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TITOLO TESI

NATURE AND DYNAMICS OF LARGE WOOD AND INTERACTIONS WITH VEGETATION IN GRAVEL-BED RIVERS

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Dedicated to my family

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Abstract

Until very recently, rivers have been considered as the result of the interaction between water and sediments, thus simplifying this very complex system. In doing so, one important component was missed. This is vegetation, namely trees growing on banks, floodplains, and bars/islands; as well as dead trees lying on river beds. Both living and dead vegetation can play a very important in determining the morphology and dynamics of a river system and they also create ecological habitats for a variety of organisms. On the other side, if wood in-channel is transported during high-magnitude events, large wood pieces can increase flood hazards in sensitive places such as bridges and narrow cross sections prone to outbank flows. However, the dynamics and mobility of logs in rivers is still poorly understood, especially in wide gravel-bed rivers. Recent studies have employed fixed video cameras to assess logs velocity, but little evidence is still available about travel length during flood events of different magnitude.

During my PhD studies, several investigations were carried out to provide a better knowledge about the various degrees of morphological impact of large wood in three gravel-bed rivers located in north-eastern Italy (Brenta, Piave, and Tagliamento). The Piave river is a gravel-bed river, which suffered intense and multiple human impacts, especially due to dam building and in-channel gravel mining. The same alterations can also be observed in the Brenta River, which also presents bank protections, hydropower schemes and water diversions. On the other hand, the Tagliamento River is a gravel-bed river characterized by a high level of naturalness and very low human pressures. A series of field surveys were carried out to analyse the physical characteristics, quantity and geomorphic effects of in-channel wood on the three gravel-bed rivers mentioned. Overall, 3430 woody elements were measured in the study sites, 535, 1049, and 1846 of which were measured in the Brenta, Piave, and Tagliamento rivers,

respectively. As to jams, 591 accumulations were surveyed, 89, 189, and 313 of which were found in the Brenta, Piave, and Tagliamento rivers, respectively. In addition to the ecological and morphological importance of wood in rivers, its quantification is also of the higher importance for the assessment of flood hazards potentially linked to the transportation of the wood during extreme flood events and their accumulation near the piers of bridges. Furthermore, to fully understand how vegetation living or dead can influence many and interrelated aspects of braided river dynamics, a series of data collected from the experiments conducted in laboratory flume observing varying presence/absence of vegetation and large wood were analysed. An improved understanding of how vegetation and large wood interact to determine the forms and processes of braided rivers was underlined on the research. An increase of ability to understand the wood mobility in gravel-bed rivers. The results can be considered an important advance in our understanding of how rivers function, particularly with a background of indirect environmental change and direct basin scale human-impacts.

Riassunto

Fino poco tempo fa, i fiumi sono stati considerati come il risultato dell'interazione tra acqua e sedimenti, semplificando così il complesso sistema fluviale e tralasciando un importante componente: la vegetazione. Questa componente comprende alberi ed arbusti che crescono sulle barre, isole, sponde e sulle pianure alluvionali; così come gli elementi legnosi morti che giacciono sul letto del fiume. Sia la vegetazione viva che quella morta esercitano un importante ruolo sulla morfologia e la dinamica di un sistema fluviale. Inoltre, evidenze hanno dimostrato la sua importanza ecologica attraverso la creazione di habitat per una varietà di organismi. Oltre agli aspetti positivi che il materiale legnoso in alveo può apportare, è fondamentale tenere in considerazione il potenziale pericolo connesso al suo trasporto durante eventi di piena di elevata magnitudo. Il materiale legnoso, ad esempio, può essere un fattore di pericolo per le strutture sensibili come i ponti, nonché lungo le sezioni trasversali soggette ad esondazione. Per queste ragioni ed altri problemi idraulici, così come l'incremento della rugosità, la tradizionale strategia di gestione della rete fluviale adottata, è stata quella di rimuovere dall'alveo il materiale legnoso morto e tagliare la vegetazione da isole e piane alluvionali. Evidenze di recenti ricerche, hanno dimostrato i positivi effetti che il legname esercita in alveo. Queste osservazioni, suggerirono di intervenire sulle strategie di gestione, agendo sulla reintroduzione del legname in alveo. Tuttavia, è evidente la necessità di rivisitare la gestione del legname nei sistemi fluviali e delle aree ripariali, le quali sono potenziali fonti di legname in alveo.

Di fondamentale importanza, per raggiungere tale obbiettivo, è la determinazione delle dinamiche del materiale legnoso presente in alveo e delle interazioni di esso con la vegetazione ripariale. In questo elaborato di tesi vengono svolte delle prime analisi in campo, necessarie per valutare se le diverse pressioni antropiche in un sistema fluviale, hanno conseguenze sulla natura del materiale legnoso in alveo. I fiumi in considerazione sono, dal

più al meno antropizzato, il fiume Brenta, Piave e Tagliamento. Inoltre, attraverso analisi sulla distanza e velocità di spostamento di alcuni elementi legnosi durante eventi di piena di diversa magnitudo nel fiume Tagliamento, si vuole incrementare la conoscenza dei processi di trasporto e deposizione del materiale legnoso in larghi fiumi ghiaiosi. Vista la simultaneità delle dinamiche osservabili in campo tra vegetazione e legname in alveo, risulta opportuno ricorrere ad analisi di laboratorio in modo da riuscire a scindere le due componenti. La serie di simulazioni, condotte in una canaletta artificiale, hanno lo scopo di rappresentare un significativo contributo alla comprensione degli effetti reciprocamente connessi tra la vegetazione e legname in alveo, nel contesto della morfologia fluviale. Con questo elaborato di tesi si vuole esprimere un importante punto di inizio per un migliore approccio alla gestione del materiale legnoso nei sistemi fluviali, aumentando le conoscenze sulle sue dinamiche ed interazioni con la vegetazione ripariale in fiumi ghiaiosi.

Chapter One - Background

1.1 State of the art

1.1.1 Large wood in river system

Large wood (hereon LW) refers to in-channel woody elements which are characterized by the presence or absence of branches, leaves, bark and rootwad. It can be of different types as tree, shrub, or trunk, and it is commonly considered as LW every woody element characterized by 1 m or more of length and diameter greater than 0.1 m, or both (Jackson and Sturm, 2002). LW exerts an important role in river systems because it contributes to geomorphic processes as bank stabilization (Brookes, 1988), sediment retention (Mosley, 1981; Marston, 1982; Keller and MacDonald, 1983; Gregory and Davis, 1992), water flow processes (Bilby and Likens, 1980), and pool-riffle succession (Grette, 1982; Heifetz et al., 1986; Robison and Beschta, 1990), as well as to habitat diversity, to the benefit of aquatic communities (e.g. Johnston and Naiman, 1987; Naiman et al., 1988; Sedell et al., 1988).

LW is generally transported floating from upstream to downstream (Abbe and Montgomery, 1996; Braudrick and Grant, 2000; Abbe and Montgomery, 2003). During the transport, large wood could be stopped and remains stable in active channel, becoming a key elements. They are typically long pieces of wood with a large diameter (e.g. Keller and Swanson, 1979; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996) and they could form some wood jams (hereon WJ) that are composed of multiple pieces of single logs of different length accumulated from upstream. LW and WJ are two components that could be cause of changes of channel morphology and sediment budget (Rice and Church, 1996; Buffington and Montgomery, 1999), and could modify the channel form and the floodplain structure (Abbe and Montgomery, 1996; Piégay and Gurnell, 1997; Abbe and Montgomery, 2003; Brooks et al., 2003; O'Connor et al., 2003). LW and WJ could trigger bank erosion (Nakamura and

Swanson, 1993), the formation of bars (Fetherston et al., 1995; Abbe and Montgomery 2003) and log steps (Keller and Swanson, 1979; Keller and Tally, 1979; Heede, 1981; Marston, 1982; Abbe and Montgomery, 2003; Curran and Wohl, 2003), creation of avulsions, meander cut-off and chutes (Keller and Swanson, 1979; Collins and Montgomery, 2002; Webb and Erskine, 2003).

1.1.2 Types of wood jams

Large wood and wood jams can be distinguished into three main categories (Abbe and Montgomery, 2003): In situ wood jams, combination jams and transported jams.

1.1.2.1 In situ (autochthonous) wood jams

A wood jams can be classified as *in situ* if it is composed by LW that remain where were recruited. *In situ* wood jams are wood accumulations that remain in the place where they have been introduced and may be laying partially or completely within the channel (Fig. 1). Bank input is a type of this category. It is composed by LW fallen into the channel due to bank erosion, windthrow or mass movement.

Figure 1: *Example of in situ (autochthonous) wood jam.*

1.1.2.2 Combination jams

Combination jams are wood accumulations formed by *in situ* LW or WJ that trap pieces of floated wood. This category of jams can form a barrier or can deflect flows around the jam (Fig. 2).

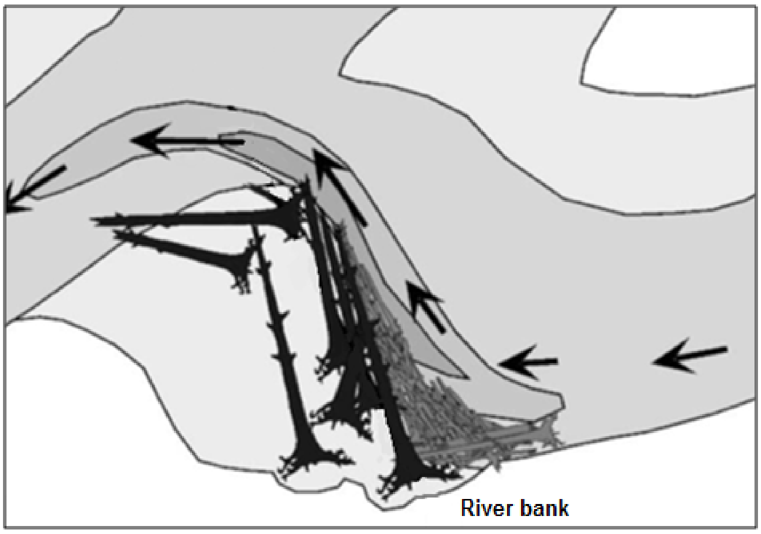

Figure 2: *Example of combination jam (after Abbe and Montgomery, 2003).*

1.1.2.3 Transported (allochthonous) wood jams

LW can be transported as a congested accumulation or as a single piece (Braudrick et al., 1997) and this depends on its specific gravity, shape, size relative to the depth and width of flow, and channel boundary conditions, as these factors influence the frictional resistance that a piece encounters (Fig. 3).

Figure 3*: Example of transport (allochthonous) jam.*

1.1.3 Effects of in-channel wood

Large wood and wood jams in channel exert several effects in river system. Some of these effects are described below, and are grouped as: ecological, geomorphic and island formation, and hazards.

Ecological effects

Macroinvertebrates use wood as refuge, as an oviposition and pupation site, as an attachment site for filter feeding, an wood is also used for building up case by several Trichoptera, and finally, invertebrates feed on the epixylic biofilms on the wood surface and on wood itself (Dudley and Anderson, 1982; Anderson et al., 1984; Harmon et al., 1986; Benke and Wallace, 2003). Invertebrate biodiversity, density, and biomass is especially high on wood compared to other substrates. Dudley and Anderson (1982) listed 185 species that are closely associated with wood in streams of the Pacific Northwest (USA). In the literature reviewed by Benke and Wallace (2003), invertebrate density and biomass on wood generally approaches or exceeds 10,000 m^{-2} and 1 g m^{-2}, respectively. Furthermore, wood exerts important ecological role in streams and rivers where other stable substrates are missing, like in sand-bed streams with shifting sand (Benke and Wallace, 2003).

Fishes use pieces of wood as a cover to decrease predation hazard, as nesting cover, for egg attachment, as a velocity refuge during high flows, and submerged wood visually isolates individual fish, therefore decreasing inter- and intraspecific interference competition (Crook and Robertson, 1999; Dolloff and Warren, 2003; Zalewski et al., 2003). LW is particularly important to contributing in stream the invertebrate diversity, habitat specific abundance, biomass, and productivity.

Figure 4*: Example of wood used as refuge for fish in the Brenta River (Italy).*

In large river systems with limited volumes of wood, fish abundance and diversity are also influenced by the structure of wood accumulations. Research on large French rivers shown that fish abundance and diversity depend on accumulations of large wood (Thévenet et al., 1998).

Sites with large wood have a more diverse fish community, with 1.3-2 times more species than sites without wood. Areas with wood were found to have 1.6-7 times more fish, both in the fall and winter (Thévenet, 1998). In the summer, fish spent most of their time near large wood or boulders provident by rip-rap bank protections. In winter, they are assembled around clusters of boulders. Because fish reduce their activities closer to feeding areas (e.g. areas of high flow velocity), which is more often true near boulders than near wood. The position of large wood in a channel reach potentially explains fish distribution apart from simply size and structure of the large roughness features.

Dolloff and Warren (2003), named 86 fish species that are associated with large wood in the south-eastern United States. Other aquatic and terrestrial vertebrates, like birds, reptiles, amphibians, and mammals use wood as habitat, shelter, and wood increases the food resources of these animals (e.g. leaf litter, insects, fish). For example, birds are known to use wood for perching, basking, and nest in wood accumulations, turtles were observed using partially submerged logs as basking sites, snakes and lizards use wood as protection from predation, amphibians use wood for egg deposition, mice built their nests under logs, and river otters, and mink at least partly rely on food resources potentially enhanced by wood (Steel et al., 2003). The vast majority of the studies mentioned above were carried out in North America. In contrast to North America, the relevance of large wood for stream ecosystems was overlooked in Central Europe, presumably due to the long term human impact on streams and the extensive management of virtually all forests over many centuries. But recently, large wood in streams is becoming a research topic of increasing interest in Central Europe. Probably because of the potential natural state of Central European streams and rivers, in fact literature shows that large wood was a key component in other pristine temperate forested ecoregions before the European settlement like in North American, and there is an urgent need for cost-effective methods for stream restoration.

Many studies indicate that large wood could be the key factors of ecosystems in temperate forested ecoregions, across a wide range of spatial and temporal scales (Harmon et al., 1986; Maser and Sedell, 1994; Gurnell et al., 1995; Gregory et al., 2003).

Large wood increases hydraulic resistance (Shields and Gippel, 1995; Buffington and Montgomery, 1999; Manga and Kirchner, 2000) and flow energy is dissipated at log steps (Keller and Swanson, 1979; Keller and Tally, 1979; Heede, 1981; Marston, 1982; Abbe and Montgomery, 2003; Curran and Wohl, 2003), yielding an increased water retention (travel time) during floods (Gregory et al., 1985; Ehrman and Lamberti, 1992). Flow diversity is enhanced spatially by acceleration and deceleration of the current (Beebe, 1997), resulting in increased niche and habitat variety (McMahon and Hartman, 1989; Rabeni and Jacobson, 1993). Decreased transport capacity in-channel reaches with high abundance of wood results in sediment storage. Such storage effects are apparent in the increase of bed load transport after the removal of wood (Beschta, 1979; Bilby, 1981; Klein et al., 1987; MacDonald and Keller, 1987; Smith et al., 1993; Webb and Erskine, 2003) or the breakage of single log jams (Mosley, 1981).

Geomorphic and island formation

LW exerts numerous geomorphic and ecological functions in streams and rivers (Harmon et al., 1986, Gregory et al., 2003), as they can influence substantially the morphology of channels by inducing step and pool formation, sediment deposition, channel avulsion, and island formation (Montgomery et al., 1995, 2003, Abbe and Montgomery, 1996).

Wood is the element that changes the most if compared with sediment and their associated bedforms. During and after a flood event it is possible to identify different interactions between flow and wood. LW is usually deposited in-channel with the trunk oriented to downstream and the rootwad upstream. Because of its orientation, it develops a scour upstream of the rootwad where coarse and organic materials can be collected in order to create a wood jam. While fine sediment is deposited around the trunk, branches and in the area downstream the rootwad (Fig. 5).

LW deposited can be a source of biomass because the material in the jam or in the sediment such as seeds can regenerate and re-sprout giving rise to branches and leaves (Francis et al., 2008).

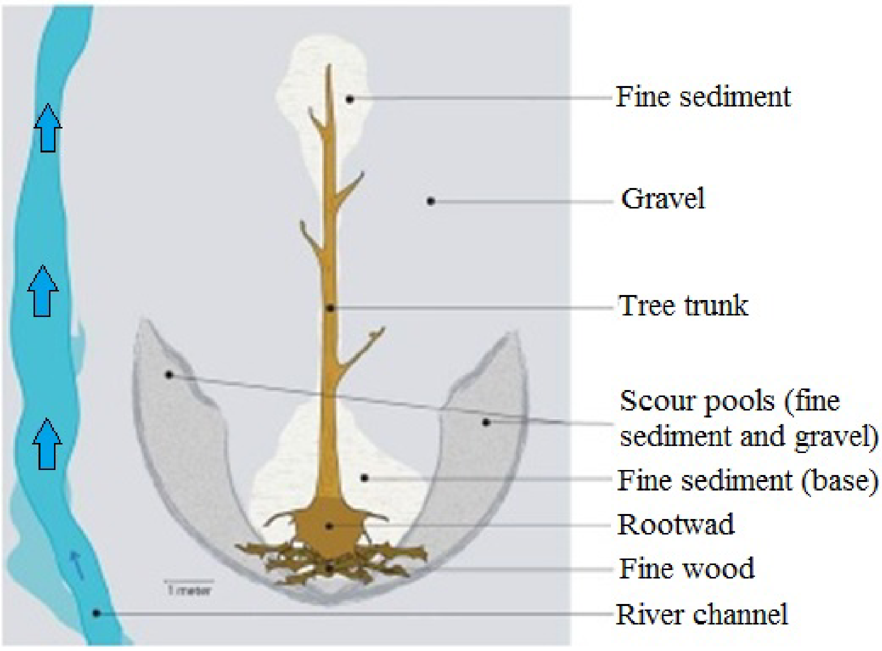

Figure 5: *Typical spatial patterning of a deposited tree (after Francis et al., 2008).*

The transport of LW depends on the quantity of the recruitment of wood and its characteristics such as size, shape, density, and the characteristics of the river such as channel dimensions, geomorphological settings and flow regime (Gurnell, 2013). The latter controls and influences the frequency for wood pieces to be transported and it also affects the flotation, the erosion, the depth and power of flows that are available to mobilize and transport the wood (Gurnell et al., 2002).

LW can be partially or completely buried from sediment mobilized, transported and deposited in-channel. Buried or partially-buried wood is more stable than exposed wood. Decaying wood tends to be buried and its conditions are strictly connected to the frequency and duration of wetting and drying. Also water depth and velocity are two elements which contribute to the decomposition of wood. These sediment processes can have an important influence in what concerns the sprouting and the growth of the living wood. However, the knowledge of interaction between wood, flow and sediment is very important to understand the reason why some sites for sediment accumulation are those of jams that extend across the entire width of the active channel.

Flow resistance is affected by quantity, position and orientation of pieces of wood and their effects can be seen in smaller rivers, increasing flow complexity, water retention (Ehrman and Lamberti, 1992) and the flood peaks and their travel times (Gregory et al., 1985).

The mobility of wood pieces leads to an interaction between river flows and degree of wood pieces moving in accumulations or in single elements depending on their size, number and shape (e.g. Braudrick et al., 1997; Johnson et al., 2000). If remove from river channel, LW and WJ can lead to an increase of sediment transport (Beschta, 1979; Klein et al., 1987; MacDonald and Keller, 1987; Smith et al., 1993). Furthermore, the role of wood jams as natural dams is represented by the channel incision that can result when wood is removed (Gurnell and Sweet, 1998). In larger rivers, wood can also be an important influence on sediment storage by helping bars formation (e.g. Nanson, 1981; Gurnell et al., 2001; Gurnell and Petts, 2002) and by playing a fundamental role in island development (e.g. Abbe and Montgomery, 1996).

Previous field observations on LW transport in different streams orders (Toews and Moore, 1982; Hogan, 1987; Lienkaemper and Swanson, 1987; Bilby and Ward, 1989; Gregory et al, 1991; Nakamura and Swanson, 1994; Young, 1994; MacVicar and Piégay, 2012; Schenk et al., 2013) show that there is more frequent LW transport in large streams than the smaller (Bilby, 1985; Lienkaemper and Swanson, 1987; Bilby and Ward, 1989, 1991). Once in motion, there is more movement and greater travel distance with small pieces of wood than the larger ones (Lienkaemper and Swanson, 1987; Young, 1994; Bocchiola et al., 2006) which have a length shorter than bankfull width. This suggests the important relation between piece size in length and the channel width to predict the piece movement and the travel distance of transported logs (Comiti et al., 2006; Iroumé et al., 2010; Iroumé et al., 2015).

There are several characteristics in addition to those mentioned that can affect the LW transport and mobility such as the rootwad and diameter. The first one may anchors a piece to the bed or bank, increasing drag and thereby decreasing mobility (Abbe and Montgomery, 1996), the second one consists on the wood stopped during its run when the channel depth is approximately half the piece diameter (Mao and Comiti, 2010).

Hydraulic hazards

Despite the ecological benefits that provides in-channel, LW could be a problem to some human activities on rivers. It may disrupt navigation, including commercial marine operations on large rivers (Gurnell et al., 2002; Piégay, 2003) and recreational navigation on smaller rivers. LW might also damage infrastructure when it accumulates on or near structures such as bridge piers by increasing hydraulic head and/or increasing bridge scours (Diehl, 1997; Wallerstein, 1998; Kothyari and Ranga Raju, 2001; Comiti et al., 2008; Mao and Comiti, 2010; Rigon et al., 2012; Riuz-Villanueva et al., 2014). For these reason, the analysis of the abundance, dynamics and the knowledge of characteristics of in-channel wood are fundamental for the design of resilient protection systems.

The presence of wood in-channel can cause hydraulic problems, as it creates obstructions, localized erosion and increases the roughness, increasing the maximum flood peak (Abbe and Montgomery, 1996). The accumulation of LW in-channel can cause problems due to the loss of efficiency of the hydroelectric works and connecting channels. Moreover, LW may also increase local flooding if log jams impede flow. Mazzorana et al. (2011) studied and defined two types of in-stream obstacles that may be source of hazard in-channel, the first one are vertical obstacles as piers or abutments that can entrapped upon collision transported logs. The second one are obstacles that cross the channel from a height on which the logs can be entrapped with their rootwad when the flow depth approaches the object’s height.

Figure 6: *Hydraulic risks associated with large wood.*

1.1.4 Riparian vegetation

Riparian vegetation is, in additional to dead wood, another important factor that may control channel morphology (e.g. Johnson, 1994; Millar, 2000; Gran and Paola, 2001; Beechie et al., 2006; Hicks et al., 2008; Tal and Paola, 2010). In particular it stabilizes banks, bars and islands and can constrain channel widths (Nanson and Knighton, 1996; Gurnell et al., 2001). Riparian vegetation exerts an important role to the in river processes, as it can influence flow velocity and bed incision by adding drags and reducing the area available for water flow (Tal and Paola, 2010). Furthermore vegetation can protect the bank by large wood transported (Simon and Collison, 2002). It can trap the floating LW and subsequently creates favourable conditions for new vegetation and increases the height of bars and islands, helping them to a greater permanency (Fig. 7). At the channel scale, the presence of pieces of wood stopped by the vegetation along the banks can slow down bank erosion, narrow the channels and enhance the bank.

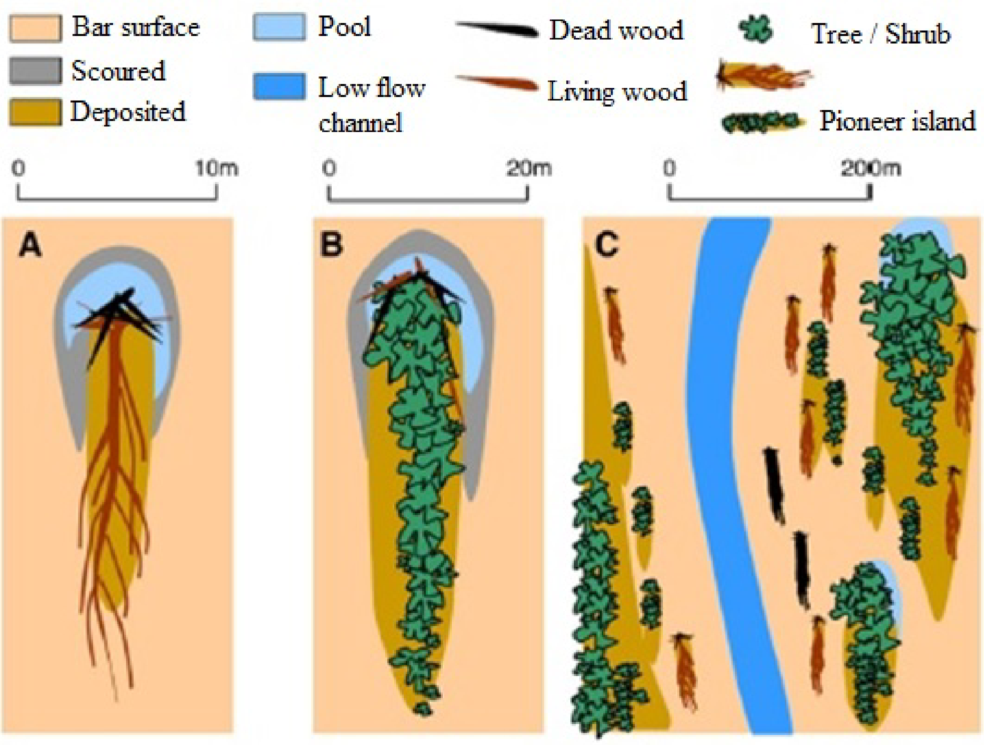

Figure 7: *Island evolution (after Gurnell et al., 2012).*

Many meandering rivers are characterized by non-cohesive materials (sand or gravel) with vegetated floodplains. Riparian vegetation that constitutes the floodplain is a factor to different sedimentation processes and can influence the flow velocity (Simon and Collison, 2002).

The flow velocity is reduced through vegetated areas, decreasing the scours and increasing the depositions of sediments transported. As a consequence, the height of bars increase, helping the islands formation (Picco et al., 2012; Picco et al., 2014). Vegetation can block small channels and prevent the formation of flow diversions. In braided rivers it can reduce the braiding index decreasing the bank erosion, narrowing channels and increasing the bank accretion.

The riparian vegetation, through the redistribution of bed shear stresses and velocities, can have numerous effects on sediment transport and river morphology depending on the type of river and the density and spatial distribution of the vegetation. It can deflect the flow becoming a potential key factor to initiate a meander (Bennett et al., 2002). However, different fluvial styles depend on interactions between hydrogeomorphic (e.g. sediment structure, vegetation and roughness) and biological ecosystem components (e.g. wood and riparian vegetation).

Riparian zones are very important because lead a major biodiversity being between aquatic and terrestrial areas especially during flood and flow pulse events (e.g. Junk et al., 1989; Fetherston et al., 1995; Tockner et al., 2000; Welty et al., 2002; Gomi et al., 2006).

On large rivers, wood can have an important role of maintenance of vegetated bars and islands and also in the creation of these (Abbe and Montgomery, 1996; Gurnell et al., 2001; Gurnell and Petts, 2002). However, in Europe because of river regulation due to human activity (Petts, 1990; Tockner and Stanford, 2002; Tockner et al., 2003), the islands are very rare and riparian biodiversity is well conserved because riparian collections of large wood is more common.

1.1.5 Wood recruitment and mobility

LW and WJ are important to understand the channel morphodynamics in fact they can be easily mobilized during a flood event. In particular, for a better management of the river system, it is important to understand where the LW moves and where it tends to accumulate (Curran, 2010). The wide, sinuous reaches and the alternate bars that characterize the braided rivers are often deposit zones of LW (Nakamura and Swanson, 1994). LW tends to deposit outside of bends and on the head of islands and bars (Nakamura and Swanson, 1994; Abbe and Montgomery, 1996). Knowledge of recruitment processes, the storage and the transport of wood in-channel is important to understand the quantity and the mass balance present in the rivers. Different natural processes may be source of input of wood in-channel such as landslides, wind, ice storm, wildfires, chronic mortality and bank erosion. The latter because of trees that are undercut tend to fall towards channels, is probably the main process of recruitment of LW in large rivers (Piégay et al., 1999). Therefore, the recruitment process of wood in-channel by bank erosion depends on the nature of streamside forests, erodibility of the banks due to the type of soil, the reinforcement of the bank by roots (Hooke, 1980) and on the frequency and magnitude of flood events (Benda and Sias, 2003).

Storage and mobility of wood in river system responds to many factors but the common patterns can be identified through the knowledge of the tree type that compose the floodplain, the degree of decay (it can influence the effects on wood buoyancy), the channel size (because broad changes in storage and dynamics may be associated with small and large river channels), the capacity of wood to stay alive during transport and deposition (in fact in rivers, the riparian tree species as well as dead wood may support extremely rapid vegetation establishment on areas of exposed sediment and can change the balance between destructive and constructive processes).

