation in the variations of LW storage because two items are not analyzed: the input from bank erosion and natural mortality. Because of the very frequent precipitation characterizing the study area that reduce the time span for field surveys at a couple of weeks, it was decided to take in consideration only the fluvial transport of LW.

According to the methodological limitations due to the selected methods or the type and characteristics of materials used, they can be listed as follows:

- The quantification of WJ volume by measuring manually all visible and accessible individual pieces within the jam has probably led to an underestimation of the total LW volume, especially in the case of the Blanco River where elements were mainly jammed in complex accumulations. However, the fact that small LW in the Blanco River are very few because of the large sizes of riparian vegetation, this allowed me to think that only few elements were neglected.
- The selected methodology to uniquely identify each tree and LW with a metal tag influenced some analyses further conducted. As with this method no data on the instantaneous movement of LW are available, the transport distance of recruited trees was not the real displacement but was approximated following the thalweg line. Moreover, the mobility rate and the retention capacity were calculated on the base of the presence/absence of tagged elements. However, if some tagged pieces have undergone internal transport and were deposited with the tag on the lower side or hidden by other pieces, is possible that some elements were erroneously classified as input instead of storage.

- Because of time constraints, the analysis of buried LW was conducted only in the Chilean study area. However, during field surveys conducted in the Piave River, the presence of elements partially or completely buried (whose presence was identified thanks to resprouts) was noted, resulting in a low percentage (3%). Therefore, I supposed the importance of buried LW in the computation of LW budget for the Piave study reach to be quite negligible.

Section Four - Results

4.1. Large wood recruitment during an over bankfull flood event

This section describes results concerning the first specific thesis objective: the analysis of lateral recruitment of LW along the Piave study reach following an over-bankfull flood.

4.1.1. Dendrometric characteristics of riparian vegetation, bank erosion and large wood recruitment

Along the Piave study reach, riparian vegetation with diameter ≥ 0.1 m was found on three morphological units: pioneer islands (P), building islands (B) and floodplain (F). A total of 3220 riparian standing trees were surveyed within the 20 m-wide buffer zone, 72 (2.2%), 161 (5.0%) and 2987 (92.8%) of which were measured on P, B and F, respectively.
Standing trees show differences in dendrometric characteristics, such as diameter, height and volume (Fig. 30, 31). Pioneer islands have vegetation of smaller dimensions, surveyed trees have a median diameter of 0.11 m and median height of 4 m, whereas the median volume per tree corresponds to 0.03 m^3. No trees larger than 0.22 m in diameter were found on pioneer islands. Trees on building islands and floodplain show higher values, in particular the median diameter is 0.13 m in both cases while median height reaches 8 and 9 m for building islands and floodplain, respectively. Volume of trees is very similar and corresponds to 0.08 and 0.09 m^3 per tree on building islands and floodplain, respectively. Concerning the maximum values recorded, the biggest surveyed element in terms of volume corresponds to a 6.35 m^3-tree located on the floodplain and having a diameter of 0.74 m and height of 24 m.

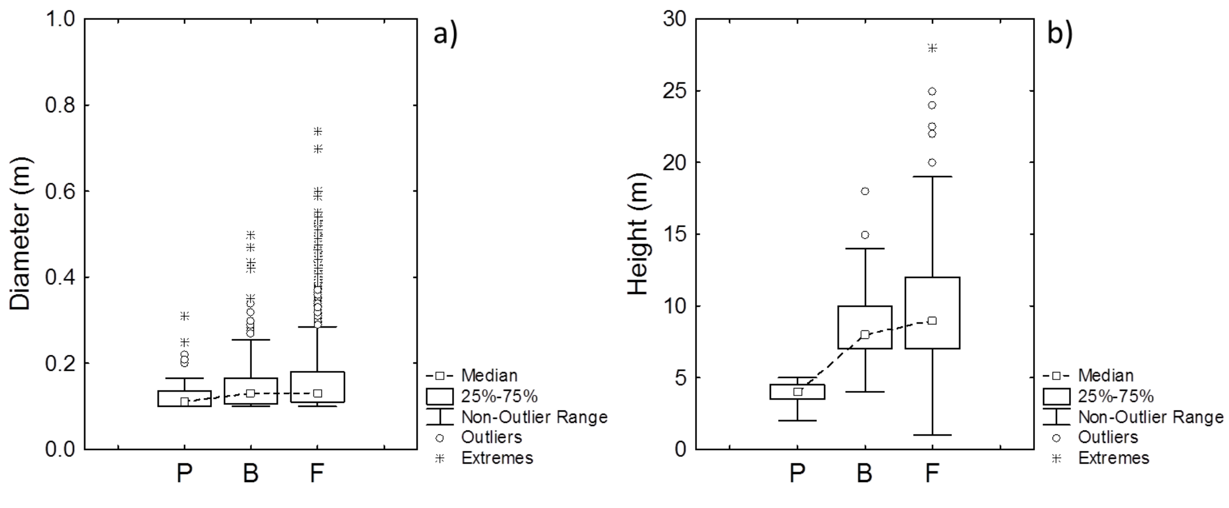


Figure 30: diameter (a) and height (b) of tagged standing trees on the different morphological units (P, pioneer islands; B, building islands; F, floodplain), (after Picco et al., 2016a).

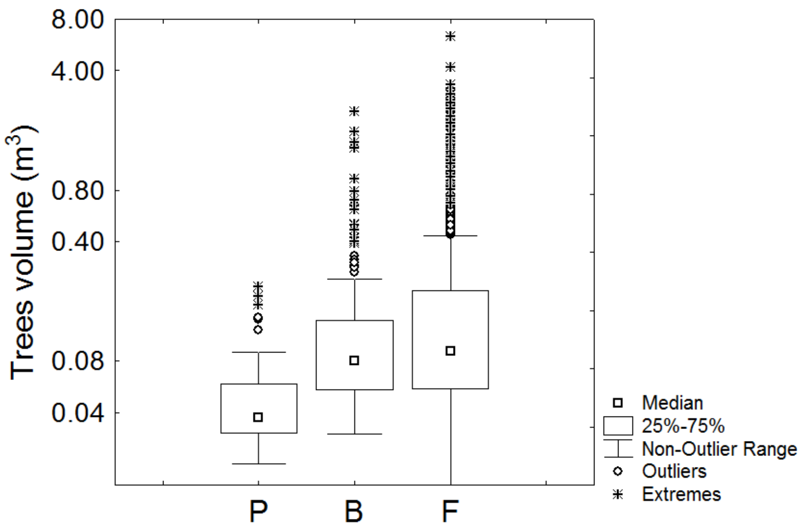


Figure 31: volume of tagged standing trees on the different morphological units (P, pioneer islands; B, building islands; F, floodplain). Values are in logarithmic scale for better visualization.

Comparing the perimeters of pioneer islands, building islands and floodplain in pre- and post-flood conditions, it was possible to check eroded areas and calculate erosion and recruitment rates.

The November 2014 flood caused erosion along many vegetated patches, both on islands and floodplain. Figure 32 illustrates the position of eroded patches along the study reach.

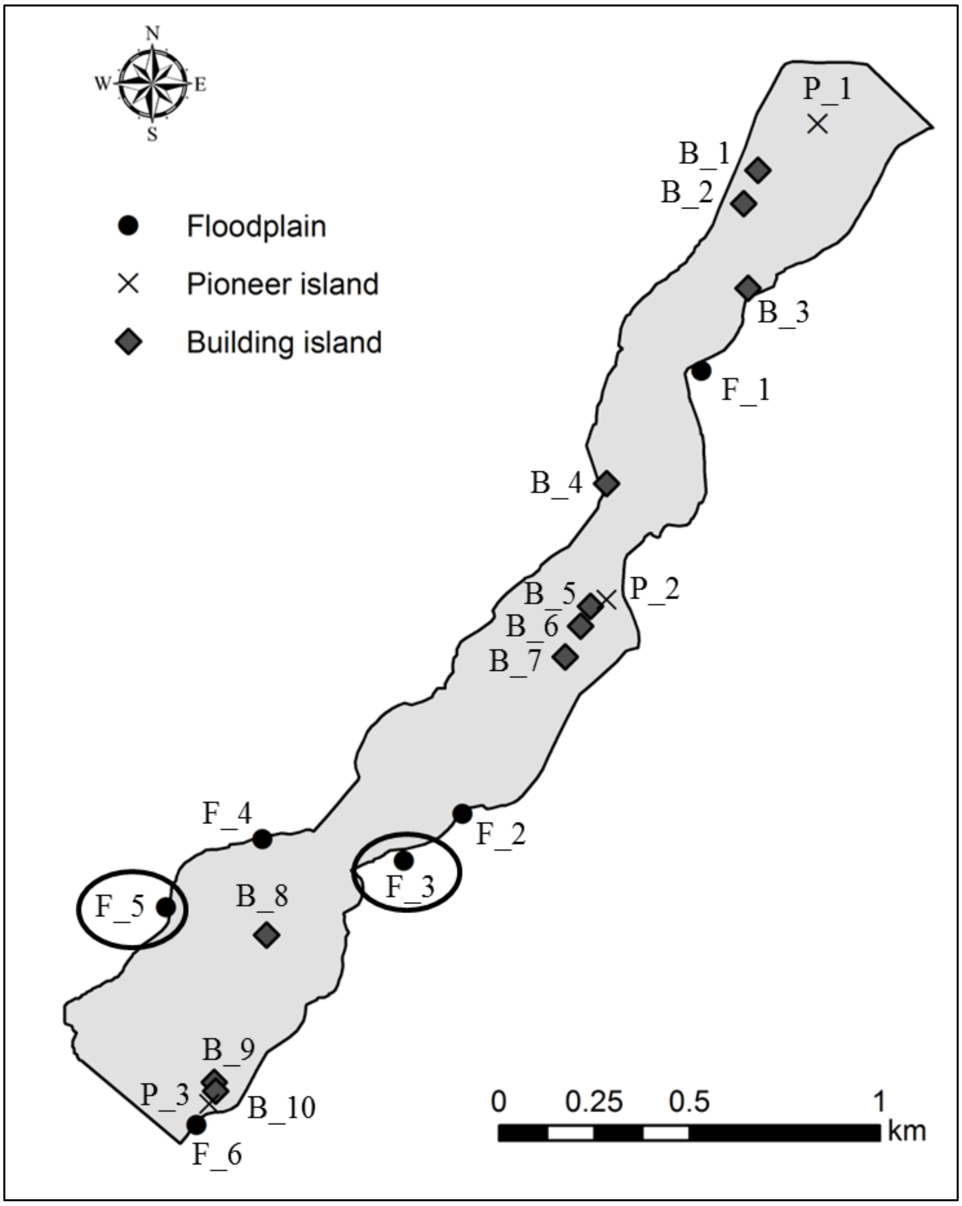


Figure 32: position of eroded patches along the Piave study reach. Each patch is identified by a code (P, pioneer islands; B, building islands, F, floodplain) having a number in progressive order downstream. Circles identify the location of two floodplain areas eroded in more than 20 m wide.

Table 7 reports in detail the eroded surface area, number of recruited trees and volume of LW input for each eroded patch. An identification code has been assigned to each area in progressive order downstream.

Table 7: erosion and recruitment values for each single patch. In bold the two areas with erosion wider than 20 m.

Morphological unit	Code	Area eroded (m^2)	Trees recruited (N)	LW input (m^3)
P	P_1	11.95	1	0.02
P	P_2	9.98	1	0.04
P	P_3	3.16	2	0.07
B	B_1	485.26	14	0.80
B	B_2	104.57	12	0.74
B	B_3	112.96	9	0.58
B	B_4	953.05	22	1.13
B	B_5	11.56	1	0.17
B	B_6	68.27	2	0.22
B	B_7	199.1	4	0.30
B	B_8	30.24	7	1.17
B	B_9	100.05	6	1.05
B	B_10	20.58	2	0.43
F	F_1	4922.99	13	0.84
F	F_2	1041.25	53	7.39
F	**F_3**	**5128.71**	**196**	**23.70**
F	F_4	216.65	7	0.63
F	**F_5**	**3893.66**	**337**	**53.65**
F	F_6	362.14	1	0.03

Pioneer islands were eroded just in three zones, with low erosion values ranging from a minimum of about 3.16 m^2 (P_3) to a maximum of about 11.95 m^2 (P_1). The number of recruited trees is also very low and corresponds to a single tree for the first two areas and two trees in the last one, introducing a total of 0.13 m^3 of LW into the active channel.

Building islands were eroded with higher and different intensity. In fact, ten building islands were eroded and erosion values feature a higher variability between 11.56 m^2 and 1 recruited tree from the smallest eroded area (B_5), and 953.05 m^2 from the largest one (B_4), which corresponds to the removal of almost an entire building island (22 recruited trees). Large wood input from building islands is substantially higher than those from pioneer islands, with three islands out of ten delivering more than 1 m^3 of LW. The highest LW input volume is 1.17 m^3 recruited from an eroded surface of 30.24 m^2 (B_8) (Tab. 7, Fig. 34a).

The greatest erosion caused by the flood was found on the floodplain, on both the left and right bank. Overall, six floodplain areas were eroded and along two of these (F_3, F_5) the bank retreated for more than 20 m, with a maximum of about 80 m along the left bank. In these two areas recruitment of LW was considered only for the data concerning the 20 m–wide buffer, however erosion of the whole surface is shown in figure 33.

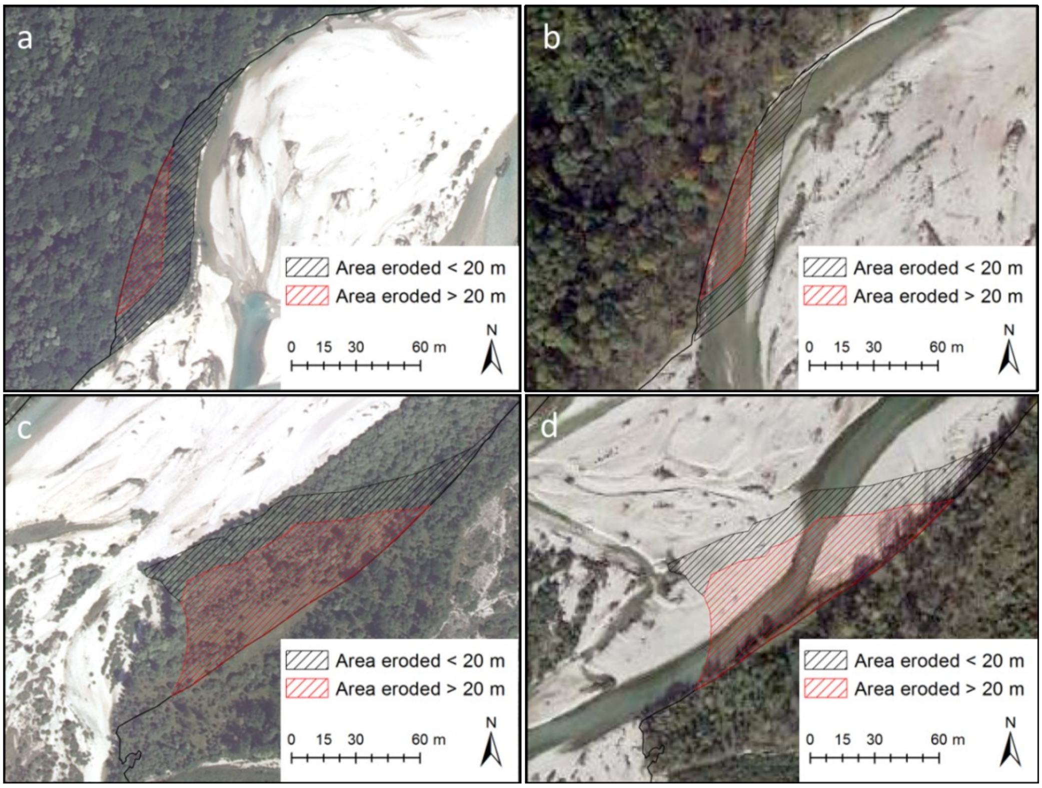


Figure 33: view of two floodplain areas (a, b: F_5; c, d: F_3) with more than 20 m width eroded. Aerial images refer to the first available photo before (a, c: 2012) and after (b, d: 2016) the November 2014 flood.

The variability in eroded area and LW recruitment from patches of the same morphological unit is more evident in the case of floodplain erosion. Indeed, looking at the six eroded areas along the floodplain it is possible to see that there is a difference in the LW volume recruited. For example, along the left riverbank two patches (F_1; F_3) of similar extension (4922.99 and 5128.71 m^2) were eroded but, because of the different tree densities (0.003 and 0.038 $N \cdot m^{-2}$ respectively), they contributed a very different amount of LW input, about 0.84 m^3 and 23.69 m^3, respectively. The biggest contribution in LW input was given by a 3893.66 m^2 eroded patch located on the right riverbank (F_5) from which 337 trees were recruited accounting for a volume of LW equal to 53.65 m^3 (Fig. 34b).

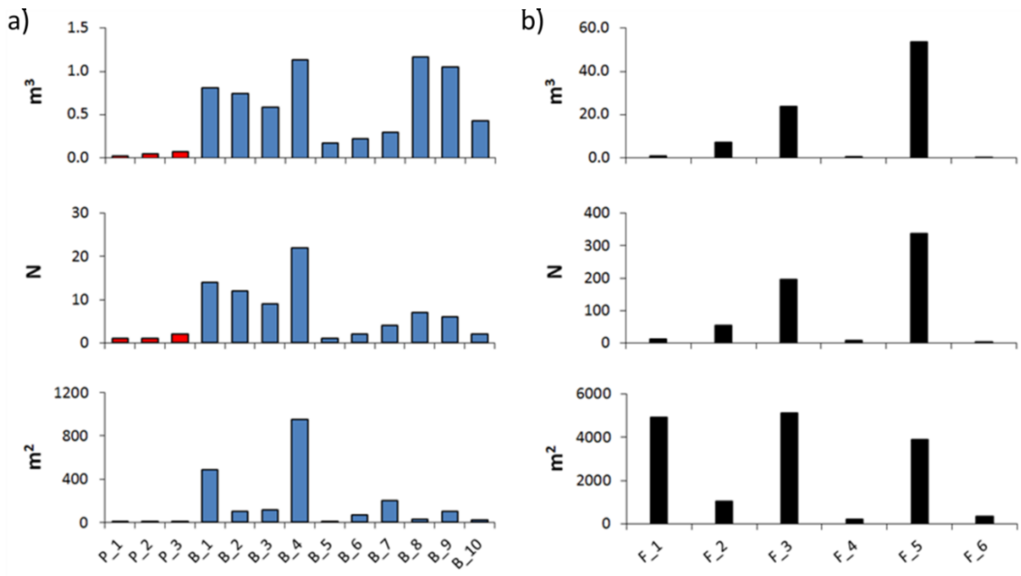


Figure 34: bank erosion (m^2), number of recruited trees (N) and LW input (m^3) for each erosion source, islands (a) and floodplain (b). Letters on x-axis indicate the feature code of each area (P, pioneer islands; B, building islands; F, floodplain) in progressive order downstream. (after Picco et al., 2016a).

Table 8 summarizes the total values of erosion and recruitment for the three morphological units. Overall, with the flood of November 2014, 93.01 m^3 of LW were introduced into the active channel corresponding to 690 recruited trees from an eroded surface of 17676.3 m^2. More in detail, we can note how the floodplain is the most intensely eroded morphological unit (15565.5 m^2), whereas pioneer and building islands have been less intensely eroded (25.2 m^2 and 2085.6 m^2, respectively). Despite the highest density (0.16 tree·m^{-2}), erosion on pioneer islands generated a negligible input of LW (0.14 m^3) because of the small eroded area (25.2 m^2) and because of their initial development they can difficultly support a large number of big trees. Instead, the greater extension of eroded area as well as the larger dimensions of recruited trees from building islands and floodplain resulted in higher LW inputs of 6.62 m^3 and 86.25 m^3, respectively.

Table 8: erosion and recruitment values for the three morphological units. Total values of erosion, recruited trees and LW input are reported. (modified from Picco et al., 2016a)

Morphological unit	Area eroded (m^2)	Trees recruited (N)	N·m^{-2}	Mean height (m)	Mean diameter (m)	Total volume (V)(m^3)	Mean volume (V·N^{-1}) (m^3)
Pioneer island	25.2	4	0.16	4.00	0.11	0.14	0.04
Building island	2085.6	79	0.04	7.10	0.13	6.62	0.08
Floodplain	15565.5	607	0.04	8.20	0.14	86.25	0.14
Total	17676.3	690	-	-	-	93.01	-

Considering the variability in erosion and recruitment rates, a linear regression analysis was performed between erosion surface as independent variable and the amount of trees and LW recruited as dependent variables. As reported in figure 35, there are no trends and no significant correlations (P value > 0.05) between the erosion surface and either the number of recruited trees (R^2=0.052) or the volume of LW input (R^2=0.037).

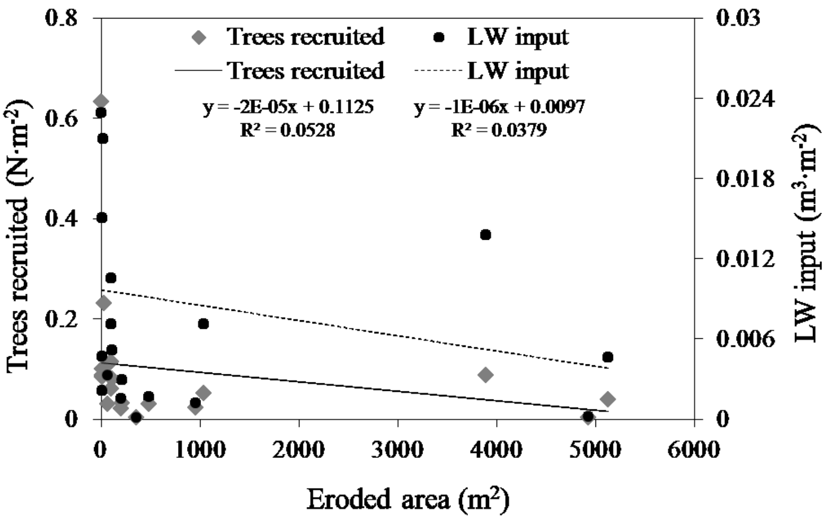


Figure 35: relationship between eroded area and recruited large wood in terms of both number of trees and volume. (modified from Picco et al., 2016a)

4.1.2. Large wood recovery and traveled distance

The applied methodology also permitted investigation of the distance travelled by the recruited trees. In fact, by means of numbered tags, it was possible to conduct a recovery analysis. Walking downstream for 10 km from the upper eroded area, every LW deposited in the active channel, on the banks and islands was checked. Of the total 690 recruited trees, 228 were recovered corresponding to a recovery rate of 33.04%. A wide range of traveled distances was observed between each morphological unit and between individual trees of the same area (Tab. 9). Considering the pioneer islands, 75% of recruited trees were recovered with a range of traveled distance from a minimum of 122 m to a maximum of 1021 m. Of a total of 79 recruited trees from building islands, only 27 (34%) were recovered with minimum and maximum traveled distances of 2 and 3737 m. The longest traveled distance (8927 m) was by a floodplain tree of 0.15 m in diameter and 7 m in height. However, the trees of this morphological unit also show the minimum recovered distance (1 m) of the overall dataset. Looking at the mean values, mean traveled distance increases moving from trees of pioneer islands (422 m), to building islands (623 m) and, finally, to floodplain (1052 m).

Table 9: recovery rates and large wood traveled distance ranges for different morphological units. (after Picco et al., 2016a)

Morphological unit	Trees recovered (N)	Recovery rate (%)	Min traveled distance (m)	Max traveled distance (m)	Mean traveled distance (m)
Pioneer island	3	75.0	122	1021	422
Building island	27	34.0	2	3737	623
Floodplain	198	32.6	1	8927	1052

Figure 36 illustrates the sizes (diameter and height) of recruited and recovered trees for those elements eroded from floodplain (Fig. 36 a-b) and islands (Fig. 36 c-d). Most recruited trees had dimensions in the range of 0.1-0.2 m in diameter (87.5% and 95.2% for trees of floodplain and islands, respectively) and 6-10 m in height (53.4% and 77.1% for trees of floodplain and islands, respectively). From fluvial islands trees of smaller dimensions were recruited, maximum values are 0.3 m and 12 m for diameter and height, respectively. Instead, the tallest trees were recruited from floodplain areas, the biggest recruited element corresponds to a tree of 0.54 m in diameter and 20 m in height but, differently to what was expected, it was not recovered along the surveyed reach, meaning that it probably covered a distance of more than 10 km.

