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Wood storage in three mountain streams of the Southern Andes and its hydro-morphological effects

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Abstract

This study analyses large wood (LW) storage and the associated effects on channel morphology and flow hydraulics in three third-order mountain basins (drainage area 9–12 km^2) covered in old-growth *Nothofagus* forests, ranging from the temperate warm Chilean Andean Cordillera to the sub-Antarctic Tierra del Fuego (Argentina). Amount, characteristics and dimensions of large wood (>10 cm diameter, >1 m long) were recorded, as well as their effects on stream morphology, hydraulics and sediment storage. Results show that major differences in LW abundance exist even between adjacent basins, as a result of different disturbance histories and basin dissection. Massive LW volumes (i.e. >1000 m^3 ha^{-1}) can be reached in basins disturbed by fires followed by mass movements and debris flows. Potential energy dissipation resulting from wood dams is about a quarter of the total elevation drop in two streams, with a gross sediment volume stored behind wood dams of around 1000 m^3 km^{-1}, which appears to be of the same order as the annual sediment yield. Finally, the presence of wood dams may increase flow resistance by up to one order of magnitude. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: woody debris; channel morphology; flow resistance; mountain basins; *Nothofagus* forests

Introduction

Large wood (LW, otherwise called large woody debris, LWD) lying within stream channels has strong consequences for stream hydraulics, morphology, sediment transport and aquatic ecology (Gurnell *et al.*, 2002; Montgomery *et al.*, 2003; Montgomery and Piegay, 2003). In particular, channel morphology in old-growth forested basins is largely controlled by LW, given the abundance of large pieces able to build up stable in-channel structures such as log steps, valley jams and flow deflection jams (Abbe and Montgomery, 2003).

Several authors (Keller and Tally, 1979; Bilby, 1979; Keller and Swanson, 1979; Swanson *et al.*, 1976; Faustini and Jones, 2003) observed variable, overall high (10–80%, but up to 100%) potential energy dissipation exerted by log steps in different regions of the US. For Alaskan headwater streams, Gomi *et al.* (2003) reported up to 35 steps per kilometre of stream formed by either large or fine woody debris, with log steps accounting for an average of 51% of the total number of steps. A similar percentage (45%) was found by Curran and Wohl (2003) in basins of less than 10 km^2 of the Cascade Range (Washington, US). Previously, the percentage of steps formed by LW had been correlated by Wohl *et al.* (1997) to basin/channel size in streams of Montana (US), with values ranging from 50 to 10%. For second- and third-order channels in the Italian Alps, Comiti *et al.* (2006) found limited numbers of log steps (13–35 log steps per km), comprising only a small fraction (~10%) of the total step number. LW dam frequencies ranging from 1 km^{-1} (fourth order) to 100 km^{-1} (second order) are reported for streams flowing in semi-natural areas in Central Europe (Kaczka, 2003).

The influence of LW on flow resistance is receiving more attention by researchers. MacFarlane and Wohl (2003) reported higher flow resistance in step-pool reaches characterized by the presence of LW. Wilcox *et al.* (2006) used flume investigations to explore patterns of flow resistance partitioning between LW, spill over steps and grains in step-pool channels. The synergistic effect of LW and spill over steps was found to dominate, whereas grain resistance is only a small component of the total flow resistance. Wilcox *et al.* (2006) also found that the interaction effects between LW and step roughness components can lead to unreliable resistance partitioning between the two components.

As can be extrapolated from the preceding brief summary, most of the geomorphological research on LW in mountain streams has been carried out in the Pacific Northwest region of North America. Among the parts of the world lacking studies on LW, the Southern Andes represent an ideal location for studying LW in mountain channels draining old-growth forested basins.

The main purpose of this study is to provide the first quantitative description of the abundance and morphological role of in-channel wood in mountain streams of the Southern Andes, where forest cover is still dominated by old-growth, native *Nothofagus* (the so-called southern beech) forests. Even though pristine conditions are now very rare and limited to the most isolated places, human impacts in some areas can still be assumed to have minimally altered river form and processes.