1.2 Motivations

The riparian vegetation is known to plays a crucial role in shaping rivers (Gurnell and Petts, 2006; Corenblit and Steiger, 2009). The significant impact of vegetation growing on bars and floodplains on channel morphology has been increasingly verified in the field (Simon and Collison, 2002), numerically (Murray and Paola, 2003) as well as experimentally (Tal and Paola, 2007, 2010; Braudrick et al., 2009). These studies have begun to directly show the influence of riparian vegetation in stabilizing banks, increasing mean channel depths, significantly reducing the number of channels per river cross section, and have been incorporated into an improved theoretical meandering-braiding transition criterion (Eaton et al., 2010). The geomorphic effect of living plants continues even after their erosion from the banks and transportation throughout the fluvial network. Dead or living pieces of large wood (LW) can exert a tremendous influence on river erosion and sedimentation processes (Jeffries et al., 2003), channel morphology (Abbe and Montgomery, 2003), channel hydraulics (Wallerstein et al., 2001) and ecological diversity of river channels (Gurnell et al., 2002). Both vegetation and LW contribute to shaping rivers such as braided systems with islands, which are the highest expression of ecosystem integrity within fluvial systems (Francis et al., 2008). In this regard, it is important to note that vegetation and LW seems to exert opposite roles in conditioning river morphology. The former tends to reduce channel width and braiding index, whereas the latter increases channel dynamics often creating pioneering islands. Despite some recent experimental study on the riparian vegetation effects on the planform of gravel-bed rivers (Coulthard, 2005, Tal and Paola, 2007, 2010), such work is in its infancy and there is a substantial lack of knowledge and evidences for the contrasting and relative effects of riparian vegetation and LW on braided river channels. Hitherto, no attempts have been made to simulate the effects of LW in a mobile bed, poor evidences exist on LW displacement and dynamics in large rivers, and thus the models incorporating the vegetation without the LW are still of limited applicability. Virtually no experimental evidence exists that examines the interacting effect of vegetation and LW on sediment transport and depositional processes, modifying the morphological patterns and dynamics of complex river systems at either local or reach scales. The proposed research will explicitly address this lack of knowledge by addressing this new area of river science. The acquired evidence and process understanding will permit a major step forward in the field of river modelling and management. Much of the recent interests on vegetation and LW impact on complex river systems is motivated by an interest in morphodynamic changes and subsequent loss of riverine habitat diversity associated with in-channel vegetation encroachment. Vegetation encroachment often results when flow variability, peak discharges and sediment inputs are reduced. This can be due to anthropogenic causes (dams, flow diversions, bank protections, gravel mining) or climate changes and can produce an increase in bank stability and flow resistance, and a reduced sediment transport. The consequent reduction in river channel dynamics can have a considerable impact on riverine and aquatic ecology, by decreasing physical habitat quality and diversity. For this reason, an increased understanding of the role of vegetation and LW on the dynamics of braided rivers is essential to support appropriate river conservation strategies, and to develop scientifically-based environmental management policies. Furthermore, a better understanding of the key processes linking vegetation, LW and morphological dynamics will improve our ability of applying informed river restoration strategies, which can take advantage of living and dead plants, logs, and engineered log jams to stabilize banks, and to increase physical complexity and habitat diversity (e.g. Shields et al., 2004). Additionally, there is an increasing need to understand the impact of vegetation on river morphology and sediment transport, which is required by environmental agencies and river boards responsible for environmental management. Indeed, there is a requirement to improved understanding of the effect of vegetation encroachment/removal and LW presence/absence on channel morphodynamics is of major importance in planning a management strategy which can then be optimized to achieve the most appropriate ecological status for river systems whilst maintaining the factor of safety levels in terms of flood defence. Until recently, the presence of in-channel wood has been considered an issue for various human activities (Ruiz-Villanueva et al., 2014), for example disturbing the normal navigation (Gurnell et al., 2002; Piégay, 2003). For these reasons and other causes of hydraulic problems as well as the increases of the roughness (Abbe and Montgomery, 1996), the traditional management strategy adopted has been to removes dead wood in-channel (Abbe and Montgomery, 2003) and cutting the vegetation from islands and floodplains. During the first half of 20th century, almost all the Alpine rivers in Europe were affected by human interventions (Tockner et al., 2003) which still persist in some countries (Ollero, 2013). However, evidences of recently researches, proved the positive effects that wood exerts in-channel. These observations suggested to invert the managements strategies, introducing wood into the river channels (Gurnell et al., 1995; Hildebrand et al., 1997; Abbe et al., 1997; Reich et al., 2003; Brooks et al., 2006; Kail et al., 2007) but, it is evident the needs of revised management of LW and of the potential sources of wood from riparian areas (Mao et al., 2008a, 2013). For this reason, the knowledge of abundance and characteristics of in-channel wood in gravel-bed rivers has generated interest of several authors (e.g. Piégay et al., 1999; Gurnell et al., 2000; Francis et al., 2008). As the amount of wood can vary considerably between rivers, it is worth to analyze the processes of wood through time (Gurnell, 2013). A knowledge of the balance of in-channel wood input/output (i.e. wood budget) in different environmental rivers could be helpful to improving the management strategies. This work want to suggest if the amount and qualitative information of in-channel large wood are able to provide some insight on the degree of human pressures at the basin scale. Further comparative studies on this direction could shed further light on how human disturbances can affect large wood nature in gravel-bed rivers. in gravel-bed rivers.

In addition to the ecological and morphological importance of wood in rivers, its quantification is also of the higher importance for the assessment of flood hazards potentially linked to the transportation of the wood during extreme flood events and their accumulation near the piers of bridges. MacVicar and Piégay (2012) explored the relationship between wood transport rate and water discharge by using a streamside video camera in a wandering piedmont river, the Ain River in France. They confirmed the observations of MacVicar et al. (2009), who reported a higher wood transport rate during the rising limb than falling limb of hydrographs. Physical modelling under steady flow conditions revealed that log travel distance depends on the wood size and density, water depth and velocity, and the channel bed roughness (Braudrick and Grant, 2001; Haga et al., 2002). Additionally, field observations suggest that relatively small and loose wood pieces are easier to move than buried logs and/or pieces that are longer than the bankfull width (Gurnell, 2013). Moreover, mobile small pieces of wood have been observed as being trapped by large wood pieces (Seo and Nakamura, 2009; Welber et al., 2013). Despite these previously studies, wood transport dynamics (such as the log displacement length and velocity) are still poorly understood, mainly for lack of direct field observations (MacVicar and Piégay, 2012) especially in large rivers. The observations could be useful for better planning of river management practices and strategies involving the use of large wood pieces and could help for calibrating wood budgets at the reach scale. These analysis could be necessary for supporting the choice of better river management practices and river ecology application, as wood transport is a possible key process for in-channel wood redistribution playing an important role to increase the number of habitat for different organisms.

1.3 Aims

The aim of this PhD project is to identify and assess the mutual effects of riparian vegetation and large wood on the morphodynamics of braided river channels, under variable flow conditions. The proposed research is based first on field surveys which will provide crucial full-scale measurements about volume and characteristics of in-channel wood in three large rivers which have suffered of different human pressures. The rivers examined are the Brenta, Piave, and Tagliamento rivers, located in northeast of Italy. The first one is very disturbed and the last one is the lesser impacted. Additional novel data on logs incipient motion and displacement lengths during flood events of different magnitude were analysed in Tagliamento River. The research was carried out in manner to increase the knowledge about the retention, transport and deposition processes that still remain poorly understood especially in large rivers. This first step of field observations was important to aid the setting of boundary and initial conditions for the experimental programme in the flume as well as helping to inform and guide the interpretation of the results obtained.

A series of physical modelling simulations were conducted in order to represent a significant contribution to the understanding of the mutually related effects of sediment transport, and the dynamics of vegetation and LW within the context of river morphology.

Chapter Two – Material and methods

2.1 Study areas

The research was carried out in three gravel-bed rivers located in North-east of Italy (Brenta, B; Piave, P; and Tagliamento, T). The three rivers drain relatively comparable basins in terms of size, climate, geological settings, and vegetation. However, the three rivers differ substantially regarding the level of human disturbances, which have relevant influence upon the morphological dynamics and the effects of vegetation and LW (piece of wood greater than 0.1 m in diameter and/or 1 m in length). The surveys were carried out in 2 sub-reaches in Piave and Tagliamento River and in 3 sub-reaches in Brenta River. In these, the rivers present a similar braided/wandering channel pattern with the presence of vegetated islands.

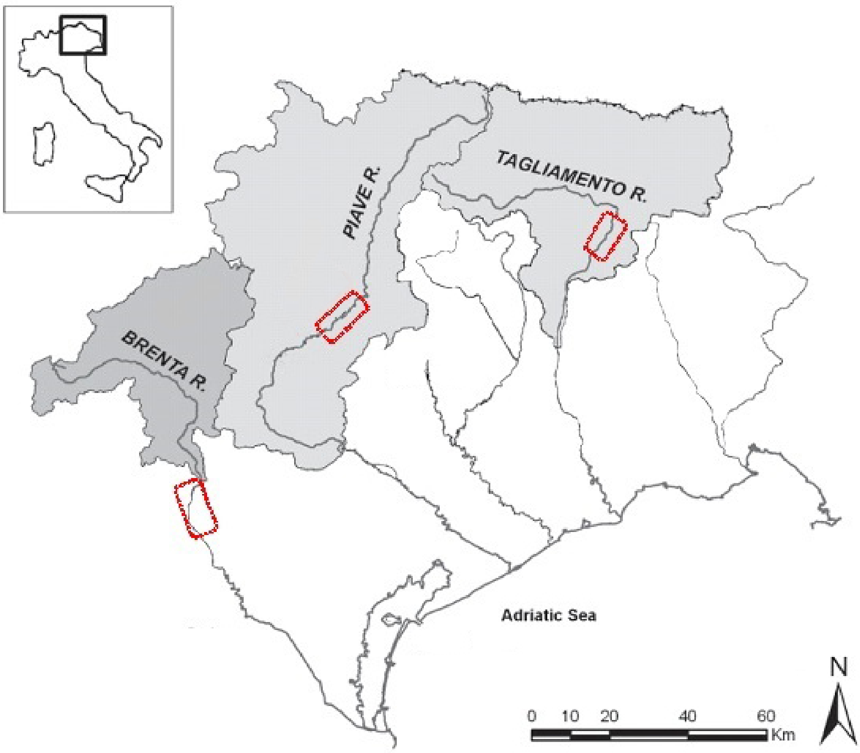

Figure 8: *Location map of the three study basins.*

2.1.1 Brenta River

The Brenta River basin is located in the eastern Italian Alps (Italy). The river has a drainage basin of approximately 1567 km^2. Its length is 174 km with an average slope of 0.003 m m^{-1}. The river length can be divided into two main reaches: an upper part of about 70 km-long which flowing within the mountain basin, and a lower part of 104 km-long which flowing within the Venetian Plain (Surian and Cisotto, 2007). The upper basin features a typical continental-Alpine climate with annual rainfall of about 1500 mm (Giuliacci et al., 2001). The landscape is very different in the upper and lower part of the basin. In the upper part the river flows through a typical glacial-fluvial valley (U-shaped), the Valsugana Valley, from the Caldonazzo Plain up to the Primolano gorge. In the lower part, the Venetian Plain can be divided into an old deposition plain (alluvial fan of Bassano, Upper Pleistocene) placed on the left side of the Brenta River, and a more modern plain, the current Brenta River floodplain (Holocene). The mountain basin has a humid temperate-continental climate. The rainy seasons have the maximum precipitations during the months of May-June and October-November. The geological setting is rather complex and includes limestone, dolomite, gneiss, phyllite, granite and volcanic rocks.

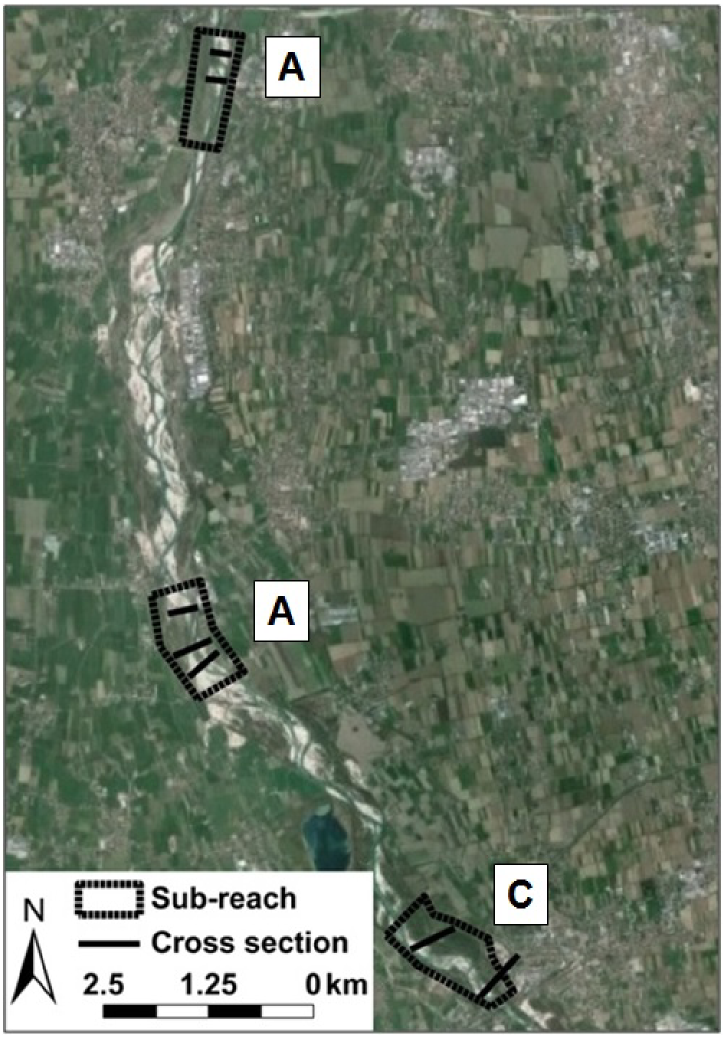

Figure 9: *Plan view of the study sites along the Brenta River. (A) Nove; (B) Friola; (C) Fontaniva.*

2.1.1.1 Human pressures in Brenta River

Especially during the second half of 20th century, intense human impacts have taken place in Brenta River (Surian and Cisotto, 2007). Dams, gravel mining, torrent control works, channelization, groins construction were some of direct interventions carried out in Brenta River. Also indirect effects on river dynamics have been conducted, such as the reforestation (Surian et al., 2009). It is possible to define Brenta as a river affected by strong human pressures, with consistent channel adjustments (incision up to 8–9 m and halving of active channel width) occurred in response to an alteration of sediment fluxes caused by different human interventions (Surian et al., 2009; Lenzi et al., 2006; Conesa-Garcia and Lenzi, 2010). Official estimates set volumes of extracted sediment to around 6-8 million m^3 from 1953 to 1977. However, these values are most likely to be far underestimated (Castiglioni and Pellegrini, 2001).

2.1.1.2 Study reaches of Brenta River

The study reach of Brenta River is located in piedmont area and it is approximately 20 km long. Its median slope is about 0.3% and the river features braided pattern with islands. Within the study reach, large wood surveys have been carried out in three sub-reaches. The sub-reaches were selected as representative of the upper-middle and downstream part of the study area and they were called “Nove, Friola and, Fontaniva”, respectively. Nove site is composed by a single channel and the average width of the active channel is of about 300 m. Friola sub-reach is formed by a more complex morphological patterns with densely vegetated island. Fontaniva reach is composed by several fluvial islands and the river is divide in different channels, featuring in a braided morphology. In this sub-reach, the river result strongly influenced by longitudinal embankments and bridges (Moretto et al., 2014; Kaless et al., 2014).

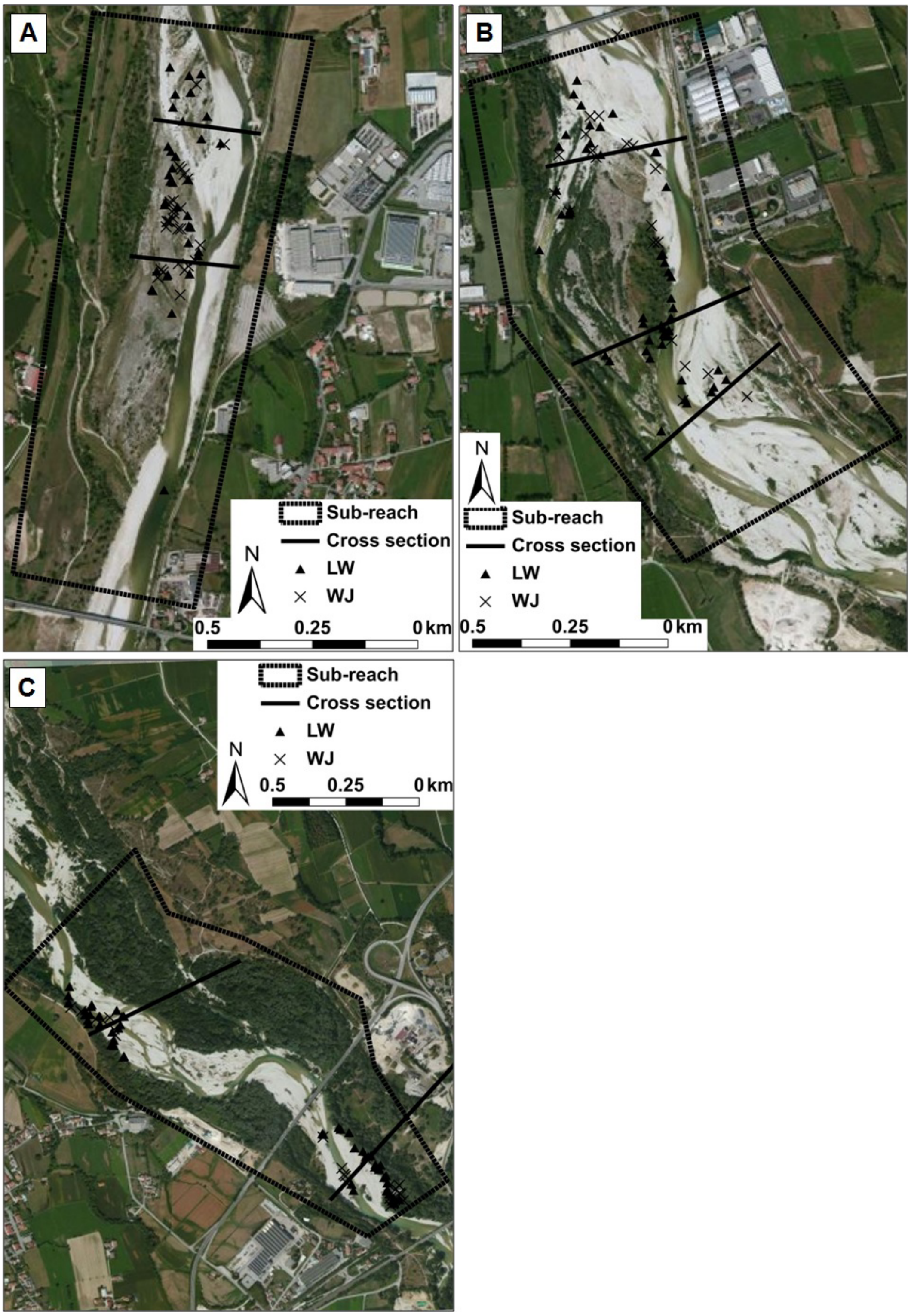

Figure 10: *Localization of large wood (LW) and wood jams (WJ) in (A) Nove, (B) Friola and (C) Fontaniva sub-reaches in Brenta River.*

2.1.2 Piave River

The Piave River is located in Veneto Region (Italy) with a basin area of ~4100 km^2. The river is about 220 km long from near Peralba Mount (Belluno Province) at an elevation of 2030 m a.s.l. and it finish to flowing in the Adriatic Sea (Venice Province). The Piave River has three principal tributaries: the Boite River that is located near Perarolo di Cadore, the Mae River that is placed near Longarone and the Cordevole River which collects water from the western region. The climate is temperate-humid with an average annual precipitation of about 1350 mm, with a minimum of 1000 mm in the north western side (including the basin of Cordevole River) and the higher is recorded in the central-eastern corner. The rainiest season is the Autumn, followed by the spring season. The high value of temperature is commonly recorded during the summer season (maximum of 33-35°C). During the winter season the temperatures decrease until 2-3°C. The torrents at the headwater flow along very narrow valley and are characterized by high slope. The valleys have the typical U-shape due to glaciers erosion. The landscape characteristics change from Ponte nelle Alpi and the river arrives to a former synclinal that directs the flow towards Feltre. After Feltre, the river enters into a narrower valley that cuts the Grappa-Tomatico-Cesen-Visentin mountain range, which stratification constitutes a long anticline arc. Finally, the river flows through a zone with a syncline disposition arriving to the deep gorge at Nervesa. This point constitutes the end of the mountain basin, and following the river flows along the Venetian plain. The mountain area of the basin is occupied by tows of median to small dimensions. In the Piave River basin several and different rock types crop out with a variety of origin, composition and age: Schist-phyllite rocks (Paleozoic), Sandstone, marlstone, argillite and sedimentary rocks (limestone and dolomite). The most diffused rocks within the Piave River basin are limestone and dolomite (Kaless, 2013).

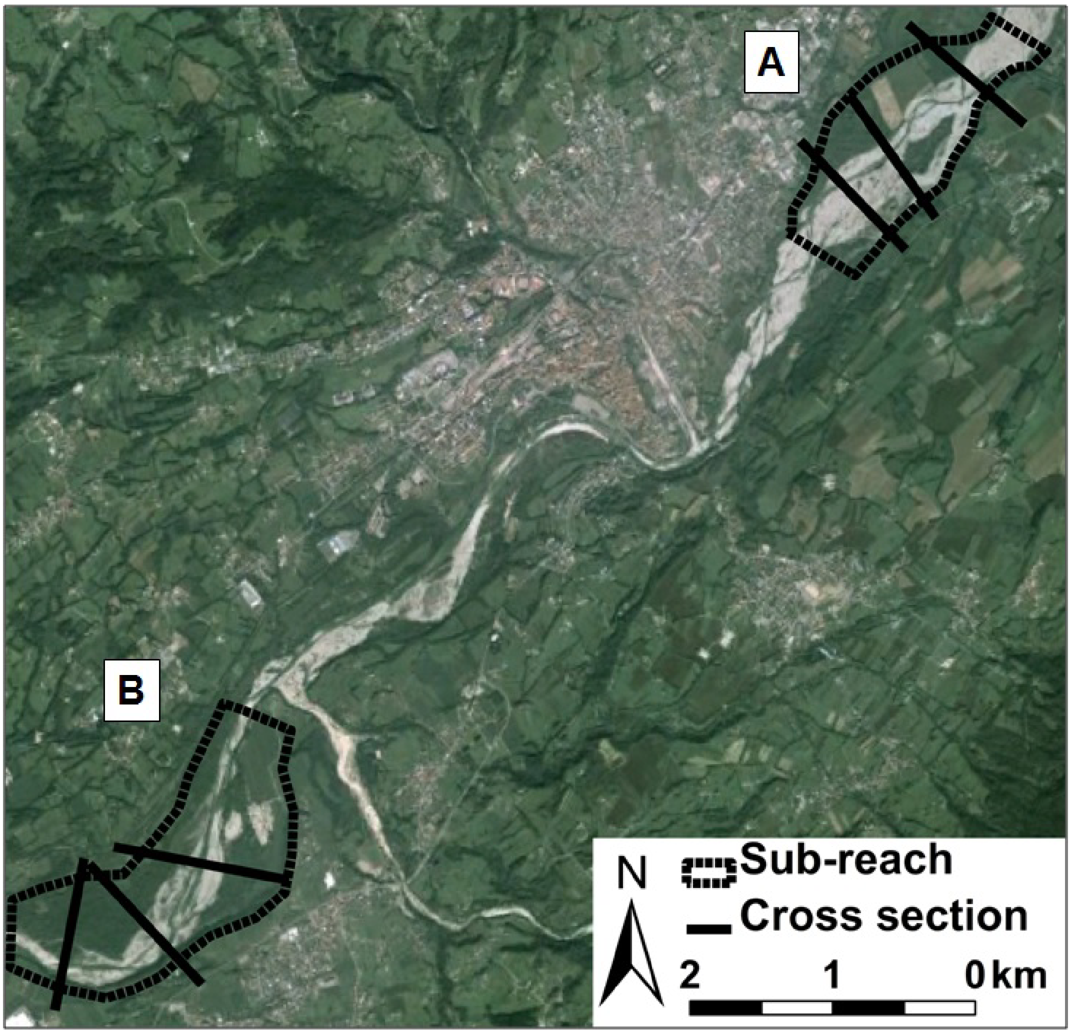

Figure 11: *Plan view of the study sites along the Piave River. (A) Quagliodromo and (B) Praloran.*

2.1.2.1 Human pressures in Piave River

The Piave is a gravel-bed river which has experienced a wide range of intensive human impacts that include phases of deforestation and reforestation, major dam building, water diversions, gravel mining and a range of bank protections. As a result, it has experienced considerable wide contraction and channel incision phases (Da Canal et al., 2007; Surian et al., 2009). Piave basin has been inhabited since prehistoric times. Its forest cover reached a minimum probably during the 19th century because of wood exploitation, cropping and farming. During 1930s-1950s dams were built along its channel network, intercepting sediments from 54% of the basin area. During the first years of the 20th century it was evident the need of electric energy generation and the development of irrigation systems. Since the '30s until the '60s all the current dams were constructed. The presence of artificial reservoirs has stopped the natural sediment flow during floods affecting the sediment balance in the fluvial network placed downstream. More recently, another human activity has altered the dynamic of these fluvial systems. Between 1960s and 1980s intense gravel mining was carried out. Natural and artificial reforestation have been taking place after World War I, most effectively after 1950s. Erosion and torrent control works started in the 1930s, but massively only after 1970s (Comiti et al., 2007; 2011).

2.1.2.2 Study reaches of Piave River

Surveys of woody material in-channel in Piave River have been carried out in piedmont area where the LW is usually transported by buoyancy, unlike of the mountain areas where the recruitment is more difficult due to the hydraulic and morphological characteristics and for the prevalent formation of wood jams. The study reach is located between Ponte delle Alpi and Busche (BL) featuring about 30 km long. The average slope is approximately 0.45% and the median surface grain size is comprised between 20 mm and 50 mm (Surian, 2002).

Survey of in-channel wood in Piave River has been carried out in two sub-reaches selected in the middle portion of the river course where the river morphology is dominated by braided and wandering channel patterns, the slope is around 0.45%. The choice of the areas has been carried out in based on a possibility of easily accessing to in-channel and for the availability of woody material with standard dimension previously predetermined. The sub-reaches were called from upstream to downstream: "Quagliodromo" and "Praloran". The first one, Quagliodromo, features a length of about 2.2 km, whereas the second study reach, Praloran, features a length of 3.2 km.