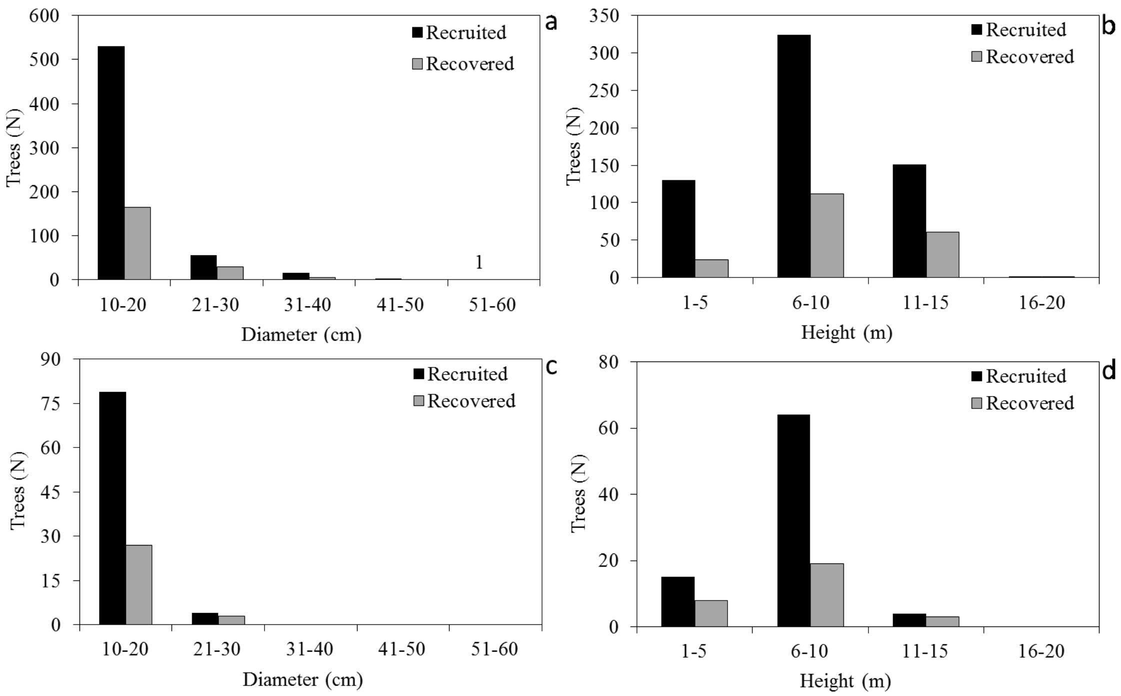


Figure 36: distribution of recruited and recovered trees according to size for trees of floodplain (a-b) and fluvial islands (c-d) (pioneer and building islands are considered together).

The variability of LW traveled distance can be better observed looking at figure 37, which shows frequency distribution of recovered trees for different ranges of traveled distance.

For the three morphological units, more than 60% of recruited and recovered trees were deposited near the recruitment sites, covering distances in the range 0-500 m. Longest distances were covered by floodplain trees, with 5.5% of recovered trees being found at a distance of more than 7.5 km.

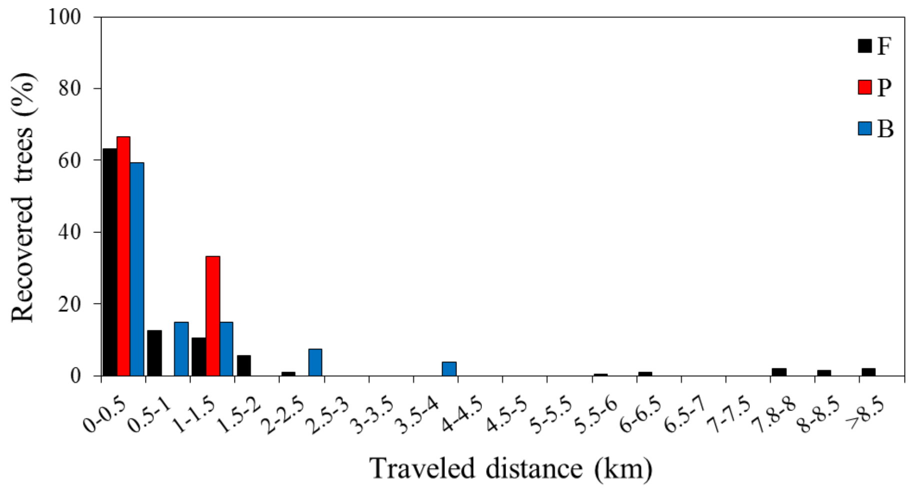


Figure 37: frequency distribution of recovered trees for different ranges of traveled distance for the three morphological units.

Independently from the morphological unit of origin, large wood traveled distances were plotted against some dendrological and physical characteristics of the recovered LW, such as diameter, length (corresponding to tree height), volume and density (Fig. 38). Looking at figure 38a, a decreasing trend in traveled distance for increasing LW diameter can be observed, however the relationship is not statistically significant. Correlation between traveled distance and LW length shows no clear relationship, similar distances were covered by LW of different lengths (Fig. 38b). In the same way, results of the regression analysis considering LW volume and density as independent variables shows no significant relationships with traveled distance. Also in this case, the distance shows a decreasing non-significant trend with increasing piece volume (Fig. 38c) whereas regarding the last variable, LW density, the correlation does not provide any clear information about the relationship with the traveled distance (Fig. 38d).

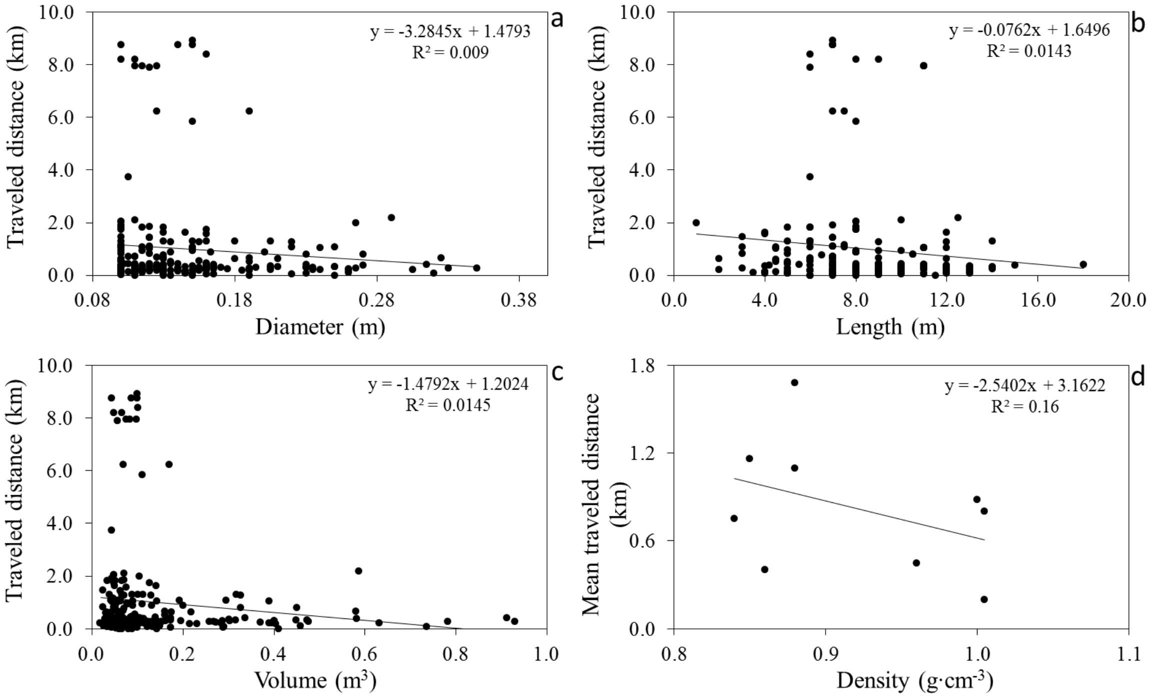


Figure 38: relationship between traveled distance and large wood diameter (a), length (b), volume (c) and density (d). (modified from Picco et al., 2016a)

The site of deposition of each recovered tree was noted and results are reported in figure 39. The most suitable deposition site is represented by gravel bars, where 93.9% of all recovered LW was found. Other elements were recovered within the flowing channel (3.1%) and upstream of building islands (1.3%). Moreover, given the over bankfull characteristic of the flood, some trees (1.8%) were deposited also on the floodplain near the border of riverbanks.

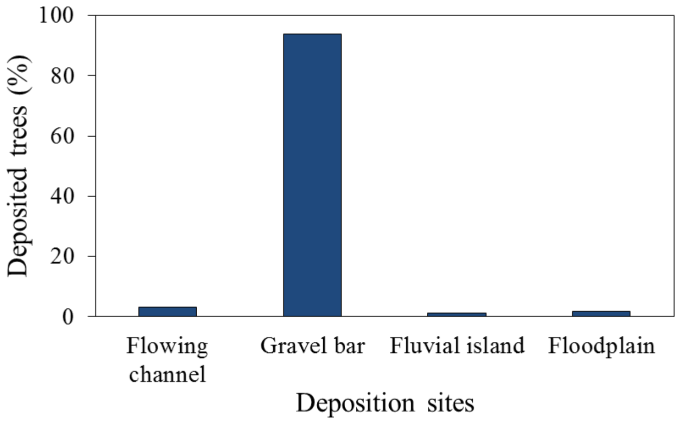


Figure 39: percentage of recovered trees according to the deposition site.

More in detail, considering the deposition sites and traveled distances, a large amount of LW was found that had stopped near the recruitment site after a very short displacement. In some cases, in fact, recruited trees had not traveled very far downstream but were deposited close to the erosion site. The most obvious case regards the F_5 area where 80% of all recruited LW was immediately deposited on the closest gravel bar downstream of the erosion area (Fig. 40). The same site retained around 30% of all LW recruited from upstream areas.

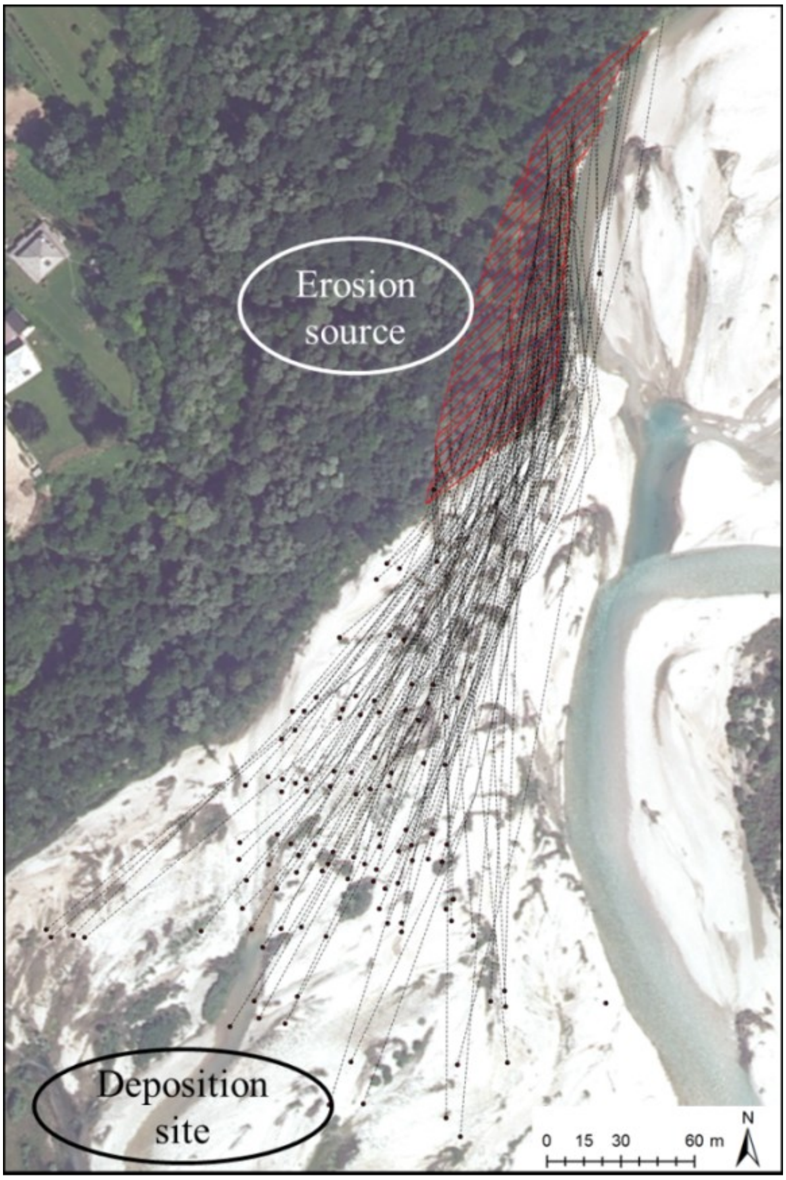


Figure 40: image showing an example of a gravel bar retaining almost all large wood recruited from the nearest upstream eroded area. Black lines have been drawn connecting the position of standing trees and the corresponding deposition point to better understand the proximity between the erosion area and deposition site.

4.2. Evaluation of large wood input from upstream

The contribution of fluvial transport to the LW input from upstream was evaluated for floods of different magnitude following the methodology described in section 3.2.2. In the Piave River, the input was calculated for a period in which only ordinary floods (RI<1) occurred, whereas in the Blanco River a summer period with ordinary floods (RI~1) and an autumn-winter period with large floods (RI 10-25) were considered (Tab. 10).

Along the Piave River, the input of LW is represented by only 39 new elements for a total volume of 1.60 m^3. Mean sizes of new delivered elements are 0.14 m and 2.61 m for diameter and length, respectively. Significantly higher values were obtained in the Blanco River, both during ordinary and large floods. In fact, large wood coming from upstream is very considerable especially during large floods (RI 10-25) when highest values were recorded. In particular, 872, 604 and 836 new woody elements were monitored in reaches 1, 2 and 3, respectively, corresponding to a volume of 222.85 m^3, 132.35 m^3 and 221.78 m^3. Ordinary floods introduced moderate amounts of LW into reach 1 with 138 elements and 38.62 m^3 of wood, and lower in reach 2 where only 6 elements were introduced accounting for a volume of just 1.91 m^3. Overall, mean sizes of new elements are almost similar in diameter ranging from 0.23 m to 0.26 m whereas LW length ranges from 2.77 m to 6.22 m.

Table 10: numbers, volume and mean sizes of LW input along the Piave and Blanco rivers.

	Piave	Blanco				
		reach 1	reach 1	reach 2	reach 2	reach 3
RI (yr)	< 1	~ 1	10-25	~ 1	10-25	10-25
N° LW	39	138	872	6	604	836
Volume LW (m^3)	1.60	38.62	222.85	1.91	132.35	221.78
Mean diameter (m)	0.14	0.25	0.25	0.26	0.23	0.24
Mean length (m)	2.61	4.23	3.28	6.22	2.77	3.10

To allow a comparison between the two rivers, table 11 reports the numbers and volume of LW input normalized per active channel area. The input is almost negligible in the Piave River during ordinary floods as it corresponds to 0.02 $m^3 \cdot ha^{-1}$ and less than one element per hectare. The input from upstream in the Blanco River is higher. The lowest LW input was recorded in reach 2 for ordinary floods (2.55 $m^3 \cdot ha^{-1}$) whereas the highest one (285.3 $m^3 \cdot ha^{-1}$) occurred in reach 1 for large floods that introduced more than one thousand elements per hectare.

Table 11: numbers and volume of LW input normalized per active channel area along the Piave and Blanco rivers.

	Piave	Blanco				
		reach 1	reach 1	reach 2	reach 2	reach 3
RI (yr)	< 1	~ 1	10-25	~ 1	10-25	10-25
N° $LW \cdot ha^{-1}$	0.40	173.80	1007.16	8.00	476.15	769.32
Volume LW ($m^3 \cdot ha^{-1}$)	0.02	46.80	285.3	2.55	108.1	204.1

Figure 41 shows the range of diameter and length of new elements classified as LW input in the Piave and Blanco rivers. In the Piave River LW input has smaller dimensions equal to 0.12 m and 2.5 m for the median diameter and length, respectively. The larger diameter is 0.30 m whereas the greatest length is 6.5 m. Comparing the dimensions of LW input among ordinary and large floods in the Blanco River, it is interesting to note that during ordinary events elements of larger sizes were deposited, in terms of both diameter and length. In fact, the median diameter ranges from 0.18 m during large floods to 0.28 m during ordinary ones and, in the same way, the median length is 2.1 m and 6.1 m in correspondence to large and ordinary events, respectively.

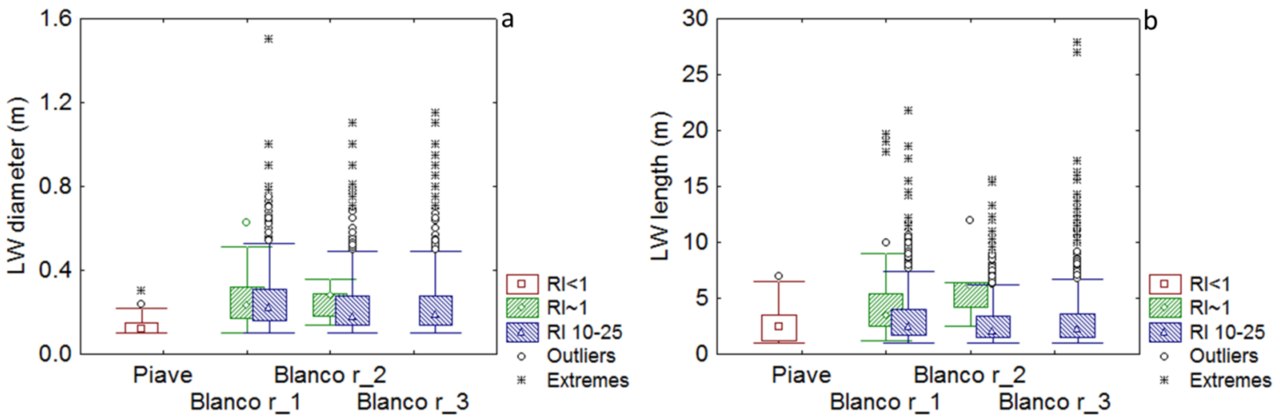


Figure 41: range of diameter (a) and length (b) of LW input in the Piave and Blanco rivers according to magnitude of flood events.

For each new element introduced into the Piave and Blanco rivers a series of qualitative characteristics were noted during the field surveys, such as type, state of aggregation and orientation to the flow in order to better describe the mechanism of LW input from upstream.

Considering the type of LW input five different categories were found: trees, logs, shrubs, roots and residues (Fig. 42). In all cases, logs are the predominant category of LW input. More in detail, in the Piave River the LW input is represented by more different types. In fact, a discrete portion of trees (~8%) and shrubs (~20%) was found even if logs remain the predominant category (~59%). It is also worth noting that ~8% of new elements are harvesting residues. Moving to Blanco River, LW input is formed almost entirely of logs especially in reach 2 where during ordinary floods only logs were delivered. Trees are present in lower quantity, from a minimum of ~3% to a maximum of ~15%. Roots, when present, are less than 1% of total delivered elements.

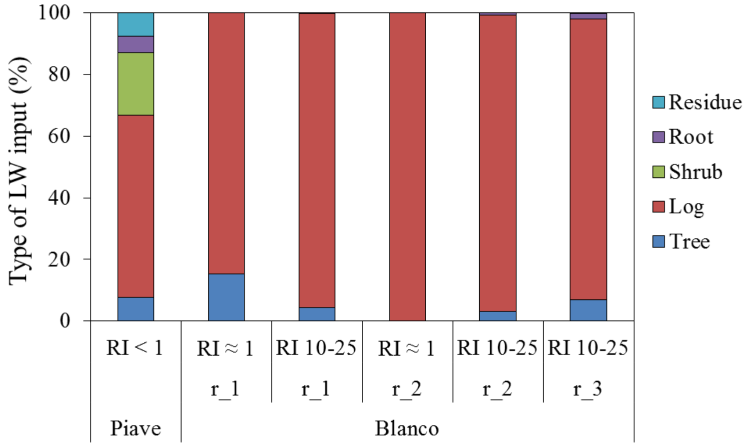


Figure 42: types of LW input along the Piave and Blanco rivers.

The second noted characteristic is the state of aggregation of new elements, distinguishing between single pieces and pieces deposited in a jam (Fig. 43). In the Piave River, the majority (~77%) of LW was deposited as single elements whereas just the 23% (9 N) has been deposited in jams. In the Blanco River the state of aggregation of new input varies among both reaches and time periods. Elements delivered during ordinary floods were deposited only as single pieces in reach 2 whereas entirely in jams in reach 1 forming five new accumulations with a mean number of 27.6 elements per jam. For the input during large floods, the predominant deposition is in the form of accumulation, in fact more than the 83% of pieces were deposited in jams.

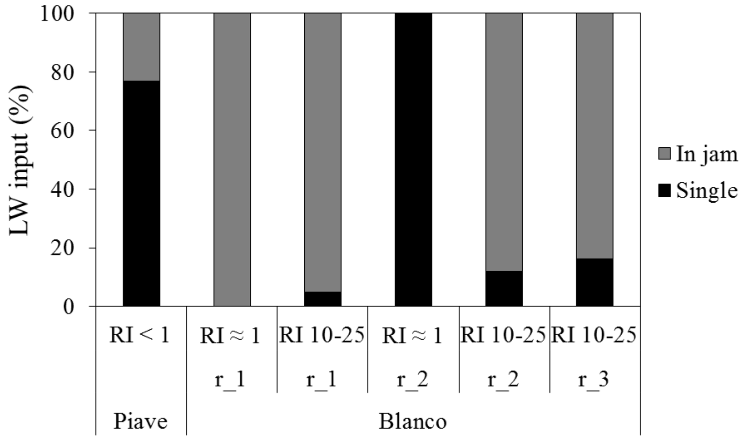


Figure 43: type of deposition of LW input according to state of aggregation along the Piave and Blanco rivers.

The third noted characteristic regards the type of deposition according to the orientation in respect to the main flow direction: parallel, orthogonal and oblique (Fig. 44). Analysis of the collected data revealed that, differently to what was expected, there is not a predominant orientation for woody elements transported with flow. In fact, the main type of deposition is represented both by parallel and oblique orientation without any relationship with the magnitude of floods. Parallel orientation is the most common in the Piave (~ 61%) and, in the Blanco, within reach 1 during ordinary events (~ 55%) and reach 2 during large floods (~ 43%). Instead, oblique orientation prevails for large floods in reach 1 (~ 52%) and 3 (~ 40%) and for ordinary floods in reach 2 (~ 67%).

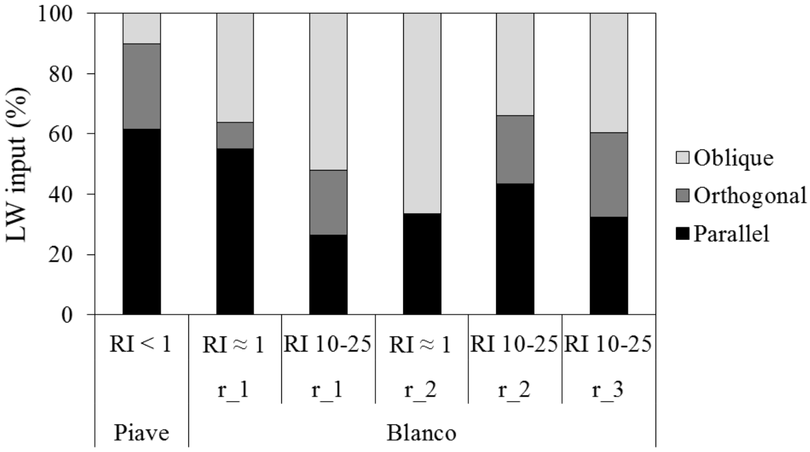


Figure 44: orientation to the flow of LW input along the Piave and Blanco rivers.