In order to cover the huge latitudinal and climatic range of this mountain chain, two geographic end points have been selected, the Chilean Araucania and the Argentinian southern Tierra del Fuego. The former, an active volcanic region, features a temperate–warm humid climate and hosts evergreen and deciduous *Nothofagus* forests, plus the endemic *Araucaria* tree. Southern Tierra del Fuego is characterized instead by broad valleys carved by glaciers into sedimentary and metamorphic rocks and features a windy, cold–humid climate with timberline at about 600 m a.s.l. and forests composed of only a few *Nothofagus* species adapted to a very harsh environment. Three study basins were examined: one located in Tierra del Fuego, and two in the Araucania that differ with regard to forest disturbance history (fires).

The analysis will address, in order, (i) channel-averaged wood spatial density (pieces and volume per hectare of channel bed), (ii) wood and jam dimensions, (iii) macro-scale morphological effects of wood and the associated sediment storage, (iv) reach-based analysis of factors influencing wood storage and (v) influence of wood structures on sediment size distribution, bed profile and flow resistance.

Field Sites and Methodology

Study basins

The three basins (Figure 1) that are the subject of the present investigation are the Tres Arroyos (TA, within Malalcahuello National Reserve, geographical coordinates 38°27′07 S; 71°33′40 W) and the Rio Toro (TO, within the Malleco Natural Reserve, 38°10′43 S; 71°46′43 W) in the Chilean Araucania region, and the Buena Esperanza (BE) in the Argentinian Tierra del Fuego near the city of Ushuaia (54°47′50 S; 68°22′00 W). Table I provides a summary of the main characteristics of the basins, and maps of the catchments are reported in Figure 2.

Table I. Main characteristics of the study basins

Basin characteristics	**Tres Arroyos (TA)**	**Toro (TO)**	**Buena Esperanza (BE)**
Basin Area (km^2)	9·1	11·1	12·9
Basin elevation (min. – max., m a.s.l.)	1000–1850	750–1750	0–1275
Mean basin slope (%)	43	20	23
Channel order*	3	3	3
Climate	Temperate warm humid	Temperate warm humid	Temperate cold humid
Hydrological regime	pluvial/nival	pluvial/nival	glacionival
Annual precipitation	2217	2480	530/1300
Geology	Volcanic/pyroclastic	Volcanic/pyroclastic	Sedimentary/metamorphic
Forest cover (%)	74	95 (98% burned)	34
Dominant forest species	*Nothofagus dombeyi* *Araucaria araucana*	*Nothofagus dombeyi* *Araucaria araucana*	*Nothofagus pumilio* *Nothofagus antarctica*
Forest disturbances	Wildfire (1920s)	Wildfire (2002)	wind blowdowns (?)
Total channel length (km)	4·9	7	7·5
Studied channel length (km)	1·54	2·17	1·85
Average channel slope (m m^{-1})	0·08	0·05	0·065
Average channel width (m)	7·7	11·9	6·3
Channel morphology	step-pool/cascade	plane-bed/step-pool	cascade/step-pool

* Channel order determined by topographical maps (1:50 000 scale).

