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Temporal variations of large wood abundance and mobility in the Blanco River affected by the Chaitén volcanic eruption, southern Chile

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ABSTRACT

The aim of this study is to analyze the temporal variation in abundance and transport of in-channel wood along a river affected by a volcanic eruption, considering the mobility and retention rates in detail. The 2008 eruption of Chaitén Volcano (Southern Chile) severely affected the Blanco River basin, causing changes in channel morphology and large wood (LW) dynamics along the fluvial corridor of the river, a fourth-order stream on the southern slope of the volcano. Temporal dynamics of LW were investigated, from January 2015 until March 2016, in three 80 m-long study reaches of the active channel in the lower course of the river. Every wood element (≥ 1 m in length and ≥ 0.1 m in diameter) within the active channel of each reach was georeferenced, measured, tagged, and characterized. Wood mobility rate, defined as the number of tagged wood pieces repositioned or not found within each study reach to total tagged LW in the same reach; and retention rate, defined as the number of tagged LW pieces found within each study reach to total tagged wood pieces in the same reach, were calculated considering two periods, one in summer and one in autumn-winter. A regional flood frequency analysis estimated flood magnitude, defining a recurrence interval of ~ 1 year for summer floods, and 10–25 years for autumn-winter floods. Results highlighted how, eight years after the eruption, the types of LW are still influenced by the impacts of pyroclastic density currents on riparian vegetation. The characteristics and abundance of monitored LW are typical of a river system with frequent wood transport. The mobility rate ranges between 42 and 94% during the summer and autumn-winter period, respectively; while the wood volume decreases during the summer and increases in autumn-winter. Large wood mobility was also found to vary according to the predominant morphological settings, with lower values in narrower channels compared to wider wetted areas. In this context the greatest abundance of LW was detected after the higher floods, corresponding to an input of LW up to 285.35 $m^3 \cdot ha^{-1}$. Along the Blanco River ordinary floods deliver LW mainly through fluvial transport, and bank erosion during higher floods appears as an additional and important wood recruitment process. The bank erosion processes, with up to 5200 m^2 of eroded area, confirmed the widening tendency occurring in river systems following volcanic disturbances. As there are dead riparian trees along the easily erodible banks, it is reasonable to suppose that the Blanco River will continue to widen for a long period, recruiting and transporting downstream huge volumes of LW. In this context these analyses appear of fundamental importance to better manage the river system, also for decreasing hazards to the downstream village of Chaitén.

1. Introduction

River systems are environments characterized by high dynamicity in response to natural (i.e. floods, debris flows, forest fires, volcanic eruptions) (Lévy et al., 2012; Surian et al., 2015; Pereira et al., 2016; Ulloa et al., 2016), and human-induced disturbances (i.e. gravel mining, dam construction, embankments, afforestation) (Comiti et al., 2011; Rigon et al., 2012a; Moretto et al., 2012, 2014; Picco et al., 2012, 2016a). These disturbances can affect and change not only the morphological settings, but also riverine vegetation (Picco et al., 2014a, 2014b, 2016b; Surian et al., 2015; Sitzia et al., 2016). Among these disturbances, volcanic eruptions are catastrophic events that severely affect hydrogeomorphic processes (Pierson and Major, 2014). Tephra fall and pyroclastic density currents (PDCs) produce a series of primary disturbances such as hillslope instability, burial of tree logs and standing vegetation, heating of air temperature and abrasion of bark, generating impact forces that, in turn, induce secondary disturbances on the ecosystem (Swanson and Major, 2005; Peters et al., 2011).

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Different authors have already documented that the river catchments can be dramatically affected by volcanic eruptions (Wisner et al., 2003; Manville et al., 2005; Pierson and Major, 2014). The deposition of tephra and volcanic sediments strongly affect the river network, altering the hydrology, vegetation cover and sediment transport dynamics (Pierson et al., 2011; Korup, 2012; Major et al., 2013; Pierson and Major, 2014). As a consequence, hazards for infrastructures and damage to urbanized areas can greatly increase (Oppenheimer, 2003).

During a volcanic eruption, tephra fallout and PDCs cause an accumulation of ash over the river basin and suffocate, bury and destroy riparian and forest vegetation (Swanson et al., 2013). Consequently, the rate of damaged trees varies according to the distance from the volcano, eruption magnitude, temperature of pyroclastic flows and type of volcanic processes (Swanson et al., 2013). In areas affected by pyroclastic flow, vegetation tends to be killed, whereas it is only slightly damaged in areas with a thin deposition of tephra (Swanson et al., 2013). All these impacts have repercussions over time, with delay in growth (Siffredi et al., 2011), compromising species germination (Úbeda et al., 2011), and reducing species richness (Ghermandi and González, 2012). The deposition of volcanic sediments fills the river channels, with consequent morphological changes (i.e. incision, aggradation, widening) (Pierson et al., 2011; Pierson and Major, 2014). Incision processes cutting channels by several meters were documented as a result of El Chichón volcano, Mexico (Inbar et al., 2001), whereas alteration in the bedload transport regime by increasing sediment supply to the channel were reported after the eruptions of both Mount St. Helens, USA (Major et al., 2000) and Pinatubo, Philippines, (Hayes et al., 2002). Considering the Chaitén Volcano, which is the case here, Ulloa et al. (2015a, 2015b, 2016) analyzed morphological changes over the surrounding basins. Differently from the methodology presented here, they compared aerial images of pre and post-eruption conditions, finding, among the common disturbances, widening of river channels, removal of fluvial islands, and recruitment of huge volumes of large wood (LW).

The presence of LW in rivers is important for morphology (Gurnell et al., 2002; Andreoli et al., 2007; Wyżga and Zawiejska, 2010; Gurnell, 2015), channel hydraulics (Faustini and Jones, 2003; Comiti et al., 2008; Ravazzolo et al., 2013), and ecology (Rosenfeld and Huato, 2003; Gurnell et al., 2005; Francis et al., 2008; Pollock and Beechie, 2014). However, it can also be associated to hazards for infrastructure, inhabitants, and river recreational users (Mazzorana et al., 2009; Wohl et al., 2016). When transported downstream, logs and wood jams (WJ) can affect infrastructure, causing local scours around bridge piers, blocking culverts generating channel avulsions and overbank flooding (Moulin and Piégay, 2004; Mazzorana et al., 2009). However, as reported by Wohl et al. (2016), physical hazards related to LW depend on the volume of in-channel wood, and the likelihood of it being transported during high floods.

The abundance (Gregory et al., 1993; Gurnell et al., 2000; Iroumé et al., 2010; Ravazzolo et al., 2015a), distribution (Piégay et al., 1999; Iroumé et al., 2010; Wohl et al., 2011), and mobility (Braudrick and Grant, 2000; MacVicar and Piégay, 2012; Iroumé et al., 2015; Ravazzolo et al., 2015b; Ruiz-Villanueva et al., 2015) of wood in rivers have been widely explored. During the last years attention also focused on wood transport and its mobility using different approaches. After the traditional metallic/plastic tags (Warren and Kraft, 2008; Iroumé et al., 2015; Picco et al., 2016b), remote tracking techniques have been used such as RFID tags (Schenk et al., 2014; Ravazzolo et al., 2015b), radio transmitters (Wyżga et al., 2016), GPS tracker (Ravazzolo et al., 2015b), and video cameras (MacVicar and Piégay, 2012). Several studies were conducted on narrow mountain streams (Swanson et al., 1976; Bilby and Ward, 1989; Robison and Beschta, 1990; May and Gresswell, 2003; Mao et al., 2008; Wohl, 2011; Rigon et al., 2012b), and on medium-large piedmont rivers (Abbe and Montgomery, 1996; Piégay and Gurnell, 1997; Gurnell et al., 2000; Francis et al., 2008). Both human-impacted rivers (MacVicar and Piégay, 2012; Schenk et al., 2014; Ravazzolo et al., 2015a; Picco et al., 2017) as well as systems disturbed by natural disasters (Lisle, 1995; Jones and Daniels, 2008; King et al., 2013; Ulloa et al., 2015b) were considered.