A further consideration on LW input was made by relating the input volume with the active channel width. In the case of Blanco River, the width was obtained on the basis of cross sections done in the field with a DGPS, whereas in the Piave River it was calculated from aerial images of 2016. In particular, the 3 km-long study reach was divided in several sub-reaches calculating a mean width for each sub-reach that was related to the volume of LW input deposited within the corresponding sub-reach.

No statistically significant relationship (p-value > 0.05) was identified, however the scatter of points in figure 45 shows that the relationship is not linear and is better explained by an exponential function. Despite the non-significance, in the case of Blanco River an increasing volume of LW input for increasing values of active channel width can be observed (Fig. 45b).

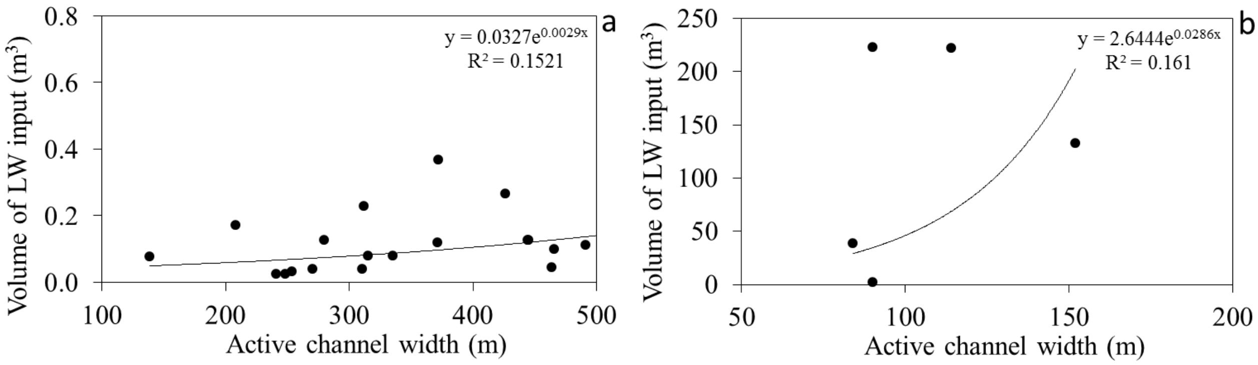


Figure 45: relationship between LW input volume and active channel width for the Piave (a) and Blanco (b) rivers.

Further analyses on LW input from upstream were performed considering the position of new deposited elements with respect to the distance from the thalweg. The analyses allowed more information to be gained regarding the wetted area, as the portion of active channel inundated during floods and the presence of possible relationships between the distance of deposition from the thalweg and the sizes of LW (i.e. diameter, length). In the case of the Piave River which also has secondary channels, the distance was measured considering the elements supposedly delivered from the main channel separately from those delivered from the other one. However, only one LW was assumed to have been transported from a secondary channel, and it was deposited 35 m away from the thalweg.

Considering the main channel of the Piave River (Fig. 46), new delivered elements were deposited up to 70 m from the thalweg, whereas the minimun deposition distance was 5 m. Looking at the deposition according to LW dimensions, an increasing distance from thalweg was expected for increasing sizes of LW. This did not occur in the Piave River, either for the diameter or length. In fact, there are no clear trends on the distance according to the LW dimensions as elements of similar sizes were deposited at different distances. In particular, in both cases, smaller pieces show a very broad range of distances. Nevertheless, it is interesting to note that, in terms of diameter, the largest transported piece (0.3 m) was deposited at the farthest distance (70 m) but this is not verified for length, as the longest element (7 m) corresponded to a distance of 21 m.

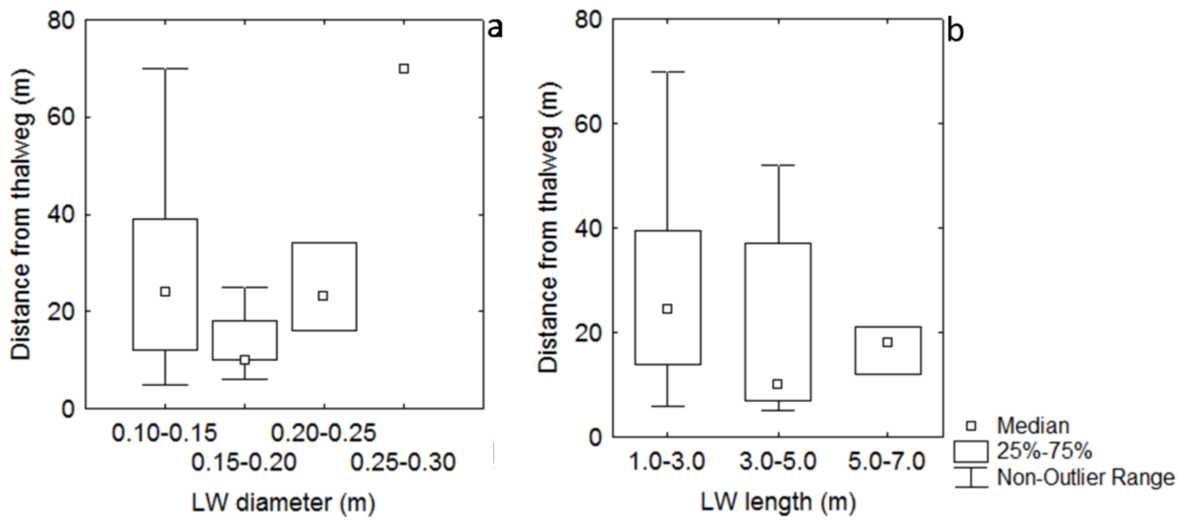


Figure 46: distance of deposition from the thalweg according to sizes (a, diameter; b, length) for the input elements deposited along the Piave River.

In the case of the Blanco River, the analysis was performed considering the input of LW delivered during ordinary (Fig. 47) and large (Fig. 48) floods separately. During ordinary floods (Fig. 47), woody elements were deposited very close to the thalweg in reach 2, with minimum and maximum distances of 0.70 m and 4.70 m, respectively. Given the very low number of input LW (6 N), further considerations about distance from thalweg and LW sizes are quite difficult to make. Instead, in reach 1 a larger area of the active channel was affected by ordinary floods as LW was deposited up to ~ 60 m from the thalweg. Also in this case there are no evident differences in the deposition of LW according to its diameter and length. Median distances, in the range 44-47 m, show similar values for different classes of diameter and length. The largest woody element, a log 0.63 m in diameter and 5.2 m in length, was recorded at a distance of 51 m from the thalweg.

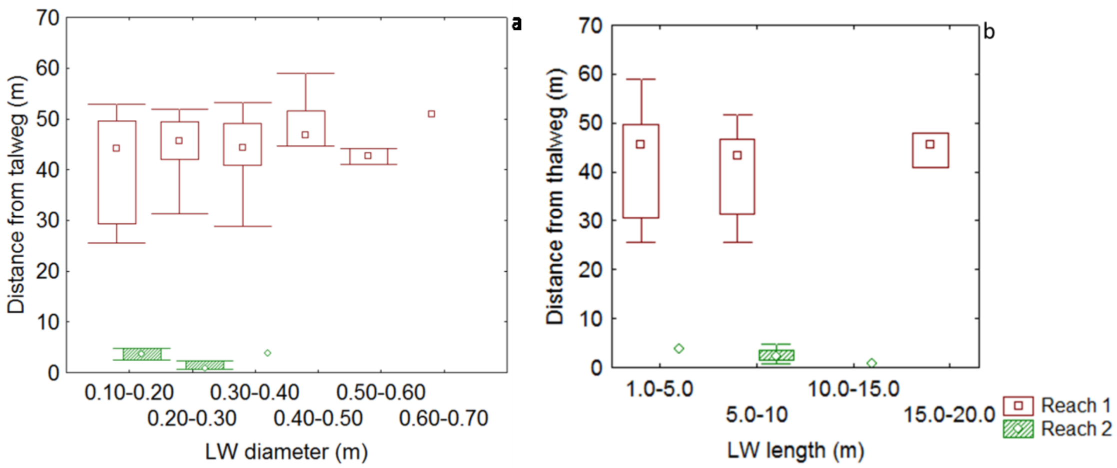


Figure 47: distance of deposition from the thalweg according to the LW diameter (a) and length (b) for the input elements deposited during ordinary floods along the Blanco River.

As expected, for large floods the inundated active channel area increased, especially in reaches 2 and 3 where maximum deposition distances are 135 m and 130 m, respectively (Fig. 48). Similarly to what was found for ordinary floods, also in this case the deposition distances appear not to be related to the diameter of woody pieces, as the median values are almost similar for each diametric class. Despite these similarities it is possible to highlight how, in reachs 2 and 3 the highest median distance was recorded for elements of larger sizes. The highest median distance of reach 2 is for LW diameters greater than 0.70 m whereas the highest median distance of reach 3 is for LW diameters of 0.60-0.70 m. The relationship between deposition and wood sizes is clearer looking at the length of transported wood, but only for reach 1. In this reach, apart from pieces of the first two classes where median distance is similar (4.5 m), the median deposition distance increases with increasing length, up to a maximum distance of 34 m recorded fo a 22 m-long log.

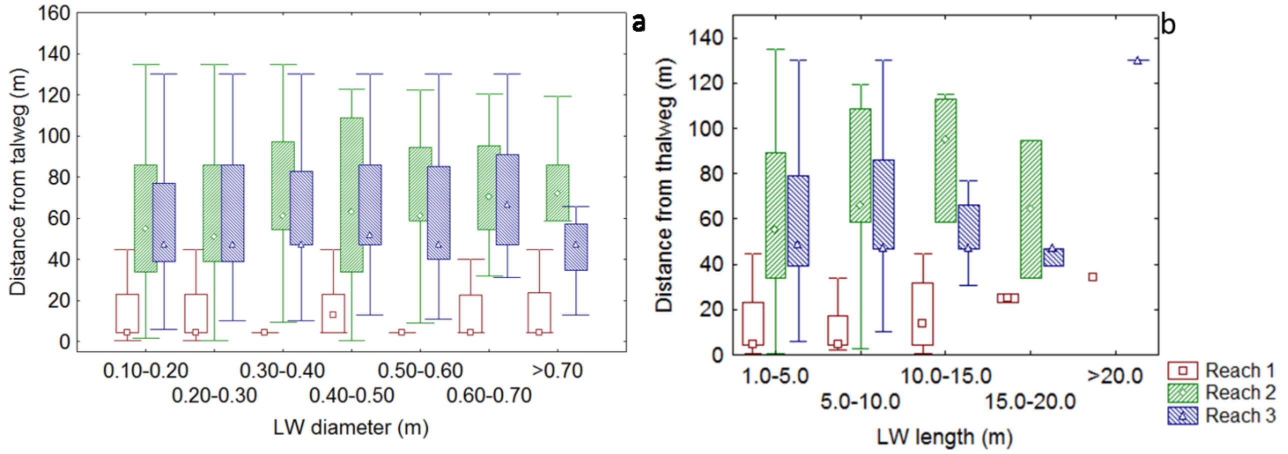


Figure 48: distance of deposition from the thalweg according to LW diameter (a) and length (b) for the input elements deposited during large floods along the Blanco River.

4.3. Evaluation of large wood output from downstream

The downstream output of LW through fluvial transport was evaluated similarly to the input from upstream presented in the previous section.

In the Piave River, only 32 elements were transported downstream during ordinary floods, representing an output of 2.65 m^3 (0.03 $m^3 \cdot ha^{-1}$). Mean sizes of moved pieces are 0.16 m and 3.60 m in diameter and length, respectively. Similarly to the input, in the Blanco River the output of LW is considerable. Similar quantities of LW were mobilized during ordinary floods in reach 1 (40.04 m^3, 50.42 $m^3 \cdot ha^{-1}$) and reach 2 (39.18 m^3, 52.25 $m^3 \cdot ha^{-1}$), even if the number of transported pieces is slightly different at 208 (261.96 $N \cdot ha^{-1}$) and 139 (185.33 $N \cdot ha^{-1}$) elements in reach 1 and 2, respectively. Considering the effects of large floods, 183 (230.48 $N \cdot ha^{-1}$) and 181 (202.44 $N \cdot ha^{-1}$) woody elements were transported downstream from reach 1 and 2, respectively, representing a loss of LW equal to 64.41 m^3 (81.12 $m^3 \cdot ha^{-1}$) and 60.04 m^3 (67.15 $m^3 \cdot ha^{-1}$). However, despite the greater magnitude (RI 10-25), the output of LW in reach 2 during large floods is the lowest recorded value of 108 pieces (144 $N \cdot ha^{-1}$) for a corresponding volume of 21.15 m^3 (28.20 $m^3 \cdot ha^{-1}$) (Tab. 12, 13).

Table 12: numbers, volume and mean sizes of LW output along the Piave and Blanco rivers.

	Piave	Blanco				
		reach 1	reach 1	reach 2	reach 2	reach 3
RI (yr)	< 1	~ 1	10-25	~ 1	10-25	10-25
N° LW	32	208	183	139	108	181
Volume LW (m^3)	2.65	40.04	64.41	39.18	21.15	60.04
Mean diameter (m)	0.16	0.21	0.25	0.25	0.25	0.24
Mean length (m)	3.60	3.49	4.81	3.61	2.77	4.59

Table 13: numbers and volume of LW output normalized per active channel area along the Piave and Blanco rivers.

	Piave	Blanco				
		reach 1	reach 1	reach 2	reach 2	reach 3
RI (yr)	< 1	~ 1	10-25	~ 1	10-25	10-25
N° $LW \cdot ha^{-1}$	0.33	261.96	230.48	185.33	144.00	202.44
Volume LW ($m^3 \cdot ha^{-1}$)	0.03	50.42	81.12	52.25	28.20	67.15

Results of the mobility and retention rates are summarized in table 14. For the study reach of Piave River, where only floods of low magnitude occurred, almost all (98.57%) of the LW was not mobilized. The mobility rate is very low, 1.43%. In the Blanco River it was possible to compare, for study reaches 1 and 2, the mobility of LW according to the magnitude of floods. In both cases, mobility rate is lower during ordinary floods than large ones, increasing from 64.20 to 72.05% in reach 1, and from 41.62 to 53.73% in reach 2. The greater capacity of large floods to remove a higher quantity of LW is confirmed observing reach 3. This reach, for which only large floods were taken into account, shows the highest mobility rate as 94.27% of LW was transported downstream and just 5.73% remained within the study reach.

Table 14: large wood retention and mobility rates (%) in the Piave and Blanco rivers according to the magnitude of flood events.

	Piave			Blanco		
		reach 1	reach 1	reach 2	reach 2	reach 3
RI (yr)	< 1	~ 1	10-25	~ 1	10-25	10-25
Retention rate (%)	98.57	35.80	27.95	58.38	46.27	5.73
Mobility rate (%)	1.43	64.20	72.05	41.62	53.73	94.27

Considering the sizes of LW output (Fig. 49), in the Piave River transported pieces are of small dimensions. In particular, they show a median diameter of 0.15 m and median length of 2.4 m. Differently to what was found for the LW input in the Blanco River, the comparison of sizes of LW output between ordinary and large floods revealed that during ordinary events elements of smaller diameter were transported downstream. In fact, comparing the median diameter of elements mobilized by events of RI~1 yr is 0.17 m for reach 1 and 0.20 m for reach 2, whereas for events of RI 10-25 yr it is 0.24 m and 0.22 m for reach 1 and 2, respectively. The same peculiarity was found in LW length but only in reach 1 where median length is 2.8 m for those elements moved during events of RI~1 yr and 3.5 m during events of RI 10-25 yr. A decrease in the median length was observed in reach 2, decreasing from 2.6 m of ordinary floods to 2.2 m of large floods. Moreover, it is interesting that the biggest elements, in terms of volume, were transported during ordinary floods. A log of 5.85 m^3 (0.7 m in diameter and 15.2 m in length) and a tree of 5.70 m^3 (0.55 m in diameter and 24 m in length) were transported downstream of reach 1 and reach 2, respectively, during floods of RI~1 yr. Instead, observing the mobilization of LW by floods of RI 10-25 yr, the biggest transported pieces are a tree of 4.68 m^3 (0.56 m in diameter and 19 m in length) in reach 1 and a tree of 2.93 m^3 (0.63 m in diameter and 9.4 m in length) in reach 2.

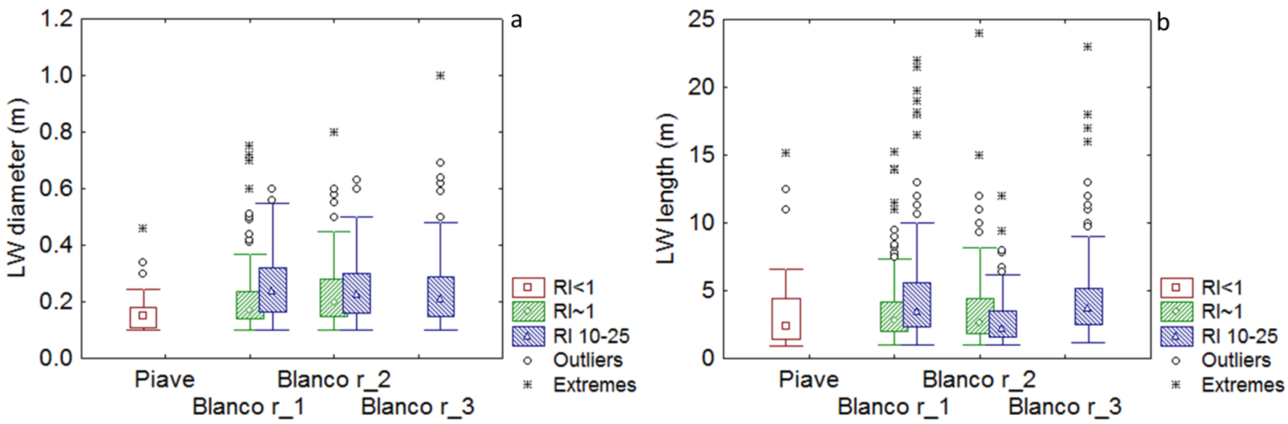


Figure 49: range of diameter (a) and length (b) of LW output in the Piave and Blanco rivers according to the magnitude of flood events.

More in detail, figure 50 illustrates, for the Piave and Blanco rivers, the distribution of moved pieces according to LW sizes. In the Piave River more than 80% of mobilized pieces were less than 0.2 m in diameter whereas more than 70% were less than 4 m in length. The largest moved elements were, considering the diameter, a 0.46 m-decaying root while, considering the length, a 15.1 m-tree partially submerged in the main channel. Also in the reaches of Blanco River the vast majority of moved LW is included in the smaller size classes. At least 55, 50 and 46% of LW in reach 1, 2 and 3, respectively, had a diameter less than 0.2 m while 67, 78 and 59% of LW in reach 1, 2 and 3, respectively, had a length less than 4 m.

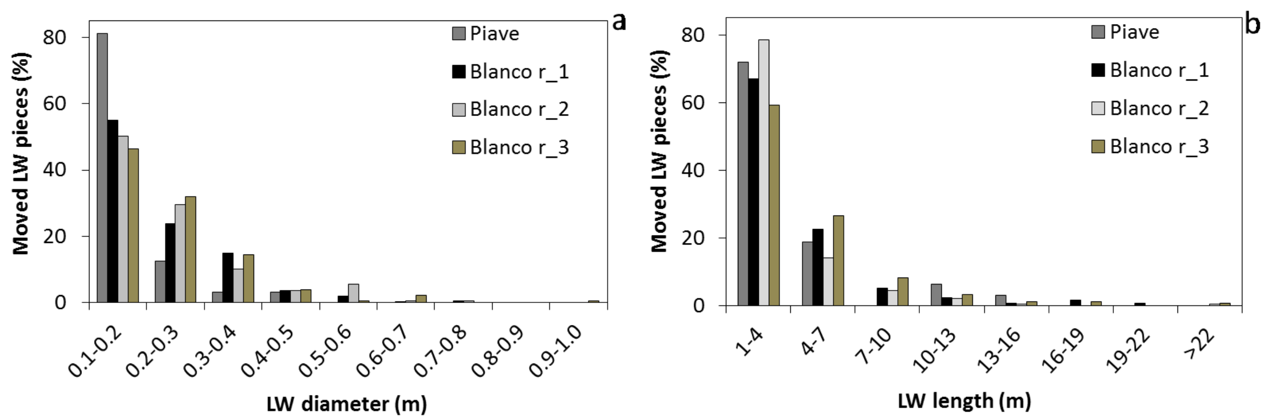


Figure 50: percentages of total moved pieces by diameter (a) and length (b) in Piave and Blanco rivers.

From the analysis of the type of LW output (Fig. 51), no differences were found with respect to the types of LW input. In fact, in the Blanco reaches LW output was almost only logs, the highest amount of transported trees (15%) was found in reach 1 for large floods, in the remaining cases the presence of trees is less than 10%. Also in this case, the Piave River shows a higher variability in the type of LW output. Logs were still the prevalent category (~40%), with a similar amount

(~18%) of trees and shrubs. Harvesting residues (~9%) and roots (~12%) were also involved in the downstream transport.

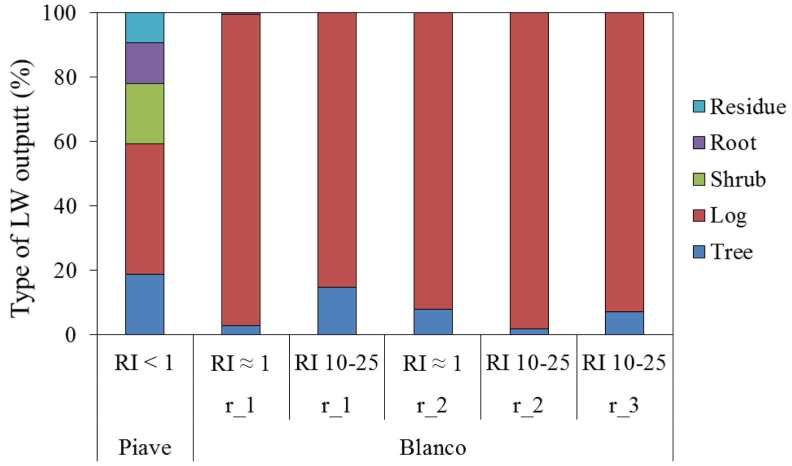


Figure 51: types of LW output along the Piave and Blanco rivers.

A further analysis was conducted considering the state of aggregation of mobilized pieces (Fig. 52). In the Piave River, the majority (62.5%, 20 N) of transported elements were previously deposited as single pieces, while only 37.5% (12 N) was jammed. Overall, 10 jams were partially modified with the removal of just 1-2 elements per jam. No accumulation was completely removed (Tab. 15). In the reaches of Blanco River the vast majority of moved LW (> 76%) was aggregated in jams and, in many cases, accumulations were entirely transported downstream. As reported in table 15, the number of reshaped accumulations varies between 4 and 20 jams per reach transporting up to 102 LW pieces per jam. Considering accumulations that have been completely removed, the largest one, in terms of number of elements was a jam formed by 57 elements where their removal accounted for an output of LW equal to 10.32 m^3.

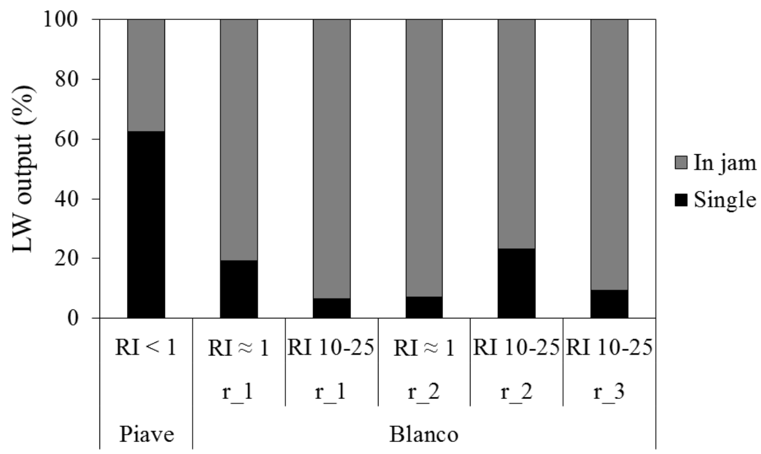


Figure 52: state of aggregation of remobilized LW along the Piave and Blanco rivers.