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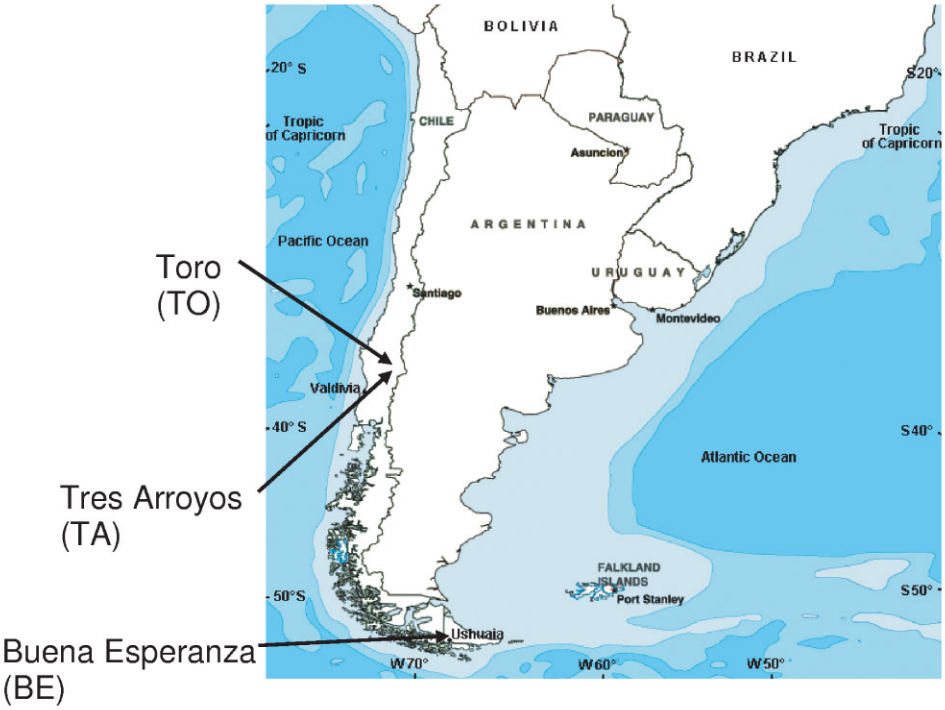

Figure 1. Location map of the three study basins. This figure is available in colour online at www.interscience.wiley.com/journal/espl

The region where the Rio Toro and the Tres Arroyos lie is identified as 'temperate warm with winter precipitation' (Fuenzalida, 1965). The presence of large and high volcanoes strongly influences the climate and the geology of the area, which is characterized by pyroclastic rocks such as andesite breccias, tuffs and ignimbrites, lavas, and sedimentary layers.

The native, old-growth forests in the Araucania basins are of two types: the araucaria forest (*Araucaria araucana*, the 'Monkey-puzzle' tree) and the southern beech forest (*Nothofagus* spp). The araucaria – an ancient conifer that grows up to 40 m tall and 2 m trunk diameter, and can live more than 1000 years – is found only in the upper part of the basin, above 1200–1300 m a.s.l. Lower elevations are covered by the mixed southern beech type dominated by *Nothofagus dombeyi* (called 'coigüe' by locals), which can grow up to 50 m in height and 2 m in diameter, and live more than 600 years, as inferred from an age–diameter curve by Veblen *et al.* (1981). The understorey of the old-growth *Nothofagus* forest is completely dominated by a very invasive autochthonous bamboo plant, the southern 'quila' (*Chusquea* spp.).

The Tres Arroyos basin is 72% forested, with 61% represented by native old-growth stands (trees up to 40–50 m tall and 1–2 m diameter, more than 500 years old). The Tres Arroyos is now heavily affected by debris flows, which deliver huge amounts of wood in steep tributaries draining the burned area as a consequence of hillslope destabilization resulting from lack of forest cover. Hydrology and sediment transport in the Tres Arroyos have been monitored since 1997 by Universidad Austral de Chile in Valdivia (Iroumé, 1997, 2003). A previous analysis of in-channel wood characteristics in the Tres Arroyos is presented by Andreoli *et al.* (in press).

The Toro basin was almost completely (95%) covered with old-growth stands of *Araucaria* and *Nothofagus* up to 2002, when catastrophic wildfires burned 98% of the forest cover. Indeed, fire is the most important disturbance shaping the *Araucaria–Nothofagus* landscape in the Araucarian region (Burns, 1993; Gonzalez *et al.*, 2005). During the 2001–02 fire season, catastrophic fires burned nearly 20 000 ha of temperate forests in the Andean Araucarian region of Chile. These were initially interpreted as an ecological novelty, but recent studies (Gonzalez *et al.*, 2005) have determined that such fires actually lie within the range of the historic fire regimes that have shaped this forested landscape.