Since the occurrence of volcanic eruptions is episodic, the analysis of LW input, its abundance and mobility in a river network altered by this disturbance, has been little investigated. The first evidence was provided by Lisle (1995), who found that the eruption of Mount St. Helens (USA) introduced large volumes of wood in rivers and that its total removal caused additional scour processes and coarsening of the bed surface.

Understanding the dynamics of wood following an eruption has important implications for post eruption river and basin management. This study explores the temporal variability in LW abundance, mobility and retention in the gravel-bed Blanco River, which was affected by the eruption of Chaitén Volcano (Chile). We focused the study on: (1) variations in the abundance of in-channel wood after different flood events able to recruit LW from banks; and (2) dynamics of wood in terms of mobility and retention rates. A better understanding of LW dynamics can support best management decisions in the Blanco River corridor, in order to reduce hazards for the nearby village of Chaitén related to the transport and deposition of wood during floods.

2. Materials and methods

2.1. The Blanco River basin and the study reaches

The study was conducted along three reaches of the Blanco River, a fourth-order system located 254 km south of Puerto Montt, southern Chile. The river flows for about 18 km from the southern slope of the Chaitén Volcano, passing through the village of Chaitén, to the Pacific Ocean (Fig. 1).

The Blanco River is directly connected to the volcano through a tributary called the Caldera Creek. The catchment area covers about 70 km^2 with elevations between 7 and 1545 m.a.s.l., with an average gradient of about 50% (Major and Lara, 2013; Pierson et al., 2013).

Soil composition of the riverbed reflects the presence of the nearby volcano and contains volcanic sediments that feature high instability, favoring creeping and landslides phenomena (Peralta, 1980).

According to the Chilean Meteorological Office, the Blanco River basin receives winter rains exceeding 3000 mm·year^{-1}, and the main floods occur during this season. Forty-three percent of the basin is covered by old growth forests with evergreen tree species, 40% by shrub forests and the remaining 16% are snowy and glacial areas located in the upper part of the basin (CONAF, 1997). The evergreen forest is mainly composed of *Nothofagus dombeyi*, *Nothofagus nitida*, and *Nothofagus betuloides* (Donoso, 1981).

The Blanco River basin was highly altered by the eruption of the Chaitén Volcano that occurred between 2008 and 2009. Preceded by minor ash emissions and a 3.5-magnitude earthquake, the eruption started on May 2, 2008 (Lara, 2009), with a first brief plinian explosive phase (~2 weeks) followed by a longer effusive phase (~18–20 months) (Pallister et al., 2013). During the explosive phase, the ash column remained up to 21 km in altitude for about seven days (Lara, 2009) resulting in 1 km^3 bulk volume of tephra (Major and Lara, 2013). More information on the Chaitén eruption can be found in Major et al. (2013) and Pallister et al. (2013). The effects of the volcanic eruption on the Blanco River basin have been documented on river bed morphology (Pierson et al., 2013), forest vegetation (Major et al., 2013; Swanson et al., 2013), and LW dynamics (Ulloa et al., 2015a). The heavy rainfall recorded just after the first eruption (up to 600–900 mm in twelve days), caused pyroclastic sediment remobilizations triggering lahar floods that resulted in 7 m aggradation along the river channel (Pierson et al., 2013). Several km^2 of the lowland forested floodplain were strongly affected by the fluvial deposition of remobilized tephra, however trees were not completely charred (Major et al., 2013;

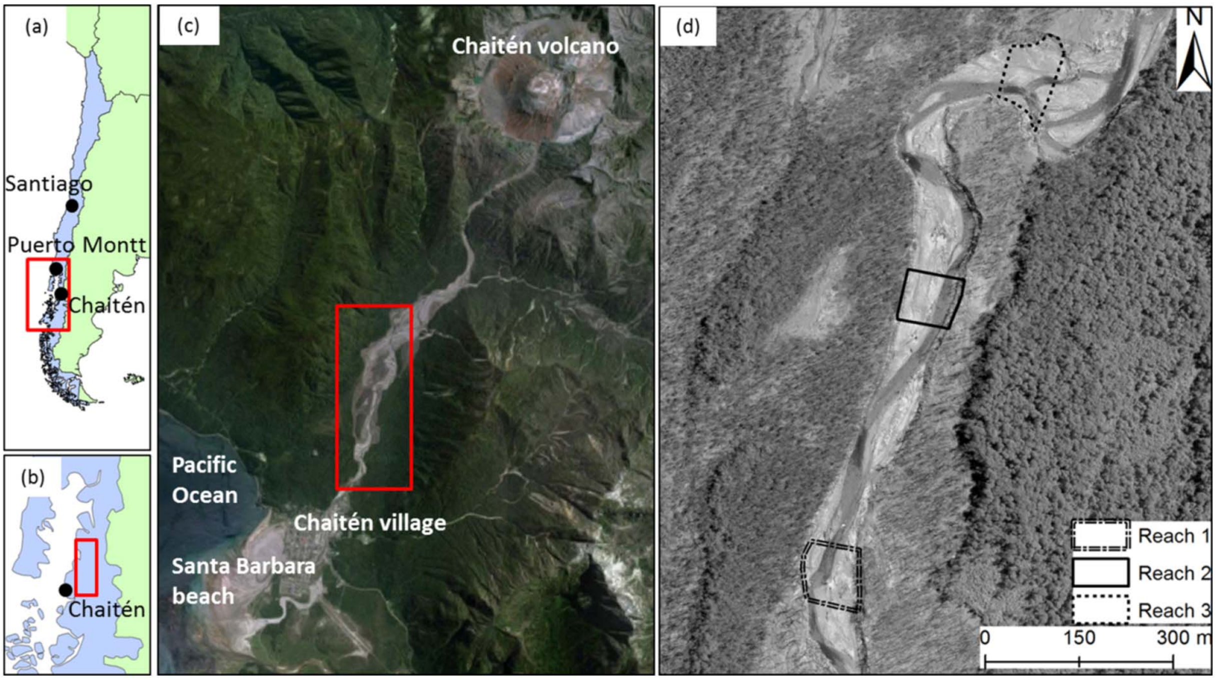

Fig. 1. location of the study area (a, b), overview of the Blanco River course (c) and location of the three study reaches (d).

Swanson et al., 2013). Another disturbance, reported by Swanson et al. (2013), was induced by the fine tephra accumulated over the tree crowns that led to breakage and bowing of old and young trees, respectively. Volcanic disturbances have also affected the dynamics of LW in the Blanco River, destroying the riparian forest and increasing the recruitment rate of trees that caused a dramatic variation of LW abundance. As already reported by Ulloa et al. (2015a), in pre-eruption conditions, the river had a mean active channel width of 36 m and the presence of wood was quite negligible, only 16 LW and no WJ were present. Instead, immediately after the eruption the active channel presented a mean width of 107 m and wood abundance increased up to 756 LW and 302 WJ (Ulloa et al., 2015a).

The analyses were conducted on three reaches within a 1.3 km-long stretch of the lower part of the river course (Figs. 1d, 2). Moving from downstream, reaches were identified as reach 1, reach 2, and reach 3. The reaches were surveyed in January and March 2015 (J15 and M15), and in January and March 2016 (J16 and M16) (Table 1).