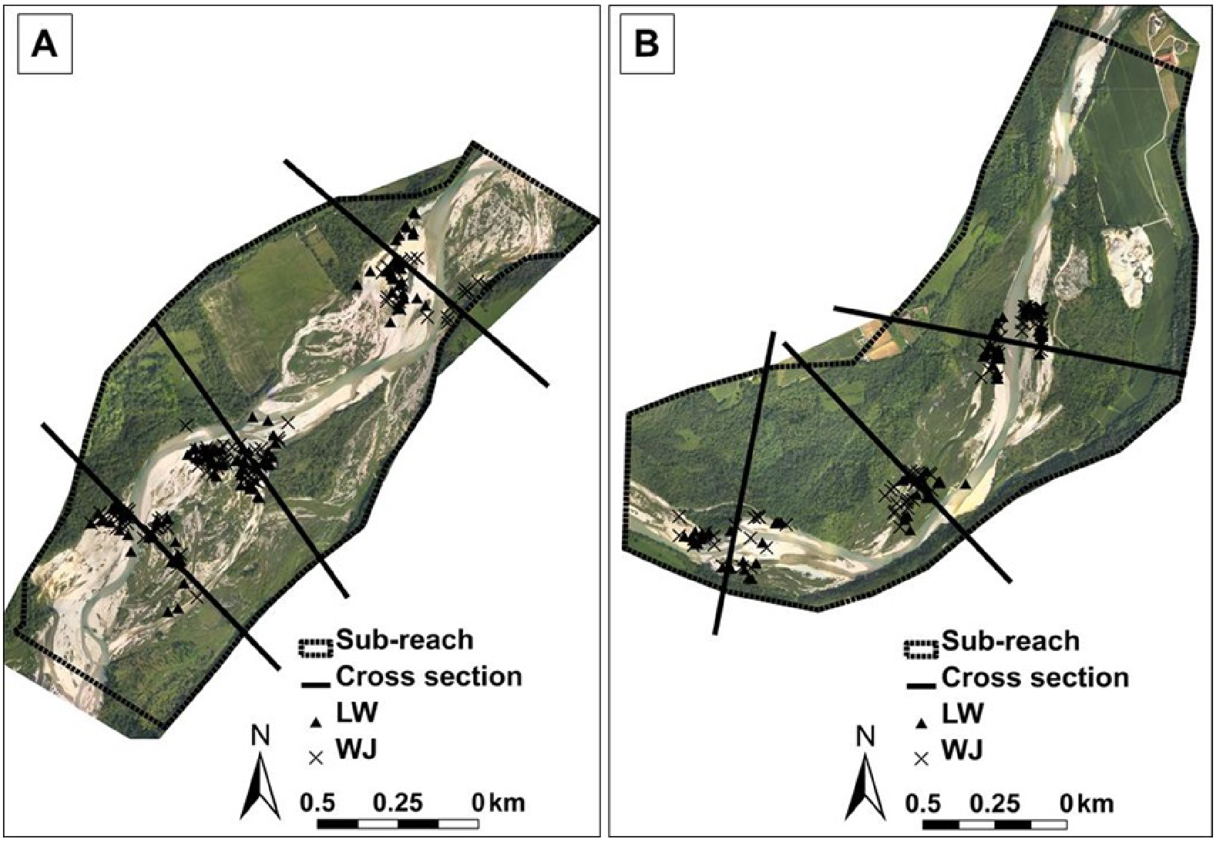

Figure 12: *Localization of large wood (LW) and wood jams (WJ) in (A) Quagliodromo and (B) Praloran sub-reaches in Piave River.*

2.1.3 Tagliamento River

The Tagliamento River is a gravel-bed river located in north-eastern Italy (Friuli Venezia Giulia region) originates at 1195 m a.s.l.. Its basin area is around 2871 km^2 and flows for 178 km from the Southern Alps to the Adriatic Sea. Multiple-thread channel pattern and numerous islands characterize most of the river, although in some segments it is closely confined between flood embankments (Gurnell et al., 2001). The river has a straight course in the upper part, while the most of its path is braided shifting to meandering in the lower part, where dykes have constrained the last 30 km. However, the upper reaches are more or less intact, thus the basic river processes, such as flooding, and sediment transport, take place under near-natural conditions. The catchment is mainly mountainous and the slopes are very steep, leading to high peak flows and sediment loads in the central and lower part of the basin. The Tagliamento River is influenced by intense and highly variable annual precipitation ranging from 1000 to 3100 mm. The flow regime is characterized by spring and autumn floods due to snowmelt and long rainfall events, respectively (Tockner et al., 2003). Minimal management is applied to vegetation on islands and within the riparian forest. For this reason, fluvial processes and natural biological dominate the vegetation establishment, and the erosion and deposition of vegetation and wood debris (Gurnell et al., 2001). As to the riparian areas, *Alnus incana* dominates on streams in the headwater (Gurnell and Petts, 2006) whereas *Populus nigra* and *Salix alba* are the most commons species on floodplains and islands in the wider reaches of the piedmont portions of the river (Francis et al., 2008; Bertoldi et al., 2013). The Tagliamento River is recognised as one of the most intact and less disturbed river in the Alps (Ward et al., 1999), as most of its longitudinal, lateral and vertical biological and sediment connectivity is still preserved (Tockner et al., 2003).

The alpine area of Friuli mainly consists of limestone, with a spatial sequence of Silurian, Devonian, Triassic, Jurassic and Cretaceous formations north to south. Limestone is occasionally intermixed with layers of gypsum that lead to high sulphate concentrations in the Tagliamento (Arscott et al., 2000). The catchment is tectonically active, continuously developing faults and overthrusts. Many tributary streams, like the Fella, have sharp bends following the direction of these faults.

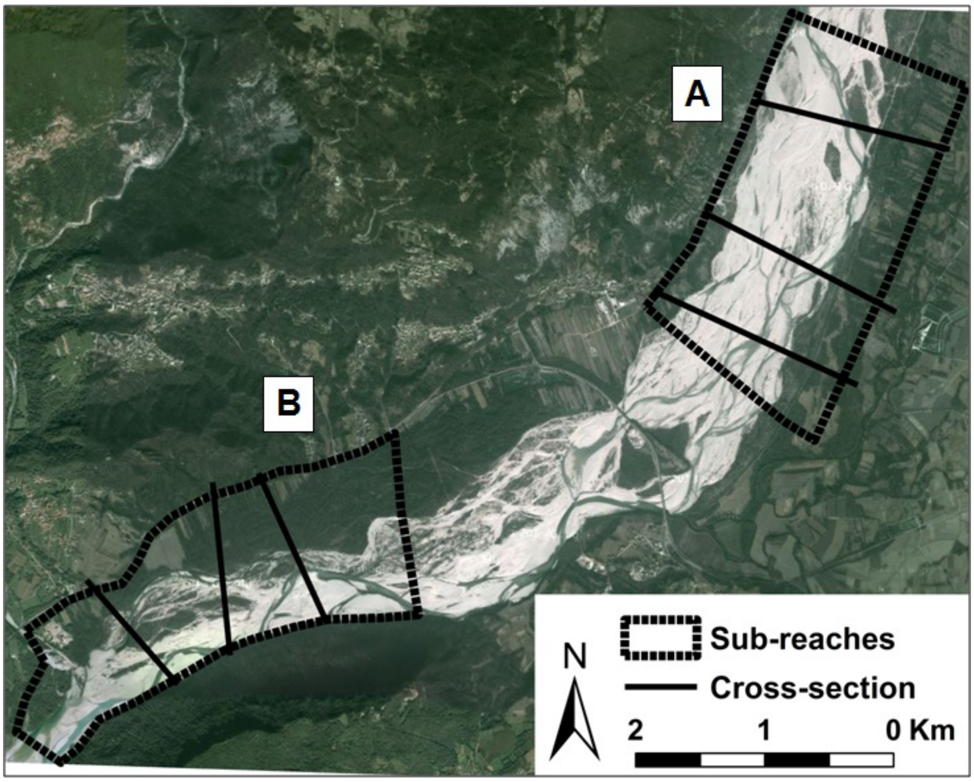

Figure 13: *Plan view of the study sites along the Tagliamento River. (A) Cornino and (B) Flagogna.*

2.1.2.1 Human pressures in Tagliamento River

Tagliamento River is not completely without human impacts, although it is considered one of the most natural river in Europe. The gravel exploitation, the water abstraction and the organic pollution are some of the major human influences on the main river corridor.

addition, the flood dynamics of the main stem of the Tagliamento is largely unaffected by water abstraction. The Tagliamento suffers from organic pollution between Tolmezzo and its confluence with the Fella, and in the channelized section downstream of Latisana; however, water quality has improved considerably in recent years. There are lateral dams along some sections (e.g. between Pioverno and Pinzano; and downstream of Dignano). However, they are far outside the active corridor and primarily used to protect agricultural land. The river corridor, which is morphologically intact along virtually its entire length, is the feature that makes the Tagliamento unique in the Alps. The corridor has escaped massive river engineering and floodplain development schemes, thus retaining the functional characteristics of a near-pristine system: strong longitudinal, lateral and vertical connectivity, high habitat heterogeneity, and a characteristic sequence of geomorphic types (Picco et al., 2013).

2.1.2.2 Study reaches of Tagliamento River

In the Tagliamento River, two sub-reaches Cornino and Flagogna were studied (Fig. 14). The two sites have similar flow conditions (no major intervening tributaries), longitudinal bed slope, and bed sediment grain size (Bertoldi et al., 2012). As in the Piave River, within each sub-reach, three cross-section transects were surveyed. The Cornino site is around 3 km long and the reach may be described as braided with an average active channel width of about 800 m. The Flagogna site is characterized by a larger number of vegetated patches (islands) and therefore shows a slightly smaller number of anabranches and a larger main channel (Bertoldi et al., 2011; Picco et al., 2013).

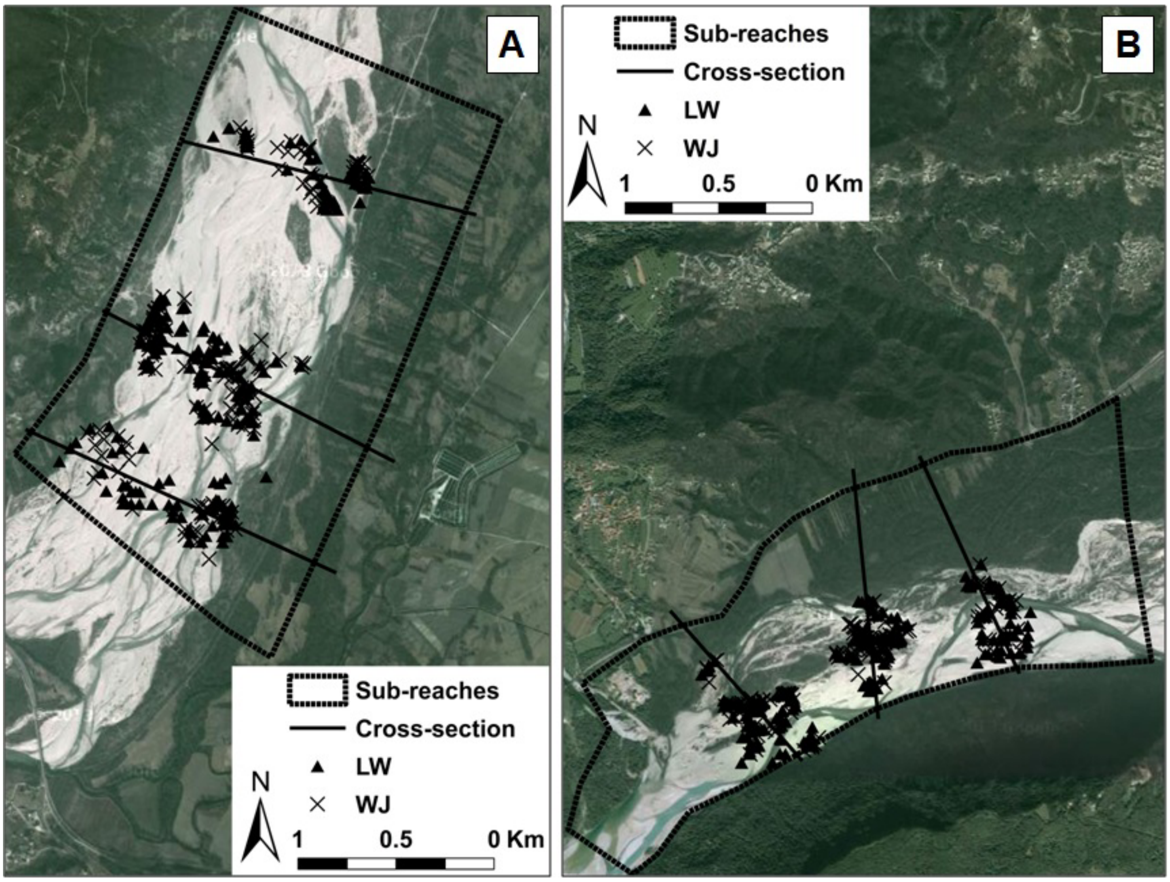

Figure 14: *Localization of large wood (LW) and wood jams (WJ) in (A) Cornino and (B) Flagogna sub-reaches in Tagliamento River.*

2.2 Research methodology

2.2.1 Field work

The field surveys were performed in the three rivers located in North-east Italy (Tagliamento, Piave, and Brenta). Because of the considerable extension of the selected reaches, large wood was surveyed on cross sectional transects within the active channel (as previously done by Gurnell et al., 2000; Andreoli et al., 2007; Sear et al., 2010). Cross sections were surveyed in June 2010 using a dGPS system, with a maximum vertical error of 0.03 m. All changes of slope along the sections were measured, with an average point density of one point per 3 m of channel width. Pre- and post- flood, LiDAR surveys were conducted in 2010 and 2011 for the rivers mentioned (Lenzi et al., 2011). LiDAR and dGPS data were used for survey the cross section transects. The choice of the cross sections were carried out in based on a possibility of easily accessing to in-channel and for the availability of LW. Transects were created spanning a buffer around the cross sections. Buffer with size that depending of the width of the active channel. Two transects were surveyed in the Nove reach of the Brenta River with length and width of about 300 m and 200 m. In the Friola reach, three transects ~300 m long and 400 m wide were surveyed. In Fontaniva, two transects of ~350 m long and 300 m wide were surveyed. In the Piave River, three transects of ~400 m were surveyed on each reach. The buffers around the cross sections ranged from about 280 m to 350 m. In the Tagliamento River, three transects were surveyed on each reach as done in the Piave River. In the Cornino reach, the buffers around the cross-sections ranged from 400 to 600 m, whereas in Flagogna the buffers were about 450 m wide.

The selected reaches represent a range of increasing human impacts, which has relevant influence upon the morphological dynamics and the effects of standing vegetation and LW.

Log displacement during flood events of different magnitude were analysed from June 2010 to October 2011 in Tagliamento River. To achieve that, logs were tagged using radio transmitters and for the first time using GPS tracker devices, which collect GPS position data at high frequency resolution (1 sec), and with RFID tags. Specific objectives are to verify the recovery rates of RFID tags after floods of different magnitude, to test the use of GPS trackers to measure log entrainment and velocity, to assess the displacement length and velocity of logs in a braided river, and to quantify logs mobility and velocity during floods.

During the study period (from June 2010 to October 2011), 14 low-magnitude floods peaking at half of the bankfull stage and a near-bankfull event occurred, as measured at the Villuzza gauging station, located 8 km downstream of the study reach (Fig. 15). Bankfull stage was considered to be about 3 m as suggested in previous studies on the Tagliamento River (see Gurnell et al., 2002 and Bertoldi et al., 2013).

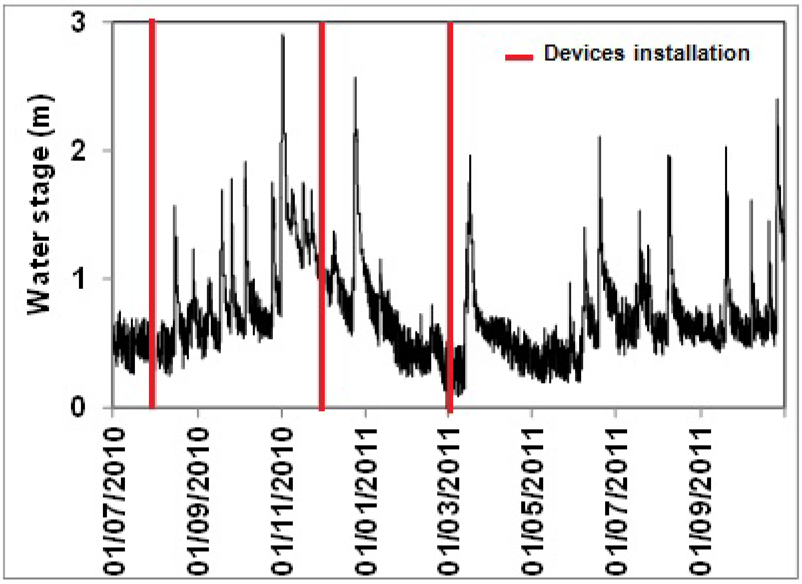

Figure 15: *Flood events occurred during the study period along the Tagliamento River. The grey lines indicate the date of device installations.*

2.2.1.1 Traditional surveys material

Field measurements were conducted in Brenta, Piave and Tagliamento. The analysis were carried out in each transect previously identified. All pieces of wood greater than 0.1 m in diameter and/or longer that 1 m (see standards proposed by Morris et al., 2010) found within the buffer areas along the cross sections were surveyed. Both single pieces of wood (large wood, hereon LW) and accumulations of large wood (wood jams, hereon WJ) were collected within the active channel, identified as the area flooded during bankfull events. Woody elements were classified as being trunks (i.e. elements lacking branches), shrubs (i.e. elements with multiple coarse branches), or trees (i.e. plants featuring nearly-complete branches and rootwad). The length and mid-diameter of each LW element were measured using a tape and a tree caliper, respectively. The precision of measurement was estimated to be ~1 cm for diameter and ~5 cm for wood piece length. The volume of logs was calculated by approximating the log to a cylinder. All visible elements composing WJ were measured as well, and the wood volume of each jam was calculated by summing them up. The geomorphic effects of LW and WJ were assessed by measuring the sediment volume stored and/or scoured around each isolated and jammed wood. These volumes were estimated as a solid wedge from length, depth and width measured in the field. Several ancillary data were taken during the field surveys as the type of woody elements (shrub, trunk, tree), orientation to flow (parallel, orthogonal, oblique), decay status (intact, porous, decaying), morphological unit on which the logs were found, and delivery mechanism of recruitment (bank erosion, natural mortality, transported from upstream reaches).

Wood jams were classified into two main categories, partially based on the classification of Abbe and Montgomery (2003) wood jams classification. We considered accumulations as autochthonous when a log recruited locally from the banks jammed further logs transported from upstream reaches, or allochthonous, when most of the composing elements appeared to have been trapped in a jam whilst floating. Allochthonous jams includes bar-apex jams, flood jams, meander jams, bar top jams, and bank edge jams (*sensu* Abbe and Montgomery, 2003). Each LW was collected using a guideline of two sheets of survey, which are composed by a number of sheets depending by the number of wood elements present in-channel. Sheets were divide into two modules: one for WJ and another for LW. The different sheets are derived from a simplification of those proposed by Thorne (1998), and at the same time by the need for greater focus on morphological changes and current trends, with particular reference to the Italian rivers taken into consideration in this research. The sheets used are the following:

A) Wood jam (WJ) sheet

Classification

Wood jams were distinguished into two main categories, which are a simplification of the Abbe and Montgomery (2003). The classification was readjusted for the large rivers. We considered a category in situ or autochthonous when wood jams remain in the place where they have been introduced. It is possible to recognize in this category the jams formed by logs fallen due to bank erosion, windthrow or mass movement. Another category is formed by transported jams, also called allochthonous, meaning that most of the composing elements were recruited to the stream far upstream and were trapped in a jam whilst floating. In this category were considered the bar-apex jams, flood jams, meander jams and the configurations composed by unstable pieces of wood which can be moved to downstream during a bankfull event (i.e. bar top, bank edge and bank-revetment jams).

Position

The term "position" refers to where the wood jam is located in the morphological unit. Six different morphological units were identified within the active channel: a) channel, b) low bar, c) high bar, d) pioneer island, e) established island and, f) floodplain. On table 1 were described the main characteristics of the different morphological units analysed.

Morphologic unit	Surface	Processes	Vegetation
Channel	Coarse sediments	Sediment transport	Absence of vegetation
Low bar	Coarse sediments	Sediment transport (active flow)	Absence of vegetation
High bar	Coarse sediments with presence of fine sediments	Sediment transport but, also transport and deposition of fine material	Presence of herbaceous and shrub vegetation. Arboreal vegetation with generally age 2-3 years
Pioneer island	Fine sediments, with limited thicknesses (generally centimeter)	Overflow and deposition of fine material	Presence of vegetation with tree age generally of 2-5 years
Established island and floodplain	Fine sediments, even with significant thickness (from a few cm to more than 1 m)	Overflow and deposition of fine material	Presence of vegetation with tree age generally greater of 5 years

Table 1: *Principal characteristics of the different morphological units.*

a) Channel

The channel (Fig. 16) is the area of river bed partially or fully covered by water. It corresponds to the section which contain the ordinary flood event. The bed is naturally limited by banks and channel shelves.

b) Low bar

The low bar is a morphological unit defined as a depositional surface with sediments similar to those present on the bottom of the channel but emerged, with a vegetation cover usually absent, although it is possible a sporadic presence of annual herbaceous plants (Fig. 16).

Figure 16: *Example of low bar and channel.*

c) High bar

An high bar (Fig. 17) is a morphological unit of gravel-bed rivers with braided or transitional channels, while more rarely observed in meandering rivers with single channel.. It is possible to observe a substantial amount of sand, but the gravel present is visible. In this morphological unit there is the presence of herbaceous and shrub vegetation.

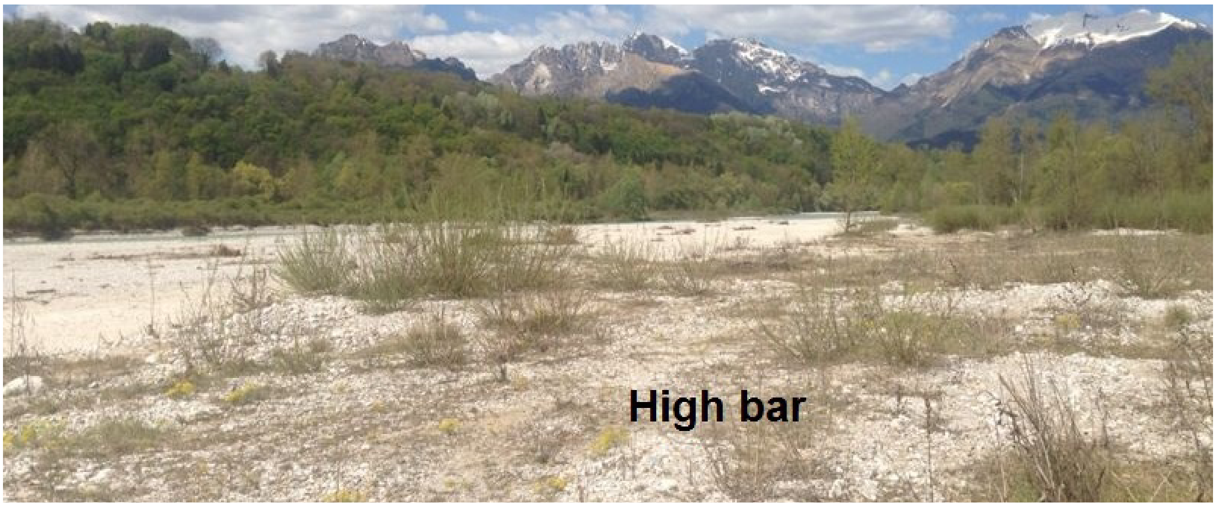

Figure 17: *Example of high bar.*

d) Pioneer island

The characteristics of the pioneer island (Fig. 18) follow the descriptions of Gurnell et al. (2005). The authors attribute the origin of the pioneer island to the end of sedimentation and colonization of vegetation that occur immediately downstream of a trunk or an accumulation of wood deposited on a bar.

Figure 18: *Example of pioneer island.*

e) Established island

The established island (Fig. 19) has a surface with the same morphological characteristics, textural and vegetational of the floodplain (see later). Unlike the floodplain, the established island is bounded on both sides by active surfaces (channel or even bar or high bar). It is considered as established island when the fine sediments that are inside the island, present a significant thicknesses and the vegetation is generally higher of 5 m.

Figure 19: *Example of established island.*

f) floodplain

The floodplain is the morphological unit that is generally subject to flooding with frequency of the order of 1 – 3 years and it represents the outer limit of riverbed active (bankfull). The floodplain is created by sedimentary depositional processes that border the river, which is shaped by the progressing sedimentation inside and outside the river bed (Fig. 20).

Figure 20: *Example of floodplain.*

Wood jam characteristics

In this section have been described the size of each wood jam (high, wide and length), the relative organization of single pieces of wood (LW) within the jam, classifying them as "clogged" or "parallel", being the logs oriented randomly in the former case, and being mainly oriented in the same direction in the latter. It was used the term "wide" when the single pieces of wood forming the wood jam have a distance equal to their length. On the other hand, it was used the term "narrow" in the case where the pieces of wood have a distance less their diameter.

Geomorphic effects

Due to their influence of local hydraulics, single and jammed logs usually produce concentrated scour on their side, and desposition of sediments in front and especially behind them. The size of local sediment scour and deposition around both LW and WJ was calculated using the geometrical measurements taken in the field when these shapes were present.

B) Large wood (LW) sheet

Wood characteristics

All pieces of wood greater than 0.1 m in diameter and/or longer that 1 m (see standards proposed by Morris et al., 2010) found within the buffer areas along the cross sections were surveyed. Three types of LW were considered:

(i) Trunk element is composed by the structure of plants including the rootwad (if it is present) but excluding branches;

Figure 21: *Example of trunk without rootwad.*

(ii) Shrub element is formed by branches separated from the central tree very closed to the ground, or whose trunk is not present at all;

Figure 22: *Example of shrub with almost all intact breaches.*

(iii) Tree is a woody plant, able to grow in height by the trunk. The set of the branches and leaves determine the canopy that can take different forms depending of the species and environmental conditions;

Figure 23: *Example of tree with rootwad, branches and dry leaves.*

Despite the typology, in the LW sheet, for each pieces of wood were reported the following characteristics:

-*Roots*: It is indicated the presence or absence of root attached to the rootwad;

-*Rootwads:* It is indicated the presence or absence of rootwad;

-*Vegetation:* It is identified the presence of resprouts along the trunk or branches;

-*Branches:* It is indicated the presence of branches, distinguishing four different classes (total absence, presence of only nodes, some branches broken, all branches intact);

-*State of decay:* It is analyzed the state of conservation of the woody element, indicating if the element is in decaying status, porous, intact with or without bark;

-*Bark:* It is a visual estimation of the percentage of bark around the woody element analyzed;

-*Orientation:* It is the degree formed between the flow direction and the woody element. The angle of inclination considered is between 0° and 100°. The value of 0° corresponds to an element with the rootwad upstream and the canopy downstream, vice versa in the case of an angle of 100°. Two classes were analyzed: one which includes the elements which range from 0° to 45° and the other class which ranges from 46° to 100°.

Position

It indicates the morphological unit where the piece of wood is located. The morphological units are the same used for the wood jams.

ID ______________
GPS Position N ________________ E ________________

Classification

Autochthons		Allochthonous	

WJ characteristics

Size		**Texiture**		**Key elements**	
wide (m)		narrow and braided		absent	
long (m)		wide and braided		single and visible	
high (m)		narrow and parallel		single partially visible	
		wide and parallel		single and presumably	
° reg. the North				more keys and visible	
° reg. the flow direction				more partially visible	
		Number of elements d>0.1 m		more and presumably	

Position

In section		**Vegetation**		**In plan**	
Channel		veg. herbaceous / shrub		lateral bar	
Low Bar		veg. (2-5 anni)		longitudinal bar	
High bar		veg. (>5 anni)			
Pioneer island					
Established island					
Floodplain					

Interactions wood - sediments

upstream		**on the trunk / accumulation**		**downstream**	
deposition		partially buried		deposition	
scour		entirely buried		scour	
lateral deposition (*Dx/Sx*)				lateral deposition (*Dx/Sx*)	
lateral scour (*Dx/Sx*)				lateral scour (*Dx/Sx*)	
length (m)				length (m)	
width (m)				width (m)	
high/depth (m)				high/depth (m)	
fine woody		fine woody		fine woody	
fine sediment		fine sediment		fine sediment	
sand		sand		sand	
gravel		gravel		gravel	

note

Figure 24: *Example of sheet of survey for wood jams (WJ).*

Type K= (*key*), R= (*racked*), L= (*loose*)
ID
GPS Position N E

Characteristics

Typology	**Branches**	**Roots** (Y/N)
Tree	total absent	entire rootwad
Shrub	some broken branches	Diameter (m)
Trunk	all branches intact	Length (m)
		Presence portion of fine roots

State of decay	**Origin**	**Size**
intact with bark	natural mortality	
intact without bark	bank erosion	**Trunk**
porous	transport, fluitation	Diameter (m)
decaying		Length (m)
bark (%)	**Orientation**	
	upstream rootwad	**Tree**
Vegetative activity (leaves)	downstream rootwad	width (m)
Absent	rootwad (Dx/Sx)	length (m)
Before the fallen	° reg. the North	high (m)
After the fallen	° reg. the flow direction	

Position

In section	**Vegetation**	**In plan**
Channel	veg. herbaceous / shrub	lateral bar
Low Bar	veg. (2-5 anni)	longitudinal bar
High bar	veg. (>5 anni)	
Pioneer island		
Established island		
Floodplain		

Interactions wood - sediments

upstream	**on the trunk / accumulation**	**downstream**
deposition	partially buried	deposition
scour	entirely buried	scour
lateral deposition (*Dx/Sx*)		lateral deposition (*Dx/Sx*)
lateral scour (*Dx/Sx*)		lateral scour (*Dx/Sx*)
length (m)		length (m)
width (m)		width (m)
high/depth (m)		high/depth (m)
fine woody	fine woody	fine woody
fine sediment	fine sediment	fine sediment
sand	sand	sand
gravel	gravel	gravel

note

Figure 25: *Example of sheet of survey for large wood (LW).*

2.2.2 Wood mobility and transport

Investigation on displacement length and velocity of logs with different size and characteristics were analysed in Tagliamento River, applying two monitoring techniques: radio frequency identification (RFID) tags (MacVicar et al., 2009) and the GPS tracker devices.

A total of 113 radio frequency identification tags (RFID) and 42 GPS tracker devices were installed in logs of different size. The most important characteristics of logs (e.g. length, diameter, presence and dimension of root wards, presence and dimension of branches) were surveyed following the common standard size (10 cm in diameter and 1m in length) of transported wood in Tagliamento River (Gurnell et al., 2000). The position of each tagged log was surveyed using a Differential Global Positioning System (dGPS). Tagged logs were selected for having size representative of logs laying in the study reach (Mao et al., 2012), and for being relatively close to the main channel and laying on low and active bars. The morphological settings of the river in the specific site were surveyed as well.

The RFID and GPS devices were mainly installed on three different occasions during the study period: twenty-one GPS trackers and 63 RFID tags were installed in June-August 2010, 6 GPS trackers and 12 RFID tags in December 2010, and 15 GPS trackers and 31 RFID tags were installed in March 2011. Further 7 RFID were installed after June 2011. Apart for the first installation, which was carried out in summer 2010 when an extensive surveys of volumes, type, degree of organization, and morphological effects of large wood took place (Mao et al., 2012), the following installation dates coincided with periods in which tagged logs were surveyed after floods.