Table 15: main characteristics of accumulations affected by LW removal during downstream transport.

	Piave	Blanco				
		reach 1	reach 1	reach 2	reach 2	reach 3
RI (yr)	<1	~1	10-25	~1	10-25	10-25
N° jams modified	10	18	17	7	20	4
Range of pieces per jam	2-14	2-67	2-72	2-109	2-50	7-104
Range of mobilized pieces per jam	1-2	2-49	2-51	2-102	2-15	7-96
N and % of jams completely removed	0-0.0	5-27.8	4-23.5	2-28.6	12-60.0	2-50.0

Considering the in-channel position of mobilized LW, the distance from the thalweg was calculated and the portion of active channel inundated by floods was estimated. However, this estimate was only made for the Blanco reaches as the presence of multiple channels in the Piave River and the scattered arrangement of output elements made the computation rather uncertain.

The histogram in figure 53 shows the frequency of moved pieces in the Piave River according to the distance from the thalweg. As already presented in section 4.2, distance was measured considering separately the elements supposedly moved from the main channel from those moved from the secondary one. Along the main channel LW was moved to distances from the thalweg of 0-90 m, with the farthest LW recorded at 104 m. The majority of LW that was transported downstream was located quite close to the thalweg, within a range of 0-10 m (25%) and 10-20 m (29%). Distances are in a narrower range in the case of the secondary channel, where LW mobilization occurred up to 70 m from the thalweg. However, differently from the main channel, in this case the majority (43%) of moved elements were not located in proximity to the thalweg but in a range of 40-50 m.

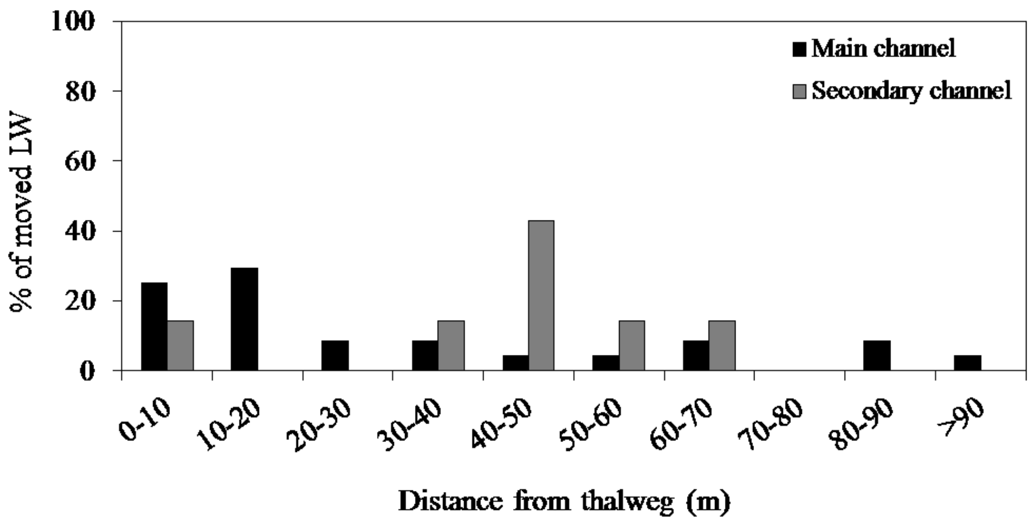


Figure 53: frequency (%) of moved pieces in the Piave River according to distance from the thalweg.

The same analysis was performed for the Blanco River considering the LW elements moved during ordinary (Fig. 54a) and large (Fig. 54b) floods separately. Results show some differences, between study reaches and magnitude of floods, in the inundated active channel area. The lowest percentage of flooded area (43%) was found for reach 2 during floods of RI~1 yr. In this case, LW mobility was concentrated just along the left side of the active channel, transporting only woody pieces that were located 5-25 m from the thalweg. The majority (~ 47%) was 10-15 m away from the thalweg. Instead, during the same period, in reach 1 there was mobility over 70% of its active width and LW was transported up to 75 m from the thalweg. Considering the mobilization of LW by floods of RI 10-25 yr, LW transport happened over the entire width of reach 1, and almost the total width (85.0%) of reach 2, confirming the higher discharge. Farthest distances were 77 m and 60 m for reach 1 and 2, respectively. Within reach 3, given the absence of LW along the right bank, it was not possible to identify the limit of the flooded area during large floods. However, LW transport was recorded over the total width of the active channel storing LW, pieces moving 65 m from the thalweg.

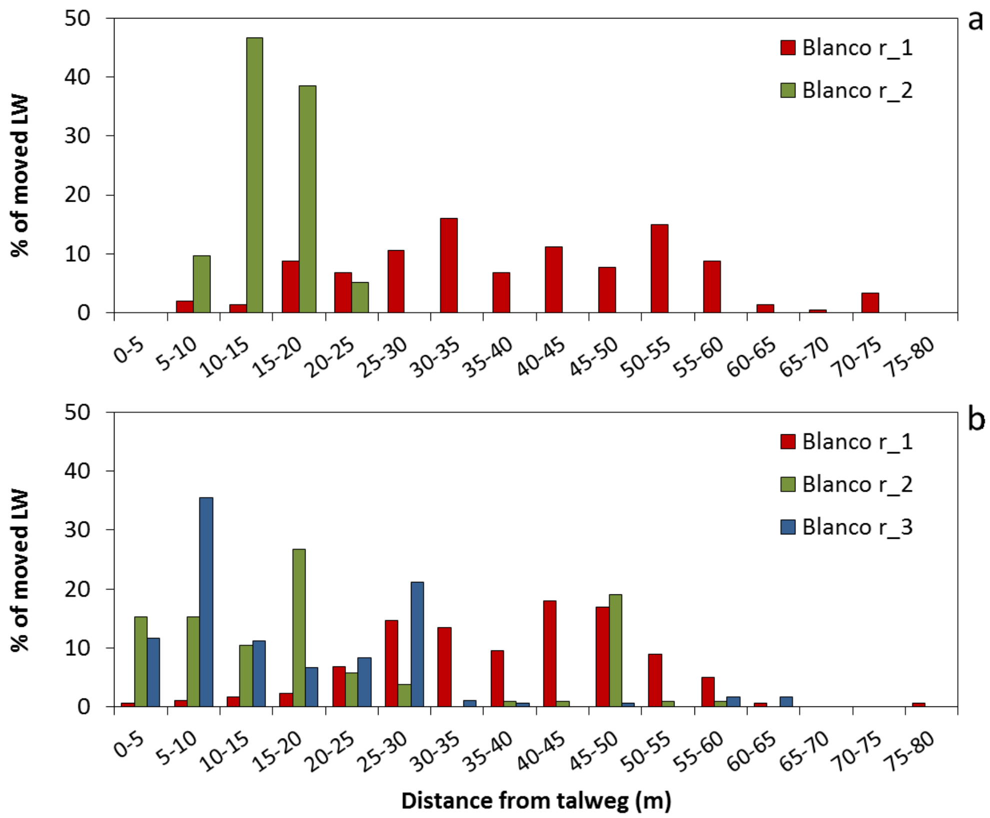


Figure 54: frequency (%) of moved pieces in the Blanco River reaches according to the distance from the thalweg during ordinary (a) and large (b) floods.

4.4. Estimation of exhumation of buried large wood

This section reports the results concerning the estimation of buried LW in the Blanco River. However, being the first attempt with GPR application to detect LW buried in a fluvial environment, results focus more on the feasibility of the methodology and calibration device rather than the amount of buried LW than could be exhumed and contribute to the budget.

The first application of GPR was devoted to its calibration on volcanic soils in terms of wave velocity propagation and resolution with different antenna frequencies (250 and 500 MHz). From the first calibration, a waves velocity propagation of 90 $m \cdot \mu s^{-1}$ and 100 $m \cdot \mu s^{-1}$ was obtained for wet and dry soils, respectively (Tab. 16). Moreover, the velocity did not appear to vary according to the antenna used but a decrease was observed in waves velocity with increasing depth of penetration. This variation was detected only in the top two meters, where the velocity decreased from 100 $m \cdot \mu s^{-1}$ to 90 $m \cdot \mu s^{-1}$.

Table 16: waves velocity propagation of GPR according to type of soil.

Soil	Waves velocity ($m \cdot \mu s^{-1}$)
Wet	90
Dry	100

Considering the two different antennas used in this study, both the 250 and 500 MHz have proved to be able to estimate the depth of recent volcanic sediments. However, the lower frequency antenna provided a better resolution of the radargram in which the separation between sediment layers is clearer (Fig. 55).

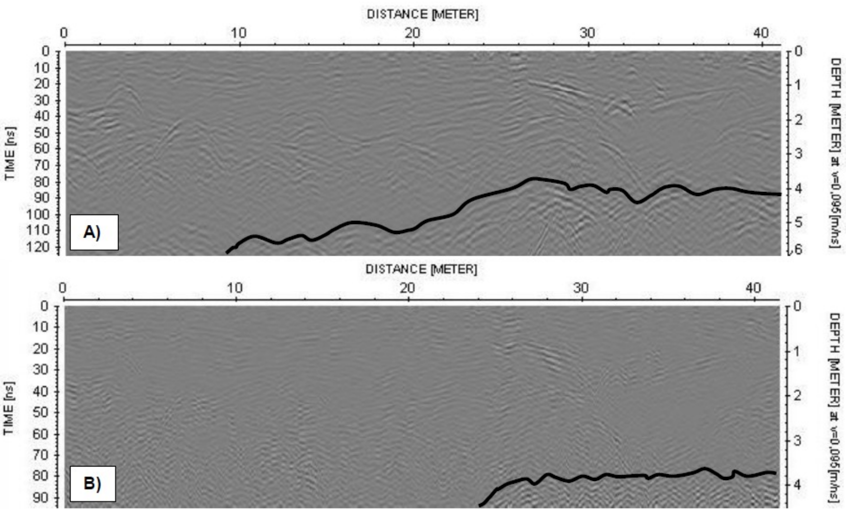


Figure 55: example of radargram obtained from the same survey with the 250 MHz (a) and 500 MHz (b) antenna. The black line indicates separation between layers. (after Valdebenito et al., 2016)

Once the waves velocity propagation was known, the GPR was tested to understand the capacity to detect buried LW. As already described in section 3.2.3, logs artificially inserted at different depths were used as “control points” in order to analyze the coincidence between reflections generated by buried objects and hyperbolas recorded on radargram. The use of “control points” revealed the ability of GPR to detect buried LW, in fact, as illustrated in figure 56, it is possible to appreciate the correspondence of hyperbolas on the radargram with the position of the inserted log. The association between each hyperbola reflection and the presence of buried LW was achieved with both antennas, however, also in this case the better resolution was obtained with 250 MHz antenna as reflections generated hyperbolas that are more easily detectable.

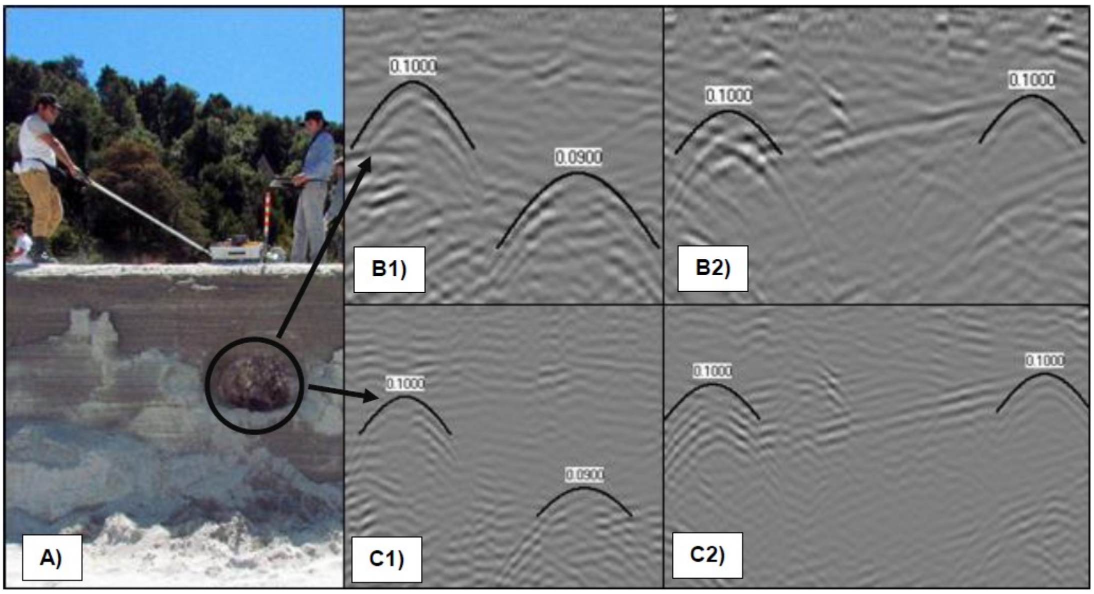


Figure 56: image showing the GPR surveying a “control point” (a) and the corresponding radargrams obtained with the 250 MHz (b1, b2) and 500 MHz (c1, c2) antenna. (after Valdebenito et al., 2016)

The GPR was subsequently used to survey the two study areas (area 1 and 2) providing different results that reflect the different survey scheme. In fact, analyzing the radargrams it was possible to associate each hyperbola reflection with the presence of buried wood in both areas, but just in study area 1 it was also possible to detect the same wood log on two parallel radargrams. This was not possible in study area 2 due to the too high inter-distance between two profiles (5 m), whereas study area 1 was surveyed with an inter-distance equal to 3 m.

Detection of the same log on multiple radargram profiles is very important because it allows the LW shape and length to be reconstructed. Considering just the radargrams of study area 1, a 3-D model representing the surveyed zone was developed intersecting longitudinal and transversal radargram profiles (Fig. 57).

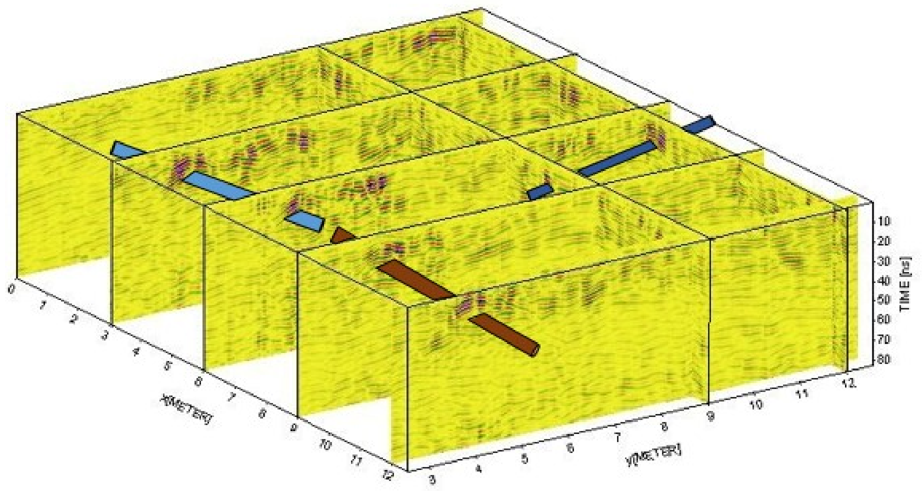


Figure 57: a 3-D model representing a portion of study area 1. The red and blue cylinders show the position of possible buried wood. (after Valdebenito et al., 2016)

From the 3-D model a first approximation of log length was made on the basis of those hyperbolas of the same elements that were visible on two adjacent profiles. Instead, it was not possible to estimate the LW diameter starting from radargrams due to the difficulty of assigning a value to the amplitude of hyperbolas. As a first approach, the diameter of buried LW was assumed to be equal to the mean diameter (0.07 m) of logs deposited above the surface. On the basis of these LW dimensions, almost 0.04% of the entire volcanic deposits was estimated to be buried wood with an approximate volume of 0.8 m^3 that, normalized per active channel area and river length, corresponds to 1.65 $m^3 \cdot ha^{-1}$ and 2.96 $m^3 \cdot km^{-1}$.

4.5. Assessment of large wood budget

4.5.1. Ordinary flood events along the Piave River

The large wood budget assessed for the study reach of the Piave River consists of a short-term balance that evaluates the variations in LW storage for a 1 year-period with very low floods. The considered study period is from June 2015 until June 2016 and the corresponding water discharge is illustrated in figure 58. Just ordinary floods occurred in this period, in particular two events with a peak discharge of ~ 100 $m^3 \cdot s^{-1}$ (R.I < 1 yr) were recorded in October 2015 and February 2016, and other two with a peak of ~ 85 $m^3 \cdot s^{-1}$ (R.I < 1 yr) were recorded in March 2016 and June 2016.

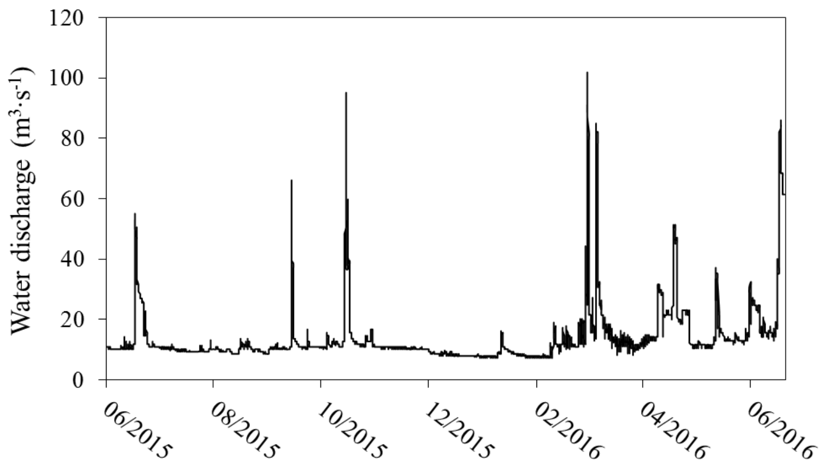


Figure 58: maximum hourly discharge on the Piave River as measured at Belluno gauging station during the period June 2015-June 2016.

The budget was developed adapting the original framework of Martin and Benda (2001) to the Piave River study case. The budget thus takes the lateral recruitment due to bank erosion and fluvial transport into and out of the river stretch into account. Moreover, as wood in the study reach is harvested by local residents, an additional component was introduced to the budget that represents the output of LW due to human actions. Although this export of LW cannot be related to flood events or other fluvial processes, we decided to consider it anyway in order to assess a more comprehensive budget.

Figure 59 reports an aerial image of the reach with the position of all LW monitored during the study period. Each color refers to a budget item, distinguishing between the position of recruited trees, new deposited LW elements, pieces transported downstream, harvested residues and, lastly, the location of all woody elements whose position was not modified during the study period.

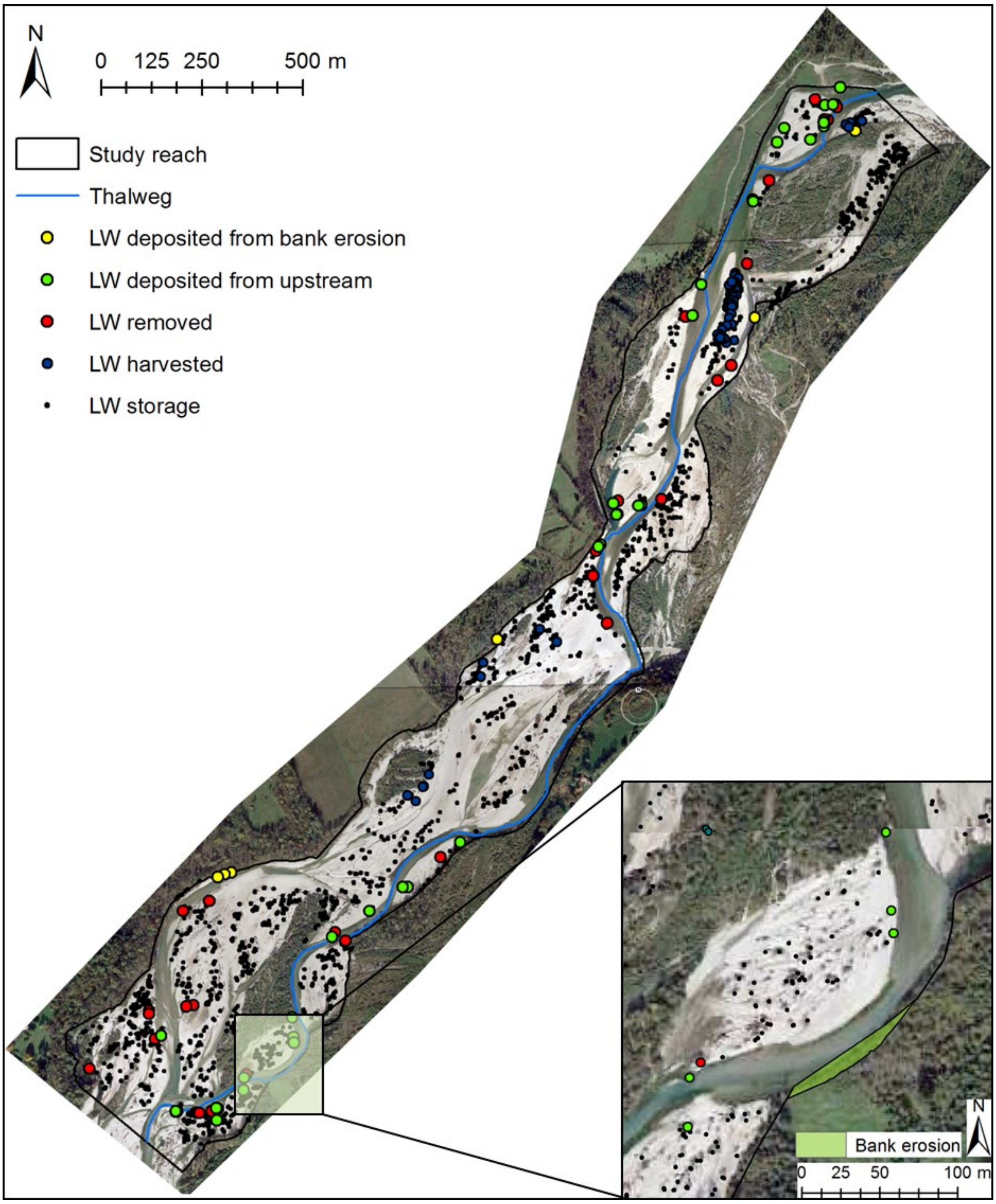


Figure 59: aerial image of the Piave River study reach showing distribution of in-channel LW according to the budget components. The zoom at bottom right shows the active channel area affected by bank erosion.

The low magnitude of the events that occurred during the study period reflects the low values of riverbank erosion, in fact bank erosion was found only in a single patch located at the downstream end of the reach, in the only stretch where the main channel flows in proximity to the bank and there is no bank protection (Fig. 59). The eroded surface is about 690 m^2 with a maximum width of 9 m. However, recruitment of LW from this eroded area is null due to the absence of trees with a diameter equal to or greater than 0.10 m. Only shrubs of small dimensions were recruited.

The lateral input of LW is instead represented by 6 trees that were located on the top and along the edge of riverbanks and that fell during the study period. Recruited trees had a mean diameter of 0.15 m and a mean length of 7.25 m, providing a total wood volume of only 0.79 m^3 (0.21 $m^3 \cdot km^{-1}$) (Tab. 17). Comparing the in-channel position of new trees with their position before recruitment, it was possible to see how they were not transported downstream after the erosion but just uprooted and deposited near the falling point. All recruited trees were deposited as single pieces.

Table 17: number, sizes and volume of recruited trees along the Piave River study reach.

	Recruited trees
N°	6
% single	100
% in jam	0
Range and mean diameter (m)	0.11-0.21 (0.15)
Range and mean length (m)	4.5-9 (7.25)
LW volume (m^3)	0.79
LW volume ($m^3 \cdot km^{-1}$)	0.21

As depicted in figure 59, recruited trees were mainly located far from the main flowing channel, except for three elements that were in proximity to a low flow channel. As the magnitude of floods was low and the fact that no bank retreat was recorded, qualitative data of standing recruited trees were considered in order to understand the possible reasons for their recruitment (i.e. state of conservation, presence or absence of branches and leaves) (Fig. 60). Differently from what I thought, only one tree was noted to be already dead before the recruitment and so more prone to falling. The analysis of the state of conservation revealed that all trees were intact with complete bark suggesting a recent recruitment, whereas the observations of the presence/absence of branches highlighted that half of them still had all branches suggesting also in this case a recent fall and that transport did not occur. Concerning leaves, the majority had none, only two trees had leaves after the fall into the active channel.