Because of the considerable amount of in-channel wood, the reach length considered was 80 m, extending 40 m upstream and downstream of a cross section (following, among others, Gurnell et al., 2000 and Ravazzolo et al., 2015a). The selection of study reaches targeted different morphologies of the lower Blanco River and were identified based on aerial images. The downstream reach 1 has a main channel

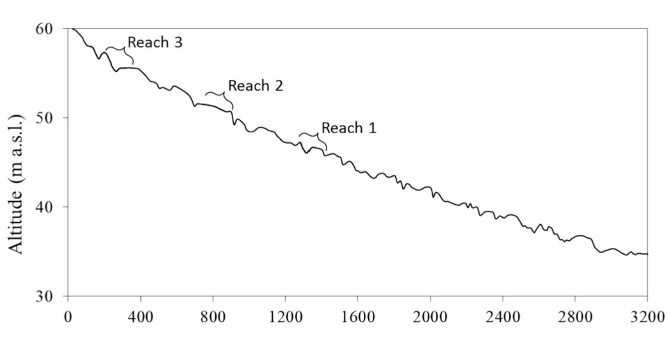

Fig. 2. longitudinal profile of the Blanco River (corresponding to the stretch marked in Fig. 1c) and location of the three study reaches.

and two secondary dry channels that are rapidly activated during the rising phase of floods, while the intermediate reach 2 is a single channel reach with a pronounced high gravel bar. Lastly, the upstream reach 3 is a single-thread channel in which the main channel flows into a well-pronounced bend. The relative elevation above the thalweg of the selected reaches, increases from 0.78 to 1.04 and 1.90 m of reach 1, 2 and 3, respectively.

2.2. Field surveys

For each survey, a cross section was measured using a Differential Global Positioning System (DGPS) (horizontal precision ± 4 cm, vertical precision ± 7 cm). Cross sections were measured in order to calculate the active channel width and to identify the different morphological units analysing their relative elevation above the thalweg. Within each of the 80-m long reaches all wood pieces > 10 cm in diameter and 1 m in length (Swanson and Lienkaemper, 1978; Mao et al., 2008; Morris et al., 2010; Wohl et al., 2010) were measured, using a measuring tape and a tree caliper. According to Iroumé et al. (2010), the measurements precision is 1 cm for diameter and 5 cm for length. When roots were detected, the length was considered as the direct distance between the top of the log and the bottom of the roots. Only LW pieces lying in the active channel and those along the riverbanks were considered (Andreoli et al., 2007; Iroumé et al., 2010; Iroumé et al., 2015). Each LW was classified according to the type of aggregation, as a single element or log forming a jam. A wood jam (WJ) was defined by the presence of at least two logs in contact with each other (Comiti et al., 2006). Following Andreoli et al. (2007), LW volume was calculated assuming the solid cylindrical shape from the mid-diameter and length. The volume of WJ was calculated by measuring all the visible and accessible logs within the jam (Wohl and Cadol, 2011; Ravazzolo et al., 2015a). Although this method may lead to an underestimation of WJ volumes, only a few elements were neglected. In fact, in the study reaches LW were characterized by quite large sizes, the mean diameter and length being 0.25 and 3.75 m, respectively. In addition, for each LW a series of qualitative characteristics were collected such as type (log, tree, branch, root), orientation to the flow (parallel, orthogonal, oblique), and delivery mechanism (floating transport from upstream, lateral bank erosion, harvested

Table 1
Date of field surveys and characteristics of the reaches during each survey.

Survey[a]	Reach 1			Reach 2			Reach 3	
	January 2015 (J15)	March 2015 (M15)	January 2016 (J16)	January 2015 (J15)	March 2015 (M15)	January 2016 (J16)	March 2015 (M15)	March 2016 (M16)
Width (m)	94	94	94	80	80	137	108	108
Area (m^2)	7940	7940	7940	7500	7500	12,685	8941	8941

[a] In brackets are the codes assigned to each survey.

residue). The delivery mechanism was identified on the basis of field evidence: logs having a rounded and smooth shape, and lacking of branches were identified as floating pieces. Instead, wood elements recruited from bank erosion were identified as those elements fallen in the active channel but still anchored to the riverbanks or partially buried under bank sediment deposits. Lastly, elements with chainsaw signs were classified as harvested residues.

In order to quantify the mobility rate, a numbered metal tag was attached to each wood element, moreover each single log and WJ were GPS positioned. In addition, colored paint and identification numbers were used to mark bigger logs for faster identification and recovery during subsequent surveys.

During each post-event survey, wood logs that were not found in their previous position or within the reach were considered as an output, whereas new elements without tags were classified as an input. Every input element was measured, classified, GPS positioned, and tagged, whereas already present LW were just GPS positioned again to detect potential transport along the reach.

By means of the numbered tags, a downstream search for moved pieces was conducted starting from downstream of reach 3 until the river delta (~5 km). For each recovered LW, the new position was recorded and traveled distance was measured as the trajectory along the thalweg between starting and ending points.

2.3. Data analyses

The LW mobility and retention rates were calculated for each reach and each study period. The mobility rate is defined as the ratio between the number of tagged elements repositioned or not found within the reach and the number of total tagged LW of the same reach, whereas the retention rate is expressed as the ratio between the number of tagged LW pieces found within the reach to total tagged wood pieces in the same reach (Iroumé et al., 2015; Ruiz-Villanueva et al., 2015). For reach 1 and reach 2 two study periods were considered, summer (J15-M15) and autumn-winter (M15-J16). Whereas for reach 3 just one study period (J15-J16) was considered.

In order to analyze the differences among LW sizes, the distributions of LW diameter and length were tested for normality using the *t*-test, as already done by Iroumé et al., 2015. Given that the distribution of these variables (LW diameter and length) was not normally distributed, a Kruskal-Wallis test was used to assess their differences across surveys. Linear regressions were used to examine possible relationships between wood abundance and mean active channel width and between LW mobility rate and a series of LW characteristics (mean diameter and length of transported logs, mean volume per transported log, abundance normalized per active channel area), and the mean active channel width. Kruskal-Wallis was used to test statistical differences of LW mobility between study reaches and periods. Regressions and differences were considered statistically significant if p value < 0.05. Statistical analyses were performed using Statistica Statsoft® and Statgraphics® Centurion XV software packages.

2.4. Flood events and recurrence interval

Prior to being damaged by a flood in April 2015, a water level gauging station was located downstream of reach 1. Thus, since there was a lack of hydrological measurements after the flood, the flood magnitude was calculated using data from three gauging stations located in the area surrounding Blanco River basin. From 26 years data of Grande River (113 km from Blanco River basin) and Vilcun River (128 km), and 17 years data of Palena River (116 km), a Gumbel flood frequency analysis was performed on the two highest discharge peaks for each year using the Hydrognomon 4.1.0.26 software.

The recurrence interval (R.I.) was estimated to be ~1 year for summer floods (J15-M15) and 10–25 year for floods occurring during the autumn-winter period (M15-J16 and J15-J16). There were no relevant floods during the summer season of 2016. During the autumn-winter rainy months several events were recorded by the surrounding stations, with the highest peaks from April to July (Fig. 3). Concerning the similarity of the precipitation recorded in the Blanco River basin with the other three basins, it is reasonable to assume that also along the Blanco River the highest events occurred starting in April.

3. Results

3.1. Characteristics and abundance of LW

Within reach 1 a total of 324, 254, and 1035 in-channel LW were measured during the surveys, with an abundance normalized by the active channel extension equal to 408, 320 and 1195 elements per hectare (hereinafter N ha^{-1}), respectively (Table 2).