Linear regressions were used to examine relationships between displacement lengths, virtual and mean velocities of logs as dependent variables, and the characteristics of transporting floods (water stage at the peaks and significant percentiles of flow duration curves) as independent variables. Regressions were considered statistically significant if $P \leq 0.05$.

2.2.2.1 Radio frequency identification tags (RFID)

Different typologies of RFID tags are commercialized, it is possible to define two main devices typologies: passive and active. In Tagliamento River were used the active radio frequency identification tags. These type of tags are powered by a replaceable coin cell battery (reliable for about 5 years) and emits a signal at 443MHz every two seconds (MacVicar et al., 2009). The signal use electromagnetic coupling on a shared radio frequency to allow the remote identification of unique devices and, it can be read by a fixed readers that permit to monitor the movement through a fixed position (i.e. bridges), or mobile readers that permit us to found logs over a study area, whose detection range is about 200 m.

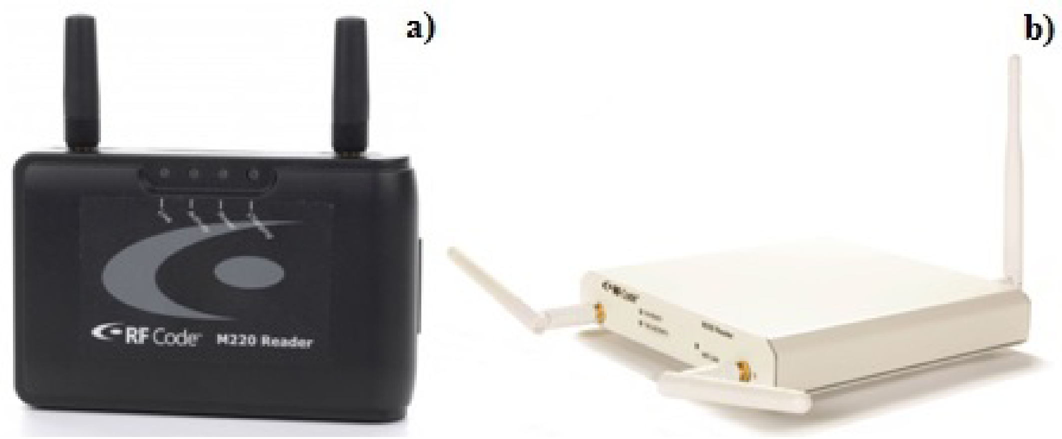

Figure 26: *Mobile reader (a) and fixed reader (b) of the company RFCode Inc.*

The best sample representation and the similar incipient motion condition are possible to have installing the active RFID tags in different logs located on the same morphological unit. The RFID tag is a device (purchased from RFcode Company) enclosed in a polycarbonate case measuring 47 x 34 x 12 mm. RFID tags were implanted in holes scoured on the trunks of 113 logs, and fixed using silicone caulk. Similar devices have been previously used in other environments for tracking logs in river systems (MacVicar et al., 2009; Schenk et al., 2013).

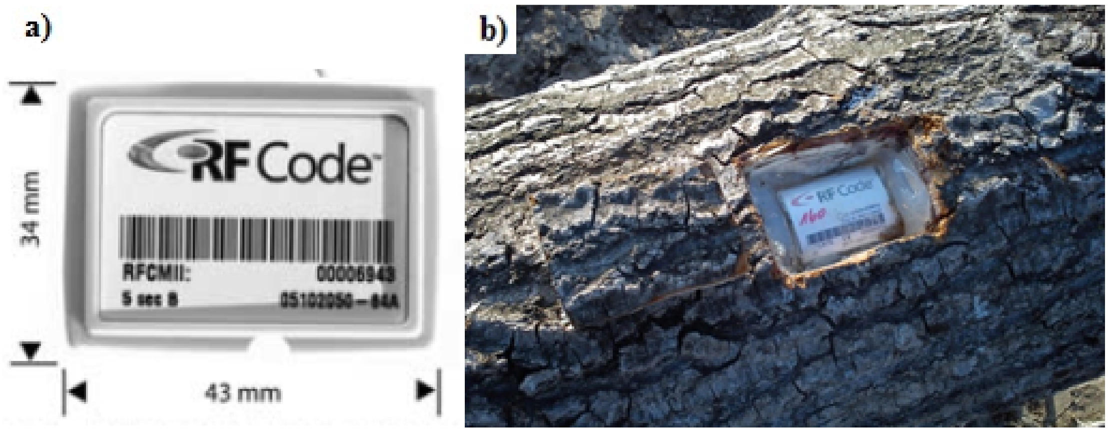

Figure 27: *Example of active RFID tag are those of the company RFCode Inc in which each tag is enclosed in shock resistant and splash resistant case that is 47-34-12 mm in size (a). Example of tag installation (b).*

The RFID tags were implanted on logs with different size (1 m to 25 m) and presence/absence of rootwads.

Figure 28: Example of field installation of a RFID tag.

The combined use of aerial photos (pre- and post-flood) and tagged logs led to the determination of source areas, travel distance and deposition sites of wood elements, along with the estimation of wood transport flux as a function of flood magnitude.

During several field surveys (July, August and December 2010, and then in March, April, May, July, August and October 2011), the whole study site and approximately 18 km of downstream area were explored with the RFID mobile antenna searching for tagged logs. Also, further river reaches of easy convenient accessibility were explored downstream (e.g. around bridges and on proximity of roads) until the village of Latisana, located 60 km downstream from the study reach. When recovered, tagged logs were measured again, and their position was taken using dGPS in order to quantify precisely their displacement length.

2.2.2.2 GPS Tracker devices

This technique of LW monitoring has never been tested before in rivers monitoring activities, consents to record the displacement length and velocity of a log during a flood event using a GPS tracker device (passive or active). The aspect that distinguish the active from a passive GPS track is the capacity to send, in real time, Short Message Service (SMS) over GSM communications network (i.e. time, position, batteries lifetime). In Tagliamento River were installed 42 passive GPS trackers in different logs in low bars in order to have the same incipient motion condition. GPS tracker devices (3100-EXT purchased from LandAirSea Company) are composed by a GPS antenna receiver, and a case (80 x 100 x 40 mm) hosting 4 AA batteries and data logger. When activated, the device acquires and stores in the data logger its position every second. The device activates with movement (warm start of 50 s), and has up to 300 hours storage-tracking capacity. In order to save battery, the dataloger stops collecting GPS position coordinates after the device remains immobile for more than 2 minutes. The GPS tracker is not waterproof but only water-resistant and tested to IP-55, for this reason it is necessary to waterproof each GPS tracker using a plastic box and seal it with silicon. It is, also, necessary to place into the box a RFID in order to help the post-event GPS trackers recovery. Plastic boxes were fixed to woody elements tying them to the trunk with a steel chain and cable ties, 0.50 m high from the base of the trunk.

Figure 29: *Example of a LandAirSea's 3100-EXT passive GPS tracker (on the left) and its installation (on the right).*

During the monitoring period it was important keeping a good maintenance of the batteries and of the correct waterproofing of the plastic box.

Post-event it was possible to identify the position of the logs with the GPS tracker installed, using a mobile reader to recognized the RFID placed into the plastic box. The Differential Global Positioning system (dGPS) was needed for each logs with GPS tracker installed, before and after each flood event.

2.2.3 Physical modelling

A series of experiments were carried out in the Total Environmental Simulator (TES) facility; a 6 m-wide, 11 m-long flume at the University of Hull (UK). Three 1.7 m-wide channels (C1, C2, and C3) were built inside the flume using concrete blocks, and were filled with homogeneous sand (D50 = 0.73 mm) with a surface slope of 0.013 m m^{-1}.

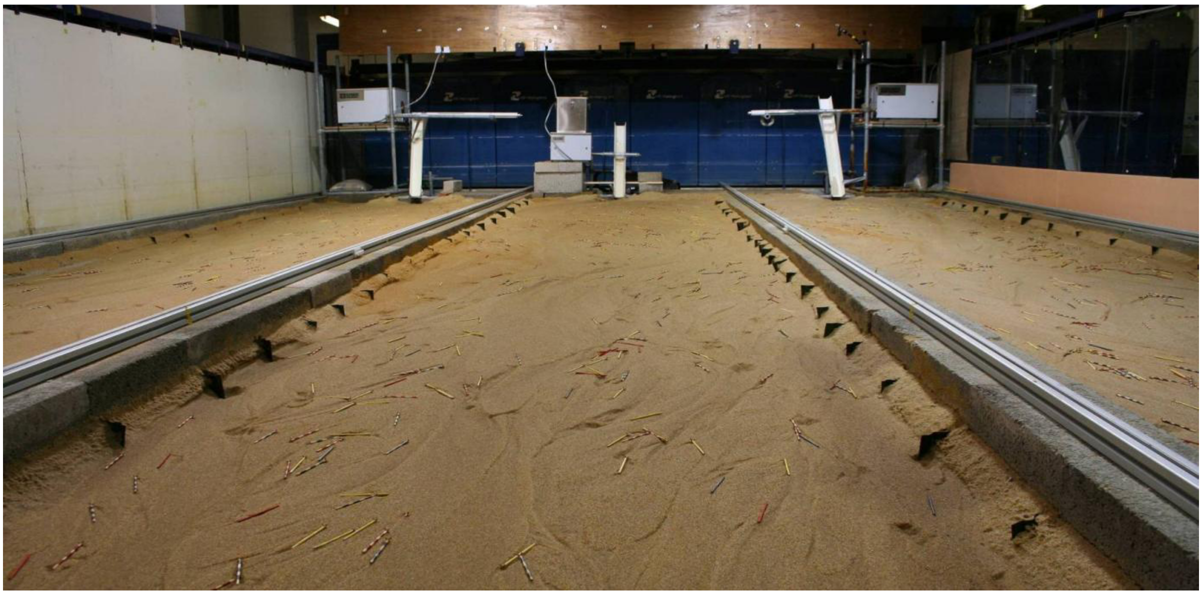

Figure 30: *The flume in the Total Environmental Simulator (TES) at the University of Hull (UK).*

Water was supplied at the upstream end of each flume using submerged pumps with a steady discharge of 1.26 l s^{-1}. Sand was fed at a constant rate of ~1.9 g s^{-1}. Transported sand was collected at the downstream end of each flume using traps. Under these conditions of steady flow discharge and sand feed rate, the initial regular channel carved in the centreline of the flume channels evolved into a braided network, which was maintained for approximately 21 hours to attain steady-state conditions in terms of morphological patterns and sediment fluxes. Then, cylindrical 8 cm-long woody dowels representing LW logs were fed into the flume channels.

Cylindrical wood dowels with and without cross-shaped rootwads were created manually in order to simulate logs. The wood dowels length (8 cm) was selected with reference to the distribution of anabranch width to ensure ‘large’ river conditions (length to width ratio <1). In particular, the root size were estimated in order to the data collected in Tagliamento River. Dowel diameter (3 mm) was scaled with median grain size and the width of the cross-shaped element (12 mm) was computed from a linear relationship between root wad diameter and log diameter (Bertoldi et al., 2014). The dowels were built using birch wood which has a wet density of 0.67 kg dm^{-3}. To this aim wooden dowels were selected to be shorter than the width of single anabranches (‘large rivers’, *sensu* Piégay and Gurnell, 1997), and logs and root wads diameter were computed from linear relationships between root wad diameter, log diameter, and grain size derived from field observation in Italian rivers. Logs were fed into the three flume channels at regular time intervals (15 minutes) but at different rates: 60, 120, and 180 logs h^{-1} in C1, C2, and C3, respectively. After the first six hours, the wood input rate was reduced to 40, 80 and 120 logs h^{-1} in channel C1, C2 and C3, respectively. Logs were collected and counted at the downstream end of the flume channels. Experimental runs with logs feeding were 18 hours in duration, which was sufficient to attain an approximate equilibrium (i.e. output equalling the input rate of logs).

Subsequently, experimental runs were designed to explore the effects of vegetation and logs under the simplest conditions. This experimental run was aimed at investigating the morphological response of braided river systems to the dynamics interactions between water, sediment, vegetation, and logs. The logs were thus removed and a self-formed, steady-state braided pattern was restored in the flume channels using steady flow and sediment input rates. Then alfalfa seeds (*Medicago sativa*) were mixed with handfuls of dry sand and manually seeded in the three flume channels with a density of approximately 1 seed cm^{-2}. In order to avoid seeds growing in the channels, a baseflow of 1 l s^{-1} was imposed to maintain flow in the channels but without moving sediment. The establishment of the alfalfa seeds was helped by using continuous artificial illumination which allowed to have a constant temperature of ~20 °C, and by maintaining the water table at the highest possible level overnight. Also, seeds were soaked in water for approximately 2 days before seeding to promote rapid germination.

Figure 31: *Example of Alfalfa seeded and the dowels (with and without rootwad) used in the flume.*

After the alfalfa seeding, a higher flow that was able to rework the channel morphology (1.26 l s^{-1}) was imposed in the flume channels. In flume channels C2 and C3 logs were also feed (at rates of 40 and 120 logs h^{-1}, respectively), whereas the flume channel C1 was left to evolve under the sole influence of vegetation growing on sand.

Similar to previously reported experiments (Tal and Paola, 2007; Clarke, 2014), alfalfa rapidly developed roots and stems up to 2 cm in length and up to 2 mm in diameter. Under this protocol, experiments were run for 8 hours per day at the base-flow, for a total of four weeks (120 hours overall). In order to replicate the vegetation growing on floodplains and high bars in natural rivers, alfalfa was seeded every 7 days under the same conditions described above, and a high-flow that was able to transport sediments and rework the channel morphology was imposed once per week for 3 hours.

Figure 32: *Example of interaction between LW and vegetation during a flood simulation.*

A reflex camera mounted on a 1.5m high overhead gantry was used to acquire a series of vertical images covering the entire length of the flume channels with a resolution of about 2 pixels mm^{-1}. A set of ground control points were used for image positioning and red dye was employed to enhance contrast between wet and dry areas. For each flume channel, pictures were geo-referenced and channel network configuration was manually characterized in terms of the reach-averaged braiding index (Egozi and Ashmore, 2008).

Pictures were acquired at the end of each of the respective runs: S (sand bed), SL (sand plus large wood), SV (sand plus vegetation) and SLV (sand plus large wood and vegetation). Additional pictures were collected on three occasions during runs SV and SLV, just after the high-flow imposed condition. With the same timings, the entire flume facility was surveyed with a terrestrial laser scanner (TLS), the Leica ScanStation2. This is a time-of-flight (first return) system with high speed dual-axis compensator which scans up to 50,000 points per second, at a maximum scan density of <1 mm^2. The laser was placed on the four corners of the flume facility, and the scans were taken setting the resolution at a cell size of 1 mm at 7.5 m from the device. Six targets were used to register and geo-reference each scan using Cyclone software (Cyra Technologies Inc.). In order to avoid areas with low point density around the edges of the flume, a 1.4 m-wide, 6 m-long area was selected for scanning all the flume channels. The scans (SLV) were underwent to a filtering step of the vegetation points. The filtering proved to be challenging because of the very dense canopy developed by alfalfa plants, especially at the end of the runs (i.e. SLVc and SLVd). The filter adopted works in three steps. The first step was conducted manually from the points cloud in Cyclone. In the second step, the filter creates a reference RGB triplet for an area with only sand. The RGB values of all points within the scan were compared to the reference triplet. Then, a point was removed if its RGB triplet diverged from the reference by more than a user-selected percentage, which was identified through trial and error. The final step was carried out by a geometrical filter, which was applied to delete the outliers points.

Each filtered scans were then interpolated with “natural neighbour” interpolation and a DEM with cell size of 1 mm was created using ArcMap (a main component of Esri's ArcGIS suite). The DEM was detrended in the streamwise direction using linear interpolation, and finally the probability density functions (PDF) of the beds were extracted. The PDF allowed to obtain the standard deviation and the skewness for each scan which were useful to a better description of the bed morphology.

Chapter Three - Analysis

3.1 Field analysis

Overall, 3430 woody elements were measured in the study sites, 535, 1049, and 1846 of which were measured in the Brenta, Piave, and Tagliamento rivers, respectively. As to jams, 591 accumulations were surveyed, 89, 189, and 313 of which were found in the Brenta, Piave, and Tagliamento rivers, respectively. Overall, 70% of the logs were found jammed in accumulations of different types

3.1.1 Characteristics of wood jams in Brenta, Piave and Tagliamento rivers

Different types of wood jams were observed along the three rivers, varying from allochthonous and autochthonous (Abbe and Montgomery, 2003). The results demonstrate that more than 90% of wood jams were classified as allochthonous, meaning that most of the logs and the key element were transported from upstream reaches.

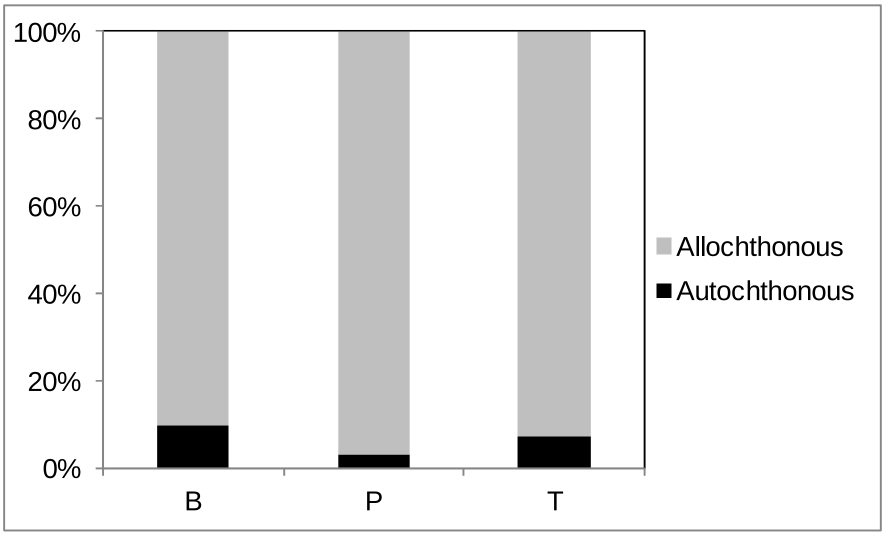

Figure 33: *Origin of the pieces of wood which composed the wood jams.*

The relative organization of single pieces of wood within the jams was considered as well, and classified as braided or parallel, being the logs oriented randomly in the former case, and being mainly oriented in the same direction in the latter. The degree of porosity of the jams (i.e. the voids within logs) was also classified as wide or narrow. Jams classified as parallel and narrow tend to dominate on the study sites (66.0, 53.5, and 40.5% in B, P, and T, respectively), followed by jams with texture braided and narrow (22.2, 38.9, and 43.5% in B, P, and T, respectively).

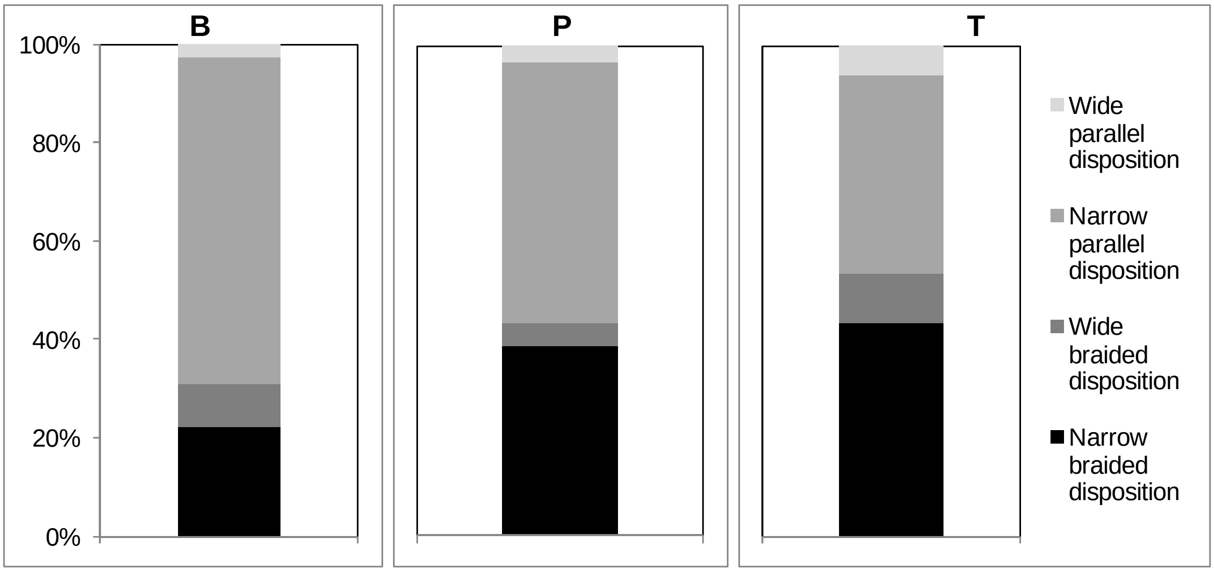

Figure 34: *The relative organization of single pieces of wood within the jams.*

3.1.2 Characteristics of large wood in Brenta, Piave and Tagliamento rivers

The analysis of the typology of large wood present in-channel shown that in all the rivers analysed, trunks were the most represented (57, 42, and 55% in B, P, and T, respectively). Trees with complete branches and rootwads were relatively common as well (32, 31, and 28% in B, P, and T, respectively), whereas isolated rootwads and shrubs were relatively less represented.

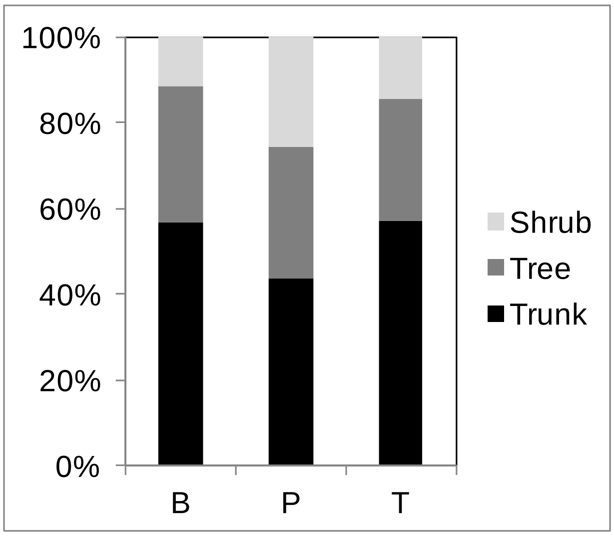

Figure 35: *Typology of large wood present in-channel.*

Ancillary data acquired in the field allowed to infer some evidence on the most probable delivery mechanism responsible for the arrival of logs within the study sites. Four different origin categories were considered: crash, transport-fluitation, bank erosion and natural chronic dead. Because logs were classified as being transported from upstream reaches or recruited from the same banks (for erosion or natural mortality), it was possible to assess that the vast majority of logs were stranded or deposited in the study sites after active transportation by flood events. In particular, floated logs represented 80.5, 89.0, and 80.7% of logs in the Brenta, Piave, and Tagliamento rivers, respectively.

More in detail, in Brenta River there are 7% of wood with origin of natural chronic dead, 11% by bank erosion and, 1.5% by crash. In Piave River the LW have origin 10.5% from bank erosion, 0.5% from crash. In Tagliamento River was observed 9% of LW arrived in-channel by chronic dead, 8.2% by bank erosion and, 11% by crash.

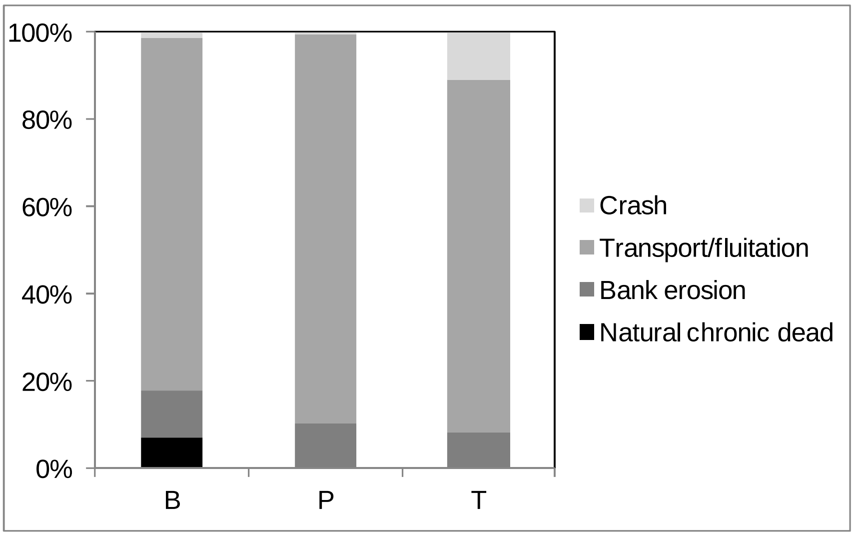

Figure 36: *Probable delivery mechanism responsible for the arrival of logs in the study sites. Four different origin categories were considered: crash, transport-fluitation, bank erosion and natural chronic dead.*

A further confirmation that logs were likely to be transported is gathered from the observation of the disposition of rootwad (facing upstream or downstream). In all rivers analysed was observed almost the totality (~88%) of the rootwads facing upstream and consequently the canopy facing downstream.

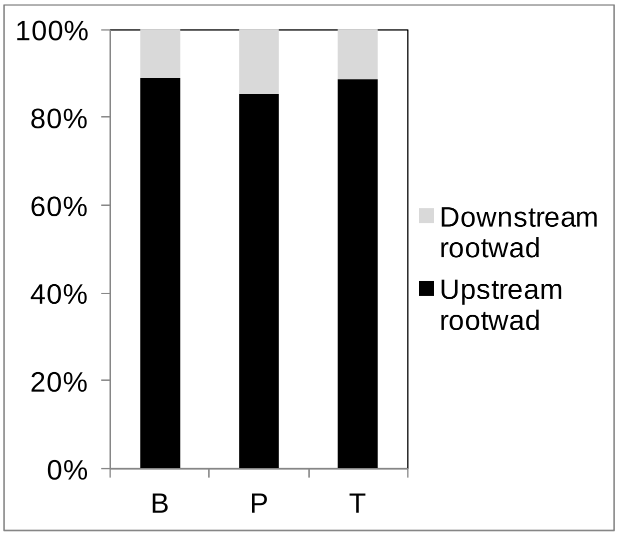

Figure 37: *Disposition of the rootwad of logs deposited in-channel.*

A further confirmation that logs were likely to be transported was gathered from the observation of their orientation respect to the main flow direction, assessed on a degree ranging from 0 to 100 for logs parallel to the flow and rootwad facing upstream and downstream, respectively (Fig. 38). The range from 34 to 66 degree corresponds to logs that feature an oblique or transversal orientation. It is interesting to note as almost 90% of all logs were oriented mostly parallel to the main flow direction, suggesting that they were floated downstream (Francis et al., 2008), and the percentage of logs with rootwad facing upstream was about 81, 90, and 71% in the Brenta, Piave, and the Tagliamento rivers, respectively. On the other hand, the logs that feature the oblique or transversal orientation were 19, 10, and 25% in Brenta, Piave, and Tagliamento rivers, respectively.

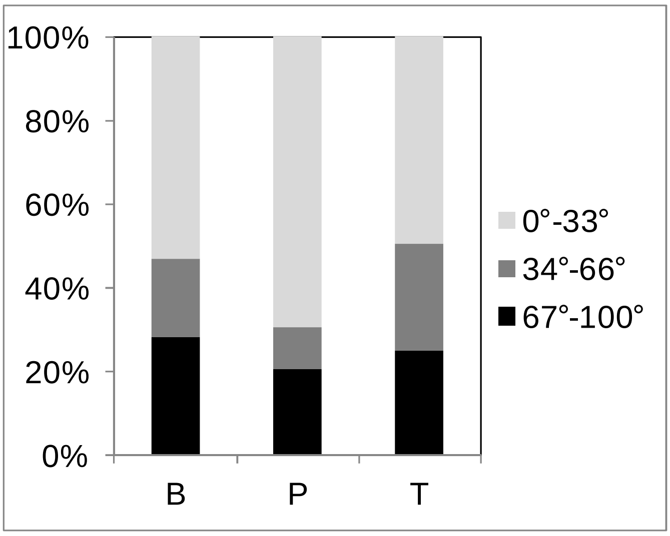

Figure 38: *Orientation of the logs, 0° meaning parallel to the flow and with the rootwad facing upstream, whereas 100° being parallel to the flow but with the rootwad facing downstream.*

The analysis of the state of conservation of the logs furher reveals that most of the logs were either intact with complete bark (i.e. recently recruited) or in an advanced state of decay (i.e. recruited long before the survey). Four different states of conservation were considered: “intact with bark”, “intact without bark”, “decaying” and “porous. Figure 39 shows that logs in advanced state of decay are more frequent in the Brenta (64.0% of logs with decaying or even porous wood) than in the Piave (57.0%) and the Tagliamento (46.5%) rivers. On the other hand, the higher percentage of elements with an intact state of conservation was collected in Tagliamento River (~52.5%) than Piave (~41%) and Brenta rivers (~35%).