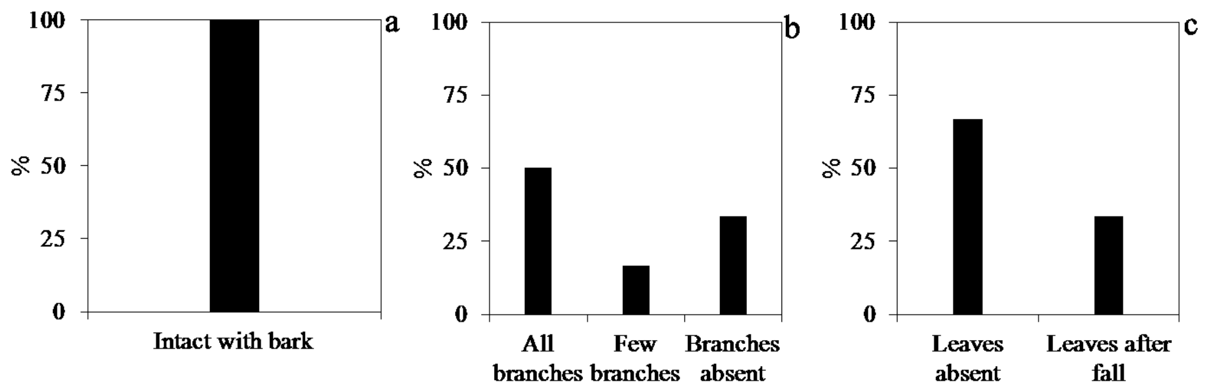


Figure 60: main qualitative characteristics of recruited trees in terms of state of conservation (a), presence or absence of branches (b) and leaves (c).

The LW budget during the study period is illustrated in Figure 61, depicting the numbers of woody elements involved in each process, and in Table 18 that reports volumetric values.

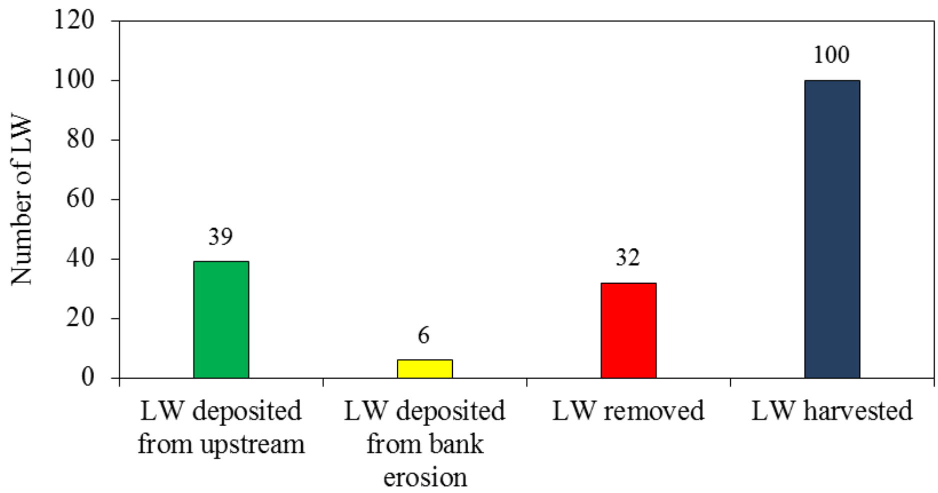


Figure 61: numbers of woody elements involved in the LW input and output processes along the study reach of the Piave River.

Among the input processes it is possible to see that, for low magnitude events, the contribution of lateral recruitment is almost half that of fluvial transport. Out of the total LW input volume (2.39 m^3, 45 N), 67% (1.60 m^3, 39 N) is due to transport from upstream while only 33% (0.79 m^3, 6 N) is from bank erosion. Regarding the output processes, given the short temporal scale and absence of over bankfull floods, only the LW mobilization and transport out of the reach was considered. In this case, the amount of LW transported downstream (2.65 m^3, 32 N) was just 0.7% of all in-channel LW population stored at the beginning of the study period but, if compared to the amount of LW deposition from upstream, a slight prevalence in mobilization can be noted. Large wood volume mobilized is, in fact, higher than the volume deposited even if the overall number of input elements is greater. Comparing the sizes (Fig. 62), no relevant differences were found between input and output elements. Median diameter is slightly higher in output (0.15 m) than input elements (0.12 m), whereas median length shows a reverse pattern as it is higher in input (2.5 m) than output (2.4 m). The unit volume is almost similar in the two categories, and corresponds to 0.03 $m^3 \cdot N^{-1}$ and 0.04 $m^3 \cdot N^{-1}$ for input and output elements, respectively. However, despite the similarities in median dimensions and volume, among the LW transported downstream there are three elements of larger sizes than most of the others that, together, contribute 40% of the total volume exported.

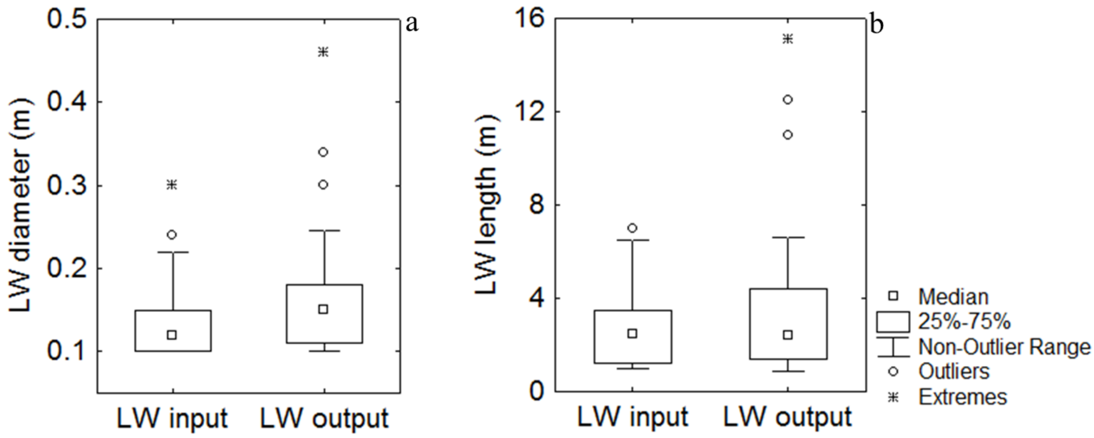


Figure 62: range of diameter (a) and length (b) for woody elements involved in the input and output processes.

As evident from figure 61, it is important to point out that, in the case of a human impacted river, the greatest variations in LW storage can be related to harvested wood. During the post event survey, one hundred tagged elements were no longer found on their original position and, in some cases, only the rootwads were present. As for their location in areas distant from any flowing channels or areas topographically too high to be flooded (on the basis of field evidences), these elements were considered to have been harvested by local residents. Overall, this output corresponds to about 34 m^3 (0.35 $m^3 \cdot ha^{-1}$) and, even if of anthropic origin, it plays an important role in the budget computation.

If anthropic output is not taken into account, the capacity of ordinary floods to induce variations in the amount of LW storage can be considered almost insignificant as input and output volumes are very balanced. The balance is negative as large wood removal tends to slightly exceed deposition, reducing the volume present at the beginning of the study period by just 0.3 m^3 (0.1 $m^3 \cdot ha^{-1}$), from 386.9 to 386.6 m^3. Instead, considering also the harvested LW, the difference between input and output processes led to a more consistent decrease (-9.7%) of in-channel LW. The volume in the first survey of 386.9 m^3 reduced to 352.6 m^3 in the second survey, with a negative variation of -34.3 m^3 (-0.35 $m^3 \cdot ha^{-1}$).

Table 18: summary of LW budget in the study reach of the Piave River for ordinary flood events (RI<1yr).

	LW volume (m^3)	LW volume ($m^3 \cdot ha^{-1}$)
Initial volume	386.9	4.0
LW deposited from upstream	1.60	0.016
LW deposited from bank erosion	0.79	0.008
LW removed	2.65	0.027
Final volume	386.6	3.9
Δs (%)	**-0.07**	**-0.07**
Δs (m^3)	**-0.3**	**-0.1**
LW harvested	34	0.35
Final volume	352.6	3.6
Δs (%)	**-9.7**	**-9.7**
Δs (m^3)	**-34.3**	**-0.35**

As depicted in figure 59, deposition and mobilization of LW occurred along the whole study reach and mainly in proximity to flowing channels. To evaluate the possible presence of preferential stretches for these processes, the position of deposited and moved LW in respect to the longitudinal profile of the river was considered.

With a length of 3.7 km and a channel slope of 0.35%, the longitudinal profile of the main channel is characterized by the riffle pool sequences typical of mountain and piedmont gravel-bed rivers. Except for a single recruited tree, which represents the highest volume of LW input (0.23 $m^3 \cdot$tree), deposition and mobilization of LW appear to have occurred in three main zones of the study reach, the upstream part, the downstream one and a zone located almost in the middle of the reach. These zones can be identified as three sub-reaches with a gradient equal to 0.37, 0.39 and 0.35% for sub-reach 1, 2 and 3, respectively (Fig. 63, 64). The mean active channel width increases from 214 m of sub-reach 1 to 350 m of sub-reach 3, whereas the maximum number of flowing channels is higher in the downstream sub-reach 3.

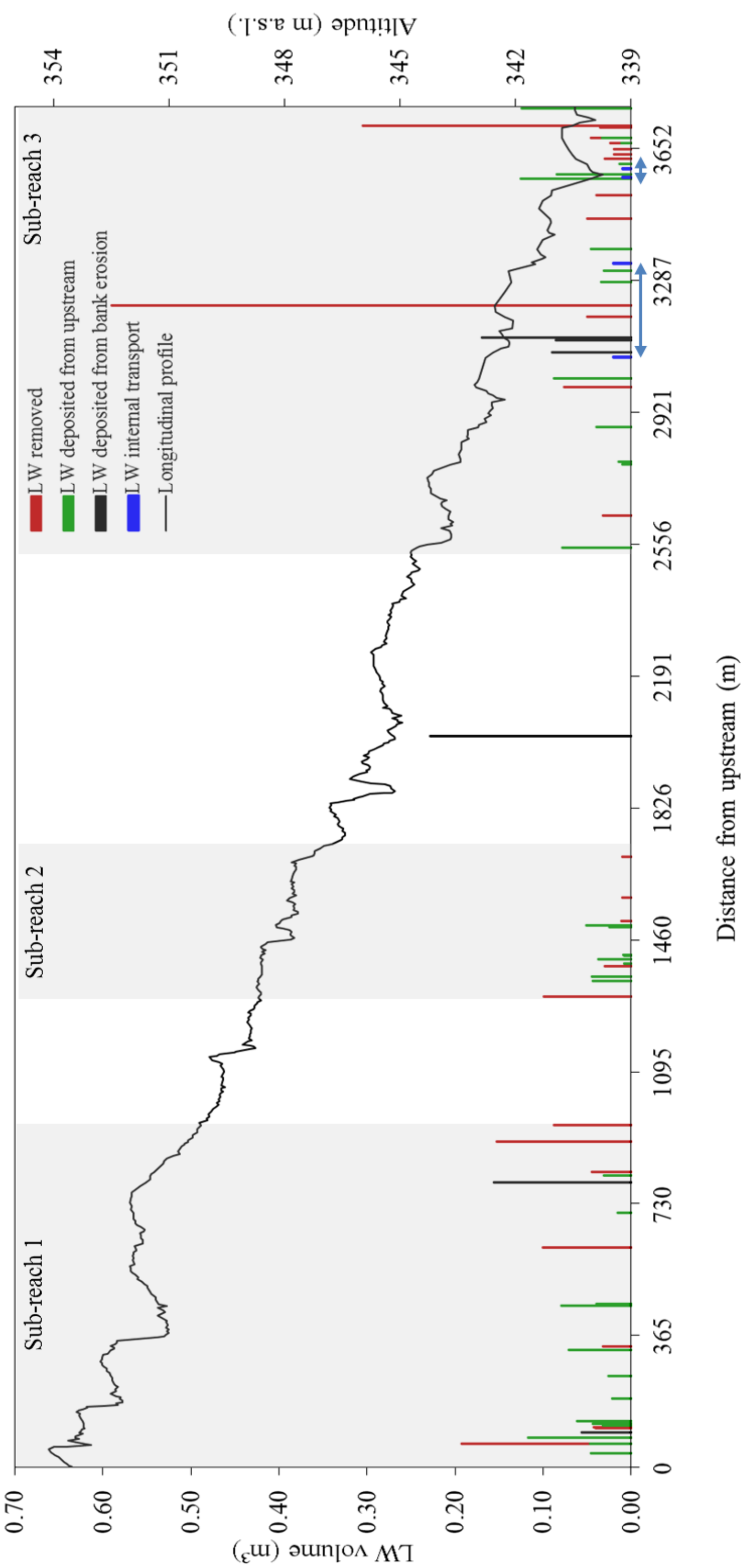


Figure 63: distribution of LW volume moved and deposited along the longitudinal profile of the main channel. (The blue arrows below the graph indicate the displacement of those two elements that moved inside the reach).

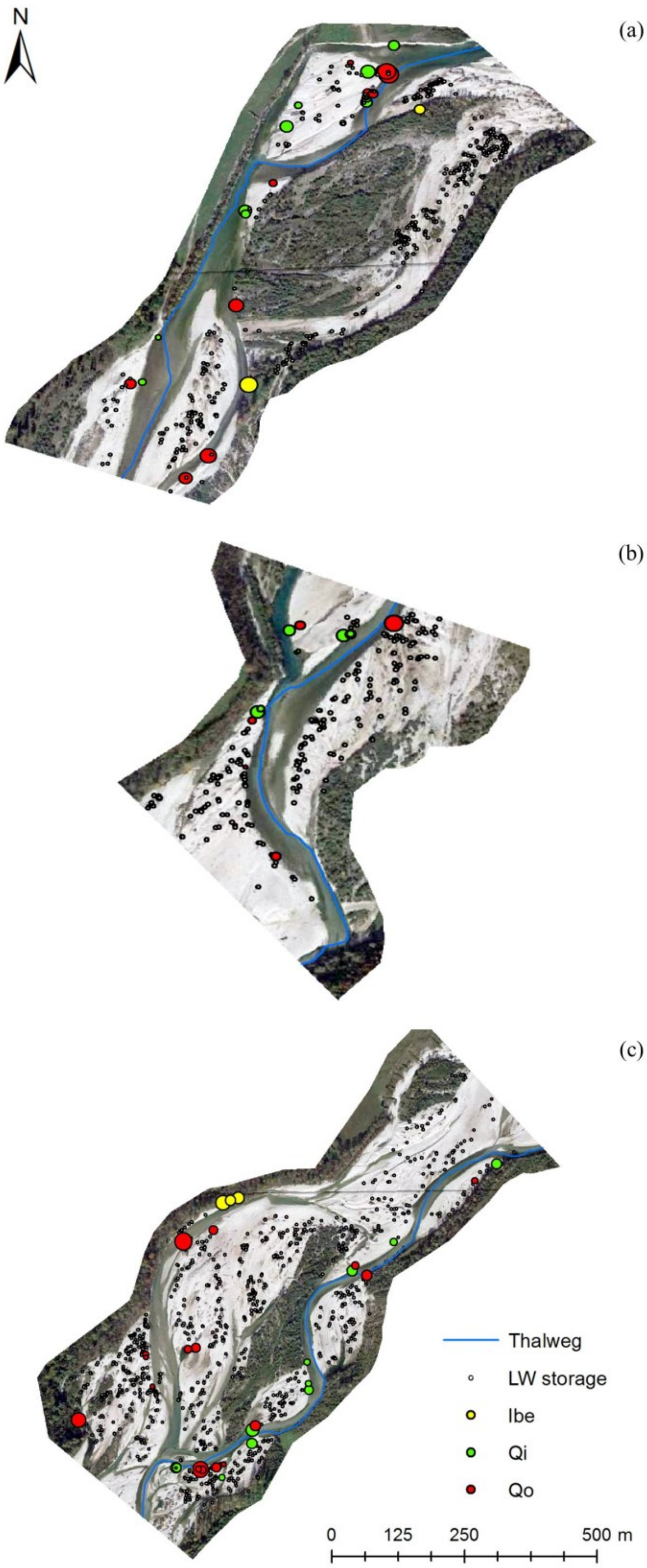


Figure 64: aerial photo of sub-reach 1 (a), 2 (b) and 3 (c) showing the position of LW recruited from bank erosion (I_{be}) and LW transported from fluvial transport into (Q_i) and out (Q_o) of sub-reaches. Sizes of input and output marks varies according the LW volume.

Out of the total LW volume mobilized, 53% was found in the upstream sub-reach (Fig. 65a), exporting 0.93 $m^3 \cdot km^{-1}$ of LW, whereas the input from upstream (0.67 $m^3 \cdot km^{-1}$) represents 40% over the total input from fluvial transport. Although lateral recruitment supplied the sub-reach with two trees for a LW volume of 0.21 m^3, deposition of LW (49%) was not able to balance the mobilization (51%) resulting in a slight reduction of LW (-0.04 $m^3 \cdot km^{-1}$).

Differently from the upstream sub-reach, in the sub-reach 2 the variations in LW storage are given only by transport processes into and out of the stretch, as no trees were recruited (Fig. 65b). Exported and imported volume is 0.39 $m^3 \cdot km^{-1}$ and 0.55 $m^3 \cdot km^{-1}$ and represents only 9.5% and 14.3% of the overall amount of output and input, respectively. Contrarily to what was found upstream, here there is a prevalence of deposition processes (59%) over those of mobilization (41%), even if this did not cause substantial variations in LW storage (+ 0.16 $m^3 \cdot km^{-1}$).

Despite the presence of a higher number of flowing channels and fluvial bars, the process of LW mobilization is dominant (57%) in the downstream sub-reach (Fig. 65c). Here, the volume per unit of channel length of LW moved during floods results as 1.17 $m^3 \cdot km^{-1}$. Deposition of LW in the sub-reach 3 represents the 43% and is given by 0.60 $m^3 \cdot km^{-1}$ by transport from upstream and by 0.28 $m^3 \cdot km^{-1}$ by lateral recruitment.

The prevalence of LW mobilization produced a negative variation (-0.29 $m^3 \cdot km^{-1}$) in the LW storage. In addition to the input and output processes, two single elements were found that moved within this sub-reach. These were a 0.02 m^3 decaying harvest residue with a diameter 0.14 m and length of 1.3 m whose traveled distance, measured following the thalweg line, was approximately 254 m, and a 0.01 m^3 decaying log with a diameter and length of 0.11 m and 1.1 m, respectively, that moved downstream for 33.5 m. However, this internal transport do not affect the budget computation as, given the short transport distance, this element remained within the study reach without influencing the LW storage.

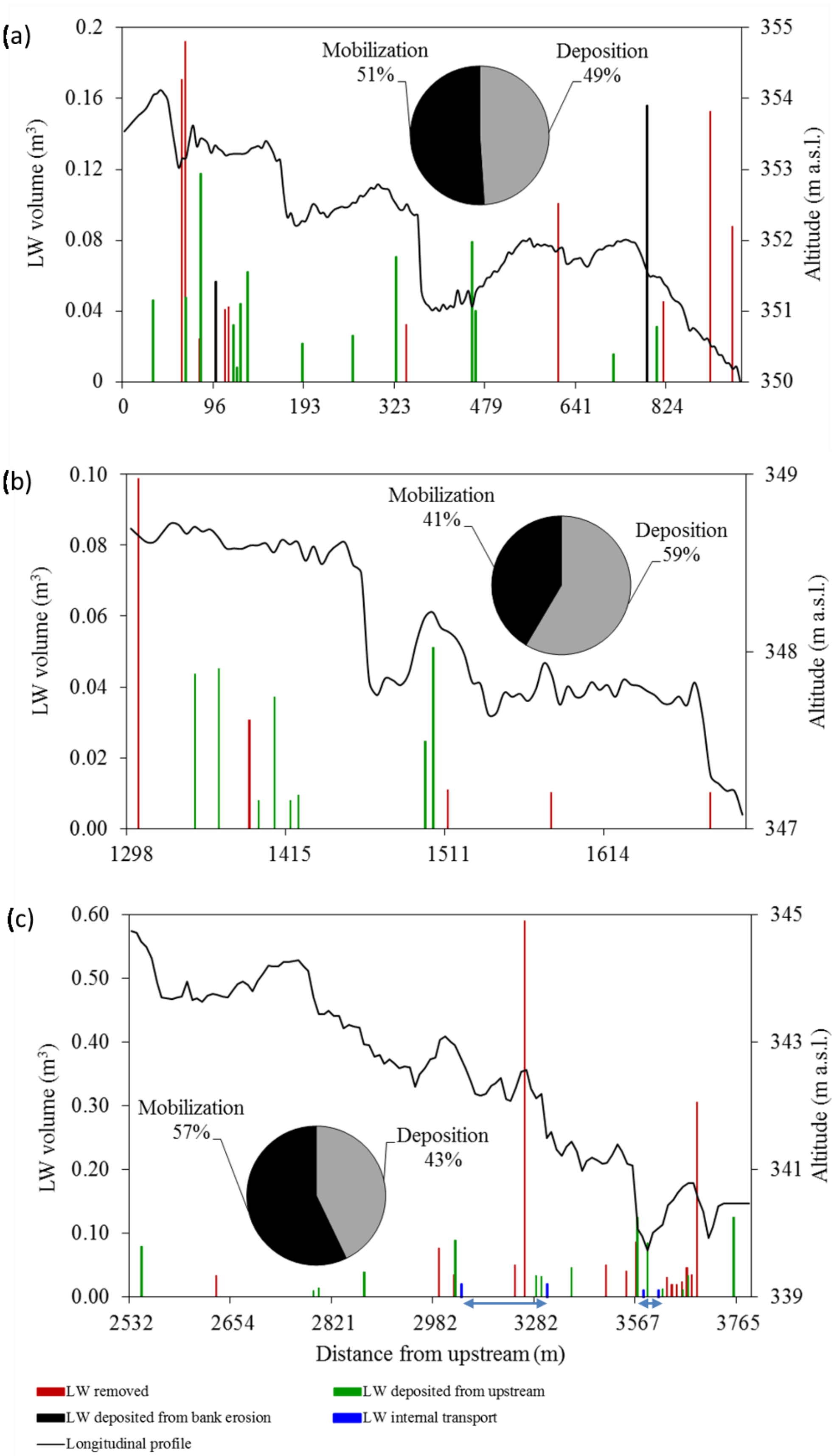


Figure 65: overview of LW volume moved and deposited within sub-reach 1 (a), 2 (b) and 3 (c). Pie charts show fractions of the dominant LW processes. (The blue arrows of the graph below indicate the displacement of those two elements that moved inside the reach).

Table 19: summary of the LW budget at a sub-reach scale along the Piave River for ordinary flood events (RI<1yr). Large wood volume is expressed in $m^3 \cdot km^{-1}$.

Sub-reach	Length (m)	Slope (%)	Mean active channel width (m)	N° max flowing channels	LW deposited from upstream	LW deposited from bank erosion	LW moved	**Δs**
1	960	0.37	214	2	0.67	0.22	0.93	- 0.04
2	416	0.39	216	1	0.55	-	0.39	+ 0.16
3	1236	0.35	350	6	0.60	0.28	1.17	- 0.29

Large wood mobilization and deposition were also investigated through the analysis of the LW elevation above the thalweg, in order to explore the presence of a different elevation among the flooded and not-flooded surfaces.

Large wood was divided into the three main budget items: stored, output and input. The relative elevation was obtained in ArcGIS® using the thalweg of the main channel as a reference surface on which to calculate the difference in elevation between each woody element.

Although the stored LW shows a very broad range of values, with highest elevation in the order of 3.3 m above the thalweg, it is evident (Fig. 66) that the non-mobilized LW lie in a higher position than the two other categories. Observing the median values, elevations of 1.48 m, 1.03 m and 1.08 m were obtained for LW stored, output and input, respectively. The range of elevation is narrower in the case of LW output and input, suggesting that flood levels remained modest.