Overall, the number of LW found as single elements varied between 4.4% (46 N) and 15.7% (51 N), whereas the number of LW found in accumulations varied from 84.3% (273 N) to 95.6% (989 N). The LW dimensions are between 0.24 m and 0.27 m for mean diameter, and between 3.38 m and 4.80 m for mean length. The Kruskal-Wallis test revealed a significant difference ($p < 0.05$) for length and diameter during these surveys. The analysis of LW characteristics did not show relevant differences in LW type, origin or orientation among each

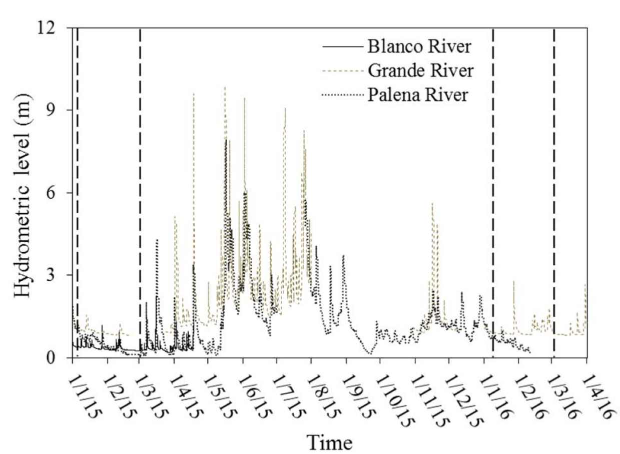

Fig. 3. hydrometric level measured during 2015 in the Blanco, Grande and Palena rivers. The end of the Blanco River recorded data corresponds to the destruction of the gauging station because of bank erosion. Vertical dashed lines indicate the dates of the surveys.

Table 2
LW abundance and sizes for the three analyzed reaches during each field survey.

	Reach 1			Reach 2			Reach 3	
Survey	J15	M15	J16	J15	M15	J16	M15	M16
N° LW	324	254	1035	334	201	709	192	847
N° LW·ha^{-1}	408	320	1195	445	268	559	214	779
% single	15.7	5.5	4.4	8.7	14.4	13.1	8.9	15.9
% in jam	84.3	94.5	95.6	91.3	85.6	86.9	91.1	84.1
N° jams	20	17	23	27	24	49	4	44
Range and mean diameter (m)	0.1–0.88 (0.24)	0.1–0.88 (0.27)	0.1–1.5 (0.25)	0.1–0.8 (0.25)	0.1–0.75 (0.26)	0.1–1.1 (0.24)	0.1–1 (0.24)	0.1–1.15 (0.24)
Range and mean length (m)	1–22 (4.20)	1–22 (4.80)	1–21.8 (3.38)	1–24 (3.36)	1–16.8 (3.27)	1–15.6 (2.94)	1.2–23 (4.77)	1–27.9 (3.16)

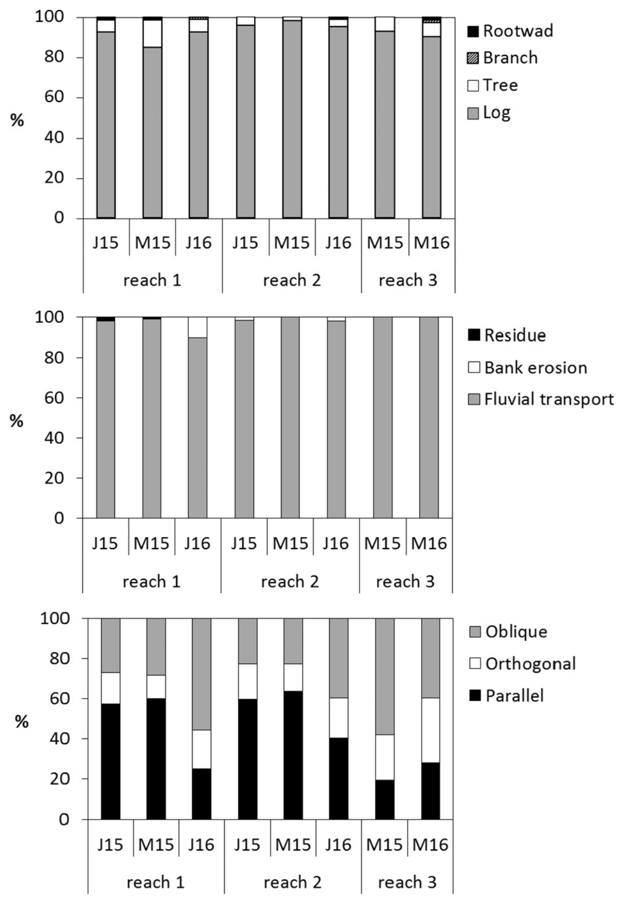

Fig. 4. overview of the main LW characteristics (type, origin, orientation to stream flow) according to each reach and the corresponding survey.

survey period (Fig. 4). > 84% of LW were logs and > 90% were probably delivered through fluvial transport. Large Wood pieces coming from the lateral zone through bank erosion or natural mortality were found just during the third survey with an amount equal to 9.8%. Considering the orientation in respect to flow direction, the LW was mainly oriented parallel during J15 and M15 (~60%) and oblique during J16 (~55%).

In reach 2 the total number of measured LW during the three surveys was 334, 201, and 709 elements, respectively, corresponding to 445, 268, and 559 N ha^{-1}, respectively (Table 2). In each survey, > 85% of LW was found in WJ, whereas the presence of single elements was lower and ranged between 8.7% (29 N) and 14.4% (29 N). According to the statistical analysis, the LW diameter and length were only significantly different between J15 and J16 ($p < 0.05$). The mean value ranged from 0.24 m to 0.26 m for the mean diameter and between 2.94 m and 3.36 m for the mean length. In every survey, LW was almost entirely represented by logs (> 95%), with a very few trees, and > 97% of them were classified as woody elements coming through fluvial transport. The LW orientation in the channel appeared to be very similar between J15 and M15 with about 60% of pieces lying parallel to the stream flow, whereas during J16 about 40% was oriented parallel, and another 40% oblique (Fig. 4).

In the most upstream reach 3, the abundance of LW ranged between 192 (214 N ha^{-1}) and 847 (779 N ha^{-1}) elements. Comparing the state of aggregation of LW during the two surveys, an increase in single elements (80%) and a decrease (7.8%) in jammed pieces were observed. A significant difference ($p < 0.05$) in LW length was observed during the two surveys, changing from 3.16 m to 4.77 m, whereas the mean diameter remained equal to 0.24 m during both surveys. The type of LW was always > 90% logs, and all the woody pieces were transported. Unlike in the other reaches, LW was mainly oriented obliquely to the flow direction (58.1% and 39.8% in M15 and M16, respectively) with a minor amount oriented parallel (Fig. 4).

3.2. Retention rates and temporal variations of LW volume

During J15, 122.1 m^3·ha^{-1} was stored within the most downstream reach 1. Considering the period J15-M15, reach 1 showed a retention rate of 36%, retaining 71.6 m^3·ha^{-1}, and losing 50.4 m^3·ha^{-1}. During M15, a total of 138 new woody elements were transported from upstream, accounting for a supply of 48.6 m^3·ha^{-1} (Fig. 5). All the new elements were deposited on a gravel bar located on the left side of the channel, forming 5 new WJ with a number of pieces ranging from 2 to 72 N·jam^{-1}. Dimensions of incoming pieces are illustrated in Fig. 6. As the volume of exported LW was slightly higher than the imported, there was a low decrease (1.5%) in the total amount of in-channel volume, equal to 120.3 m^3·ha^{-1} (Table 3). If the period M15-J16 is considered, the retention rate decreased to 27.9%, losing 681.1 m^3·ha^{-1} and retaining 39.2 m^3·ha^{-1}. However, a considerable amount of wood was introduced into the reach increasing the volume of stored LW by about 162.7% (316 m^3·ha^{-1}) (Table 3; Fig. 5). More specifically, 964 elements were transported generating an input of

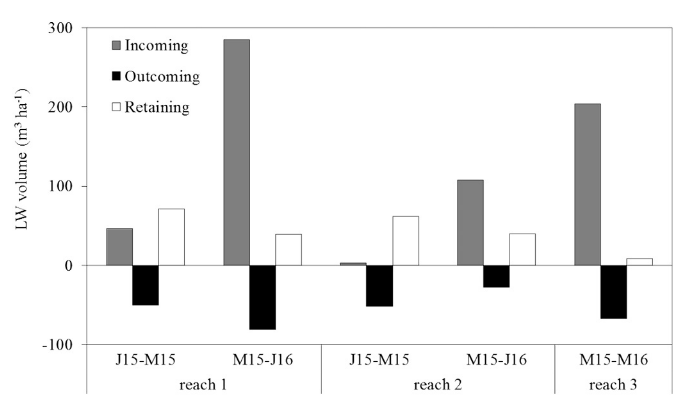

Fig. 5. amount of incoming, outcoming and retaining LW volume in the different reaches and periods.