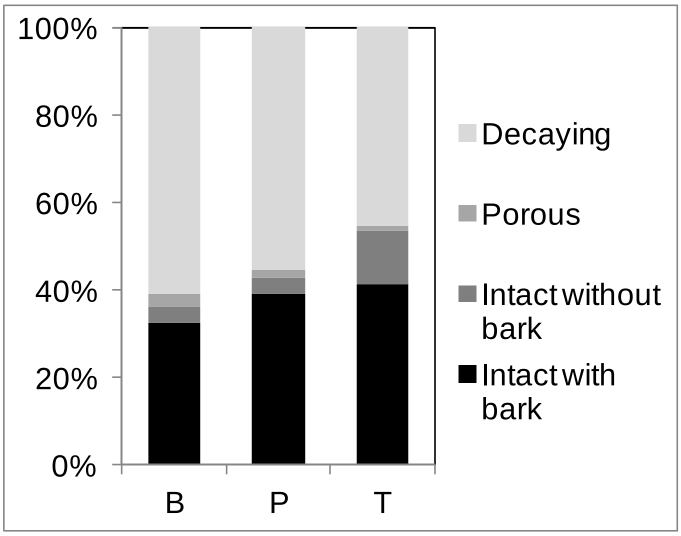

Figure 39: *State of conservation of logs in the Brenta (B), Piave (P), and Tagliamento (T) rivers.*

However, the results in figure 40 show that wood elements located in the morphological units more "mature" (i.e. islands and high bars), have a worst state of conservation of the trunk. On the other hand, the elements located in the more dynamic morphological units (i.e. channels and low bars), have a better state of conservation of the trunk. It was possible to note that in all the three rivers, the state of conservation “porous” was detected in high bars but, a high percentage was collected in more dynamic morphological units in Brenta and Tagliamento rivers.

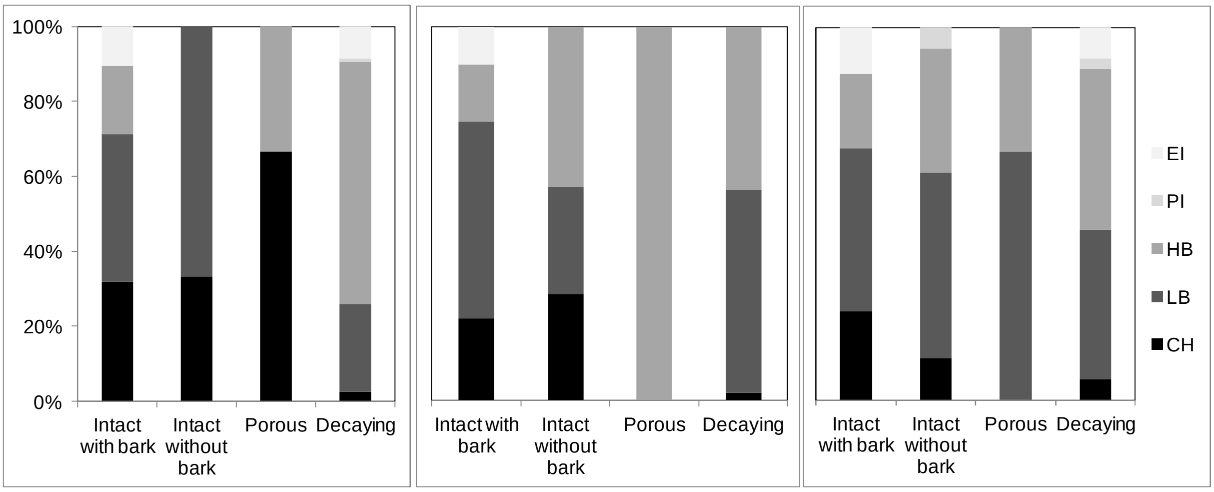

Figure 40: *Distribution of the state of conservation of logs in the morphological units. (CH: main and secondary channels; LB: low bars; HB: high bars; PI: pioneer islands; EI: established islands).*

Analogously to the state of conservation of the trunk, also the presence/absence of bark play an important role on qualitative aspects of woody elements on the three rivers in exam. In order to provides a better interpretation of the results, two categories of percentage of bark were distinguished. One that includes large wood elements with total absence of bark up to 50% of the presence of it, and the other category that includes elements that have from 51% to the totality of the presence of bark. Evidence shown that on the three rivers there is a similar percentage of wood with bark (around 55%). On the other hand, in Brenta River there is a tendency of woody elements to have a greater presence of bark (60%) than the other two rivers.

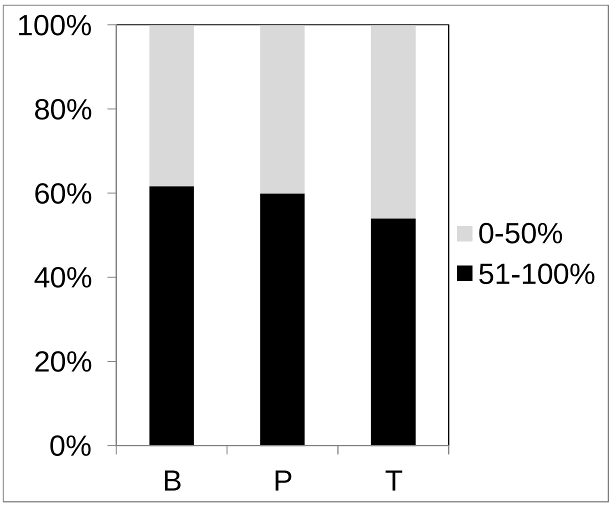

Figure 41: *Large wood elements with total absence of bark up to 50% of the presence of it, and large wood that have from 51% to the totality of the presence of bark.*

The observation of the presence/absence of bark further support this observations as approximately half of the trunks were covered by less than 30% of bark, and the other half by complete and fresh bark. In the three rivers, more than 70% of logs did not feature leaves, especially in the Piave River (up to 83%), suggesting that recruitment and transport did not occur on the same or previous year of the survey.

If only intact logs with good state of conservation (nearly complete and fresh bark) are considered, Figure 6 shows that half of them lacked leaves or featured leaves in resprouts from the main branches (i.e. logs were likely recruited the year before the survey). It is interesting to note that the higher percentage of logs with resprouts was found in the Brenta River, where indeed more logs were lying in the main and secondary channels if compared with the other two study sites.

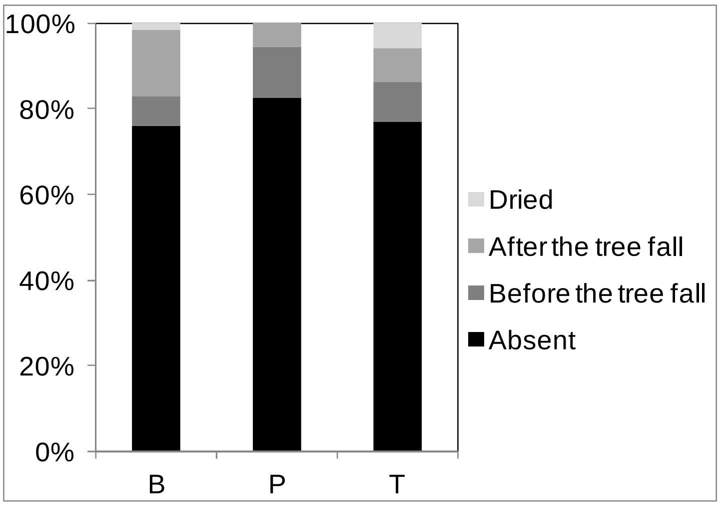

Figure 42: *Presence or absence of leaves in LW. In the case of woody element with leaves, it was analyzed if their origin was before or after the tree fallen.*

It was possible to note in Tagliamento that the elements with intact state of conservation feature 15% of dry leaves, 15% of the elements are characterized by leaves after the fallen in-channels and 15% before the fallen (Fig. 43). Indeed, a small but relevant percentage of logs in the Brenta and Piave was found in the main or secondary channels (24% in B and 7% in P of the elements in main or secondary channels), featuring leaves on resprouts from the main trunks. It highlights the importance of the vegetative characteristics of broadleaf species in stabilizing the bed and acting as an active driver in modifying channel morphology and increasing the possibility to develops pioneer islands.

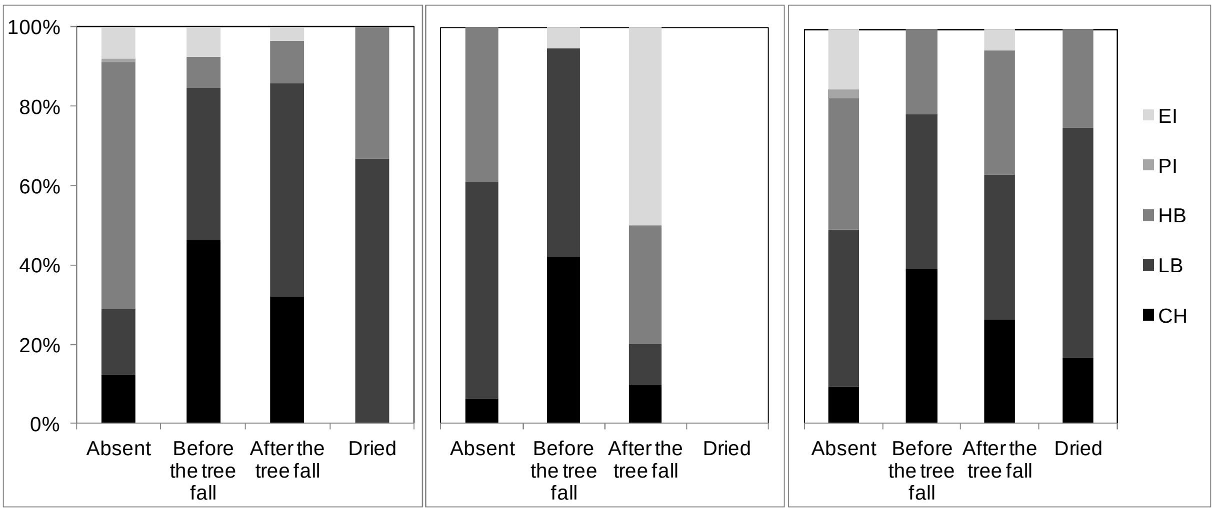

Figure 43: *Analysis of the leaves on the morphological units in Brenta (on the left), Piave (in the middle) and Tagliamento (on the right) rivers. (CH: main and secondary channels; LB: low bars; HB: high bars; PI: pioneer islands; EI: established islands).*

Analysis on the presence or absence of the branches was conducted, investigating if they were all or few broken. The interesting result is that in Tagliamento River there is a higher presence of tree without branches (65%) than Brenta (58%) and Piave rivers (40%).

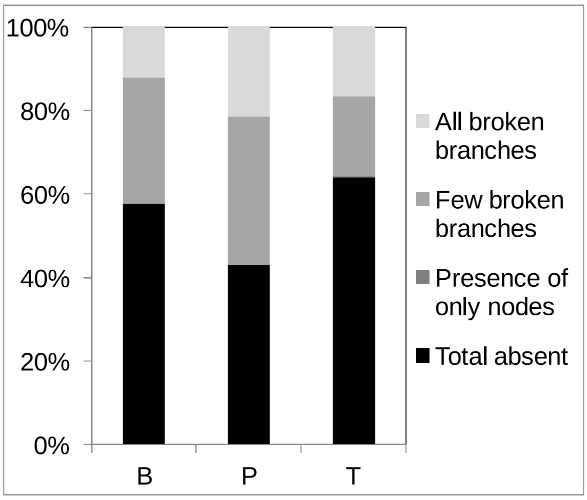

Figure 44: *Analysis of the breaches of logs in-channel. Four categories were identified: All broken branches, few broken branches, presence of only nodes and the total absent of branches.*

As expected, the results show that wood elements with the worst state of conservation of trunk (i.e. decaying and porous) and less bark, were found in higher morphological units such as high bars, islands and floodplain. Moreover, the elements tend to be without branches and leaves. On the other hand, the elements which present a better state of conservation of trunk and higher percentage of bark coverage, were collected in more dynamic morphological units (such as channels and low bars) but they were observed a percentage of these elements in higher morphological units in all the three rivers (10, 21 and 15% in Brenta Piave and Tagliamento, respectively) that corresponds to elements eroded by recently flood events which was not able to recruits the elements in-channel.

3.1.3 Wood dimensions and abundance in Brenta, Piave and Tagliamento rivers

The median length and diameter of logs were quite comparable among the three study rivers. The median lengths were 3.5, 4.1, and 2.6 m for the Brenta, Piave, and Tagliamento, respectively (Fig. 46, B). The longest log was surveyed in the Brenta, and measured 26 m.

It is important to take into consideration that it was surveyed a different number of single pieces of wood between the three rivers. Nevertheless, the length measured results quite similar although in Brenta River were detected less elements (535) than Piave (1049) and Tagliamento River (1846), which corresponds to ~8.5, 13.9 and 10.7 elements per hectare, respectively (Fig. 45).

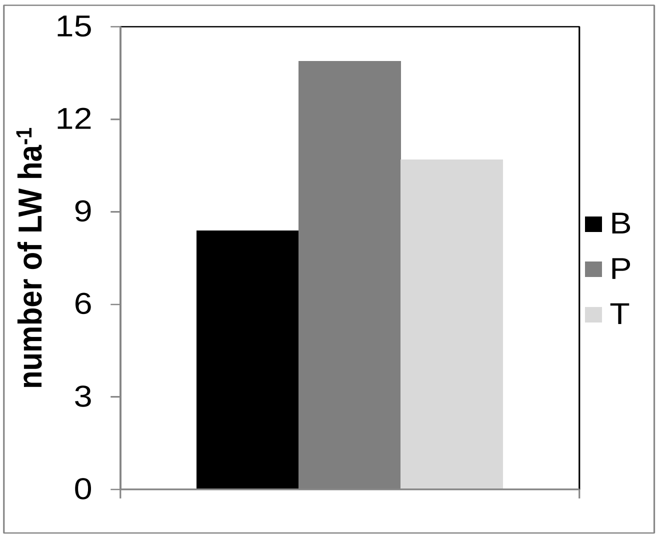

Figure 45: *Number of LW per hectare in Brenta, Piave and Tagliamento rivers.*

The mean diameter of logs were quite comparable among rivers as well, being around 0.13, 0.08, and 0.10 m in the Brenta, Piave, and Tagliamento rivers, respectively The greater diameter was 0.96 m, and was surveyed in the Tagliamento River. (Fig. 46, A).

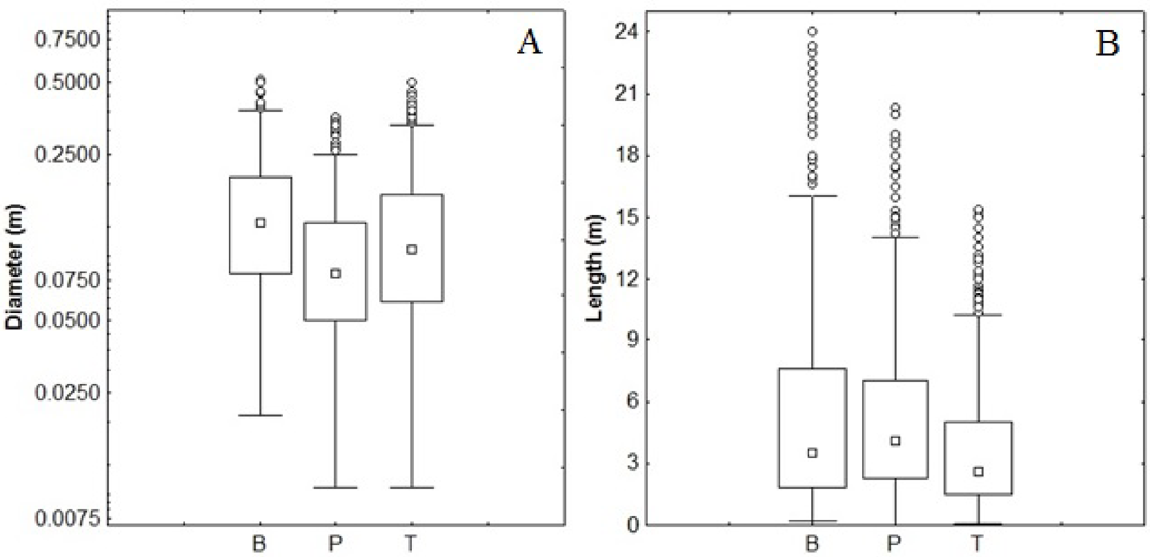

Figure 46: *Diameter (A) and length (B) of logs surveyed in Brenta (B), Piave (P) and Tagliamento (T) rivers.*

The wood volume was calculated for each river and related to the area surveyed (i.e. $m^3 ha^{-1}$) in order to be comparable. Figure 8 shows that the three rivers feature a comparable volume of wood per hectare of river surface, being slightly higher in the Piave (11.46 $m^3 ha^{-1}$) than in the Brenta (9.76 $m^3 ha^{-1}$) and Tagliamento (7.41 $m^3 ha^{-1}$).

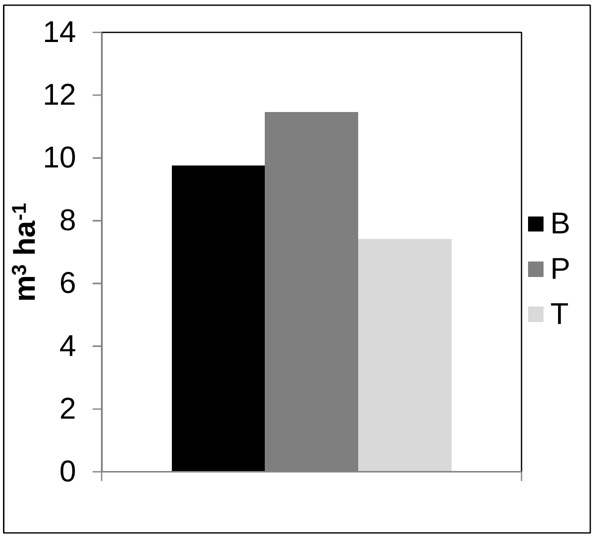

Figure 47: *Wood volume per hectare in Brenta, Piave and Tagliamento rivers.*

The wood volume obtained from the single pieces of wood was 3.65, 3.20 and 1.03 $m^3 ha^{-1}$ for Brenta, Piave and Tagliamento rivers, respectively. As to the jams, their air-wood volume was calculated assuming a solid parallelepiped shape (as commonly done in literature, see for instance Thévenet et al., 1998), and the obtained volumes are around 273.76, 509.24, and 209.20 $m^3 ha^{-1}$ for the Brenta, Piave, and Tagliamento, rivers, respectively. If the proportion of air is discounted using the same percentages calculated by Thévenet et al. (1998) equal to 93% for jams, the net volume of wood of the WJ per hectare results to be 27.37, 18.38, and 9.23 $m^3 ha^{-1}$ in Brenta, Piave, and Tagliamento rivers, respectively. Considering also the volume of the isolated wood calculated with the proportion of air of 18 and 90% for trunks and shrubs, the overall volume of wood per hectare was 47.95, 19.85 and 10.47 $m^3 ha^{-1}$ in Brenta, Piave and Tagliamento rivers, respectively.

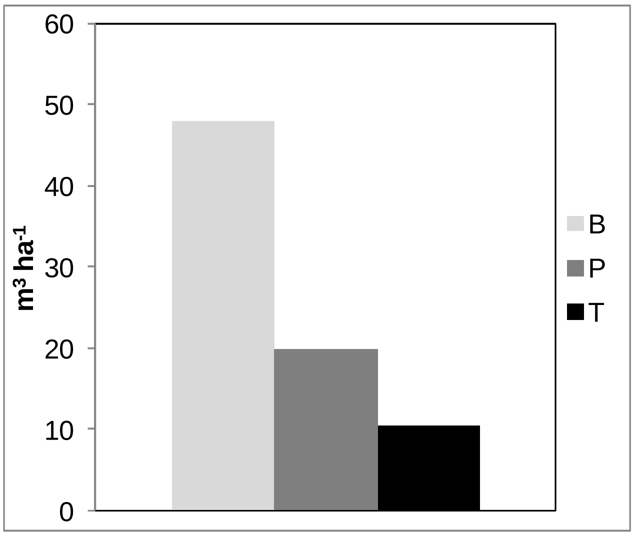

Figure 48: *Wood volume per hectare obtained using the Thévenet et al. (1998) formulas.*

The percentage of wood volume in the different morphological units varies among the three study rivers (Fig. 9). Almost 75% of wood volume in Brenta was found in low bars and channels. This percentage is reduced to 62% in the Piave and to only 38% in the Tagliamento River. Indeed, in the Tagliamento River more than 60% of wood volume was surveyed in high bars, islands and floodplain. Despite the fact that fewer LW and WJ were found in the most dynamic morphological units of the Brenta River, these feature high volumes, likely because the dimension of elements were generally higher.

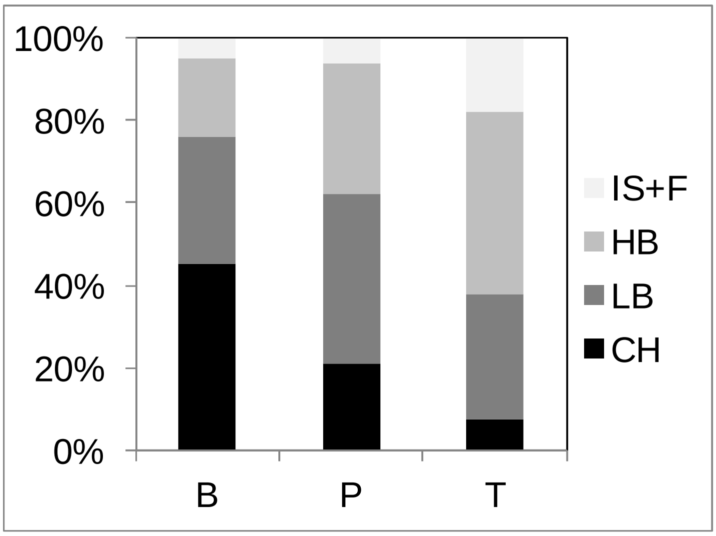

Figure 49: *The percentage of wood volume in the different morphological units on the Brenta, Piave, and Tagliamento rivers (CH: main and secondary channels; LB: low bars; HB: high bars; IS-F: islands and floodplain).*

3.1.4 Geomorphic effects of wood in-channel in Brenta, Piave and Tagliamento rivers

Due to their influence on local hydraulics, single and jammed logs usually produce concentrated scour on their side, and desposition of sediments in front and especially behind them. The size of local sediment scour and deposition around both LW and WJ was calculated using the geometrical measurements taken in the field when these shapes were present. The overall ammont of scour and deposition, scaled to the areal size of the surveyed area is showed on figure 10. It apperas that the logs and jams on the Brenta River are less effective in generating local geomorphic effects, as the volumes of scour and deposition (1.97 m^3 ha^{-1} and 5.44 m^3 ha^{-1}, respectivelly) is lower than values obtained in the Piave (6.19 m^3 ha^{-1} and 12.53 m^3 ha^{-1}, respectivelly) and Tagliamento rivers (6.74 m^3 ha^{-1} and 11.7 m^3 ha^{-1}, respectivelly).

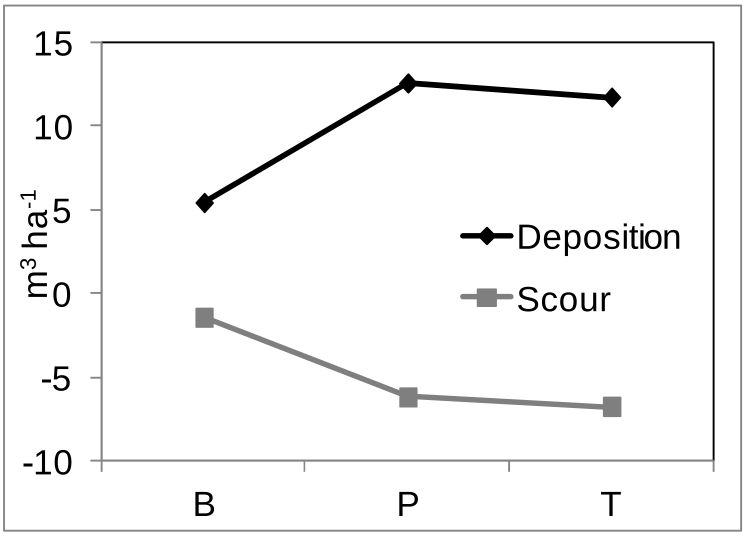

Figure 50: *Geomorphic effects of large wood in the Brenta (B), Piave (P), and Tagliamento (T) rivers, measured as the volumetric scour and deposition around single logs and jams.*

Even if scour and deposition volumes appear positively correllated with the wood volume (both jams and single pieces of wood are considered) that created them (Fig. 11), these relationships resulted not statistically significant (R^2 = 0.132 and R^2 = 0.166, respectively).

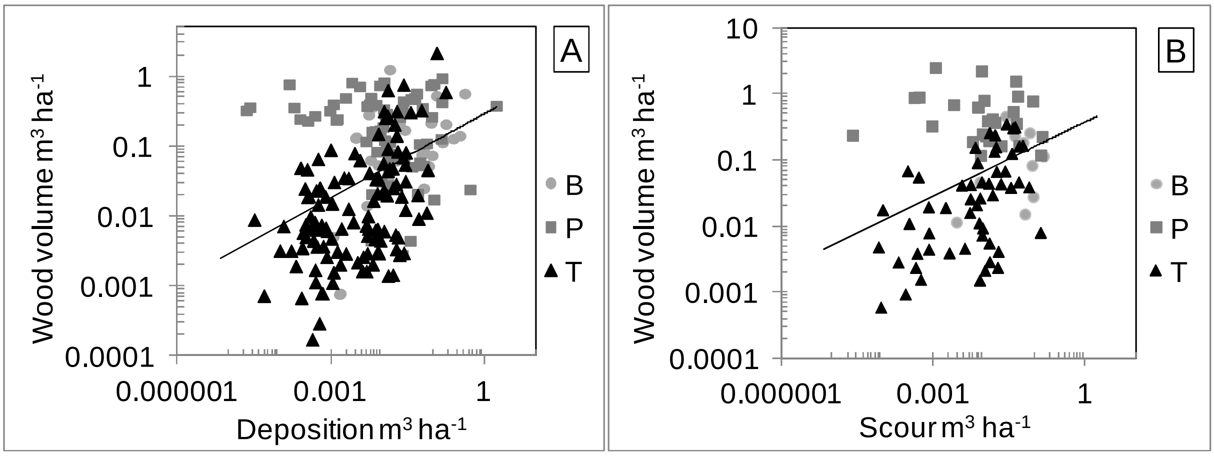

Figure 51: *Relationship between wood volumetric deposition (A) and scour (B) due to the amount of in-channel wood in the Brenta (B), Piave (P) and Tagliamento (T) rivers.*

The volumes of scour and depositon around jams is comparable among the Brenta and Piave rivers, (Fig. 52), where most of sediment despostion is associated with jams in high bars, whereas scours around jams is mostly accounted in low bars. In the Tagliamento River, sediment desposition is more concentrated in high bars, and scour of sediments is fairly distributed among low and high bars, and is also recognisable around jams found in the secondary channels and pioneering islands.

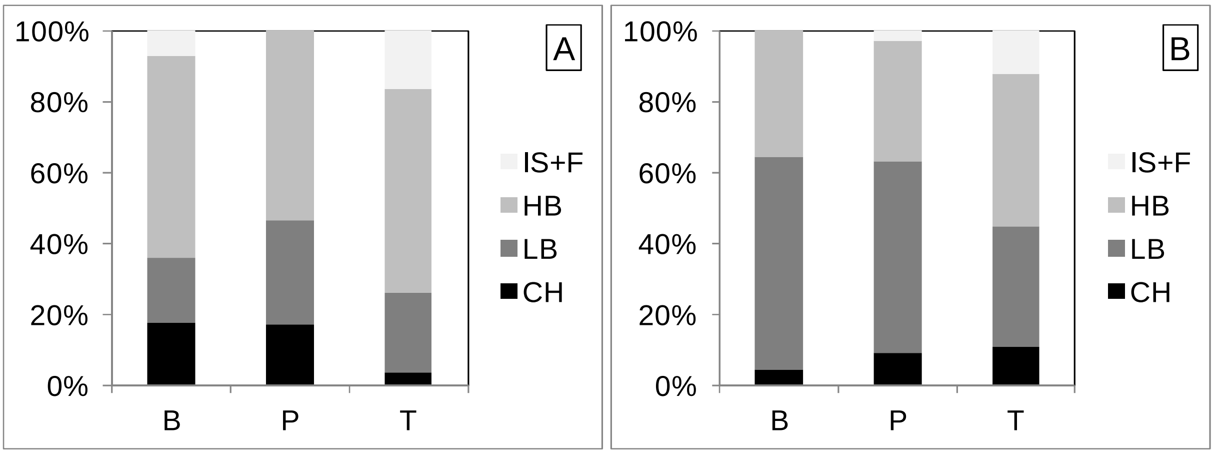

Figure 52: *Percentage of volumes deposition (A) and scour (B) around jams in different morphological units on the Brenta, Piave, and Tagliamento rivers. (CH: main and secondary channels; LB: low bars; HB: high bars; IS+F: islands and floodplain).*

3.1.5 Comparison of wood characteristics of Brenta, Piave and Tagliamento rivers (Italy) and Blanco River (Chile)

In January 2013 and 2014 a series of field surveys were conducted, as part of a complementary PhD activity in Chile (Which is briefly reported here for the sake of comparison with the field studies in Italy), along a sub-reach of 2 km-long in Blanco River (or Chaitén River) located in the Southern Chile. On May 2nd 2008 the volcano Chaitén initiated its eruption, affecting the fluvial corridor and the riparian forest of the Blanco River (Major and Lara 2013). Pyroclastic flows, landslides and lahars caused by the partial collapse of the dome and the eruption column, and by the seismic activity (magnitudes between 3 and 5

Mw), generated volcanic material deposits which reached up to about 8 m high in the Blanco River valley, and damaged (destroyed) more than 400 km^2 of forest adjacent to the volcano (Major et al., 2013). Precipitations after the eruption mobilized large volumes of material downstream, generating from May 11th 2008 an elevation of the bed of the Blanco River at Chaitén village that reached a height of 7 m on the 14th of that month (Ulloa et al., 2015).