It is interesting to note that these ranges are quite similar, especially in the maximum value. The highest elevation above the thalweg was found to be 1.99 m for deposited and 2.20 m for mobilized elements, which could represent the maximum water stage of the occurred floods. The fact that the maximum elevations for LW deposition are lower than those of LW mobilization can lead to the hypothesis that, in agreement with Ravazzolo et al. (2015a), mobilization may have occurred during the rising limb of the hydrograph until the peak of the flood, while deposition probably started shortly after the peak and continued during the receding phase of the flood.

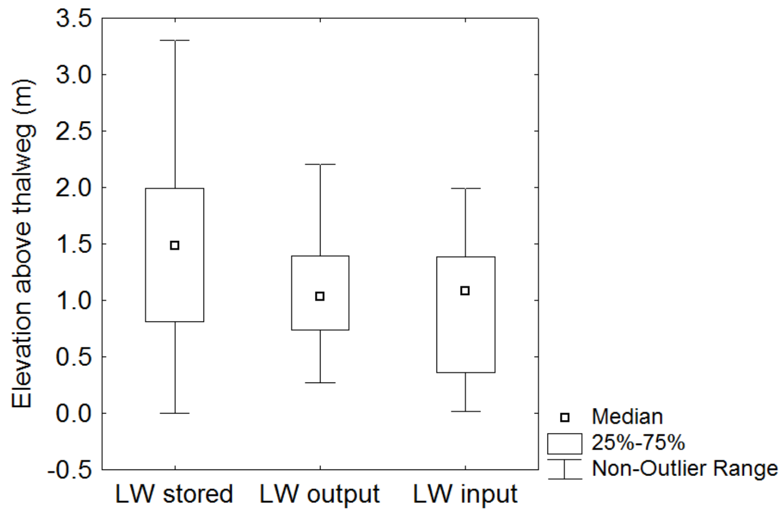


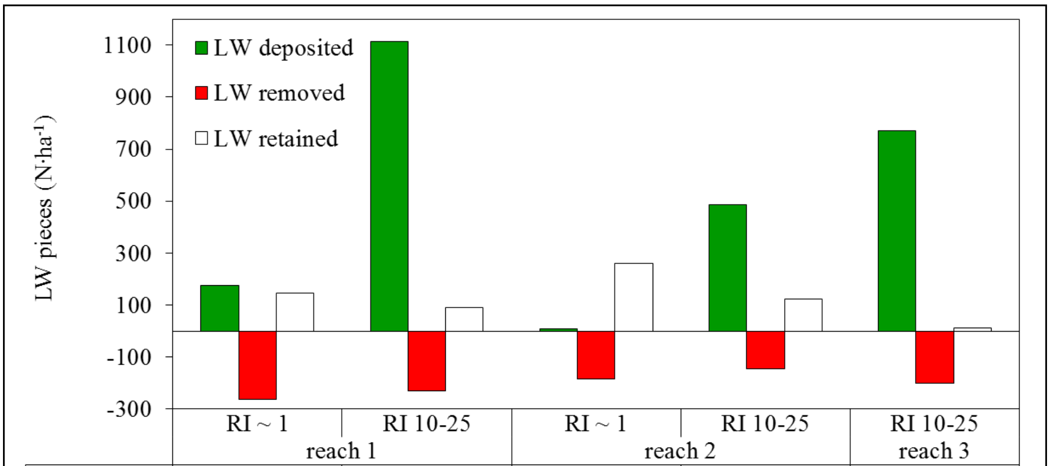
Figure 66: range of elevation above the thalweg for stored, output and input woody elements.

4.5.2. Ordinary and large flood events along the Blanco River

This section presents the assessment of large wood budget for the study reaches of Blanco River. Two different budgets were constructed, one for a short period of about two months (January 2015-March 2015) considering the variations in LW storage for summer floods within reaches 1 and 2, and another for variations induced by autumn-winter floods occurred during a period of nine months (March 2015-January 2016) for reaches 1 and 2, and one year (March 2015-March 2016) for reach 3. Because of a lack of hydrological measurements after summer floods of 2015 as the gauging station was damaged, the magnitude of floods occurred during the overall study period (January 2015-March 2016) was calculated using data from three monitoring stations located in the area surrounding the Blanco River basin. Summer floods were classified as ordinary events because the recurrence interval (R.I.) was estimated to be ~1 yr, whereas floods occurred during the autumn-winter period were classified as large floods with a R.I. of 10-25 yr. There were no relevant floods during the summer season of 2016, so the budget assessed for reach 3 refers only to large floods.

The budget of LW in the Blanco River takes into account only variations in LW storage due to fluvial transport, as the differences between LW deposited from upstream and LW transported downstream. The budget was constructed for each reach and study period, highlighting differences among reaches and periods. Results are expressed both in terms of variations in numbers and volume. To allow a comparison among study reaches, values normalized per active channel area are reported.

The Blanco River is characterized by a great flux of LW also during lower magnitude events. During ordinary floods (RI~1), the amount of LW deposited in the reach 1 is 46.8 $m^3 \cdot ha^{-1}$, almost twenty times higher than in reach 2, where the input volume is in the order of only 2.5 $m^3 \cdot ha^{-1}$. Instead, the amount of LW transported outside the reaches is similar in terms of volume as 50.4 and 52.2 $m^3 \cdot ha^{-1}$ of LW were removed from the first and second reach, respectively. However, there is a difference between reaches in the number of exported elements. From reach 1 the LW output was ~261 $N \cdot ha^{-1}$ having mean sizes of 0.21 m in diameter and 3.49 m in length whereas fewer elements (~185 $N \cdot ha^{-1}$) with higher mean dimensions (0.25 m and 3.61 m for diameter and length, respectively) were removed from reach 2 (Fig. 67).



	RI ~ 1 (reach 1)	RI 10-25 (reach 1)	RI ~ 1 (reach 2)	RI 10-25 (reach 2)	RI 10-25 (reach 3)
LW deposited	173.80	1113.42	8	485.61	769.32
LW removed	-261.96	-230.48	-185.33	-144	-202.44
LW retained	146.10	89.42	260	124	12.30

Figure 67: LW budget expressed in terms of number of deposited, removed and retained LW elements along the three study reaches of the Blanco River.

In both reaches (1 and 2) the balance of LW for ordinary floods results in a negative budget, as the LW mobilization capacity was greater than the deposition capacity. However, the almost equal input and output in reach 1 caused a very low variation in wood storage of -1.78 $m^3 \cdot ha^{-1}$ that corresponds to a decrease of 1.5% of in-channel LW volume reducing from 122.1 $m^3 \cdot ha^{-1}$ of pre-flood conditions to 120.3 $m^3 \cdot ha^{-1}$ of post-flood conditions. Reach 2 shows a different behavior as the very low wood input unbalanced the output causing a stronger variation (-49.7 $m^3 \cdot ha^{-1}$) in the in-channel wood storage that reduced by 43.5%, decreasing from 114.1 to 64.4 $m^3 \cdot ha^{-1}$ (Tab. 20).

Table 20: summary of the LW budget in the study reaches of the Blanco River for ordinary flood events (RI~1yr).

Volume ($m^3 \cdot ha^{-1}$)	Reach 1	Reach 2
Initial volume	122.1	114.1
LW deposited from upstream	46.8	2.5
LW removed	50.4	52.2
Final volume	120.3	64.4
Δs (%)	**-1.5**	**-43.5**
Δs ($m^3 \cdot ha^{-1}$)	**-1.78**	**-49.7**

Looking at the LW dynamics during large floods (RI 10-25), all three study reaches have a positive budget with a surplus of LW due to the large quantity of deposited wood. In fact, the transport of LW from upstream played an important role in the budget computation, increasing the amount of in-channel LW by 162, 104 and 179% in reach 1, 2 and 3, respectively. The greatest variation in wood storage was recorded in the downstream reach 1, where new deposited elements, more than one thousand per hectare (Fig. 67), were more than three times those transported downstream. Here, the difference between input and output resulted in a positive variation of 204.2 $m^3 \cdot ha^{-1}$.

However, if the increase in the total in-channel LW is considered, the highest increment (179%) was found in the upstream reach 3, where the volume increased from 75.4 $m^3 \cdot ha^{-1}$ measured after ordinary floods, to 210.3 $m^3 \cdot ha^{-1}$ following large floods (Tab. 21).

Table 21: summary of the LW budget in the study reaches of the Blanco River for large flood events (RI 10-25yr).

Volume ($m^3 \cdot ha^{-1}$)	Reach 1	Reach 2	Reach 3
Initial volume	120.3	64.4	75.4
LW deposited from upstream	285.3	108.1	204.1
LW removed	81.1	28.2	67.1
Final volume	316.0	131.6	210.3
Δs (%)	**162**	**104**	**179**
Δs ($m^3 \cdot ha^{-1}$)	**+ 204.2**	**+ 79.9**	**+ 136.9**

Figure 68 shows the values of deposited and moved LW volume from each reach, reporting also the variations in longitudinal profile and active channel width along the whole stretch containing the study reaches. The mean slope of the study reaches decreases from 1.1% in reach 3 to 0.7% in reach 1, even if the lowest gradient (0.6%) is in reach 2. Regarding active channel width, the stretch shows a decrease in the upper part reaching the minimum width (43 m) downstream the reach 3, then increasing and remaining almost constant until the end of the stretch. The channel width of each reach, measured in correspondence to cross section, is 108 m, 80 m and 94 m for reach 1, 2 and 3 respectively, and remained the same for all the study period, except in reach 2 where an enlargement was recorded as large floods caused erosion along the left riverbank, widening the channel up to 137 m.

Looking at LW processes, in terms of deposition and mobilization, we can see that for lower events (histograms below the graph) the two processes are almost similar in the downstream reach where deposition contributes 40% (46.8 $m^3 \cdot ha^{-1}$) of variations in LW storage and mobilization 41% (50.4 $m^3 \cdot ha^{-1}$), whereas in reach 2 there is a great prevalence of mobilization (52.2 $m^3 \cdot ha^{-1}$) that corresponds to ~45% of all in-channel LW. As the two reaches are similar in gradient and width, it is reasonable to think that the LW dynamics were not influenced by channel geometry and channel slope.

For higher events (histograms above the graph), the dominant LW process is deposition. Contrary to what had been expected, there is no increasing trend in downstream deposition. Of the overall in-channel population monitored post-event, LW deposition represents 82% in reach 2, whereas in reach 1 and 3 it corresponds to 90 and 96%, respectively.

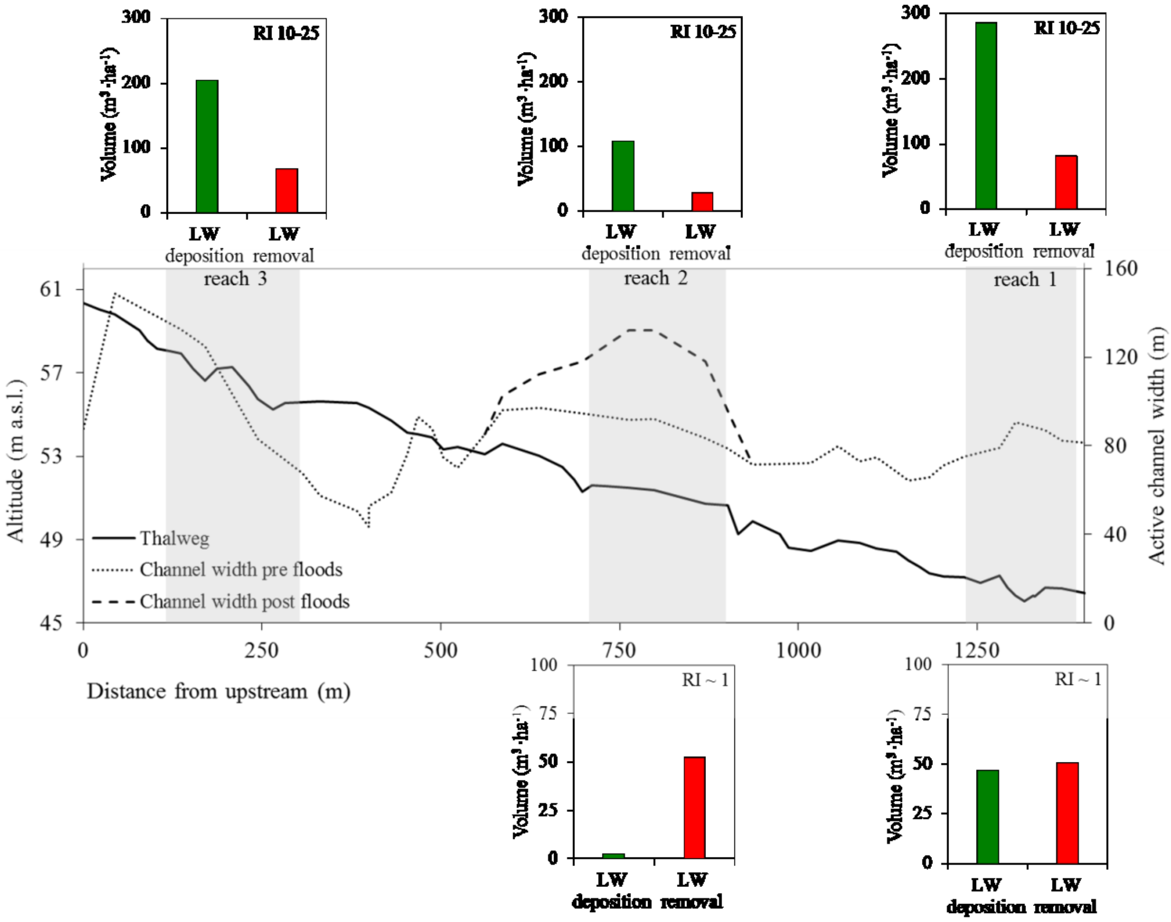


Figure 68: longitudinal profile and active channel width of the Blanco River stretch containing the three study reaches. Histograms show volume of deposition and mobilization of LW for ordinary (below graph) and large (above graph) floods.

Comparing the budget for ordinary floods, some differences emerged in the wood dynamics between the first and second study reach that could be related to the different local-scale morphology. Figures 69 and 70 illustrate the LW dynamics for reach 1 and 2 are in, respectively, discretizing between the position of elements transported outside the reach, the new elements deposited from upstream and those pieces whose position was not modified (aerial images refer to pre-flood conditions). The presumed maximum water stage reached during floods was delineated based on the position of deposited and mobilized LW pieces. Below the aerial image a graph represents the relative cross section. The cross sections and highlighted morphological units refer to post-event conditions.

The cross section of reach 1 (Fig. 69) has a width, measured at the base of riverbanks, of 94 m and a relative mean bed elevation of 0.78 m above the thalweg. The local morphology of the study reach appears similar to a multiple thread channel because the presence of one main channel and two dry channels adjacent to the riverbanks. The main channel flows almost in the center of the section and is bordered, on the hydrographic right, by a high bar with a maximum relative elevation of 2 m above the thalweg and, on the hydrographic left, by a low bar just 1 m above the thalweg.

Looking at the LW dynamics, wood mobilization covered 70% of the active channel area and occurred mainly on the low bar, where 84.3% of all in-channel LW was stored. Out of the total LW transported downstream of the reach, 95.2% was removed from the low bar, while just 4.8% was removed from the high bar on the hydrographic right. In addition, looking at new delivered elements, all LW input was deposited on the low bar. The water depth of lower magnitude events (RI~1yr) seems to have not been deep enough to completely flood the high bar.

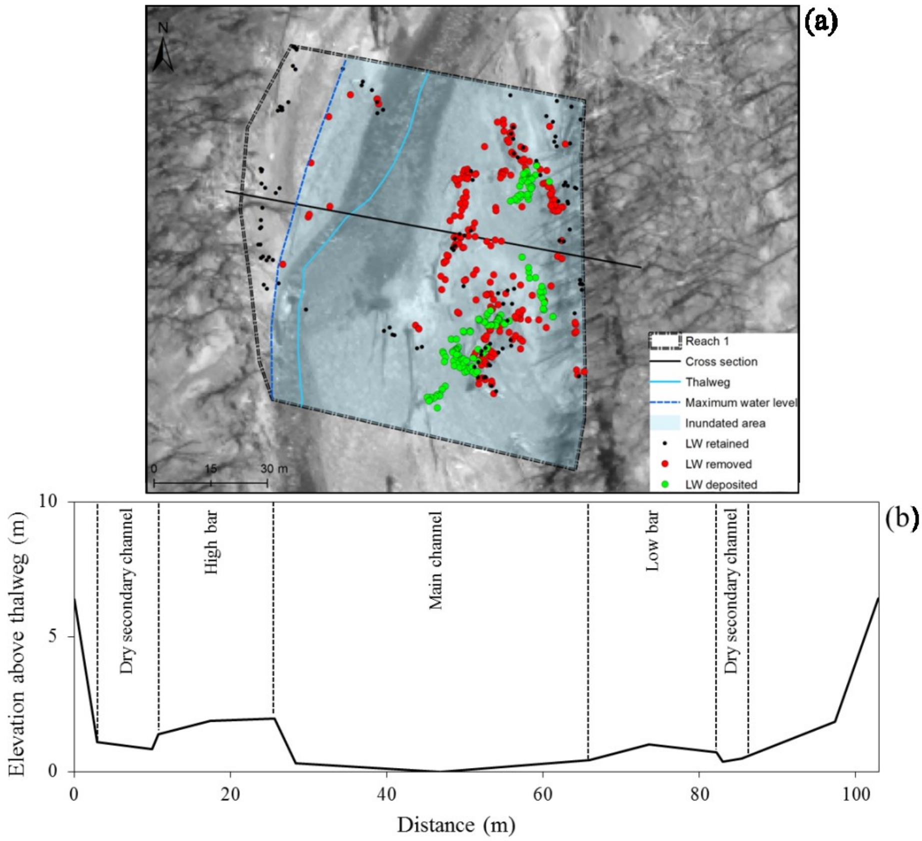


Figure 69: aerial image (a) of reach 1 showing the position of retained (black), removed (red) and deposited (green) LW elements after ordinary floods (flow direction is down the figure), and cross section (b) of the study reach highlighting the morphological units.

The second study reach, featuring a channel width of 80 m and a mean relative bed elevation of 1.31 m, shows a morphology that is similar to the single-thread pattern. The main channel flows in proximity to the left riverbank and is separated from the bank by a low narrow bar whereas, on the hydrographic right the channel is well-confined by a high bar with an elevation of 2.2 m above the thalweg (Fig. 70). A dry channel is present near the right riverbank and has a shallow depth as the difference between its thalweg and the highest point of the central bar is in the order of 0.6 m. In this case ordinary floods affected only 43% of the active channel and LW mobilization occurred only in proximity to the main channel, mobilizing those elements located on the left low bar and along the right bank of the channel. As can be seen in figure 70, none of the LW pieces stored on the high bar were mobilized, probably because the adjacent high bar hindered the submergence of a wider part of the active channel. A further confirmation of this hypothesis derives from the position of new LW transported from upstream. These elements were deposited along the same longitudinal line that corresponds to the top of the left bank of the channel, suggesting that this is probably the limit reached by the peak flood.

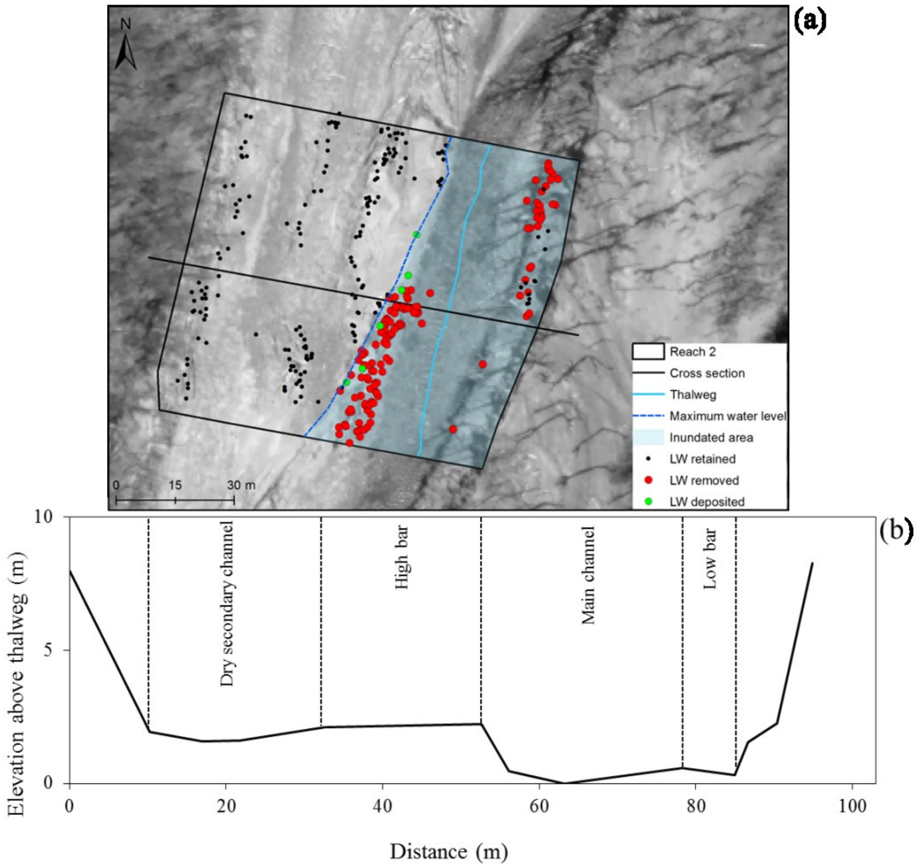


Figure 70: aerial image (a) of reach 2 showing the position of retained (black), removed (red) and deposited (green) LW elements after ordinary floods (flow direction is down the figure), and cross section (b) of the study reach highlighting the morphological units.

For large floods (RI 10-25 yr) the local-scale morphology of the study reaches seems to have had a minor role in the mobilization and deposition of LW, as due to the higher magnitude of the events the active channel area of the three reaches was entirely flooded. However, some differences in the LW dynamics can be highlighted. As shown for ordinary floods, figures 71, 72 and 73 illustrate the LW dynamics for large floods on reach 1, 2 and 3, respectively (aerial images refer to post-flood conditions).

Reach 1 still features a multiple-thread channel morphology. No enlargement of the active channel width occurred but the main channel laterally shifted to the hydrographic left of the reach, and deposition and mobilization of LW mainly occurred once again on the low bar. However, differently to what happened during ordinary floods where all LW input were deposited only on the low bar, in this case the LW deposition was recorded over the entire channel area, especially on the high bar. Because of the lateral shifting of the channel, mobilization of LW occurred mainly along the new channel course mobilizing the 83% of the total LW deposited during the previous ordinary floods.

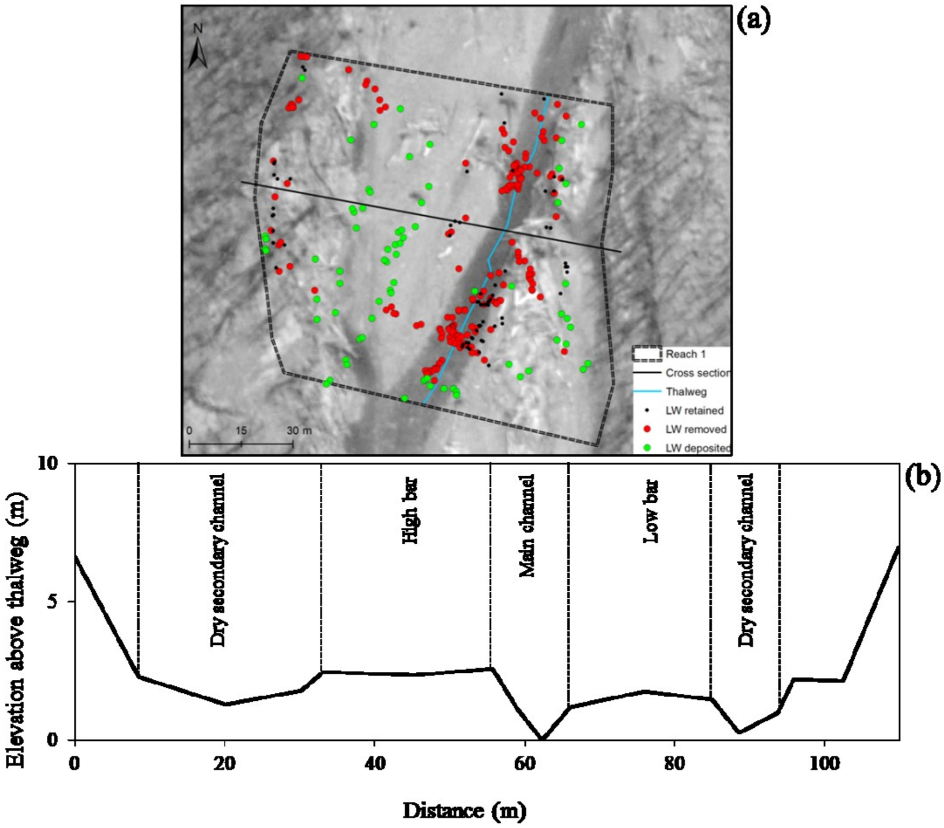


Figure 71: aerial image (a) of reach 1 showing the position of retained (black), removed (red) and deposited (green) LW elements after large floods (flow direction is down the figure), and cross section (b) of the study reach highlighting the morphological units.