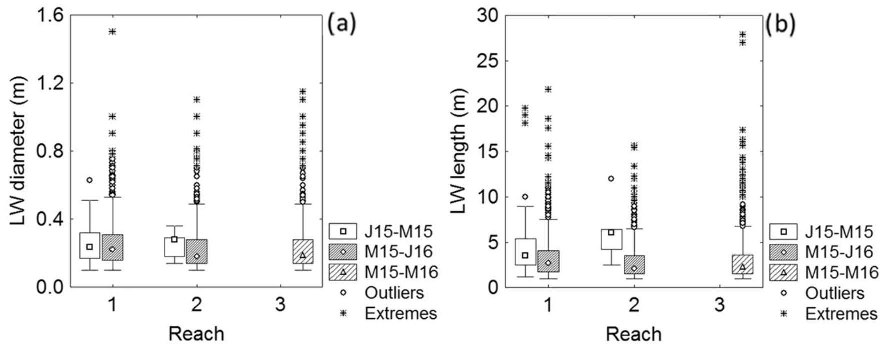

Fig. 6. range of diameter (a) and length (b) of incoming LW in the different reaches and periods.

Table 3
Amount of in-channel LW volume and variations between two successive surveys for each study reach.

Reach	LW volume ($m^3 \cdot ha^{-1}$)				Variation %		
	J15	M15	J16	M16	J15-M15	M15-J16	J15-J16
1	122.1	120.3	316.0	–	− 1.5	+ 162.7	–
2	114.1	64.4	131.6	–	− 43.5	+ 104.3	–
3	–	75.4	–	210.3	–	–	+ 179.5

about 285.3 $m^3 \cdot ha^{-1}$. Few pieces (4.5%; 44 N) were deposited as single log while the majority (95.4%, 920 N) were deposited in WJ.

The analyses of reach 2 revealed a different pattern in the temporal variations of LW volume. Despite the higher retention rate (58%) in summer (J15-M15), during the two surveys the wood volume decreased by 43.5%, from 114.1 $m^3 \cdot ha^{-1}$ to 64.4 $m^3 \cdot ha^{-1}$ (Table 3). This was due to the quite negligible LW input with respect to output (Fig. 5). In fact, the wood input was only 6 pieces for a total amount of 2.5 $m^3 \cdot ha^{-1}$, whereas 52.2 $m^3 \cdot ha^{-1}$ were transported downstream. Instead, during the winter season (M15-J16) the retention rate decreased to 46%, retaining 39.8 $m^3 \cdot ha^{-1}$ and losing 28.2 $m^3 \cdot ha^{-1}$. Similar to what was found for reach 1, also in this case the high input produced an increase (104.3%) of LW.

The lowest retention rate (6%), was recorded in reach 3 (Fig. 5). Here, around 89% of previously stored wood (75.4 $m^3 \cdot ha^{-1}$) was transported downstream during the period M15-M16. However, as for reach 1, the huge quantity of LW transported from upstream (204.1 $m^3 \cdot ha^{-1}$) increased the in-channel volume by 179.5% (Table 3).

3.3. Large wood mobilization

If just the period J15-M15 is considered, the number of transported logs was 208 and 139 pieces in reach 1 and reach 2, respectively. Instead, if all the study periods are considered, the amount of transported wood was 391, 247, and 181 pieces in reach 1, reach 2 and reach 3, respectively (Table 4). The LW mobility rate showed variability (range of 42 to 94%) among different reaches and periods. The higher percentage of wood mobility was found for reach 3 during the 1-year long period (M15-M16) and corresponded to 94% (Table 4).

For each reach, more than the 40 and 60% of transported LW were ≤ 0.2 m and ≤ 4 m in diameter and length, respectively (Fig. 7). The mean diameter of the transported LW ranged between 0.21 m and 0.25 m, while the length ranged between 2.77 m and 4.81 m (Table 4). The biggest element transported downstream was 15.2 m in length, and had a diameter of 0.7 m (5.8 m^3); it was found in r_1 and had been transported during the M15-J16 period.

No significant relationships ($p > 0.05$) were found among the mobility rate and a series of features (mean diameter and length, mean volume, abundance per active channel area unit), as well as among the mean active channel widths.

Table 4
Mobility rates and dimensions of transported LW pieces in the different reaches and periods.

	Reach 1		Reach 2		Reach 3
Period	J15–M15	M15–J16	J15–M15	M15–J16	J15–J16
Transported pieces (N)	208	183	139	108	181
Mobility rate (%)	64	72	42	54	94
Range and mean diameter of transported pieces (m)	0.1–0.75 (0.21)	0.1–0.60 (0.25)	0.1–0.8 (0.25)	0.1–0.63 (0.25)	0.1–1 (0.24)
Range and mean length of transported pieces (m)	1–15.2 (3.49)	1–22 (4.81)	1–24 (3.61)	1–12 (2.77)	1.2–23 (4.59)

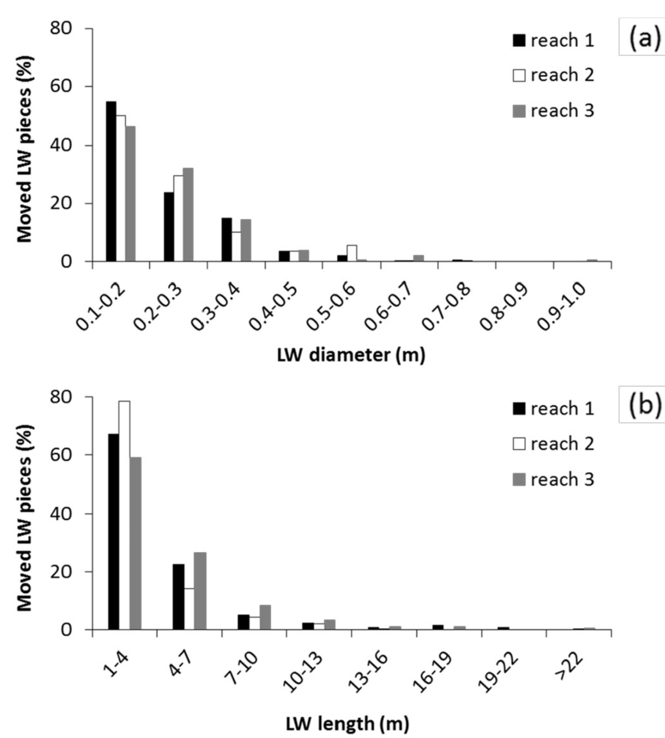

Fig. 7. percentage of moved pieces for different diameter (a) and length (b) in the three study reaches.