With the exception of the work carried out by Lisle (1995) which reports the effects of large wood material (LW) in channels affected by the eruption of Mount Saint Helens, the processes of LW recruitment, abundance, spatial distribution and mobility in the fluvial corridor are very little explored. Although the better knowledge of the variation and distribution of LW is fundamental to understand the river channel behaviours (e.g. Piégay and Marston, 1998).

This study investigates the characteristics of in-channel large wood and wood jams generated by the 2008 Chaitén volcanic eruption in a channel segment of the Blanco River. Aerial and satellite images was used to analyse the LW and WJ before the eruption (2005). The image of 2005 was obtained from Google Earth® from the pre-volcanic eruption period (Digital Globe satellite image dated 2005, natural colour and 0.6 m spatial resolution). Two field surveys have been carried out in Blanco River in January 2012 and 2013. Finally, a comparison a comparison with the characteristics of three European rivers (Brenta, Piave and Tagliamento) was conducted.

The European rivers are characterized by similar slope, grain size and present a quite similar morphological pattern of the Blanco River. In Blanco River the surveys have been conducted in a segment 6.5 km-long characterized by a slope of 1.3% (Ulloa et al., 2015). The segment was divided into 7 individual reaches and numbered from downstream to upstream, according to Rosgen (1994). Reach length ranges from 400 to 1200 m. Before the eruption, the entire study segment featured a single channel, and 4 out of 7 reaches were wandering and 3 reaches were straight. During the 2012 and 2013, the channel geometry was more similar to the pre-eruption condition with the most reaches wandering, and the river returned to a single channel pattern (Ulloa et al., 2015). Pyroclastic flows and lahars caused the destruction of vegetation along the entire fluvial corridor, increasing the amount of dead wood in the Blanco River channel. In January 2012 and 2013, single pieces of wood (LW) and jammed wood (WJ) within the active channel along the 6.5 km-long river segment were measured. Woody material was characterized at reach scale, calculating the number of isolated and jammed wood (N ha^{-1}), mean length of the single pieces of wood, the area of wood jams per channel area (m^2 ha^{-1}) and minimum and maximum size of wood jams (m^2).

The total number of individual elements was 16, 528 and 777 (3.26, 43.50 and 62.28 in N ha^{-1}) for the years 2005, 2012 and 2013, respectively. Considering all 6.5 km-long segment, the mean length of the individual wood pieces was 10 m in 2012 and 7.4 m in 2013. Due to the low resolution of the images of 2005 (0.6 m spatial resolution), it was not possible to calculate the length of LW. No wood jams were collected in 2005. On the other hand, 289 and 340 (23.80 and 26.80 in N ha^{-1}) wood jams were collected in 2012 and 2013, respectively.

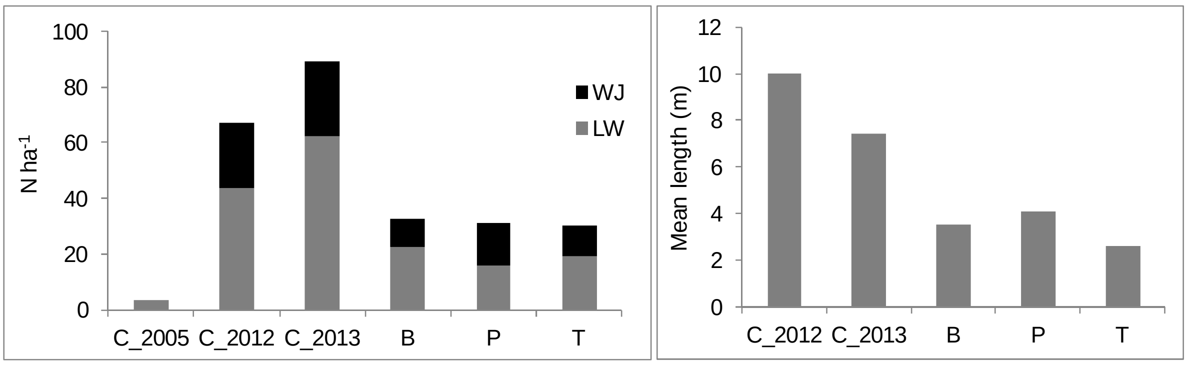

Figure 53: *Comparison of number of wood per hectare (on the left) and mean length (on the right) between the European rivers (Brenta, Piave and Tagliamento) and Blanco River.*

The mean size area calculated of the wood jams were 201 m^2 in 2012 and 267 m^2 in 2013, with minimum and maximum area of 12 and 5609 m^2 in 2012, and 11.8 and 4738 m^2 in 2013.

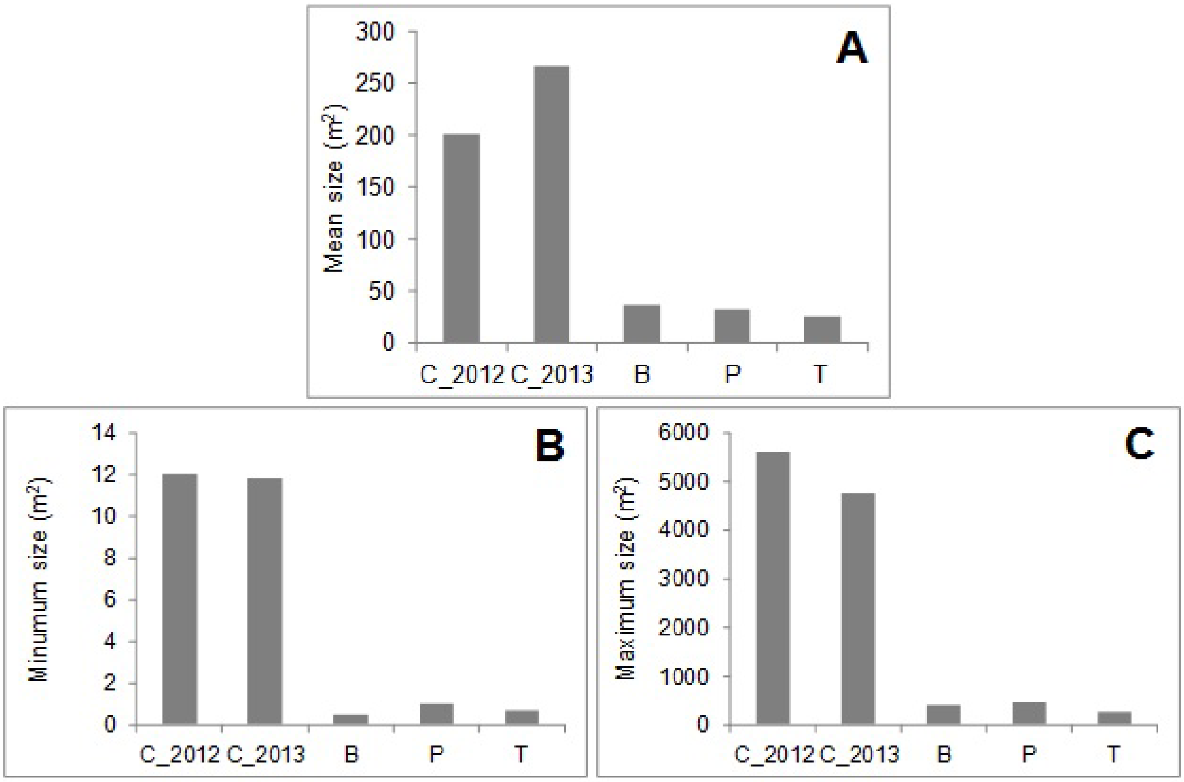

Figure 54: *Comparison of the mean size (A), minimum size (B) and the maximum size (C) of the wood jams between European rivers and Blanco River.*

The Chaitén volcanic eruption provides a rare opportunity to study post-eruption landscape adjustments in southern of Chile (Major et al., 2013). The total wood pieces increased from 16 to 777 elements between 2005 and 2013. After the eruption there was a huge amount of large wood material along the study segment. Lisle (1995) also report abundance of wood elements in channels affected by pyroclastic flows at Mount Saint Helens.

Although the three European rivers (Brenta, Piave and Tagliamento) are similar of the Chaitén River from grain size, morphology and slope, it was observed an enormous difference of number of large wood in-channel per hectare. Probably, this result is due to the different phenomena of wood recruitment. In the European rivers case, the recruitment of wood is mainly attributable to different processes such as wind throw, bank erosion and, landslides on the upper part. In Blanco River case, the huge quantity of wood is mainly due to the volcano eruption event which destroyed more than 400 km^2 of forest adjacent to the volcano. Moreover, it was collected a high different wood jams size-area between European rivers and Blanco River. The result is probably the response to the higher number of logs and, also to the bigger size of the single piece of wood which is in Blanco River approximately 2.5 times greater than European rivers size.

This study highlights the importance of large wood dynamics in river systems affected by paroxystic events such as eruptions in comparison with rivers affected by ordinary events. Further investigation on this study site will allow monitoring the rates of channel incision over pyroclastic deposits until reaching the original channel bed and the dynamics of large wood that will be supplied from buried bank deposit of logs due to lateral channel erosion.

3.2 Wood mobility and transport

Log displacement length and velocity in a large gravel-bed river (Tagliamento River, Italy) during near-bankfull floods that occurred from June 2010 to October 2011. Specific objectives are to verify the recovery rates of RFID tags after floods of different magnitude to test the use of GPS trackers to measure log entrainment and velocity, to assess the displacement length and velocity of logs in a braided river, and to quantify log mobility and velocity during floods.

3.2.1 RFID tags and GPS trackers recovery rates

From June 2010 to March 2011, a whole of 113 RFID tags and 42 GPS trackers were installed in single log elements (Tab. 2).

Period	h_{max}	Device	Installed tags	Immobile tags	Transported tags	Lost tags	Available tags for next period	% Recovered
06/07/2010 - 21/10/2010	1.91	RFID	63	19	2	42	21	33.3
		GPS	21	15	2	4	17	81.0
21/10/2010 - 01/06/2011	2.90	RFID	106	1	10	10	54	52.4
		GPS	42	3	1	13	25	23.5
01/06/2011 - 04/10/2011	2.11	RFID	113	16	8	30	31	44.4
		GPS	42	3	2	20	5	20.0

Table 2: *Number of installed, immobile, transported, and lost RFID tags and GPS tracker devices on the three main periods of searching after major floods.*

The tagged LW elements have a median length of about 11.50 m and median diameter of 0.19 m, being the longest and ticker logs of about 21 and 2 m, respectively.

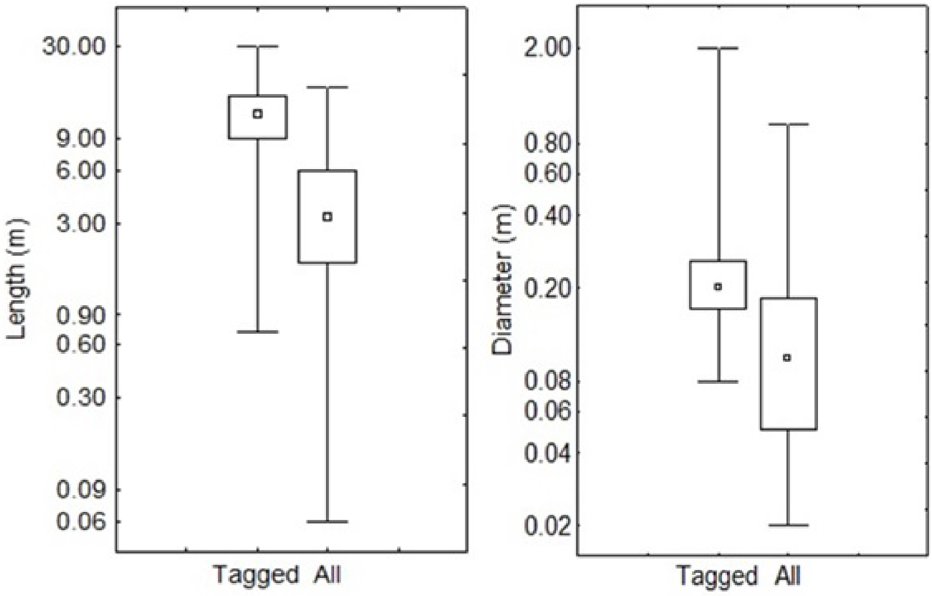

Figure 55: *Length (on the left) and diameter (on the right) of tagged logs and all logs surveyed in the study reach.*

Approximately 70% of tagged elements were trees with rootwad and branches, and about 30% were trunks with no branches. The recovery rates of RFID tag and GPS tracker devices range from 33 to 52%, and from 20 to 81%, respectively, depending on the amount of time available for searching the devices after floods. The overall recovery rates are around 43 and 42% for the RFID tags and GPS trackers, respectively. All logs, except one, were recovered on the edge of the channels or in low bars. Both RFID tags and GPS trackers proved to perform fairly well over the study period, and no issues with low battery levels or filtration of water inside the device were noted. Because of that, and because tagged logs were always searched on their last available position point, all unrecovered logs are very likely to have been transported from that position, further downstream of the maximum extent of searching distance. More unlikely, unrecovered logs could have been submerged by water or buried by sediments to the extent that could not been detected by the portable antenna.

3.2.2 Logs mobility during flood events

Logs mobility and displacement length during flood events occurred during the study period have been analysed. The percentage of immobile tagged logs ranges from 15 to 50% depending on the flood events (Tab. 2). Considering the errors associated to GPS data and the fact that most logs were longer than 5 m, a minimum difference of 10 m between pre and post GPS position was assumed for considering that a log was actually displaced by a flood event. Taking this minimum displacement length into account, 20 logs tagged with RFID and 5 logs tagged with GPS were considered as transported.

Interestingly, because GPS devices were activated by movements, GPS trackers started register point positions when water stage reached the logs on which they were attached by a metal chain. Overall, 15 GPS devices did not register any displacement but registered movements during flood events. GPS devices were activated within a range of flow stages ranging from 0.20 to 1.80 m (as measured at the Villuzza gauging station), corresponding to 10 to 60% of bankfull stage, and the median value is approximately 40% of bankfull stage (Fig. 56). On the other end, the water stage needed to entrain and transport logs stranded on low bars for more than 10 m is higher than 40% of bankfull stage.

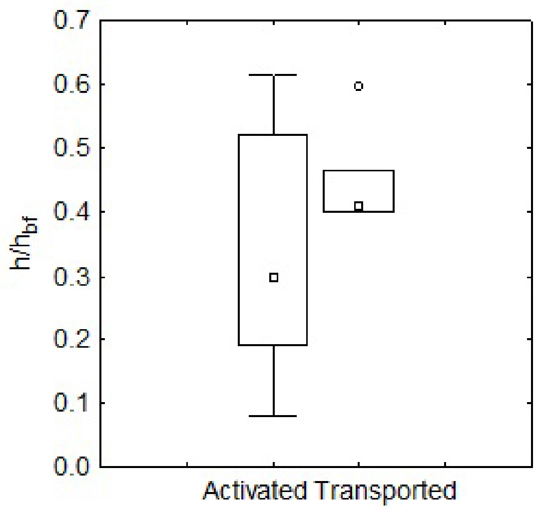

Figure 56: *Water stage relative to bankfull level needed to activate and to actually entrain and transport GPS tracker devices attached to logs stranded on low bars of the Tagliamento River. The whiskers represent the 10th and 90th percentiles, the box limits indicate the 25th and 75th percentiles and the square icon within the box marks the median.*

3.2.3 Logs transport during flood events

The mean distance travelled by entrained logs was about 13 km, with a minimum displacement length of 111 m for a tree tagged with a RFID (14 m long, 4.70 m wide considering the branches, and diameter of 0.33 m). The maximum displacement length was about 51.10 km, corresponding to a small log (1 m long, 0.15 m diameter) tagged with a GPS tracker device. Interestingly, both maximum and minimum log travel distances were caused by the same flood events occurred in 19/06/2011, which reached approximately 70% of bankfull stage.

The peaks of floods which were competent enough to entrain and move tagged logs range from 1.91 to 2.90 m (63 to 96% of the bankfull stage). The log displacement lengths are positively correlated with the magnitude of the floods ($R^2 = 0.27$), but the correlation is not statistically significant ($p > 0.05$).

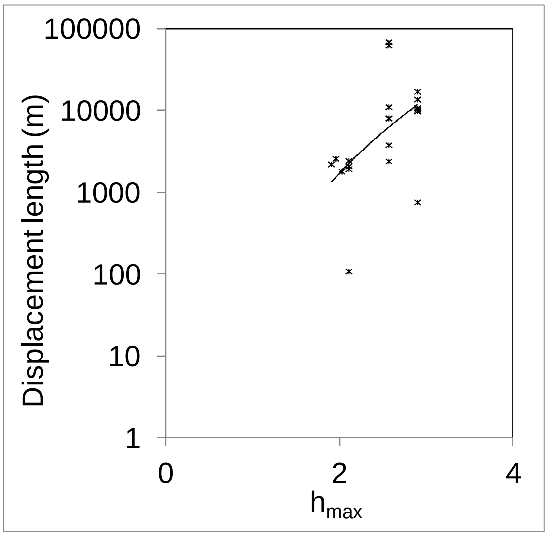

Figure 57: *Relationship between the maximum peak flow and the displacement length of logs.*

In fact, because the peak might not be the only or most important parameter characterizing a flood event, the whole flow duration curve from installation (or last recovery) to recovery was calculated (Fig. 58). Significant percentiles of the flow durations curves were calculated as well, and their relevance in increasing the significance of the relationships between flow characteristics and logs displacement lengths were tested.

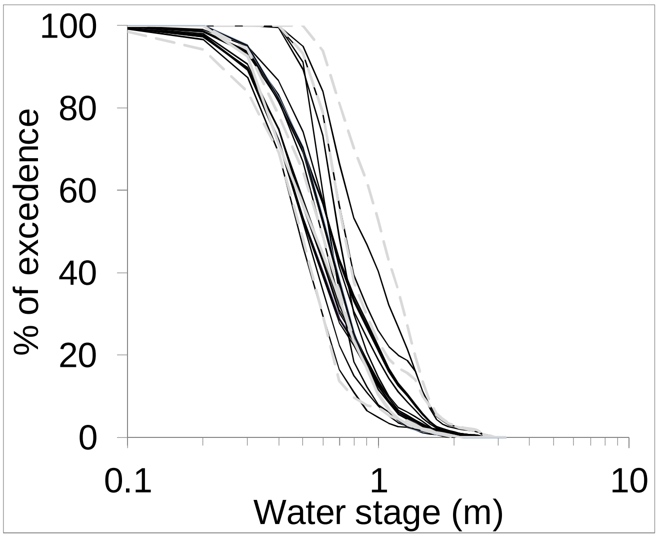

Figure 58: *Flow duration curves of RFID tags (black lines) and GPS tracker devices (grey dashed lines).*

Flow percentiles close to the peak proved to be the most relevant descriptors of flow duration curves. In fact, the ratio h_{max}/h_{25} (being h_{25} the water stage exceeded for 25% of time) is better related to the displacement lengths ($R^2 = 0.42$; $p < 0.05$; Fig. 59).

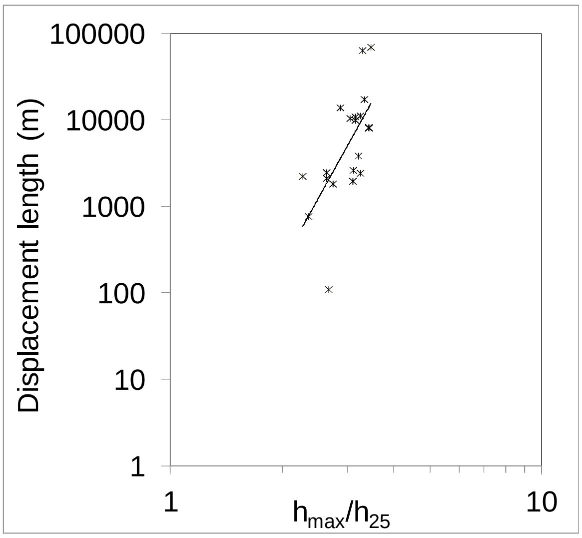

Figure 59: *Relationship between the maximum peak flow and the water stage exceeded for 25% of the time in the flow duration curve (h_{25}), and the displacement length of logs.*

Displacement lengths were used to define the transport velocity of logs. Naturally, logs moved only for a fraction of the time passed between their marking and recovery, and because of that the velocity is considered "virtual" (*sensu* Wilcock, 1997). As expected, the correlation between the log velocity and the peak flow is positive ($R^2 = 0.20$) but poorly significant ($p > 0.05$; Fig. 60; A). However, if the ratio h_{max}/h_{25} is considered, the correlation increases and becomes statistically significant ($R^2 = 0.44$; $p < 0.05$; Fig. 60; B).

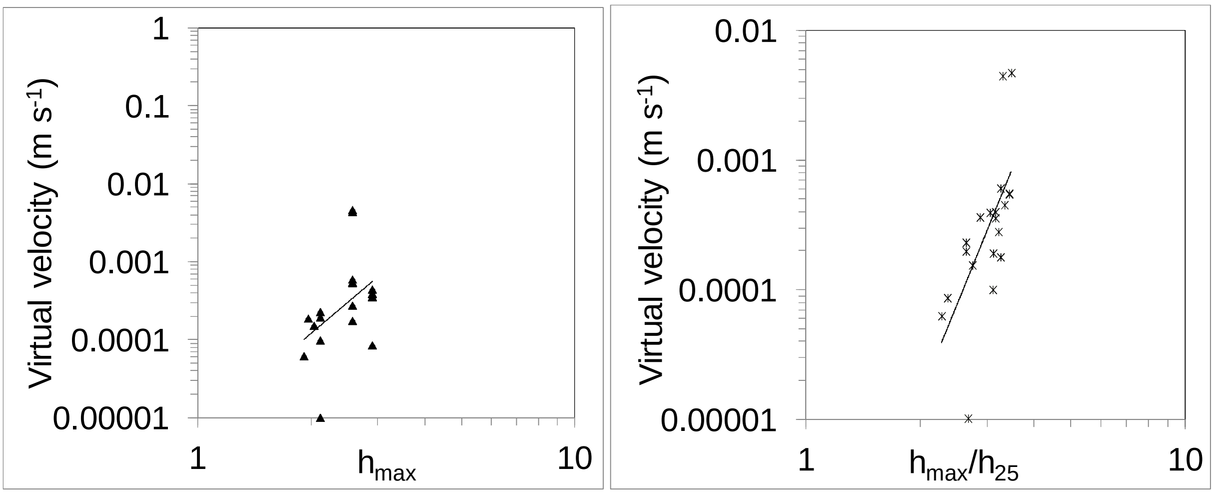

Figure 60: *(A) Relationship between maximum peak flow and the virtual velocity of logs (which includes long periods of rest during low flows). (B) Relationship between the ratio of maximum peak flow, and the water stage exceeded for 25th of the time in the flow duration curve (h_{25}).*

In order to avoid considering low flows that could not have been able to move logs in log velocity calculation, flow duration curves were recalculated considering only flows higher than a threshold of 1.20 m, corresponding to 40% of bankfull stage (see Fig. 56), that proved to be able to entrain logs (Fig. 61).

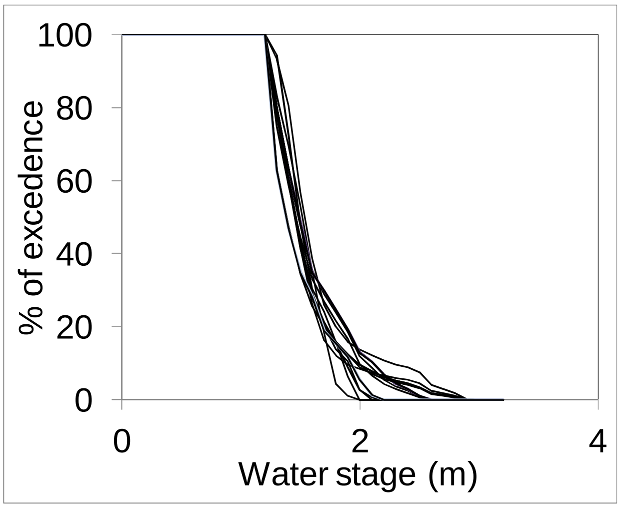

Figure 61: *Flow duration curves of the RFID tags (black lines) and GPS tracker devices (grey dashed lines), considering only flows higher than a threshold of 1.20 m (40% of bankfull stage).*

Even doing that, displacement length is only slightly better related to the ratio h_{max}/h_{25} (R^2 = 0.28; $p > 0.05$), and a poor correlation with logs velocity was found (R^2 = 0.19; $p > 0.05$).

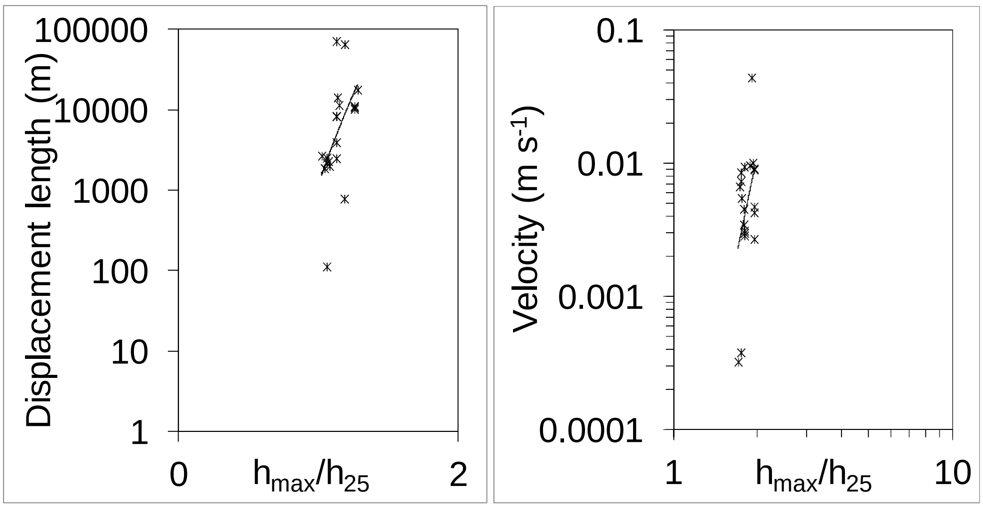

Figure 62: *(A) Relationship between the ratio of maximum peak flow and the water stage exceeded for 25% of the time in the flow duration curve (h_{25}), and the displacement length of logs. (B) Relationship between the ratio of maximum peak flow and the water stage exceeded for 25% of the time in the flow duration curve (h_{25}), and the velocity of logs.*

Because RFID tags proved to provide measurements of virtual velocity that can be hardly related to the real log velocity during floods, the data provided by the GPS tracker devices was considered. Figure 63 shows the movement of four tagged logs during single flood events. It is worth observing that logs were all entrained during the rising limbs of hydrographs at a water stage of approximately 1.20 m (apart for GPS tracker 2, which is entrained at 1.60 m). Also, logs stop near the peak of floods, and are not entrained and transported any further during the falling limbs. Mean log velocity during their actual transport ranges from 0.50 to 1.80 m s^{-1}, with an average value of around 1 m s^{-1}. Interestingly, the smaller log (1 m long, diameter 0.15 m) was transported with the highest velocity (1.88 m s^{-1}), whereas the largest tagged log (a tree 30 m long, diameter 0.45 m, with a canopy having a diameter of approximately 4.50 m) was transported with a mean velocity of 0.51 m s^{-1}. The smaller log was also transported for the higher distance, of approximately 51 km. A 16.70 m long log (0.26 m as diameter) tagged with the GPS2 (Fig. 63, B) was entrained at a stage of 1.60 m, and after a stop of about 15 hours was entrained again at a flow stage of 2.50 m. Even if transported at two different stages of the same hydrograph, its velocity is quite comparable, having being transported at 0.90 and 0.72 m s^{-1} during the first and the second displacements, respectively. Overall, LW velocity is not significantly related with the magnitude of the floods ($p > 0.05$).