Reach 2 is the only reach showing variations in the channel width and morphology induced by autumn-winter floods. In the post-events, in fact, an increase in channel width was recorded, due to a great erosion along the left riverbank. The main channel eroded about 60 m along the entire length of the reach, corresponding to almost 5200 m^2 and the active channel width widened from 80 to 137 m. Moreover, differently to what occurred during ordinary floods in which the variations in LW storage were caused only by the main channel, in this case the higher water stage of large floods was able to overtop the lateral bar and to activate the low-flow channel thus causing inundation on the entire channel area. In fact, looking at the aerial image which was taken after the floods (Fig.

72a), we can see how the reach is characterized by a multiple-thread channel morphology with three flowing channel that have contributed to a higher mobilization and deposition of LW. However, despite all the fluvial bars were flooded, only the 43.7% of stored LW was involved in the downstream transport, including the total elements deposited with previous summer floods.

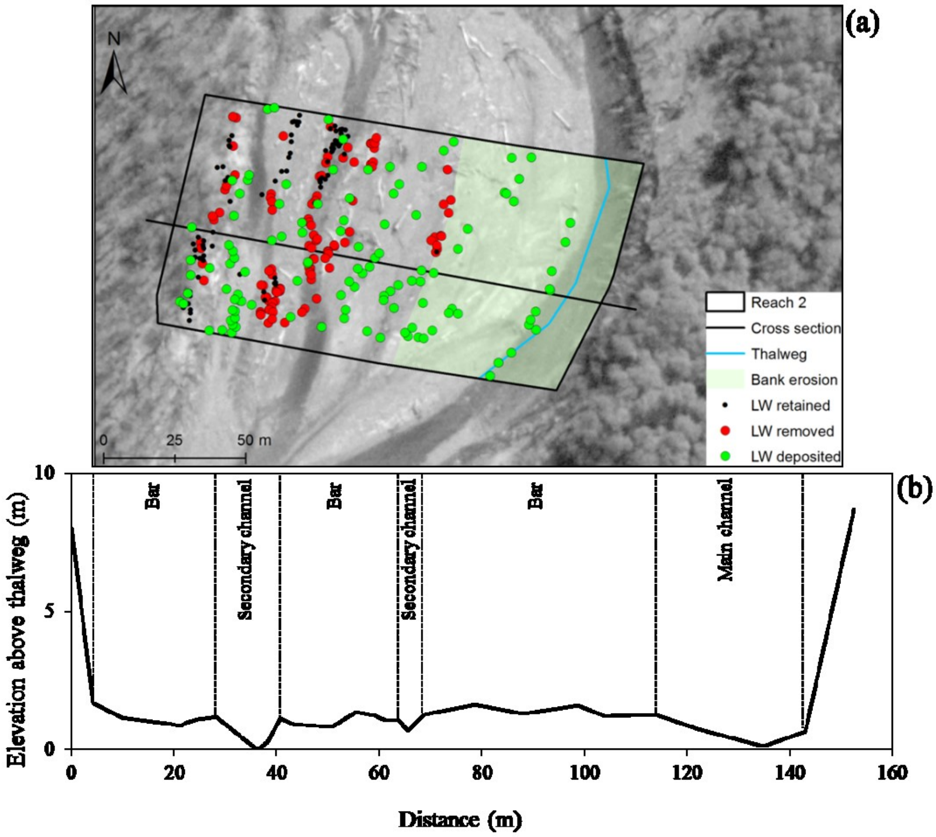


Figure 72: aerial image (a) of reach 2 showing the position of retained (black), removed (red) and deposited (green) LW elements after large floods (flow direction is down the figure), and cross section (b) of the study reach highlighting the morphological units.

The upstream reach 3 features a particular configuration as the flowing channel creates a bend in proximity to the left riverbank causing a variation in the channel direction. Looking at the position of mobilized and retained elements, a difference in the LW distribution before and after floods can be observed. In the pre-flood conditions, LW was mainly jammed (91%) covering only half of the active channel area while the rest of the reach was devoid of LW. This lack suggests that, as found in reach 2, previous lower floods were concentrated only in the area of the main channel without causing complete flooding and dispersal of LW. Instead, considering the distribution of LW deposited during large floods, it is reasonable to think that, similarly to what was found for reach 1 and 2, the flood magnitude affected all the active channel area with a predominant deposition on the central bar and along the downstream part of the right bank (Fig. 73).

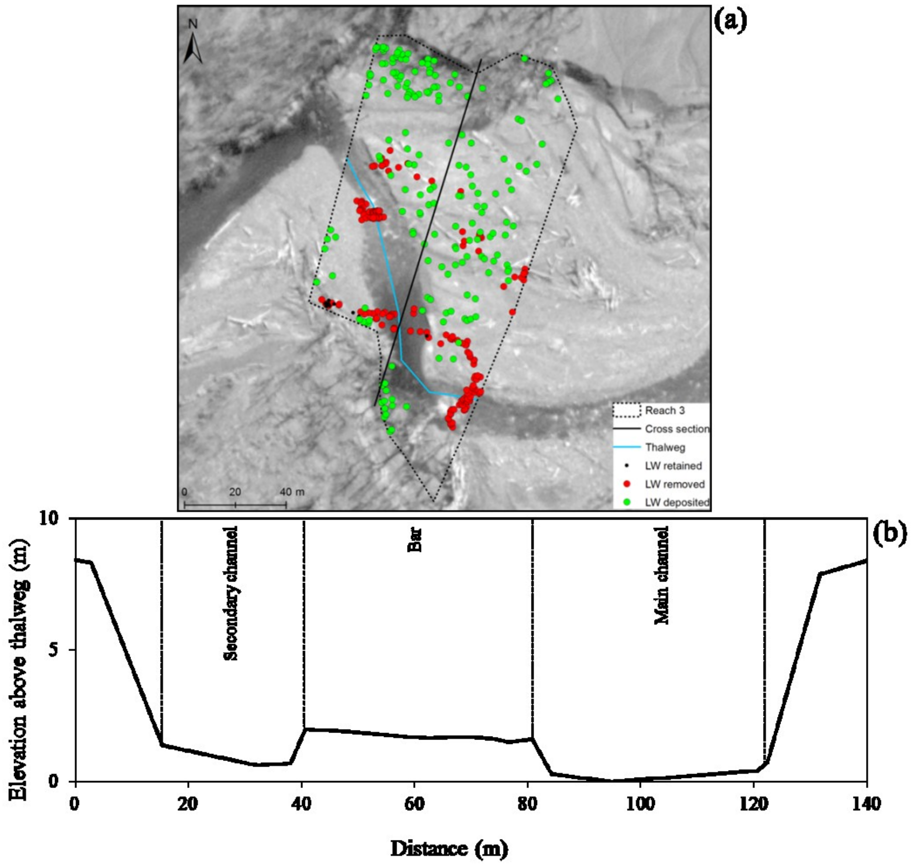


Figure 73: aerial image (a) of reach 3 showing the position of retained (black), removed (red) and deposited (green) LW elements after large floods (flow direction is down the figure), and cross section (b) of the study reach highlighting the morphological units.

As the study reaches of the Blanco River showed a different behavior in LW mobilization, additionally to the role of local-scale morphology, the role of LW characteristics was also investigated as possible factors controlling LW mobilization. In particular, the main factors influencing wood movement that were considered are wood dimensions (mean diameter and length of moved pieces), volume, abundance, channel width and the ratio of piece length to channel width. Results of relationships between LW mobility rates and these factors are illustrated in figure 74.

Overall, a lack of statistically significant correlations ($p>0.05$) between wood mobility and controlling variables was found, and results of correlations are often weak and difficult to explain. More in detail, factors such as LW sizes show relationships with mobility having opposite signs. The mobility rate is correlated positively with the length of LW and negatively with the LW diameter with a very low coefficient of correlation. Differently to what had been expected, the number of pieces in transport does not correlate negatively with piece volume but a positive relationship was found. The active channel width seems not to affect wood movement even if a surprising positive correlation was obtained from the ratio between LW length and channel width. Shorter pieces appear to be less easily transported than longer elements. Finally, the LW mobility rate correlates negatively with the abundance of in-channel LW, with a number of transported pieces that decreases for increasing values of wood abundance. Summarizing the correlation analysis results, LW mobility rate is poorly correlated with any of the tested variables.

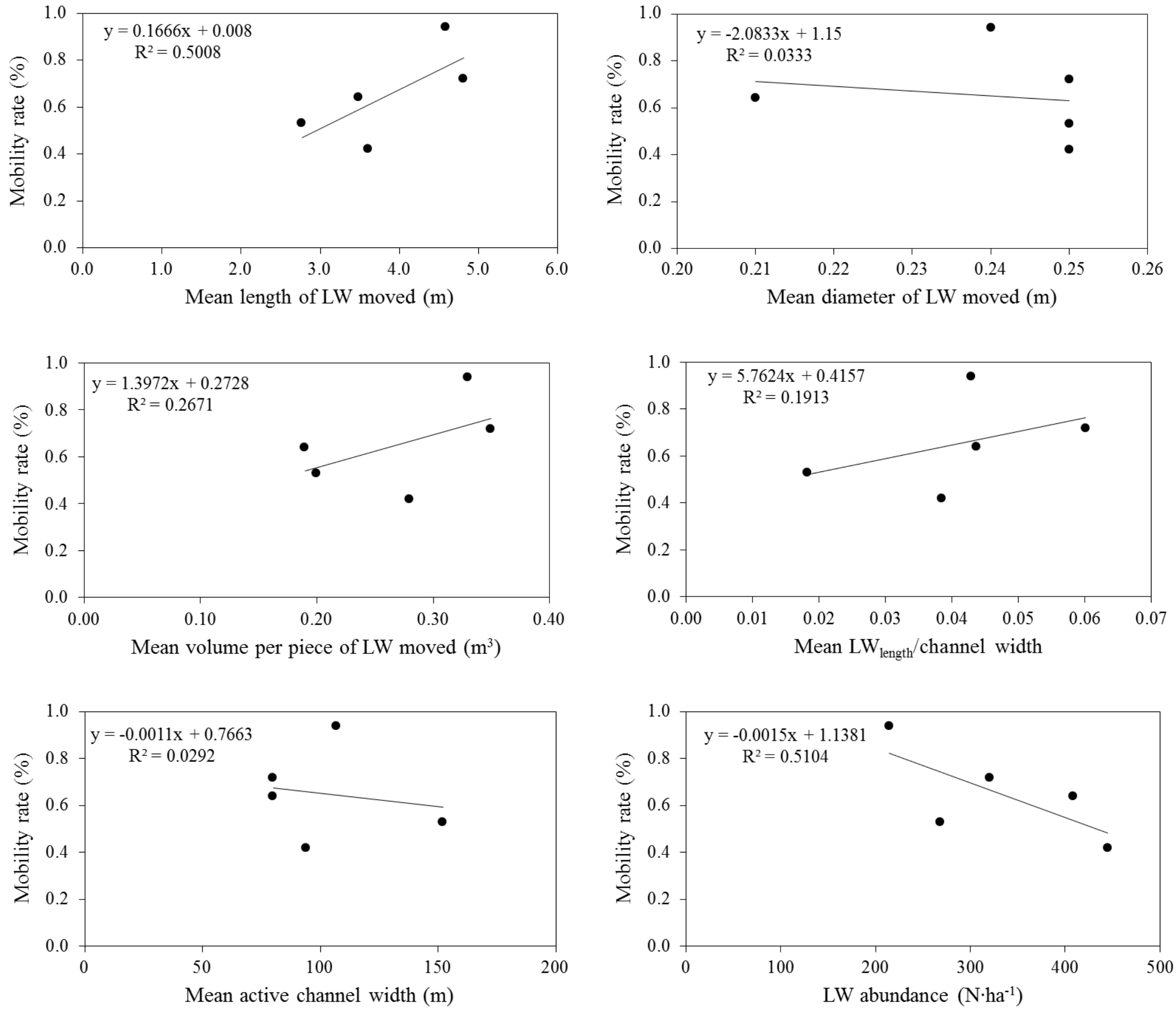


Figure 74: scatterplots and estimated regression relationships between large wood mobility rate and a series of LW characteristics and between mobility rate and mean active channel width.

A final analysis was conducted in order to investigate the presence of possible differences among the sizes of wood pieces that were transported downstream and those that remained in their original position. The analysis was performed considering LW mobilization during ordinary and large floods separately. For ordinary floods, only elements laying in the flooded area were taken into consideration.

Looking at figure 75a, which refers to the mobilization induced by ordinary events, we can note that only in reach 1 the retained elements had a median diameter (0.26 m) larger than removed ones (0.17 m), even if some LW pieces bigger than 0.70 m in diameter were also removed. In reach 2 an opposite behavior was found as the median diameter (0.20 m) of LW transported downstream was slightly larger than that of retained pieces (0.19 m). In figure 75b, which reports differences in LW length, both study reaches show a median value of retained LW, 3.2 m and 4.0 m for reach 1 and 2 respectively, which is higher than the value of removed LW that corresponds to 2.8 for the first reach and 2.6 m for the second one.

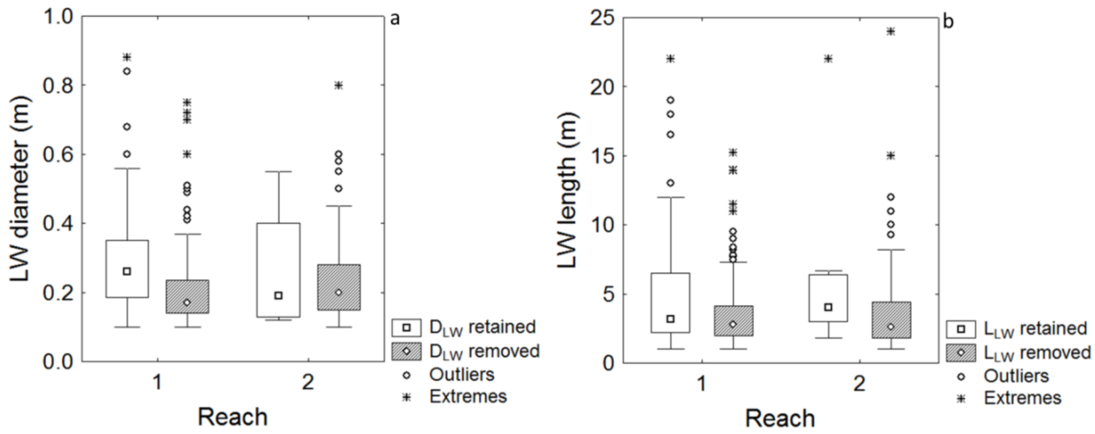


Figure 75: range of the LW diameter (a) and length (b) of retained and removed woody elements during ordinary floods.

The same analysis, performed for the mobilization and retention of LW during large floods (Fig. 76), highlighted that also in this case the sizes of mobilized elements are smaller than those of non-mobilized. The median values of diameter in reach 1, 2 and 3 are 0.24, 0.22, and 0.21 m for mobilized pieces and 0.28, 0.25 and 0.25 m for retained ones (Fig. 76a). In turn, the median length of LW removed from reach 1, 2 and 3 corresponds to 3.5 m, 2.2 m and 3.7 m, respectively, whereas for retained elements it is 3.6 m, 3.2 m and 5 m. Nevertheless, it is worth noting that the length of removed LW is characterized by a high range of variability, with highest values of removed elements that are greater than that of retained one (Fig. 76b).

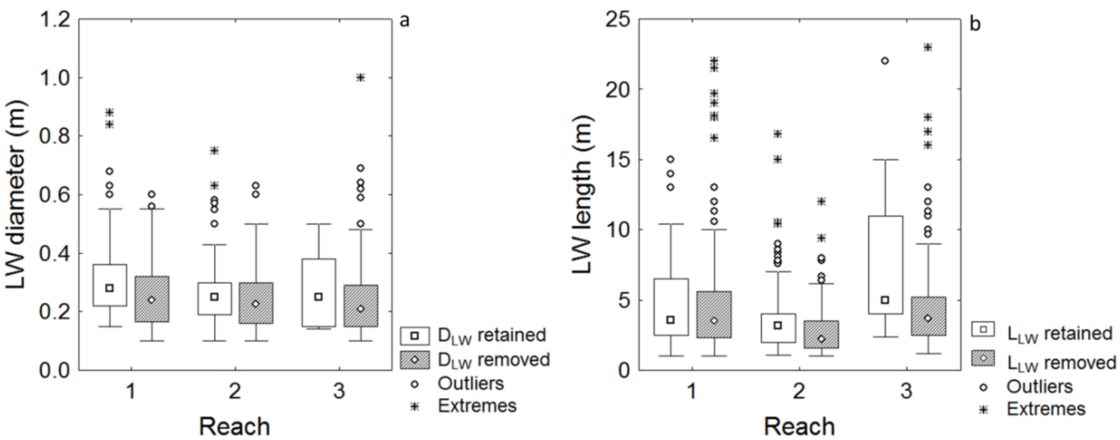


Figure 76: range of the LW diameter (a) and length (b) of retained and removed woody elements during large floods.

Section Five - Discussion

5.1. Considerations on the recruitment and transport of LW during over-bankfull floods

All three analyzed morphological units in the Piave River (floodplain, pioneer islands and building islands) suffered erosion during the over-bankfull flood in November 2014, contributing to the delivery of LW into the channel. The number and volume of recruited trees were influenced by the different vegetation density and dendrometric sizes characterizing these units, which are directly related to their morphological development that permitted the generation and stabilization of different vegetated communities (Sitzia et al., 2015; Picco et al., 2016b). Pioneer islands, due to the highest tree density (0.16 $N \cdot m^{-2}$) should be the most important unit in supplying the channel with LW but, since erosion is the lowest (25.2 m^2) and the vegetation is of lowest dimensions, the recruited LW is negligible (0.14 m^3). Therefore, the effect of the initial characteristics of riparian trees on pioneer islands influences the volume of LW recruited from these units. On the contrary, the greater erosion and larger tree sizes on floodplain and building islands caused a higher LW input from these morphological units, especially the floodplain where 92.7% of the total recruited LW volume comes from (86.25 m^3). The important role played by floodplain trees in the recruitment of LW was already verified by Piégay et al. (1999) along a wandering French river. These authors found that the floodplain contribution was in the range of 62-82%. The significant vegetation erosion during the flood in November 2014 which had a R.I. of 7 years suggests that the current perception of the role of floods on vegetation removal should be re-evaluated. Until now, indeed, many authors have highlighted that significant vegetation erosion is more likely to occur only with large floods (R.I.>10-20 years) (Bertoldi et al., 2009; Comiti et al., 2011; Mikuś et al., 2013; Moretto et al., 2014). Similar findings were emphasized by Surian et al. (2015) reporting that relatively frequent, low magnitude floods (1≤R.I. ≤2-3years) also have the capacity to erode vegetated patches along a large gravel-bed river similar to our study case and reducing the threshold for vegetation erosion previously found by Bertoldi et al. (2009) from 3 to 2.5 years.

The recovery rate obtained during the post-flood field survey (33%) is quite similar to other rates published in the literature. Using RFID tags, Schenk et al. (2014) reported a recovery rate lower than 40% along the large sand-bed Roanoke River, while Ravazzolo et al. (2015a) obtained a recovery rate ranging from 42 to 43% in the large gravel-bed Tagliamento River. Our recovery rate was also better if compared to MacVicar et al. (2009) who, again using RFID tags, recovered 13-27% of trees fallen after near and twice-bankfull floods along the large gravel-bed Ain River. Therefore, the recovery rate obtained is comparable, or even better, than the proportion of tagged logs recovered using radio markers. This is probably because the functionality of radio marker devices can be affected by a prolonged period in wet conditions that can compromise their mode of operation (Picco et al., 2016b). However, recovery rates may have been influenced by the mechanical destruction of LW during transport, especially for smaller pieces coming from islands.

On the basis of LW displacement distances it was possible to hypothesize about recruitment mechanisms. Pioneer islands, because of their lower elevation (Picco et al., 2014) and younger, less mature vegetation (Edwards et al., 1999; Picco et al., 2014; Mikus et al., 2013), were expected to be the first morphological unit to be removed during floods. However, the fact that longer travel distances were recorded for trees recruited from the floodplain suggests that this unit was probably eroded during the rising limb of the hydrograph, while the shorter displacement of trees recovered from islands suggests that they were probably recruited during the long decreasing limb. Pioneer islands, and to a lesser extent building islands, have shown a great capacity to resist the flood and maintain their position in the active channel. The presence of LW, especially wood jams, upstream of these islands probably protected them from the erosional forces of the flood. In fact, the accumulation of wood on the head of fluvial islands was proved to enhance the stability of islands through deflection of the flood and reduction of flow velocity (Gurnell et al., 2005). Moreover, as fluvial islands were mainly composed of highly flexible species, this probably increased their capacity to survive floods (Picco et al., 2016b).

From the post-event field data it was possible to identify the most suitable sites for LW deposition. The results confirmed that LW is preferentially deposited along gravel bars (Mao et al., 2012; Ravazzolo et al., 2015a), but the presence of fluvial islands also represents a trapping element that can block in-transport wood and induce its deposition (Gurnell, 2005; Ruiz-Villanueva et al., 2016a). In this case, only a pair of trees (1.3%) were deposited upstream of building islands but this corroborates the well-known role of fluvial islands in interacting with LW and thus promoting island development (Gurnell et al., 2005). Moreover, we found that during over-bankfull floods LW can also be deposited outside of the active channel area, for example above the riverbanks on the floodplain. This suggests that, in the case of budget assessment for periods in which floods exceeding the bankfull level occurred, it would be important to also consider the output by overbank deposition (Martin and Benda, 2001; Benda and Sias, 2003) although it is not simple to discriminate between pieces deposited during the flood from those already stored on the floodplain (Wohl, 2016).

Considering other sites of LW deposition, some gravel bars positioned downstream of eroded patches have shown a great capacity for LW retention. In many cases, when a bar was located just downstream of the erosion site, the recruited LW had not traveled far downstream but were deposited close to the erosion site after a very short displacement. Similar LW deposition dynamics were obtained by Bertoldi et al. (2013) on the braided Tagliamento River, where up to 40% of trees recruited from the floodplain were deposited on the nearest downstream bar. This particular deposition process can be connected to the behavior of sediments delivered into channels during bank erosion. Pyrce and Ashmore (2003) documented that these sediments are usually deposited on the first bar downstream of the erosion source and this enhances the development of suitable sites (i.e. gravel bars) for LW deposition. On the other hand, LW deposition could also be affected by the type of LW transport. Following Braudrick et al. (1997), the ratio between LW volume recruited and water discharge (Q_{LW}/Q_W) suggested that LW transport occurred in a congested way, in which pieces moved together as a single mass and this high degree of interaction between elements usually results in short transport distances and deposition in jams (Braudrick et al., 1997).

Although a comparison among digital elevation models (DEM) referred to the pre and post flood was not possible, the great recorded bank erosion and the high large wood recruitment suggest that the over bankfull flood may have induced changes in the morphology of bars and channels caused by sediment and wood deposition. In this sense, it is important to highlight that these processes need to be considered when LW dynamics are simulated with numerical models (Ruiz-Villanueva et al., 2015).