The comparison between sizes of mobilized and non-mobilized elements was performed considering the LW mobilization during lower (Fig. 8a,b) and higher (Fig. 8c,d) events separately. The analysis revealed that the median sizes of mobilized LW were smaller than

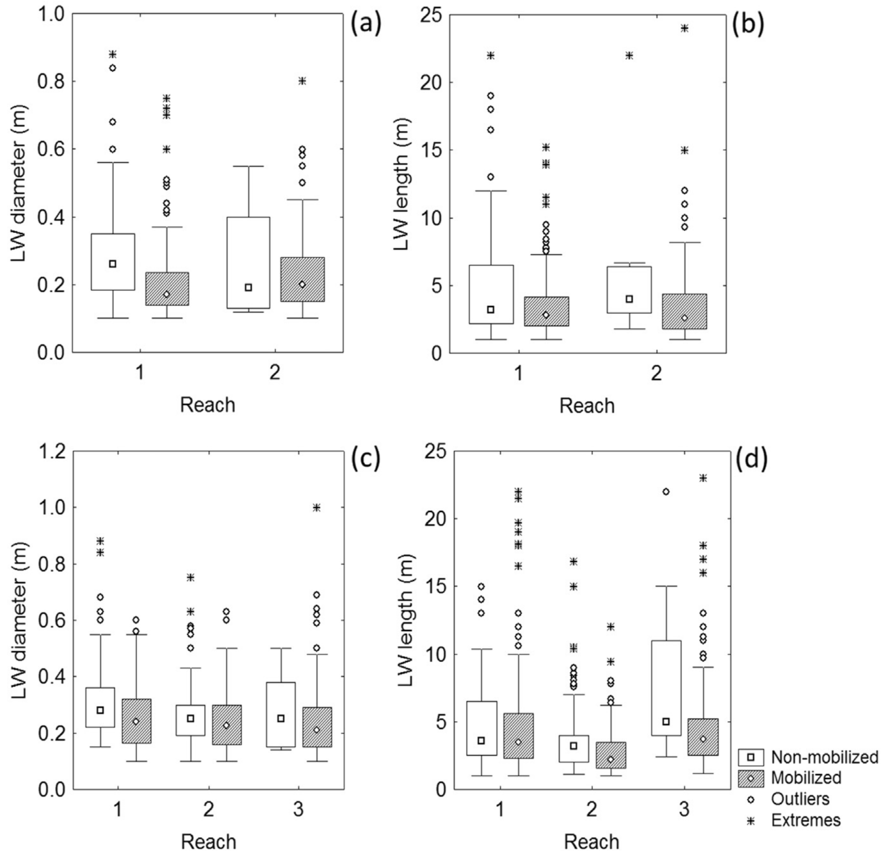

Fig. 8. range of diameter and length of non-mobilized and mobilized LW during the summer period (J15-M15) (a,b) and the autumn-winter period (M15-J16 and M15-M16) (c,d).

those non-mobilized, except for reach 2 during the period J15-M15 in which the median of mobilized elements (0.2 m) was slightly larger than those non-mobilized (0.19 m). Differences are more evident considering the mobilization during large floods. In these cases, the sizes of mobilized LW were more variable, with larger dimensions of mobilized pieces than non-mobilized ones.

Considering the in-channel position of transported wood as the limit of the flooded area, it was possible to identify the presumed maximum water level reached by the floods during the surveyed periods. The study reaches showed differences in the active channel width affected by floods. The lowest percentage of active channel inundated by floods (43%) was found for reach 2 during J15-M15. In this case, the LW mobility was concentrated just along the left side of the active channel (Fig. 9a), transporting only woody pieces that were located 5–25 m from the thalweg (Fig. 10). Instead, during the same period, in reach 1 there was mobility over 70% of its active width (Fig. 9b) and LW was transported up to 75 m from the thalweg (Fig. 10).

In the M15-J16 period, LW transport happened over the entire width of reach 1, and almost the total width (85%) of reach 2, suggesting higher discharge. Within reach 3, given the absence of LW along the right bank, it was not possible to identify the maximum water stage reached during the M15-M16 period. However, the LW transport happened over the total width of the active channel storing LW, moving pieces 65 m from the thalweg (Fig. 10).

The higher magnitude of flood events during the M15-J16 period is also supported by lateral erosion that occurred along the total length of reach 2. In particular, the eroded area was calculated to be about 5200 m^2 (Fig. 11b).

Considering the position of moved pieces in respect to the distance from the thalweg, a different LW mobilization was observed. The differences were significant among reaches (Kruskall-Wallis test, $p < 0.05$), but not among floods. Of the total 819 wood pieces transported between January 2015 and March 2016, just 1.1% (9 N) was recovered along the ~5 km-length downstream from reach 3, until the river delta. Considering the recovered pieces, the traveled distance ranged between 77 and 927 m. The most downstream piece was found 1430 m from the downstream end of reach 1 (Fig. 12).

4. Discussion

The types of woody pieces in the Blanco River reflect the effects of volcanic eruption on the surrounding riparian vegetation. In fact, the analyzed LW was almost entirely logs with very few trees and roots. This can be related to the impact of PDCs on riverine vegetation. These results are in agreement with Swanson et al. (2013) and Major et al. (2013); these authors found that the PDCs produced by the eruption damaged the forested area, breaking branches and snapping tree trunks (Fig. 13). Most of the affected trees were felled at the level of volcanic deposit thickness (Major et al., 2013), leaving the lower part of the trunk dead and the root system buried under up to 7 m of ash.

Almost all of the LW measured were classified as transported by the floods, suggesting that along the Blanco River there is a consistent transport also during not extraordinary flood events. The prevailing orientation parallel to the flow direction corroborates the hypothesis on the predominant LW origin. In fact, as reported by Nakamura and Swanson (1994) and Francis et al. (2008), floated logs tend to be deposited with this orientation.

Although channel width has been described as a variable able to significantly influence the abundance of LW (Iroumé et al., 2011; Ruiz-Villanueva et al., 2015; Wyżga et al., 2015), in the case of the Blanco River no significant relationships were found between the abundance of wood and its mean channel width, probably because of the very smaller log length compared to the channel width. Instead, the LW dynamics appeared to be subject to spatial and temporal changes. In fact, as

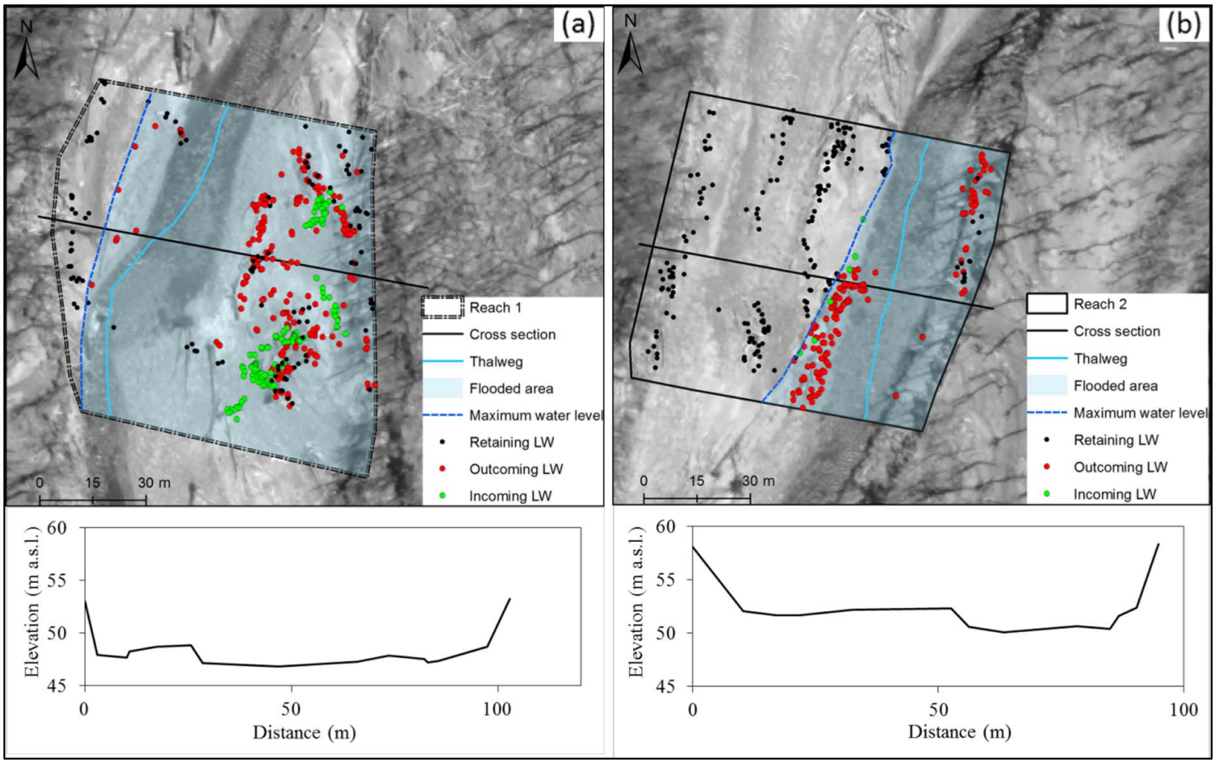

Fig. 9. position of retaining, outcoming and incoming LW within the reach 1 (a) and reach 2 (b) during the summer period J15-M15 and the relative cross section. The dashed blue line indicates the presumed maximum water level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