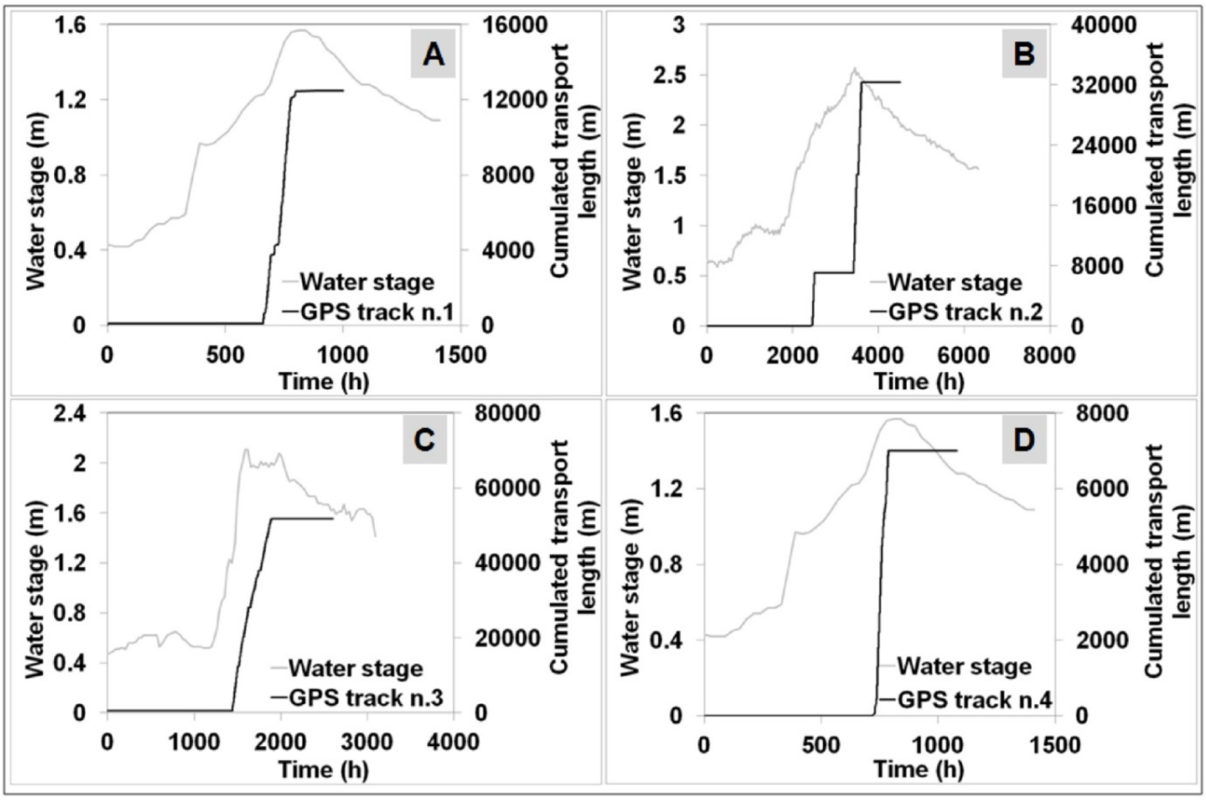

Figure 63: *Water stage and cumulated transport distance of logs tagged with GPS tracker devices. Times were set at zero for GPS tracker 1 at 00:00:00 of the 15/08/2010 event (A), at 17:00:00 of the 22/12/2010 event for GPS tracker 2 (B), at 00:00:00 of the 19/06/2011 event for GPS tracker 3 (C), and at 12:00:00 of the 15/08/2010 event for GPS tracker 4 (D). (Ravazzolo et al., 2015).*

Instead, as expected LW velocity is negatively and significantly correlated with the volume of logs ($p < 0.01$; Fig. 64). In order to compare the range of LW velocities with the average flow velocity during floods, the hydrographs registered at the Villuzza and Braulins gauging stations (the latter located 15.80 km upstream of the former) were used to calculate the celerity of the peaks between the two positions. Even if no significant relationship was found between log velocity and flood celerity ($p > 0.05$), it is worth noting that logs moved at approximately 40% of the floods celerity.

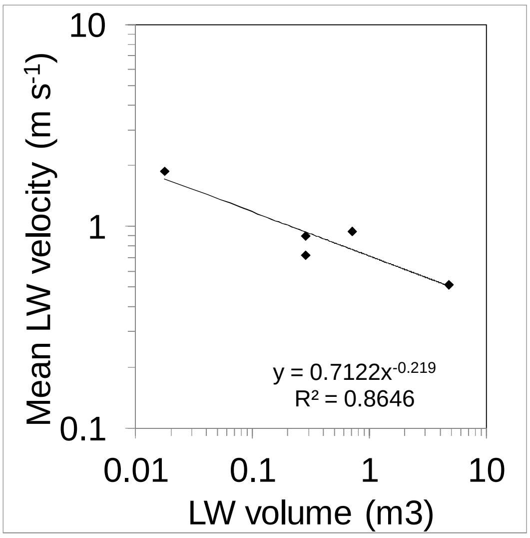

Figure 64: *Correlation between volume and mean velocity of transported logs.*

3.3 Physical modelling

During the first six hours of simulation log input rate was set to 60, 120 and 180 logs hour^{-1} for channel C1, C2 and C3, respectively (Tab. 3).

RUN	C1	C2	C3
S (only sand bed)	Steady flow and sand feeding	Steady flow and sand feeding	Steady flow and sand feeding
SL (sand and logs)	Steady flow, sand feeding and logs feeding (40 logs h^{-1})	Steady flow, sand feeding and logs feeding (80 logs h^{-1})	Steady flow, sand feeding and logs feeding (120 logs h^{-1})
SV (sand and vegetation) SVa at 1/4of the run SVb at 1/2of the run SVc at 3/4of the run SVd at the end of the run	Vegetation growing and re-seed every 7 days; Steady base-flow with four high-flow pulses (1.26 l s^{-1}) every 7 days		
SLV (sand, logs and vegetation) SLVa at 1/4of the run SLVb at 1/2of the run SLVc at 3/4of the run SLVd at the end of the run		Vegetation growing and re-seed every 7 days; Steady base-flow with four high-flow pulses (1.26 l s^{-1}) every 7 days, and logs feeding (40 logs h^{-1})	Vegetation growing and re-seed every 7 days; Steady base-flow with four high-flow pulses (1.26 l s^{-1}) every 7 days, and logs feeding (120 logs h^{-1})

Table 3: *Details of the conditions during the experiments in the flumes. Vertical images of the flumes and laser scan surveys were taken at the end of each run, and on three further occasions on runs SV and SLV.*

Rapid accumulation of wood was observed in all flume channels, with higher rates for larger input (Fig. 65). The flume channels exhibited different responses to the reduction in wood input rates that occurred after six hours (to 40, 80 and 120 logs h^{-1} for channel C1, C2 and C3, respectively). Channel C1 continually accumulated wood, albeit at a slower rate, approaching equilibrium only in the last few hours. Channel C2 showed a strong output flux between t = 7 hours and t = 9 hours and then stabilized around a total storage of about 400–450 logs. Wood volume in C3 steadily increased up to t = 7 hours and then was fairly constant during the interval t=7–14 hours, with a total of approximately 800 logs in the channel, corresponding to a spatial density of about 75 logs m^{-2}.

A marked change in wood dynamics was observed for a wood input rate exceeding approximately 100 logs h^{-1}. Above this threshold, the amount of stored logs increased remarkably.

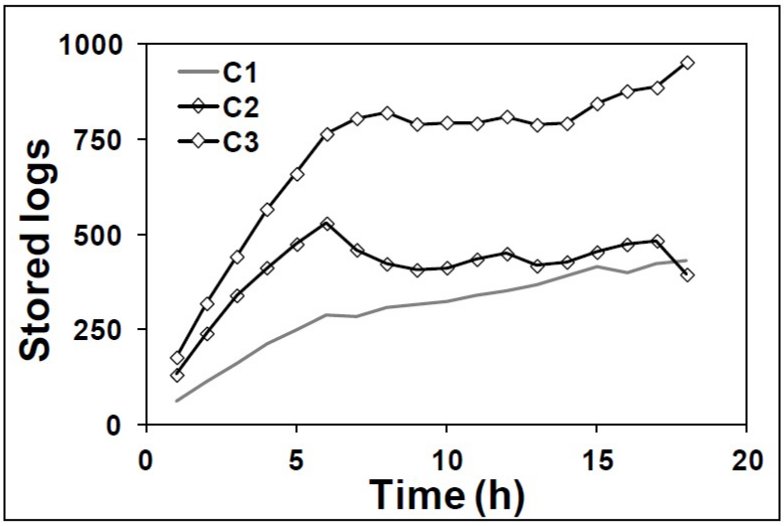

Figure 65: *Storage of wood in the three channels over time (modified from Bertoldi et al., 2014).*

Wood remobilization and turnover rate were investigated through the analysis of sequential images of each channel. The percentage of logs displaced after one-hour intervals was quite large and showed large fluctuations in time, ranging between 20 and 60% (Fig. 66). No obvious difference was observed in wood turnover rates between the three flume channels, suggesting that intense log turnover occurred over a one-hour interval regardless of wood input rate. Wood retention was also evaluated in terms of site persistence, computed as the number of consecutive vertical images of the flume channels in which individual accumulations were present. Cumulative frequency distributions of site age were similar between flume channels both for isolated logs and for jams. The average age of depositional sites was very short, being less than 2 hours in 60% of the cases. In all flume channels, jams were slightly less prone to erosion compared to isolated logs. However, 40% of large jams persisted for more than five hours, as the rapid erosion of jams with more than 10 elements has been observed to be a rare event (Bertoldi et al., 2014). Wood stability can be linked to morphological change induced by the dynamic behaviour of multi-thread systems. The turnover rate of dry bars (i.e. the persistence of dry bar surfaces) was remarkably similar to that of wood deposits, with about 40% of the areas turning into submerged surfaces in less than two hours. Up to 95% of the dry bars were eroded or flooded in less than seven hours, mirroring the high turnover rate of wood deposits. The dominant effect of morphology in controlling wood dynamics was evident, as all three flume channels experienced similar turnover rates, regardless of wood storage.

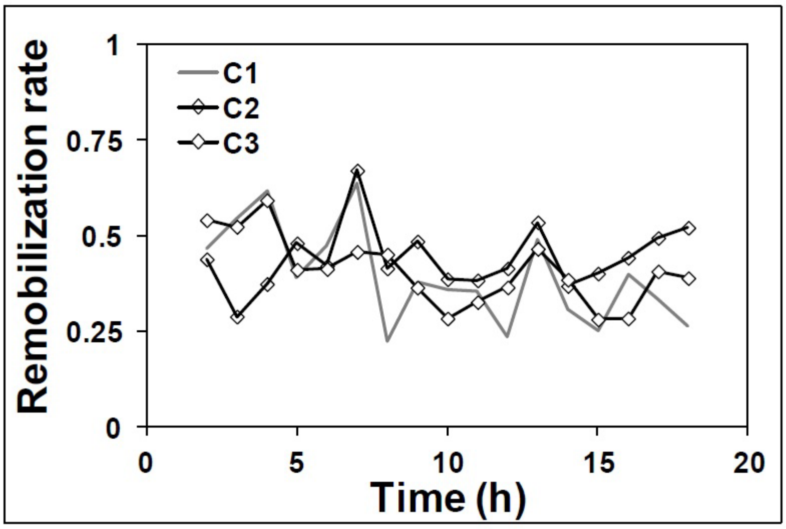

Figure 66: *Remobilization rate of logs in the three channels over time (modified from Bertoldi et al., 2014).*

Previous studies have shown that wood deposits in multi-thread rivers tend to increase the complexity (i.e. the braiding index) of the active braid (Coulthard et al., 2005; Sear et al., 2010; Cadol and Wohl, 2011). However, vegetation growing within the river planform is often linked to a decrease in braiding index (Tal and Paola, 2007, 2010) since it stabilizes bars and concentrates the flow in deeper channels. The temporal evolution of braiding index in the three flume channels was measured before and during wood dispersal simulations. Braiding index ranges between 3.5 and 5, and no statistically significant difference was observed between pre- and post-wood input configurations (Fig. 67). The present experiments show that wood alone, when free to move and deposit on a self-formed braided topography, does not significantly affect sediment transport and bed morphology at the reach scale (Bertoldi et al., 2014).

From hour 19 of the experiments, Alfalfa seeds were manually seeded and progressively grew on the dry surfaces of the three flume channels. The establishment of vegetation in the flume channels tended to reduce channel network complexity by reducing the braiding index (Fig. 67), which reduced from around 4.5 to around 2.5. It is particularly interesting to note that the simultaneous presence of vegetation and LW (fed at the same rates as prior to vegetation seeding in channels 2 and 3) tended to reduce the braiding index further (Fig. 67), and caused a shift towards an almost single-thread morphology (Fig. 68 and 69).

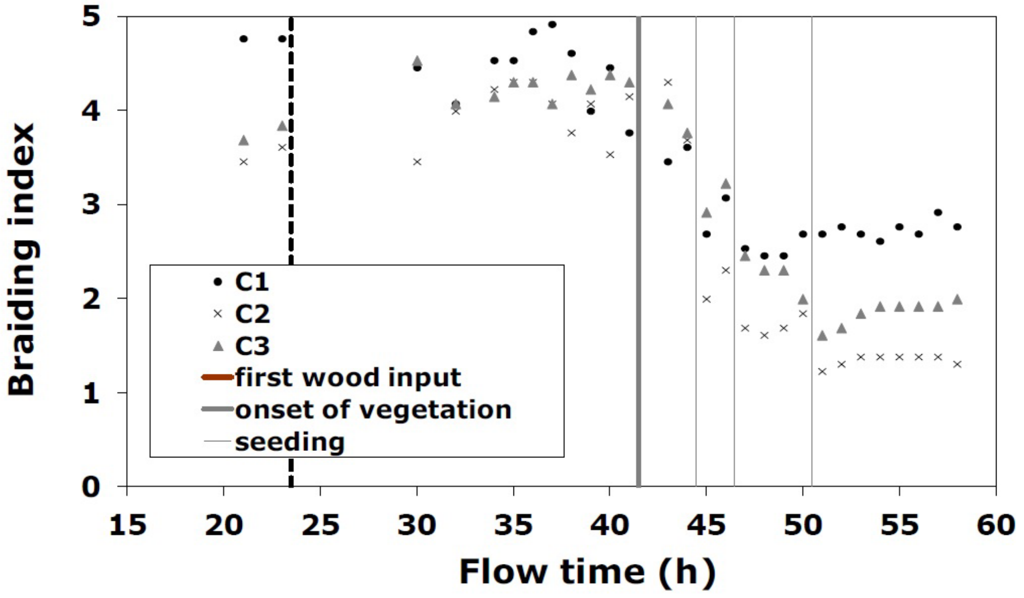

Figure 67: *Reach-averaged braiding index.*

When vegetation and LW exerted their geomorphic role together, the percentage of wood deposited as single elements reduced from 45 to 25%, and jams tended to become larger and much more stable. Under these circumstances, wood remobilization decreased dramatically to < 5%, and newly introduced logs were more likely to jam on already existing accumulations. Large jams formed under high wood input rate (channel 3, Fig. 69) were particularly stable, and tended to deflect the flow, as commonly reported in single-threads rivers (e.g. Abbe and Montgomery, 2003).

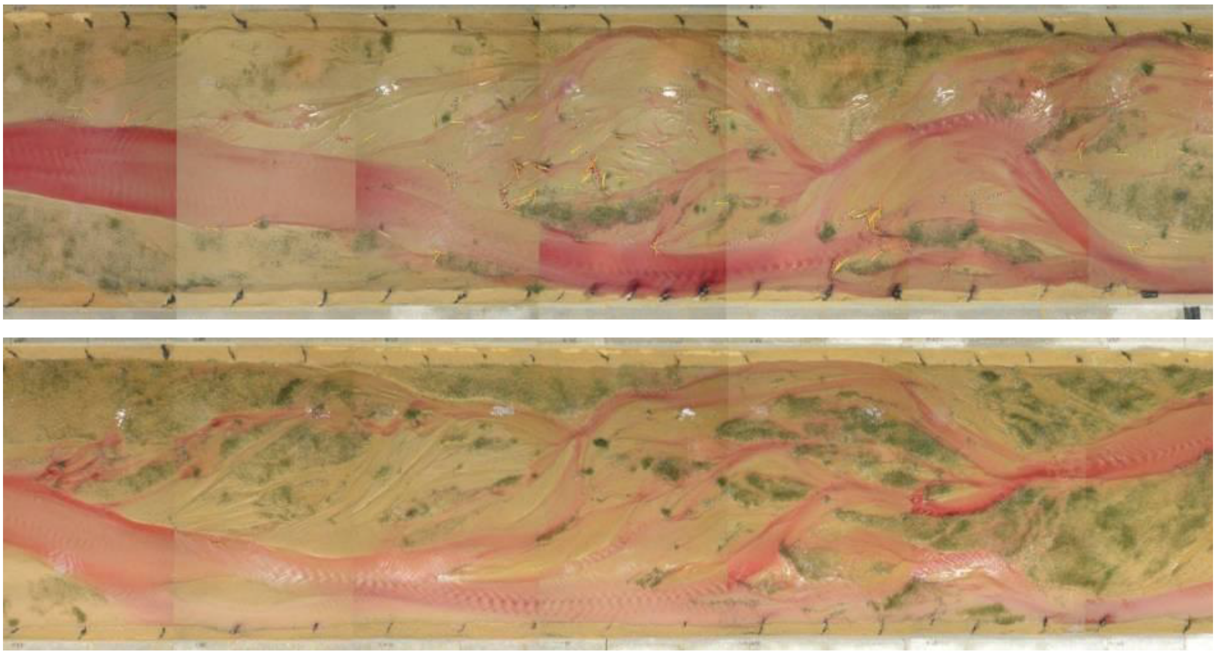

Figure 68: *Vertical photos of channel 3 (above) and channel 1 (below) taken a few days after the Alfalfa seeding. On channel 3, logs were fed at a rate of 120 logs* h^{-1}*, whereas no logs were fed into channel 1. The flow was from left to right.*

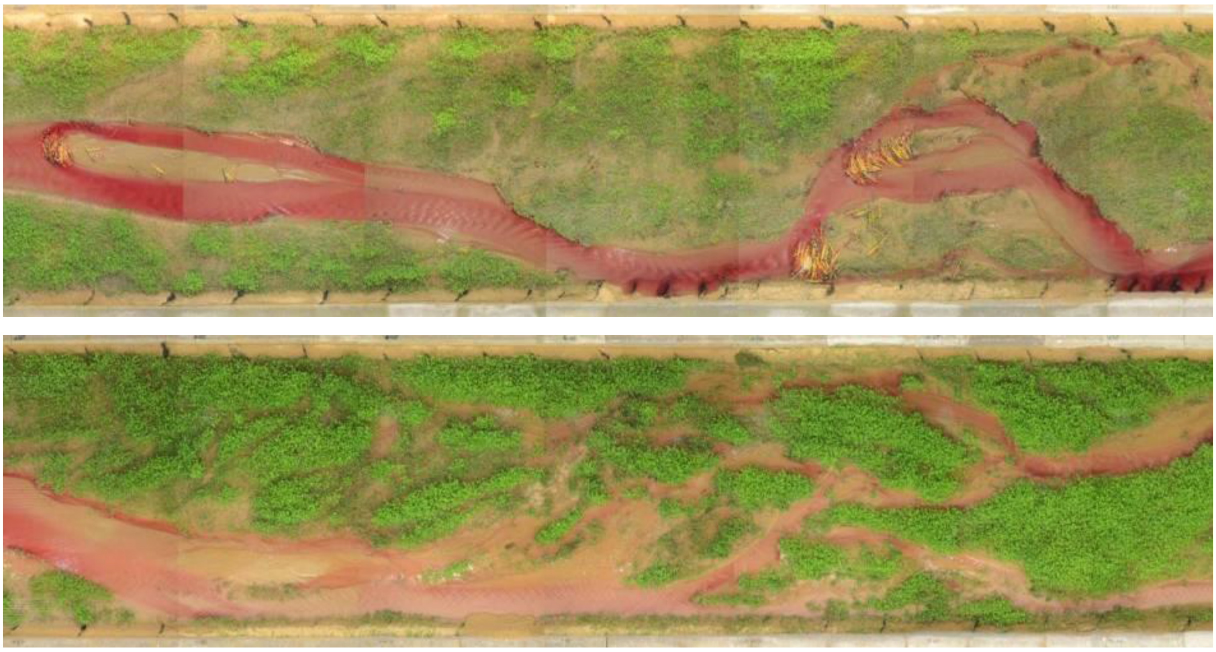

Figure 69: *Vertical photos of channel 3 (above) and channel 1 (below) taken towards the end of the experiments.*

Filtering the scans of runs SLV proved to be challenging because of the very dense canopy developed by alfalfa plant, especially at the end of the runs (i.e. SLVc and SLVd). The ground points were extracted from the scans using a script developed in Matlab. The filter is based on the colour associated to each point of the scans. A reference RGB curve distribution for an area with only sand is created, and the script deletes all points of the scan which colour diverge more than a certain percentage (which can be set manually) from the reference curve. Various attempt were needed to accomplish the better colour-filter calibration. A geometrical filter was then applied to delete outliers (Moretto, 2014). The filtered scans were then interpolated and a DEM with cell size of 1 mm was created using ArcMap. The DEM was detrended in the stream-wise direction using a linear interpolation, and finally the probability density functions of the beds were extracted. The PDFs of the three flume channels featuring no vegetation nor LW are almost identical in shape and distribution, suggesting that there is a good deal of similarity in the surface distribution of elevations due to bar braiding within the three channels. PDFs derived from laser scanner surveys of channels with vegetation and LW are all bell-shaped, but tend to be broader, with greater deviation of the values away from the zero central value.

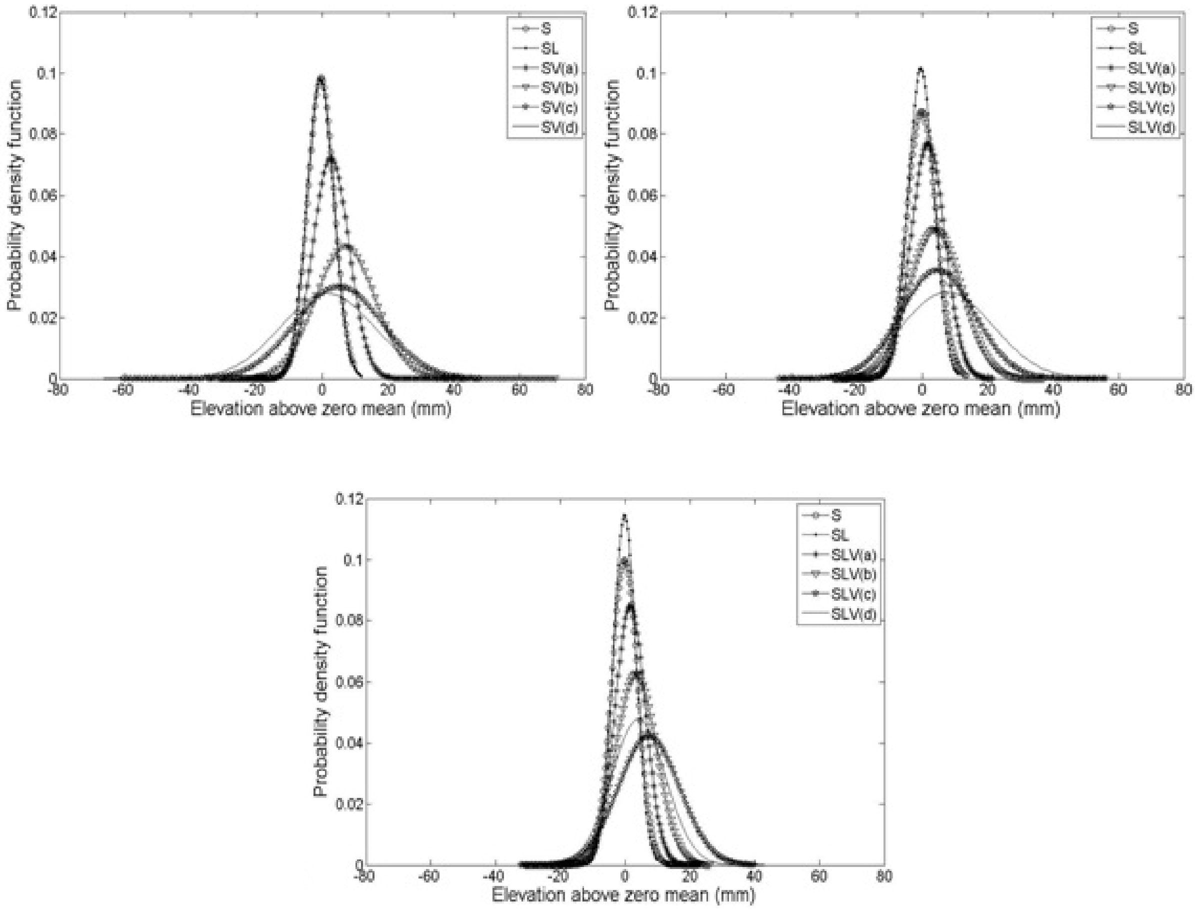

Figure 70: *The probability density function of the bed elevations at the end of each run (C1, C2 and C3 from left to right).*

The standard deviation of the bed surface elevations (σ), which can be interpreted as the characteristic vertical roughness length scale of channel morphology, was derived for all available laser surveys (Fig. 71).

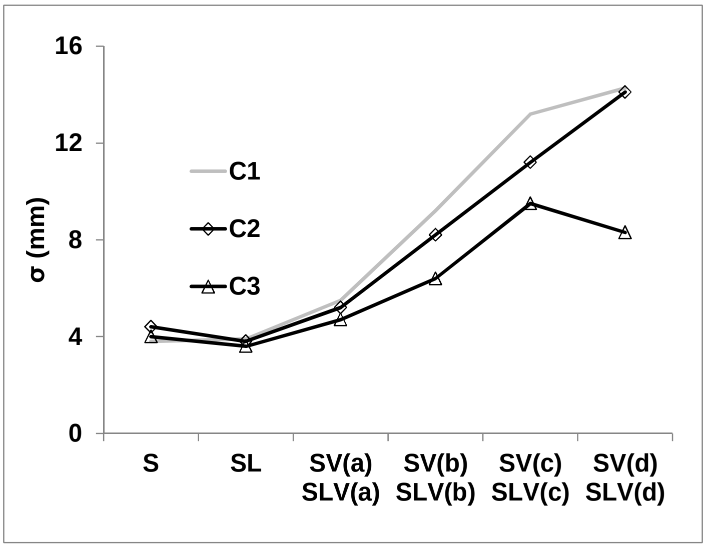

Figure 71: *Standard deviation (σ) of bed elevations for the three channels (S: only sand; SL: sand bed plus large wood; SV: sand bed plus vegetation; SLV: sand bed plus large wood and vegetation; a to d represent the laser scanner surveys taken over time* during the experiments, d being the last one).

Figure 71 shows that the range of bed elevations on a braided planform with or without logs is very similar. In fact, as shown by the log remobilization and the braiding index, large wood by itself seems unable to significantly alter the dynamics and thus the bed morphology at the reach scale. Instead, vegetation growing in the flume channels reduces the space available for the flowing water, and channels become narrower and deeper, increasing the standard deviation of the elevations (channel 1 in Fig. 71). Interestingly, when logs and live vegetation act together, the standard deviation of elevations increases over time, but at a lower rate if compared to channel 1 (e.g. see especially the results for channel 3, in which logs were introduced at the highest rate).

Chapter Four – Discussions and conclusions

4.1 Discussions

4.1.1 Abundance and wood distribution

During the study period (June-August 2010), field surveys of isolated and jammed wood have been carried out in the Brenta, Piave and Tagliamento rivers. Wood was collected on wide buffers along 7 cross-sections in the Brenta and 6 cross-sections in both the Piave and Tagliamento rivers. The volume of wood was quite comparable in all the three rivers, although the Piave River featured the higher values. Both diameter and length of elements found in the three rivers were quite comparable as well. Because the size of elements is quite similar, the difference in wood volumes among the study rivers is likely due to the higher abundance of wood in Piave (13.9 elements per ha) than Brenta (8.4 elements per ha) and Tagliamento rivers (10.7 elements per ha).

Using for weight-to-volume conversion a reasonable wood density of 500 kg m^{-3}, in the Tagliamento River we would have surveyed 3.7 t ha^{-1} which is within the range of 1 to 6 t ha^{-1} of wood quantity reported in the gravel bar surfaces by Gurnell et al. (2000), who used the same wood density. On the other hand, Van der Nat et al. (2003) collected in braided reaches a variable range of wood volume from 15 to 70 t ha^{-1}. These different amount of wood are probably due to the high dynamic nature of Tagliamento River and the high capacity to recruits wood from islands and floodplains.