The statistical analysis of LW displacement computed in this study does not identify clear relationships between the traveled distance and LW characteristics, highlighting that the mobility of LW is probably also governed by others factors. Only a significantly decreasing trend ($P \leq 0.05$) was found for the mean traveled distance for increasing values of LW diameter, confirming how the diameter is the main LW property controlling the traveled distance in large gravel bed-rivers (Welber et al., 2013). However, the findings about the role of diameter should be extended considering also the bed morphology and channel geometrics. In fact, as first suggested by Braudrick et al. (1997), the ratio between diameter and mean channel depth can be considered as the main driver of wood mobility influencing the traveled distance. Similar results were found more recently by Ruiz-Villanueva et al. (2015) confirming that in wide multithread channels the diameter exerts the main control on LW mobility. In contrast, the role of LW length on piece mobility appears to be less clear. In fact, even if no significant relationship was found, the decreasing trend of traveled distance for increasing values of length confirms the suggestion of Ruiz-Villanueva et al. (2015) that the importance of the LW length in wide multithread reaches is not as evident as in single-thread narrowing reaches.

Differently from the results of Ruiz-Villanueva et al. (2015) in which the volume and density also appear to be factors controlling LW transport, we observed no statistical relationships between these variables. As wood density is considered one of the main factors conditioning the initial mobility of wood in rivers (Ruiz-Villanueva et al., 2014c) and the likelihood of its movement (Ruiz-Villanueva et al., 2015), we expected to obtain lower values of traveled distance for heavier LW. However, in this study the displacement of LW does not seem to be influenced by the wood density. Only high values of density (depending on the species) corresponding to fresh wood were used. As wood density is subjected to a rapid increase during the first hour of immersion (Welber et al., 2013), the relation with the traveled distance should probably also consider these fluctuations. Some better explanations of how tree species influence the LW mobility could be obtained by also considering the presence and type of roots. In fact, due to the usually higher density of roots in respect to the stem and the capacity to incorporate sediments during transport, the presence of roots can increase the tree weight (MacVicar et al., 2009) and especially in the case of trees just uprooted this could play a crucial role in the LW mobility control.

5.2. Mobilization and deposition of LW during floods of different magnitude

In this section the results concerning the input and output of LW by fluvial transport are discussed.

Following the classification proposed by Gurnell et al. (2002), both the Piave and Blanco rivers can be classified as large rivers, having a width greater than the length of all of the wood pieces delivered. Several authors (Gurnell, 2003; Moulin and Piégay, 2004) reported that LW mobilization is usually more frequent in large rivers than in small and medium ones. Indeed, because of the very small dimensions of wood in respect to the channel width, LW is not in contact with the channel margins during the transport (Schenk et al., 2014) and this facilitates its mobilization. Nonetheless, great differences between the two rivers were identified in the volume of LW transported, which reflect different LW dynamics. In the Piave River the fluvial transport of LW was found to be in the order of only 0.02 and 0.03 $m^3 \cdot ha^{-1}$ for deposition and mobilization, respectively; whereas in the Blanco River significantly higher deposition (maximum of 285.3 $m^3 \cdot ha^{-1}$) and mobilization (maximum of 81.12 $m^3 \cdot ha^{-1}$) volumes were found. Although the two analyzed rivers are quite similar in terms of grain sizes, slope and ratio LW length/channel width, an enormous difference in the number and volume per hectare of in-channel LW was observed, and it is clear that these differences in the LW storage can affect the amount of in-transport LW. The Piave River shows values of in-channel LW similar with those of other Italian rivers with comparable morphological patterns and riparian forests (Pecorari, 2008; Ravazzolo, 2015b), but lower when compared to two French rivers of similar size (Piégay et al., 1999; Piégay and Marston, 1998). The smaller amount of LW storage in the Piave River can be probably attributed to the high degree of anthropic pressure. In fact, several human activities (i.e. gravel mining, hydropower scheme, land use changes, vegetation management) took place over the last century along the Piave River, affecting the morphological settings of the river as well as the characteristics of riparian vegetation (Comiti et al., 2011; Picco et al., 2016a) and, in this way, the supply of LW. Moreover, an artificial dam located 7 km upstream of the study reach may limit the supply of LW. In the case of the Blanco River, the huge presence of in-channel LW can be attributed to the recent volcanic eruption that, destroying more than 400 ha of adjacent forest (Major et al., 2013), dramatically increased the supply of LW into the active channels (Ulloa et al., 2015a).

Differently from the Piave River in which the mobility rate for ordinary events was found to be 1.43%, the Blanco River featured very high mobility rates, between 41.6 and 94.3% during ordinary and not-ordinary floods, respectively. This high dynamicity of LW in the Blanco River was already shown by Ulloa et al. (2015a), who reported a mobility rate of 78% and 48% for single logs and WJ, respectively. In addition to the already explained difference in LW storage, another possible explanation for the high mobility rate of the Blanco River can be given by the characteristics of in-channel LW. In fact, 93% of transported pieces were logs, and many authors (Braudrick and Grant, 2000; Moulin and Piégay, 2004), demonstrated that this type of LW is the easiest to be transported. Instead, the LW in the Piave River is also composed of trees, shrubs and rootwads and these types, which are more flexible and irregularly shaped than logs, are less easily transported because they are more susceptible to becoming trapped around obstacles (Gurnell, 2013) or anchored to the river bed, increasing drag and thereby decreasing mobility (Abbe and Montgomery, 1996; Welber et al., 2013).

Differences in the hydrological regime of flood events can also affect the LW transport. Unfortunately, the 2015-2016 study period was very dry and no significant events occurred, just two peak discharges ~100 $m^3 \cdot s^{-1}$ and another two <100 $m^3 \cdot s^{-1}$ were measured in the Piave River. The very low intensity of the events resulted in small wetted areas, flooding just the low fluvial bars located in proximity to the flowing channels. In this way, the low transport of LW in the Piave River can also be due to the fact that the amount of wood that is usually stored on high bars and fluvial islands in a braided-wandering morphology was not reached by the floods (Pecorari, 2008).

On the other hand, in the Blanco River floods of higher magnitude (RI~1 and RI 10-25 yr) resulted in bigger wetted areas. The only exception was found for reach 2 with summer floods, during which just 43% of the active channel was flooded and the lowest amount of LW deposited and mobilized corresponded to the smallest wetted area. In the other cases almost all the active channel was inundated and in this sense, the bigger the wetted area is, the larger is the amount of LW available for transport and, at the same time, the sites available for deposition.

The difference in flooded area was also found to affect the way in which LW is deposited (i.e. state of aggregation). For smaller wetted area the LW was found to be deposited mainly as single elements, whereas for bigger wetted areas the predominant deposition was in the form of wood jams. This different behavior can be explained considering the morphological units flooded during events of different magnitude. Higher magnitudes are usually able to flood the entire floodplain (Mikus et al., 2013; Picco et al., 2014, 2016b) and LW is more easily deposited in jams because it is intercepted by fluvial islands and vegetated bars (Gurnell, 2005; Picco et al., 2015a), while during events of lower magnitude when just low bars tend to be flooded LW is usually deposited as single pieces. In the Blanco River where there are no fluvial islands able to intercept LW, the prevalent jammed deposition could be because of the presence along the active channel of several rough elements that can retain a certain quantity of wood. Indeed, the standing dead trees near the riverbanks as well as the presence of big WJ can cause, at a local scale, variations in flow environment and average velocity (Gippel, 1995; Seo and Nakamura, 2009; Welber et al., 2013) favoring the deposition and retention of wood.

Moreover, since LW transport is conditioned by LW sizes (Braudrick and Grant, 2000; Ruiz-Villanueva et al., 2015) and water depth (Ruiz-Villanueva et al., 2016a) and because LW deposition usually starts at the peak flow (Ravazzolo et al., 2015a) when the wetted area is larger, bigger elements were expected to be deposited at greater distances from the thalweg. However, we observed that in both rivers woody elements of the same sizes were deposited independently of the distance from the thalweg and this can confirm that, as recently observed by Ravazzolo et al. (2015a), the transport of LW can also occur over the bars and not necessarily along the thalweg line (Braudrick and Grant, 2001; MacVicar and Piégay, 2012). In this way, slight differences in the topographic elevation of fluvial bars have probably affected the wood deposition.

5.3. The budget of LW in the human-impacted Piave River during ordinary events

The short temporal scale and the absence of over bankfull floods allowed the assessment of a comprehensive wood budget, evaluating the fluvial transport of LW and the lateral recruitment for very frequent floods.

In the study reach the lateral supply of LW is given by bank erosion, which is a process that can occur not only during high bankfull floods but also during low magnitude events. However, our results confirmed that the characteristics and density of riparian vegetation influence rates of wood recruitment (Benda and Sias, 2003). In fact, bank erosion was found to occur in a floodplain area devoid of tree vegetation so the recruitment of LW from this eroded area was null. The riverbank was probably eroded due to the presence of just shrubby vegetation with a lower capacity of soil reinforcement (Hooke, 1980). On the other hand, the lateral input of LW was due to some trees growing close to the riverbank and that had fallen into the river. In some cases, recruited trees were found to form ramp logs, with one side resting on the bank and the other on the riverbed (Ruiz-Villanueva et al., 2016c), so the effective erosion of the riverbank was null. Despite the recruitment of LW in piedmont environment being commonly related to large floods (Bertoldi et al., 2013; Picco et al., 2016b), in this case the LW recruitment was probably facilitated by the fact that trees had already been weakened by the last over-bankfull flood in November 2014, so also small variations in the water depth may induced their collapse. Differently to what was observed for the recruitment of LW during an over-bankfull flood (sections 4.1 and 5.1), trees recruited during ordinary events were not involved in downstream transport but were just uprooted and deposited near the recruitment site. The absence of additional transport can be explained if the type of recruited elements is considered. In fact, all the recruited elements were represented by trees and the majority had branches and rootwads. This type of LW is less easily mobilized because the tree canopy and rootwads tend to attach the tree to the river bed and inhibit the movement (Abbe and Montgomery, 1996; Braudrick and Grant, 2000; Bocchiola et al., 2006; Iroumé et al., 2015). Moreover, considering the low magnitude of recorded events, the water depth was probably too shallow to induce movement of this type of LW and this is in agreement with what MacVicar and Piégay (2012) reported in the French Ain River. They observed that many trees growing in loose and unstable positions had fallen into the river during low flow conditions but remained near where they fell because the water depth was insufficient for their mobilization.

A discrete mobilization of LW was also observed during very low flow conditions corresponding to 10% of bankfull discharge (~100 $m^3 \cdot s^{-1}$). In a previous study on LW transport along the Piave River (Pecorari, 2008), the authors reported that events lower than 388 $m^3 \cdot s^{-1}$ were not able to mobilize the monitored woody elements. This discrepancy can be explained considering the sizes and characteristics of LW. Pecorari (2008), in fact, only monitored trees with rootwads in a range 0.12-0.42 m in diameter and 4.75-17.6 m in length. In this case, the mobilized elements were mainly logs without rootwads (40%) and, concerning the sizes, 80% were less than 0.2 m in diameter and 70% less than 4 m in length. This comparison confirms that, among other factors, mobility of LW also depends on its size (Gurnell, 2003; Wohl, 2011, Iroumé et al., 2015) and the presence of rootwads can inhibit the movement and decrease mobility by anchoring pieces to the bed (Abbe and Montgomery, 1996; Braudrick and Grant, 2001).

Overall, mobilization and deposition of LW were observed to occur in proximity to the flowing channels, both main and secondary channels, even if the main contribution was given by the main channel. The three sub-reaches identified on the basis of where LW mobilization and deposition occurred, revealed that in the most braided morphology mobilization was higher than deposition. This phenomenon differs from what was expected. In fact, because LW is usually deposited on bars (MacVicar and Piégay, 2012; Ravazzolo et al., 2015a; Ruiz-Villanueva et al., 2016b), the presence of numerous bars had led me to hypothesize a greater amount of deposited LW. Moreover, in contrast to single-thread reaches, multi-thread reaches were defined by Wyzga et al. (2016) as "natural wood traps" because the lower values of water depth, flow velocity and unit stream power provide more favorable conditions for LW to be stranded on the bars. The fact that we could not find this, is probably due to the very low water level of secondary channels for low-flow events that was not able to deposit a considerable quantity of LW.

In general, the LW budget assessed for the Piave River during the period 2015-2016 resulted in no quantitative important variations in the LW storage (-0.26 $m^3 \cdot ha^{-1}$), because input and output volumes are quite similar. Moreover, no variations were found in the LW distribution, confirming what was reported by Gurnell et al. (2002), that very frequent events are not able to redistribute the in-channel LW. The low numbers of elements involved in the LW-related processes reflect the low regime of occurred events suggesting that the area flooded during frequent floods is mainly limited to the main channels and low bars (Ruiz-Villanueva et al., 2016), the morphological units that are usually flooded with greater frequency. The low recurrence interval (<1yr) of recorded events means that the low discharge and, consequently, the low water depth resulted in the flooding of morphological units with lower elevation in respect to the water surface. Indeed, a difference was found in the relative elevation above the thalweg between the surfaces in which mobilization and deposition of LW occurred and those areas in which LW was not mobilized. Overall, a difference of about 0.4-0.45 m among flooded and not-flooded areas was observed. In the Piave River case, where there are high and low bars (Ravazzolo et al., 2015b) and fluvial islands placed at different elevations (Picco et al., 2014), the lower morphological units flooded during low magnitude events can be represented only by low bars and the margins of flowing channels corresponding to the areas in which LW mobilization and deposition were observed. In this sense, these findings ratify the recent observations of Ruiz-Villanueva et al. (2016a) on how the relative elevation of the different geomorphic units in relation to the water level is a significant factor controlling the transport and deposition of woody elements.

Finally, in the Piave River case the dynamics of LW (i.e. wood budgeting) were found to be altered by anthropic activities. In fact, wood harvesting by local residents resulted in an additional output of LW that is mentioned but almost never considered in the literature. Harvested wood was found to be mainly bigger trees, especially those recruited during the event in November 2014. Despite this activity being controlled by special regulations of the local administrations, this anthropic action can lead to misleading information of the natural dynamics of wood in rivers because it can cause uncertainties in the quantification of input and output processes.

5.4. The budget of LW in the affected Blanco River during ordinary and not-ordinary events

The budget assessed for the Blanco River is not a comprehensive budget because there is a missing item: lateral recruitment. However, as floods of different magnitude occurred during the study period, it was possible to compare the variations in LW storage among the events.

In fact, the abundance of LW was found to be subject to temporal variations also over short time periods because of two main factors: the magnitude of floods and the local-scale morphology of the study reaches. Considering flood magnitude, there was a consistent reduction of LW after low floods (RI~1yr), while the abundance and volume increased following large events (RI 10-25yr). These temporal fluctuations can be connected to the strong differences in the seasonality of the hydrological conditions of the Blanco basin. Higher precipitation occurring during the autumn-winter season results in higher discharges in respect to those of summer season, and higher the flood magnitude is, greater the variations in LW storage can be. These results are in accordance with Gurnell et al. (2000), who highlighted that the larger volume of stored LW is usually reached after major flood events because the amount of in-transport wood and the tendency of deposition are greater. As pointed out by MacVicar and Piégay (2012), there is an increase in wood transport for increasing discharge. With the increase in both water depth and wetted channel area, bars are progressively inundated and, in this way, the quantity of LW available to be transported is greater. The higher magnitude of floods during the autumn-winter months resulted in a larger wetted channel area able to mobilize greater wood volume. At the same time, as wood is preferentially deposited on bars during the peak and receding phase of floods (MacVicar and Piégay, 2012; Mao et al., 2012; Ravazzolo et al., 2015a), the larger is the wetted channel area and the bigger is the area prone to wood deposition. In fact, it was found that there is a prevalence of LW mobilization during low floods while LW deposition is prevalent during large events. Again, the low amount of LW input recorded for summer floods is probably related to the low quantity of in-transport wood and, at the same time, to the smaller flooded area. In this sense, the differences in flooded area can also be explained by the different morphological configuration of the river reaches. The lower relative mean bed elevation of reach 1 as well as the morphology that could be likened to a multiple-thread channel pattern allowed a faster increase of the wetted area, whereas the higher relative mean bed elevation of reach 2 and the presence of a single channel confined the wetted area just to the proximity of the flowing channel, reducing the mobilization and deposition of LW. Additionally, the greater input and deposition of LW found during higher discharge was probably also related to the observed bank erosion. Although LW recruitment was not measured, the large volume of riparian trees (271.5 $m^3 \cdot ha^{-1}$, unpublished data) suggests that a considerable amount of LW was introduced into the channel. Similarly to what was already discussed for the Piave River, also in this case bank erosion appears to be affected by flood magnitude and be more likely to occur with higher discharge. Indeed, erosion was recorded only during autumn-winter floods while for lesser events (RI~1yr) no bank erosion was measured along the study stretch of the Blanco River.

The documented erosion of riverbanks also confirmed previous findings on the widening tendency that occurs following volcanic disturbances. As already reported by Ulloa et al. (2015a), the Blanco River, like other similar rivers in the surroundings of the Chaitén volcano, drastically changed its morphology as a consequence of the eruption with the active channel widening up to 3.5 times. These results confirmed that riverbank erosion is still an active process that can induce significant enlargement of the river; reach 2 almost doubled its channel width from 80 to 137 m. In particular, as bank erosion occurred in correspondence to dead riparian vegetation, this suggests that the Blanco River will continue to widen for a long period until all the damaged riparian trees have been removed, recruiting a huge volume of wood. In fact, the presence of several non-cohesive sediments can increase the facility with which erosion occurs.

Contextually to the recruitment of LW from standing trees, the erosion of riverbanks along the Blanco River can also cause the recruitment of LW through another process: the exhumation of buried wood. The deposition of volcanic material caused the formation of sediment layers up to six-seven meters in depth (Pierson et al., 2013), burying both standing trees and in-channel LW. Because volcanic sediments are mainly formed by non-cohesive materials (Gob et al., 2016), they are easily eroded and the buried wood can be exhumed and reintroduced into the active channel. With the application of GPR an estimated mean volume of buried wood was 1.65 $m^3 \cdot ha^{-1}$, however it is important to remember that the investigated depth was only the top two meters, so probably this was an underestimation of the real wood volume.

As a first approach, the GPR was proved to be a valid technique for the detection of buried LW, also due to its non-destructive and non-invasive characteristics. However, the different behavior of radar waves suggests that during the radargram interpretation the distance of the surveyed area from the flowing channel (i.e. proxy for the soil moisture content) needs to be taken into account. As this was the first attempt to detect LW buried under river sediments with GPR, a comparison with similar studies is difficult. Indeed, the GPR had already been used in a fluvial environment to measure the moisture content (Daniels et al., 2005; Grote et al., 2003), monitor the water table (Porsani et al., 2004; Roth et al., 2004) and stream discharge by noncontact methods (Costa et al., 2006), but there are no specific studies on the measurement of buried wood, so the estimation of LW potentially recruitable from exhumation still remains a research topic to be better explored.

Section Six – Conclusions and future research directions

In order to synthesize the results reported in this thesis, the main achievements can be summarized as follows:

- Variations in the LW abundance were found during short-time periods (≤1year) suggesting that the LW budget can also be quantified over short temporal scales. Large wood is a very dynamic element that can undergo fluctuations due to the effects of single floods.
- Bank erosion is an important process for the supply of LW to the active channel in wide gravel-bed rivers. In the Piave River, volumes of LW recruited from bank erosion vary not only according to the eroded area, but also on the basis of the eroded morphological units and riparian vegetation characteristics (i.e. sizes, spatial density). The floodplain was found to be the morphological unit undergoing the greatest erosion and because of the bigger vegetation, a considerable amount (23.3 $m^3 \cdot km^{-1}$) of LW can be introduced to the river.
- The recruitment of LW from bank erosion is also conditioned by flood magnitude, being very much lower (0.21 $m^3 \cdot km^{-1}$) during low events than during over-bankfull floods (25.1 $m^3 \cdot km^{-1}$). Although this process occurs easily during larger events, there can also be input from lateral zones during lower floods, for example due to bank failure.
- In the two analyzed large rivers, where LW length is smaller than the channel width, woody elements are also subject to being mobilized and deposited during ordinary events but the differences observed in the amount of in-transport LW are a consequence of different processes that occurred in the past. The eruption of the Chaitén volcano destroyed much of the riparian vegetation, increasing the recruitment and abundance of in-channel LW and, consequently, the amount of wood available for transport. Instead, the high degree of human pressure in the Piave River and the presence of a dam upstream of the study reach result in lesser quantity of in-channel LW that can be mobilized.
- The flood magnitude as well as the morphological configuration of the river can be identified as the main factors influencing the temporal fluctuations of LW storage:
    a) A decrease in LW storage (negative budget) may be attributed to the occurrence of ordinary events when the smaller wetted area reduces the possibility of LW being transported. Instead, an increase in storage (positive budget) can be observed following not-ordinary events because the wetted area is usually larger and the progressive inundation of fluvial bars allows the mobilization and deposition of LW. The prevalence of deposition over mobilization during not-ordinary events may also be associated to the additional input of LW from riverbank erosion.

b) According to the local-scale morphology, the multiple-thread channel pattern was proved to be characterized by a greater movement of LW than single-thread reaches, because the faster increase in wetted area allows a larger amount of LW to be involved in the fluvial transport.

- In this study a method to analyze the buried LW was proposed, that is often mentioned in the literature but poorly investigated. With the methodology based on the GPR, a value of buried LW was provided for the Blanco River (1.65 $m^3 \cdot ha^{-1}$). Because it was a first attempt, further studies are needed in order to better calculate the diameter of buried wood, increase the investigated depth and broaden the types of soils (gravel, sand, ash) in which the GPR can be used.

The results obtained with this study demonstrated the usefulness of the budget as an approach to evaluate the temporal variations of LW in rivers, and identify which processes are prevalent (i.e. recruitment, deposition, mobilization) in particular river reaches and during specific flood events. Despite the advances attained by the present research, further studies could be important in order to better clarify the effects of floods of different magnitude on LW recruitment and mobilization/deposition processes. Indeed, the recurrence interval of 7 years for which vegetation erosion in the Piave River was observed, suggests that the previous threshold of RI>10-25 years proposed by many authors should be reviewed. So, further research may be useful to better define the threshold for LW recruitment. Understanding when LW can enter rivers as well as the fate of eroded trees is essential to avoid LW-related hazards. In fact, the significant wood retention observed on gravel bars positioned close to the recruitment sites indicates that some depositional locations for LW are predominant and, if sensitive infrastructures are located downstream, these sites should be constantly monitored.

Improving the understanding of LW recruitment, deposition and mobilization is therefore essential given its geomorphic and ecological importance, but also in order to minimize potential LW-related hazards. In fact, if negligible variations in LW storage and low mobility rate were found in the Piave River, the Blanco River showed considerable increases in storage and very high mobility rates suggesting that constant monitoring activities on LW quantification and its mobility are crucial for understanding and managing large wood in river.

Perspective and future research directions

Looking at those that may represent the future research directions on scientific LW studies, a better link between changes in storage and peak flow frequency should be reached. Understanding temporal variations of LW abundance related to flow variability still represent a challenge because of the numerous data needed for their quantification and the variability of flood magnitude. In this sense, extending the temporal scale of analyses, also over decades, is fundamental to collect a greater variability of flood that could help in the quantification of storage changes. In the same way, efforts to better define the thresholds for LW entrainment and entrapment may prove useful to yield significant insights on wood dynamics.

In terms of methodological approaches, numerous efforts have been made to apply remote technologies in the analysis of LW. Because remote technologies and data sources are increasingly accessible, future research directions may be oriented to the greater improvement of numerical models that are currently under development. Indeed, LW modeling might be extremely useful to river managers because they can allow a prediction of LW dynamics and, thus, the associated hazards. However, models are also known for being a simplified representation of a given process and are limited by a series of assumptions. Therefore, further researches are needed before their real application is feasible, especially concerning model calibration and results validation. In this sense, the traditional field data collected and analyzed in this work may represent an important and solid database to improve modeling and increase the range of its application. Notably in this time in which modeling is under development, the combination of numerical models with field observations could represent a current step to be advanced.

Section Seven - References

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