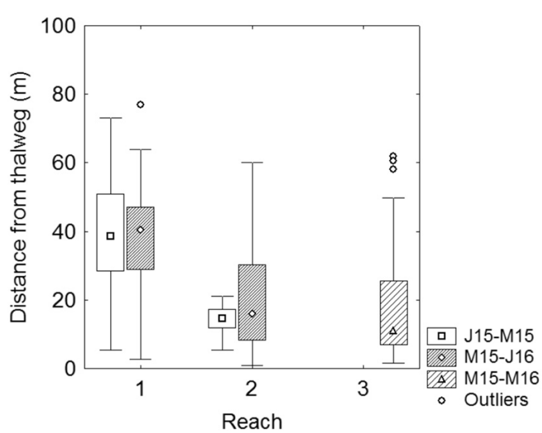

Fig. 10. distance from the thalweg of moved pieces in reach 1, 2 and 3 according the three analyzed periods.

demonstrated by the presented results, also during a short time period there was a considerable transport of LW. During this short period (a couple of months), there were major changes in the abundance and mobility of in-channel LW due to seasonal fluctuations induced by both ordinary and large floods. This increase in knowledge may also help to better define the management of LW and, potentially, the assessment of actions that reduces risk. During the summer period (J15-M15), there was a consistent reduction of LW, particularly along reach 2, while the LW volume increased during the autumn-winter (M15-J16). This result can be associated to the strong differences in the seasonality of the hydrological conditions recorded. According to Gurnell et al. (2000), the higher volume of stored LW can be found after major flood events. As highlighted by MacVicar and Piégay (2012), wood transport tends to increase with the discharge because of the increasing of both water depth and wetted channel area. So, increasing the wetted area an increasing amount of LW can be mobilized and transported downstream. The high-magnitude floods occurring during the autumn-winter months (R.I. 10–25 year) resulted in a larger wetted channel area able to mobilize higher wood volume. At the same time, it was observed that the larger the wetted channel area is, the bigger is the area prone to wood deposition. In fact, wood is preferentially deposited on bars during the peak and receding phase of the floods (MacVicar and Piégay, 2012; Ravazzolo et al., 2015a). Moreover, in this sense, the great availability of dead wood along all the riverbanks must be considered; particularly during high floods, when erosion of riverbanks is more likely to occur, the probability of LW recruitment is higher than during ordinary floods.

However, LW dynamics were found to change, during the same period, also among study reaches. The different retention and mobility rates found for reach 1 and reach 2 during the same summer period (J15-M15), could be explained considering the differences in the local-scale morphology. In reach 2, wood mobility was localized just near the flowing channel, probably because of the presence of an adjacent high bar that hindered the submergence of a wider part of the active channel (Fig. 9b). Instead, in reach 1 the predominant morphology appears to be more similar to a multiple thread channel, with the presence of two secondary dry channels that, increasing the discharge, can be activated causing a progressive inundation of the active channel and mobilizing more LW (Fig. 9a).

In terms of LW transport, the Blanco River has very high mobility rates, between 42 and 94%. The high dynamicity of wood in the Blanco River was already shown by Ulloa et al. (2015a), who reported a mobility rate of 78% and 48% for single logs and WJ, respectively. As the study deals with the uncommon situation of a river severely altered by a volcanic eruption, a comparison with similar studies is rather difficult. In a third-order mountain stream (Buena Esperanza) of Southern Tierra del Fuego (Argentina), Mao et al. (2008) found that after one year of ordinary floods the LW mobility was about 16%, whereas Iroumé et al. (2015) reported annual mobility rates up to 28% for three-order mountain streams (Pichún, El Toro, Tres Arroyos and Vuelta de Zorra in Chile). A similar mobility rate, of about 26%, was reported by Warren and Kraft (2008) during four years of surveys along

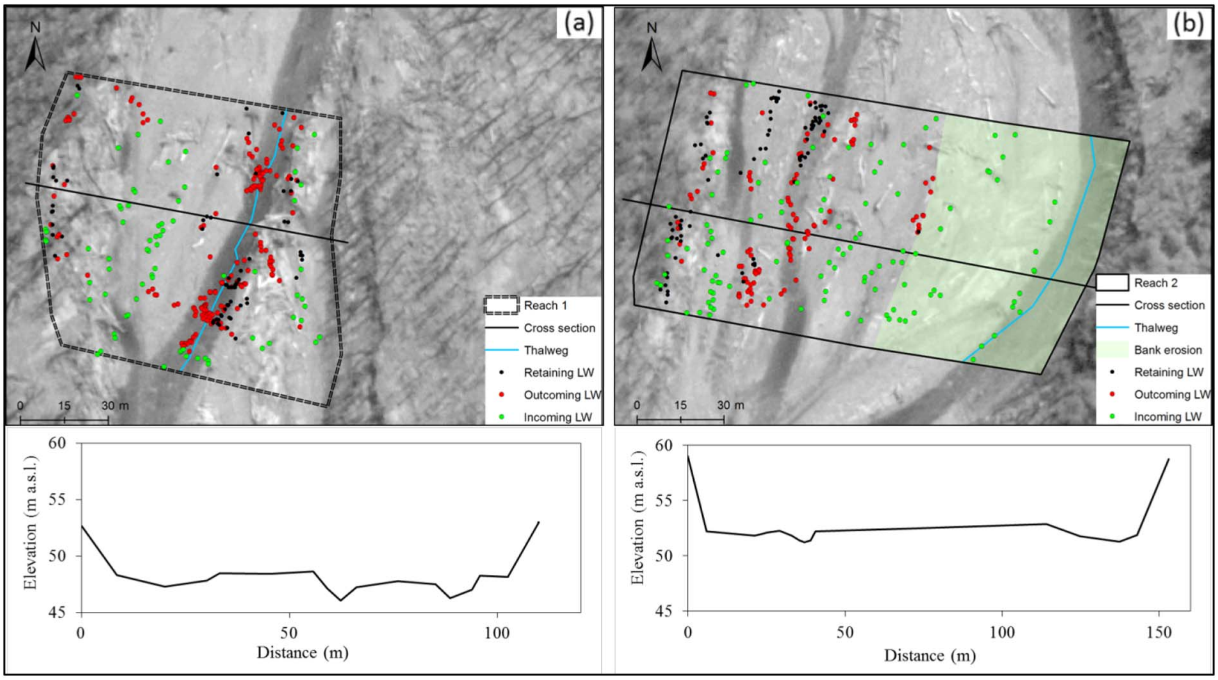

Fig. 11. position of retaining, outcoming and incoming LW within reach 1 (a) and reach 2 (b) during the autumn-winter period M15-J16 and the relative cross section. Area affected by bank erosion in reach 2 is also shown.