In the Piave River, a range of 4 to 9 m^3 ha^{-1} of wood storage was estimated by Pecorari (2008), who reported a higher abundance of logs in braided than wandering reaches. In the same river, we detected higher volumes of wood (~11.46 m^3 ha^{-1}) probably due to the wider area surveyed. Contrary to Pecorari (2008), we found lower volumes in the braided reach Quagliodromo (3.43 m^3 ha^{-1}; 32% as isolated logs and 67% as wood jams), than in the wandering reach Praloran (8.03 m^3 ha^{-1}; 25% as isolated logs and 75% as wood jams). In the Brenta River this distribution of logs among braided and wandering reaches is quite similar, as we measured higher quantity of wood per hectare in braided reach (Nove; 0.28 m^3 ha^{-1}) than in the wandering reaches (Friola and Fontaniva, 1.81 and 3.95 m^3 ha^{-1}, respectively). The fact that Nove reach appears quite depleted of large wood could partially attributed to the presence of longitudinal defenses, which reduce the active channel width and increase water stage, thus diminishing the chances of logs to be trapped on bars. In addition, because of the presence of dams and torrent control works in the mountain basin, very little amount of wood (as little amount of sediments, see Surian and Cisotto, 2007) is likely to reach Nove. Conversely, logs are more likely to be recruited from bank erosion on floodplains and islands along in reached further downstream, and in fact Friola and Fontaniva feature higher volumes of large wood. Also, Friola and Fontaniva reaches are much wider than Nove, and feature denser riparian vegetation, probably due to the lower presence of human disturbances (Moretto et al., 2014).

4.1.2 Geomorphic effects of large wood

Both isolated large wood and jams exert a remarkable morphological effects on the channel bed, especially in terms of scours and depositions. Evidence suggest that in-channel wood exerts a higher important geomorphic role in the Piave and Tagliamento rivers than in the Brenta River. As reported elsewhere (e.g. Mao et al., 2008b) a positive relationship was found between wood volume and the volumes of both sediment deposition and scour. It is worth to note that the geomorphic effects of logs were identified in all morphological units in the more natural Tagliamento River, whereas in the Brenta and Piave were more evident in lower morphological units. This is probably due to the fact that in the Tagliamento River, the frequent and more natural fluctuation of discharges are able to move more sediment around the single pieces of wood and jams, increasing the local scours and depositions, including in higher units. It is worth stressing that fine sediment deposition around of behind logs increases the chances of logs to resprout and of trapped seeds and vegetative tissues to sprout, leading to the development of pioneer island (Nilsson and Grelsson, 1990; Manners and Doyle, 2008; Gurnell and Petts, 2006), which appear more frequent in the Tagliamento River than in the Piave and Brenta rivers, due probably to the higher thickness of sand and fine sediments along bars of the Tagliamento River (Sitzia et al., in preparation).

4.1.3 Wood characteristics and dynamic in the study rivers

Field evidence suggest that, in all the three rivers, the pieces of wood which compose the jams were mostly transported from upstream reaches. Overall, because of the conditions of conservation of wood, it appears that most logs were not transported for long distances, and thus could have been recruited from bank erosion from upstream reaches. In the Tagliamento River, Van der Nat et al. (2003) observed that at least 30% of deposited wood came from species that grew upstream and Gurnell et al. (2002) observed that the overwhelming majority of the LW was detected with rootwad facing upstream, which is the typical disposition of LW transported in large rivers (Francis et al., 2008). The condition of rootwad, and the presence of bark and branches can also provide information about the history of single pieces of wood. In fact, wood with fragments of bark, branches, and their roots indicate that the tree entered the channel in its entirety instead of as a fragment from in situ decay (Moulin et al., 2011). The state of conservation and the morphology of wood suggest the rate of movement and the wood residence time (Gurnell et al., 2002). Logs in the Tagliamento River featured a better state of conservation than in the Piave and Brenta rivers. This suggests that logs are generally easily transported downstream in the Tagliamento River, and that the residence time of logs within the same reach is shorter than in the Piave and Brenta rivers, at least in more active morphological units (channels and low bars). Indeed, the time and location of deposited in-channel wood are two important factors controlling the change of logs to decay or resprout (Francis et al., 2006; Francis, 2007). The resprouts of wood is a dynamic usually associated to wood deposited in low bars, river margins (Gurnell, 2013) and the degree to which the wood is able to sprout could be the key factor to vegetation regeneration with a stabilization of islands. Field evidence on presence of leaves in stranded trees suggest that in the Tagliamento River the elements closer to the channels lead to a higher presence of freshly leaves.

Along with the effect of LW, the magnitude and timing of flood disturbance can exert a fundamental control on the occurrence and persistence of islands (e.g. Mikuś et al., 2012). In the Tagliamento River, Surian et al. (2014) reported relevant bank and vegetation erosion during low-magnitude floods ($1 \leq RI \leq 2\text{-}3$ years), even if other authors (e.g. Bertoldi et al., 2009; Comiti et al., 2011) stressed the importance of high floods in determining the channel dynamics and persistence of vegetated islands.

If the importance of low-magnitude events holds for the Brenta and Piave rivers, the much higher presence of structures that regulate their flow conditions could exert a further role on reducing LW recruitment, along with the reduced bank erosion due to longitudinal protections, from more dynamic morphological units. The higher presence of wood in high bars and islands in the Brenta River (65%) suggests that probably logs were recruited, transported and deposited during high-magnitude events of the past. These logs appeared more degraded (i.e. decaying and porous) and with less bark and branches, which likely provide an evidence of long residence time. The presence of wood elements on higher morphological units in Brenta River is likely to be ascribed to the relative scarcity of high-magnitude floods limited by many dams and water diversions which provide consistent flood events of limited duration and magnitude as observed in Lower Roanoke River by Moulin et al. (2011). Moreover, the considerable human pressures have lead to a bed incision of the main channel in the Brenta (Surian et al., 2009) and this could be another reason of the worst state of conservation of trunk and the lower presence of pioneer islands along the low bars than Piave and Tagliamento rivers. The lower residence time of logs within the same reach in the Tagliamento River is probably due to the higher dynamicity of the channel and wood recruitment from islands and floodplain because of the much less lateral constrains (artificial banks, and rip raps) than in the Piave and Brenta rivers. The presence of deposited wood along the bars with a better state of conservation increase the capacity to resprouts, which allows the wood to remains alive. This highlights the importance of the vegetative characteristics of broadleaf species in stabilizing the bed and acting as an active driver in modifying channel morphology and increasing the possibility to develop pioneer islands. Indeed, the Tagliamento is characterized by very natural fluctuating discharge, which lead to a very dynamic channels migration (Welber et al., 2012; Picco et al., 2013), increasing the rapid turnover of in-channel vegetation (50% persist for less than 5 – 6 years as observed by Surian et al., 2014). For this reason the Tagliamento River features an high LW recruitment of younger and freshly plant with a diameter slightly smaller than Brenta and Piave rivers.

In a relatively unimpacted fluvial system (as the Tagliamento River could be considered), with natural flood disturbances and hydrological regime, large wood appears to be relatively smaller, freshly recruited, and with broken branches (i.e. actively transported during floods) and deposited in all morphological units, including low bars. Logs are in a better state of conservation, and their higher capacity to resprouts results in a higher number of pioneering islands. The relatively young in-channel vegetation in the Tagliamento River (Surian et al., 2014) and scarce capacity of islands to remain stable for more than 24 years (Zanoni et al., 2008) further reinforce the evidence that recruited logs are smaller and that wood is highly dynamic in this low-impacted river. On the contrary, logs in more impacted rivers (i.e. Brenta and Piave) are bigger, suggesting recruitment from floodplains and established islands during infrequent high-magnitude floods, and feature a worst state of decay.

If compared with the Tagliamento, the higher amount of wood measured in the Brenta River seems to be due to the amount of very big logs in bad conservation state, stranded in very high bars, thus eroded from established islands and floodplains during very high-magnitude/low-recurrence events of the past.

4.1.4 RFID tags and GPS trackers recovery rates

During the study period, which featured one near-bankfull and few lower magnitude flood events, 25 over 155 tagged logs (113 RFID and 42 GPS) were entrained and transported. Recovery rate of transported logs is very similar for GPS trackers than for RFID tags, being 42 and 43%, respectively, due to the fact that the recovery of GPS trackers was dependent on the RFID tag placed in the same box with the GPS tracker. These recovery rates are only slightly higher than what could be obtained using other LW tagging techniques (MacVicar et al., 2009). MacVicar et al. (2009) first used 51 RFID for LW tracking in the Ain River (France) using a fixed antenna. The system proved very promising, albeit certain issues could be experienced during flood events, when transported logs are likely to be at least partially submerged, and RFID signals are absorbed by water. Schenk et al. (2013) inserted 290 RFID tags in the Roanoke River (USA) and used both fixed and mobile antennas for surveying the transport of tagged logs up to 100 km, reporting a recovery rate slightly lower than 40%. Great novelty in this kind of studies was carried out by using GPS trackers, in fact no attempts have been previously made to use GPS trackers for quantifying log transport. Because the devices used in this study are collecting position data inside the device, recruitment rate is obviously dependent on the RFID installed in the same log. However, GPS allows following overtime the transport of a single log, in a manner that could not be achieved by any other devices tested in the field. In fact, it allows to measure log movements overnight, where fixed cameras can experience serious difficulties as recently reported by MacVicar and Piégay (2012) and Bertoldi et al. (2013). Similar devices have been successfully used in fluvial systems to measure surface flow velocities (Stockdale et al., 2007). In order to increase the recruitment rate, logs tagged with GPS could be additionally equipped with a GSM transmitting system, able to send overtime the GPS position. An experimental use of these devices is undergoing in the Piave River (southern Italian Alps), and is proving encouraging as it warrant recruitment and the data collection overtime (Ravazzolo et al., in preparation).

4.1.5 Logs mobility and transport during flood events in the Tagliamento River

Despite the importance of log transport for the morphodynamics of river systems (e.g. Bertoldi et al., 2014), only little field evidence is available on the transport distance of logs during flood events. MacVicar and Piégay (2012) observed that logs tend to move when a certain threshold, needed to lift logs, is passed. The existence of this threshold has been confirmed in the present study. For the study reach of the Tagliamento River, this threshold has been identified as 40% of bankfull stage, and corresponds to a discharge flooding secondary channels and low bars. The amount of logs stranded in low bars is relatively high, especially near the floodplains and densely vegetated islands. In a previous research, Mao et al. (2012) conducted in 2010 field surveys of isolated and jammed logs along three cross-sections located within the study segment revealing that main, secondary channels and low bars account for up to 0.40 m^3 ha^{-1}, which corresponds to approximately 30% of the total amount of wood on the river bed. This suggests that even ordinary flood events have a potential of entraining and transporting logs. Furthermore, it has been observed in the same reach of the Tagliamento River that near-bankfull events are able to erode banks (Picco et al., 2013) and islands, recruiting relevant volumes of wood in low bars (Bertoldi et al., 2013).

GPS trackers allowed gaining a proper insight on the movements of single logs during floods. Even if direct observations are limited to movements of four logs, it is remarkable that their transport dynamics have been quite consistent. Logs were entrained during the rising limbs of hydrographs, and were deposited on bars at or shortly after the peak of the floods. This is consistent with observations of Bertoldi et al. (2013) who observed log transport in the Cornino field site using a fixed camera. The fact that logs stopped right at the peak of floods, is likely related to the morphological conditions of the Tagliamento River, which is a wide and very dynamic multi-thread river. The main channel tends to switch position quite frequently (e.g. Welber et al., 2012; Picco et al., 2013), and logs are not necessarily transported along the thalweg as observed in the Ain River by MacVicar and Piégay (2012) and in flume experiments by Braudrick and Grant (2001). Instead, logs are transported above the bars as suggested by the travelling paths revealed by the GPS trackers (Fig. 72).

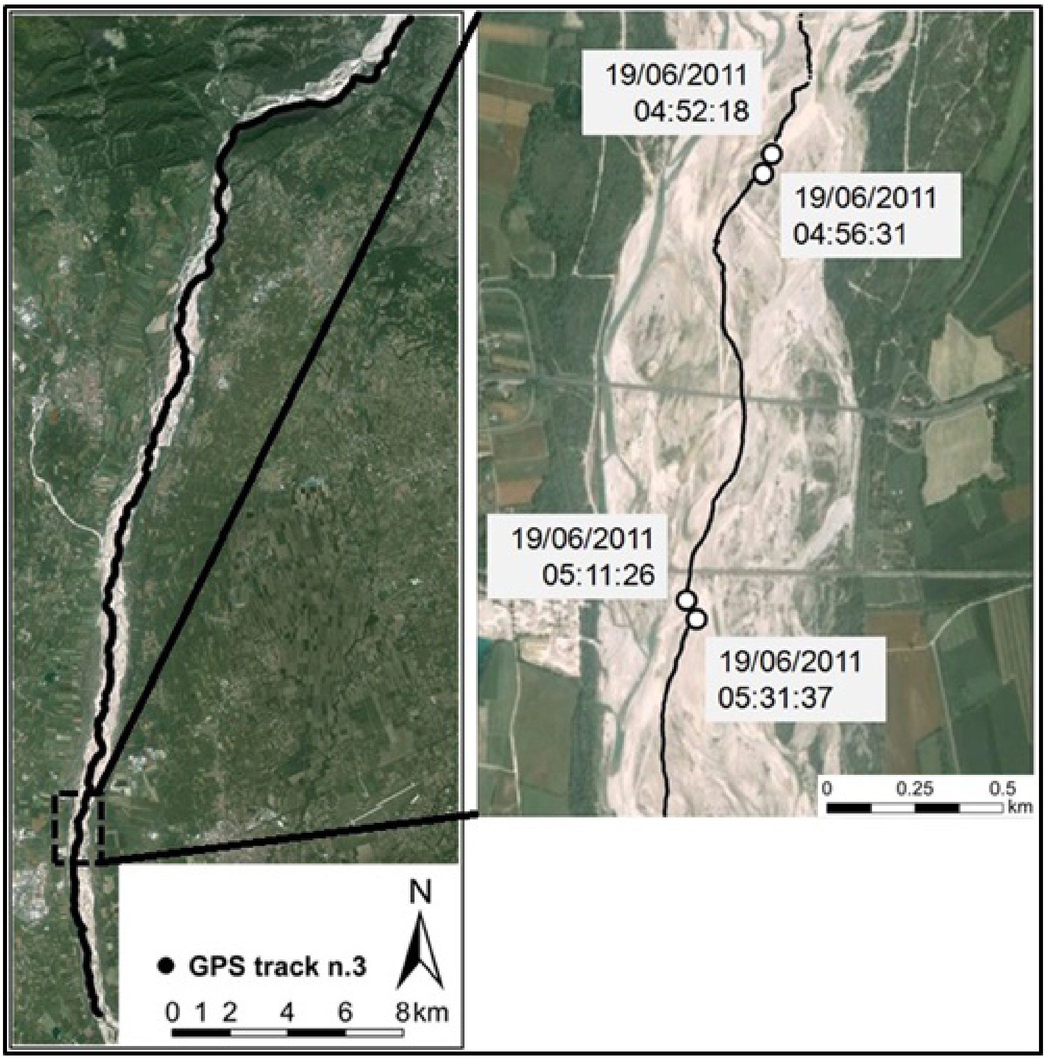

Figure 72: *Example of a travelled path followed by a log equipped with a GPS tracker device.*

As soon as discharge begins to reduce, the logs have much more chances of being deposited in a bar. In fact, braided river are very effective in retaining logs, as recently showed by Bertoldi et al. (2014) in a series of laboratory experiments involving log transport in a sand-bed braided channel. It is indeed interesting to note that 50% of transported logs (considering both RFID and GPS tagged logs) have been recovered in high bars or in pioneering islands. Bertoldi et al. (2013) suggest that up to 50% of trees recruited from lateral erosion of densely vegetated islands and floodplains in the Tagliamento tend to be trapped locally or on the bar immediately downstream. If they resprout rapidly, this can lead to the development of vegetated nucleus near floodplains and islands (Gurnell et al., 2005). However, logs which are already stranded in the active bars can actually be transported far downstream. Interestingly, half of transported logs in the Tagliamento were deposited as individuals, and half were found trapped in a wood jam. Very stable jams and pioneering islands are probably more able to trap further logs if they are transported during events of higher magnitude, which are able to flood the entire floodplain (Picco et al., 2014; Mikus et al., 2012). Ordinary events are instead more likely to entrain and transport isolated logs. Physical modelling of wood transport in braided rivers suggests that larger and thicker logs require higher discharge to be entrained and transported, if compared with smaller elements. Moreover, shorter and smaller logs tend to be transported for longer distances during flood events of comparable magnitude (Welber et al., 2013). However, in the present study we could not find any significant relationship between these variables, probably due to the relatively low and limited range of discharges that were analysed. A lack of relationship between these variables has been reported by Schenk et al. (2013) in the Roanoke River as well.

As to the relationship between the flood peak discharge and the displacement length, even if the ratio h_{max}/h_{25} performs better than the h_{max} itself, the relationship appears quite weak. An analogous weak relationship has been observed in flume experiments as well (Welber et al., 2013), and has been related to the fact that at relatively low flows, the potential deposition sites are limited, thus conditioning the displacement lengths. In the study site, the reason for this weak relationship can be ascribed to the relatively limited dataset and range of discharge. However, because GPS trackers proved that logs were deposited during the flood peaks, it is also likely that displacement length is related to the duration of rising limb of hydrographs as it is to the magnitude. The relationship between displacement length, flood magnitude and duration of rising limb is beyond the extent to which the current available data can be analysed, but would deserve future efforts to be properly explored. In fact, as also stressed by MacVicar and Piégay (2012), the shape of floods is likely to have a strong influence on wood recruitment and transport.

Because the wood balance of a certain river reach depends on the input from upstream, recruitment within the reach, output, and decay (Benda and Sias, 2003), the fluvial transport of wood into and out of the reach are important variables in the mass balance. The fluvial transport is usually derived from the mean transport distance of logs (Benda and Sias, 2003; Benda and Bigelow, 2014), but the velocity of logs could also prove useful in assessing the actual magnitude of log transport in and out a reach. Very few evidence on log velocity during floods are available, with the notable exception of MacVicar and Piégay (2012), who showed that logs move at around 2.5 - 4 m s^{-1} during a near-bankfull event, and that average velocity of logs is comparable with the surface velocity in a single thread wandering river. Because of its higher width/depth ratio, in a wide braided river as the Tagliamento, velocities during a near-bankfull event proved to be lower, ranging around 1 m s^{-1}, and this velocity was approximately half the celerity of the flood. Although preliminary, these type of evidence could help developing transport functions for logs to be introduced on wood balances.

4.1.6 Large wood, vegetation, and river morphology: preliminary evidence from the physical modelling

Flume experiments were used to study the wood transport, deposition, and remobilization in a braided system subject to varying wood input rates. The results show that there was a rapid accumulation of wood in all flume channels, with higher rates for larger input, probably due to the remarkable retention capacity of empty braided networks (Fig. 65).

The amount of logs stored in the channel at steady flow and sediment rates depends non-linearly on wood input rate. Interestingly, the volume of stored wood was relatively insensitive to input rate if the latter was low. The changes in wood dynamics obtained above the threshold of ~100 logs h^{-1} of wood input rate were mainly due to a different degree of organization of wood pieces in the channel. (Bertoldi et al., 2014).

The remobilization of wood was mainly due to bar erosion, driven by morphological changes. Rapid migration of sediment bars in the main anabranch was the main process responsible for rapid morphological change (Bertoldi, 2012), and also determined the formation and shifting of potential depositional sites where a large proportion of logs were stored (see also Bertoldi et al., 2013).

Results could be described in a conceptual model (Fig. 73), in which it is possible to see that neither wood storage volume nor wood input rate seems to affect braided channel morphology as expressed by the braiding index. Possibly this is due to the anabranch dynamics that controls wood storage and remobilization rather than the opposite. In addition, the vertical changes due to logs accumulations are too small to be depicted by scans. This is in contrast from the observation collected in a warm temperate rainforest of southeast Australia by Brooks et al. (2003). In fact, the authors observed how removal of forest vegetation lead to an increase of channel depth with a rate of lateral channel migration by up to 150-fold.

As expected, when acting alone, vegetation growing in the flume rapidly reduces the braiding index, forces the flow in narrower and deeper channels, increases the sediment accumulation in the bars with a consequent increasing of the standard deviation of the bed surface elevations.

Gurnell et al. (2005) observed in Tagliamento River that if pioneer islands survive for long enough, they are able to trap more sediment and propagules, forming large buildings islands on gravel bar surfaces. This process maintains a dynamic island-braided morphology (Bertoldi et al., 2011).

With the addition of logs in vegetated braided rivers, there was a forced formation of fewer but larger jams, which lead to scour deeper channels, eventually reducing further the braiding index. Although the increasing of in-channel logs number, the braiding index remains constant until the end of run. Cadol and Wohl (2011) reported a similar observation, ascribing to the key pieces of large wood the response for maintaining the multithread pattern of island braided channels. Large jams and vegetation also limit the lateral mobility of anabranch channels. In fact, as observed by Abbe and Montgomery (1996), wood is often effective to forming stable channels able to control stream hydraulics and the riparian-forest development. Because the anabranches channels tend to be wider, the elevation of bed surfaces feature a lower standard deviation than a vegetated flume without large wood inputs. Large jams and vegetation also limits the lateral mobility of anabranch channels.

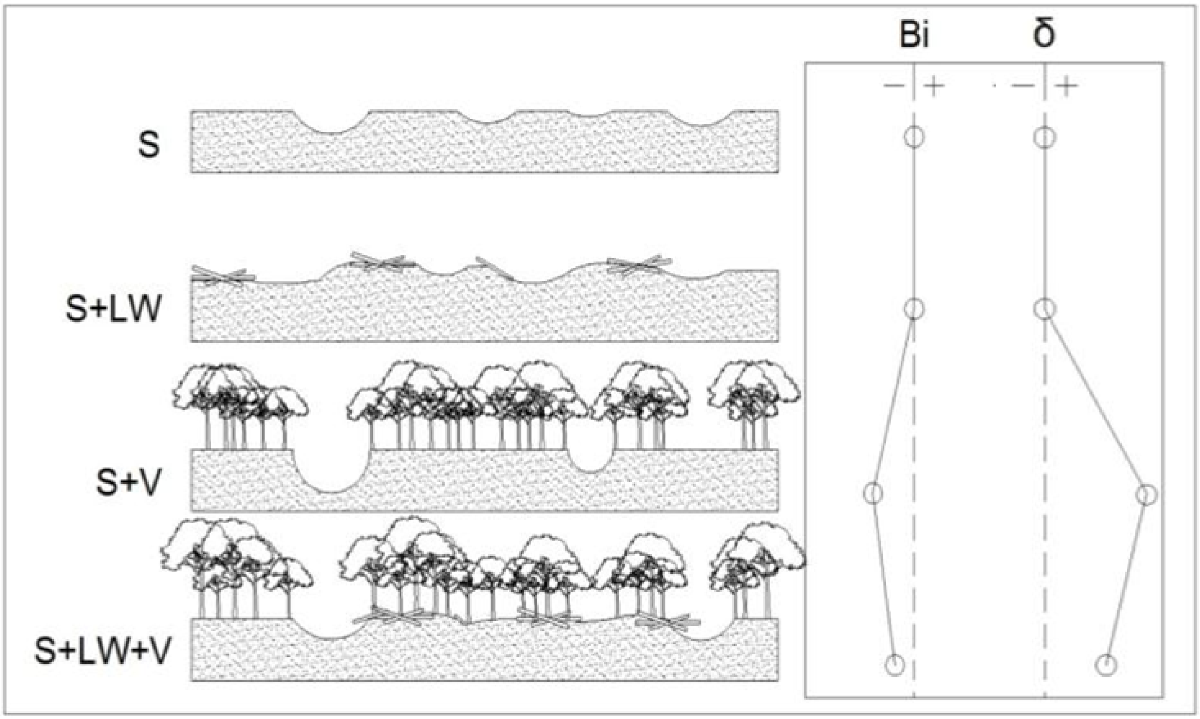

Figure 73: *Braiding index (Bi) and standard deviation (δ) of the bed of multithread rivers due to the action of large wood (S+LW), vegetation (S+V), and large wood and vegetation acting together (S+LW+V).*

4.2 Final remarks

4.2.1 Abundance and wood characteristics in Brenta, Piave and Tagliamento rivers

This study focuses on the characteristics, quantity, distribution, and geomorphic effects of in-channel wood in three gravel-bed rivers, the Brenta, Piave and Tagliamento) characterized by increasing ranges of human pressures. Evidence shown that the three rivers have comparable abundance of wood per hectare. Field observations on the origin and probable dynamic of in-channel wood suggest that in all the three rivers, wood was transported from upstream reaches. The observation was confirmed from the higher presence of wood in-channel with the rootwad facing upstream. Also the presence of broken branches and absence of leaves support this evidence. This is especially true in the Tagliamento River, where the percentage of log recruited from upstream were higher than in the Piave and Brenta rivers. Also, in the Tagliamento the logs appear to be smaller, in better state of conservation, and higher to resprout. These logs are likely recruited from islands and floodplains of a wide range of ages and by a wide range of flood magnitude. On the contrary, on the river featuring the higher disturbances at both the reach and basin scales the logs are in a worst state of conservation (suggesting the lower wood dynamic and a higher residence time of wood) probably due to more infrequent floods. In addition, it was possible to note that, irrespective on the amount of wood per ha, the Tagliamento featured higher geomorphic effects (scour and deposition of sediment around LW or WJ) of wood, especially on lower morphological units. These geomorphic interactions between wood and sediments are crucial in determining the number of potential habitat for different organisms (Abbe and Montgomery, 1996). Isolated wood and jams provide a wide variety of habitats, hydraulic refugia, as well as a food source for many organisms. For these reasons, in the river corridor there is the need to maintain an appropriate loads and dynamics of wood within river systems (Crispin et al., 1993).

This work suggest that the amount and qualitative information of in-channel large wood can provide some insight on the degree of human pressures at the basin scale, and that further comparative studies on this direction could shed further light on how human disturbances can affect large wood nature in gravel-bed rivers. For future studies, it could be worth improving the analysis of the interactions between wood pieces and accumulation, standing vegetation and the channel dynamics. In addition, the analysis of the abundance and characteristics of buried wood from floodplains and channel bed should be taken into account to the wood storage understanding, given their geomorphological and ecological interests. Understanding the many aspects of wood and geomorphology, the wood loading and distribution is crucial to the sustainable management of rivers under contemporary human pressures (Gurnell, 2013). For these reasons, these studies could be necessary for increase the knowledge to a better river management practices and river ecology application.

4.2.2 Tracking log displacement during floods in the Tagliamento River using RFID and GPS tracker devices

This study attempts to provide a better understanding on the processes of entrainment, transport, and deposition of LW during floods in a gravel-bed river in Italy. Displacement length and velocity data have been analysed using active radio frequency identification (RFID) tags and GPS devices fixed to logs lying on low, active bars. Both devices operated reasonably well, allowing a recovery rate comparable with the study of MacVicar et al. (2009). Fixed antennas, especially if multiple, could provide even better insights on log dynamics, as GPS equipped with a GSM transmitting system could as well, being able to send to a receiver the GPS position of a transported log overtime. The GPS tracker devices allow us to collect data overnight and thus could complement data collected by video cameras as used by MacVicar and Piégay (2012). In the Tagliamento River, the log entrainment is higher during the rising limb of hydrographs. Even if wood transport distance is only weakly related with flood peak stage, a better correlation has been found between transport distance and the ratio h_{max}/h_{25}. Limited movements were recorded for GPS devices, but consistent dynamics were analysed and they indicate an entrainment threshold around 40% of bankfull stage in Tagliamento River.

Field observations on location where logs were deposited suggest that pioneer islands and stable jams probably play an important role in trapping logs transported during major flood events, whereas logs are more likely to be deposited on low bars during ordinary events. However, studies of this kind should be enriched by considering the species, density, and state of conservation of wood transported with the travel distance and velocity, along with the presence and dimension of rootwad and major branches. These studies could be necessary for supporting the choice of better river management practices and river ecology application, as wood transport is a possible key process for in-channel wood redistribution playing an important role to increase the number of habitat for different organisms.

4.2.3 Physical modelling

These preliminary experiments are the first attempt to simulate the effects of vegetation and large wood simultaneously in braided river systems. The flume observations allowed to infer that wood storage and deposition patterns at near equilibrium conditions strongly depend non-linearly on upstream wood input, and large log jams formed only at the highest input rates. Log remobilization rates strongly depend on the dynamics of the braided network, which not only govern the persistence of anabranches and bars, but also the formation of potential log depositional sites. The presence of wood in unvegetated braided river is probably not the key factor to change the braided index and the standard deviation of the bed surface. The PDFs curves confirm the similarity in the surface distribution of elevations.

Otherwise, vegetation growing on the flume rapidly reduces the braiding index, and forces the flow in narrower and deeper channels, increasing the standard deviation of the bed surface elevations. On vegetated flume channels, the addition of logs forces the formation of fewer but larger jams, which further reduces the braiding index and limits the lateral mobility of anabranches. Because the anabranches channels tend to be wider, the elevations of bed surfaces feature a lower standard deviation than a vegetated flume without large wood inputs. This indicates that logs tend to reduce the tendency of channels to narrow due to vegetation encroachment within the braid belt.

Even if experimental conditions do not fully represent a specific field site (i.e. woody dowels do not resprout as most riparian plants), the present set of runs is the first successful attempt to simulate vegetation and large wood together in a flume. The results are very promising since they shed light on processes that cannot be fully observed in the field, due to the long-time scales they act over. Also, despite the simplicity of the experiments, the complex morphology that is typical of island-braided rivers appear to have been effectively reproduced (Fig. 74).

Figure 74: *Pieces of large wood stranded on a bar next to a big island in the flume (on the left) and on the Tagliamento River, in Italy (on the right).*

Chapter Five – References

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