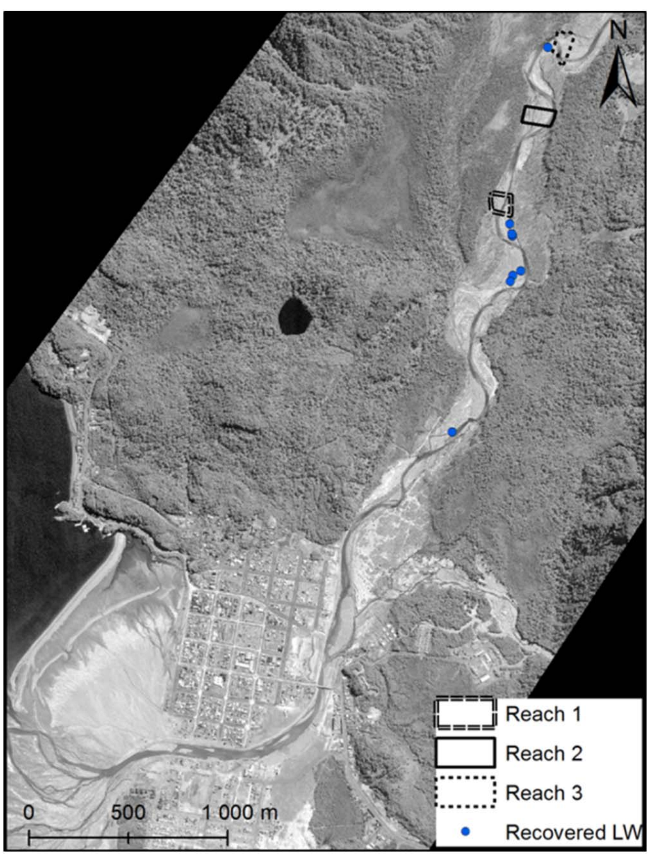

Fig. 12. position of recovered tagged pieces within the surveyed study stretch.

Fig. 13. photograph showing standing broken trees as a results of PDCs effects along the fluvial corridor of Blanco River (photo provided by H. Ulloa, January 2010).

a second-order stream (Rocky Branch, U.S.A.). Cadol and Wohl (2010), for the headwater streams of La Selva Biological Station (Costa Rica), found a wood mobility between 8% and 59%, while Schenk et al. (2014), reported a mobility rate of about 41% along a low-gradient sand-bed river (Lower Roanoke River, U.S.A.) that in terms of channel width can be compared with the river studied here.

A possible explanation for the high mobility rate of the Blanco River, can be given by the characteristics and type of in-channel LW. In fact, 93% of transported pieces were logs, whereas only 7% were trees or roots. Many authors (Braudrick and Grant, 2000; Moulin and Piégay, 2004), demonstrated that this type of LW is the easiest to be transported. Furthermore, most (48.3%) mobilized pieces were oriented parallel to the flow direction, and according to Schenk et al. (2014), pieces oriented in this way are more easily transported by floods. Mobilized LW was found to be smaller than the non-mobilized elements, confirming previous findings (Gurnell, 2003; Wohl, 2011; Iroumé et al., 2015).

Moreover, LW mobility is closely connected with the size of river channel, in particular with the channel width and depth (Gurnell et al., 2002; Warren and Kraft, 2008; Cadol and Wohl, 2010). Among the channel reworking occurred following the eruption, the active channel of Blanco River widened 3.5 fold with a maximum widening of nine

Fig. 14. photograph showing removal of clogged LW at the bridge of Chaitén village during a winter flood in 2015 (photo provided by El Llanquihue newspaper, daily paper of Puerto Montt city).

times the original channel width (Ulloa et al., 2015a). In this way, the Blanco river is now classified as a large river (Gurnell et al., 2002), having a width greater than the length of all of the wood pieces delivered. Thus, on large rivers where LW is not regularly in contact with the channel margins during transport (Schenk et al., 2014), mobilization is more frequent (Gurnell, 2003). The not significant relationships found between mobility rate and characteristics of the moved pieces suggest that, in the Blanco River, the wood mobility is probably mainly conditioned by the morphology of the reaches. This hypothesis seems to be confirmed considering the position of mobilized elements along the active channel. In fact, the mobilization of LW into the three reaches during the same period is different, but it is always similar considering reach by reach. This contrasting behavior seems to indicate that wood mobilization is mostly related to the reach local-scale morphology than the magnitude of floods. The mobility occurring during the summer season (J15-M15) was associated to normal peak flows (R.I. ~ 1 year), so it can be considered as a minimum mobility rate at annual level, whereas increasing flood events are able to transport a huge quantity of LW and cause major riverbank erosions.

The very low recovery rate (1.1%) of mobilized pieces suggests that a huge amount of wood was transported downstream to the end of the river, crossing the village, until being deposited in the river delta or reach the ocean. In fact, a lot of LW has been trapped at the bridge of Chaitén (Fig. 14) clogging the flow section and other elements were found deposited along the Santa Barbara beach (Fig. 1c).

It is worth noting that, as the recovery analysis was based on tag searching and given the high degree of wood jamming, it is likely that some tagged pieces were not found because the tag was deposited on the lower side of the logs or hidden by other pieces. However, a similar methodology had already been adopted in other LW studies, showing the efficiency of tags. Dixon and Sear (2014) reported, for a low gradient stream (Highland Water, UK), a recovery rate of 70.1% of all moved pieces, whereas Picco et al. (2016b) recovered 33% of all tagged elements recruited from riverbanks in a large gravel-bed river (Piave River, Italy). These comparable results can validate the hypothesis that the low recovery rate in Blanco River is due to the fact that LW was transported until the river delta, accounting for a major output of LW.

This considerable LW output may represent a potential hazard for Chaitén village. However, there are many different sites along the active channel where flowing logs can be retained. Both, standing trees and big WJ, can cause variations in flow environment and average velocity (Gippel, 1995; Seo and Nakamura, 2009; Welber et al., 2013) favoring the deposition and retention of wood.

5. Conclusions

This study attempted to analyze how the dynamics of in-channel LW (i.e. abundance and type) can be influenced by post eruption disturbances. The PDCs produced during the explosive activity of Chaitén Volcano have seriously damaged the riparian vegetation along the Blanco River with the breaking of standing trees. Eight years after the eruption, this still affects the types of LW. Field observations on the LW characteristics indicate that the Blanco River is a course with an intense transport of wood.

Our results also highlighted that the local-scale morphology is a crucial factor for the dynamics of LW. Independently of the magnitude of flood events, the analyzed study reaches revealed a different pattern in the mobility and retention rate of wood due to the different morphology that affects the inundated channel area. The fluvial transport was found to play an important role in supplying the active channel with LW also during ordinary floods, whereas the recruitment from bank erosion is an active process that contributes to delivering LW during higher magnitude events. The documented erosion of riverbanks confirmed previous findings on the widening tendency that occurs following volcanic disturbances. In particular, as bank erosion occurred in correspondence to dead riparian vegetation this suggests that the active channel will continue to widen until all the damaged riparian trees are completely removed, recruiting a huge amount of wood. The Blanco River is, in fact, a complex river system that reflects the volcanic disturbances and will be subjected to continuous adjustments for a long time. Moreover, the fluctuations in LW abundance and its dynamics also during short periods and relatively low flow conditions, suggests that in such riverine environments, hydrological conditions play a key role in affecting LW dynamics. This is also because of the huge amount of wood material deposited into the active corridor that may be transported easier than in less disturbed channels. In this context we highlight the need for constant monitoring activities to better clarify the effects of floods of different magnitude on LW recruitment and mobilization processes, as well as the effects on river channel morphology. Further research will allow the evolution pattern of Blanco River to be detected, ensuring a correct management of the river system and preventing possible hazards to the downstream village of Chaitén and its infrastructure.

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