In Tierra del Fuego, the vast majority of river basins (98%) are heavily impacted by the damming activity of beavers (*Castor canadensis*), which were artificially introduced in 1946 (Lizarralde, 1993; Coronato *et al.*, 2003). The study basin of Buena Esperanza represents one of the few channels not impacted by these mammals. The basin lies in

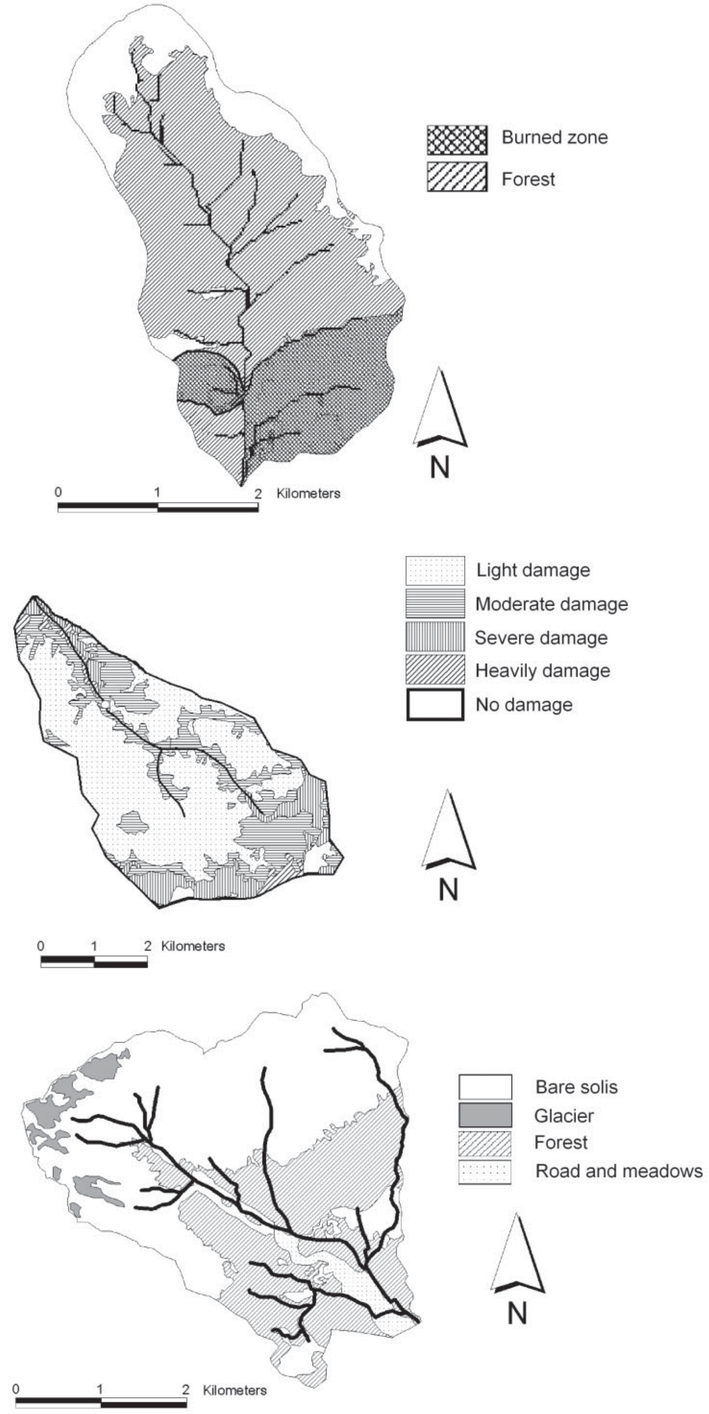

Figure 2. Land cover maps of the study basins: Tres Arroyos (top); Rio Toro (middle); Buena Esperanza (bottom). The Rio Toro is completely forested, and the damage level refers to the 2002 wildfire.

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front of the Beagle Channel, above the sprawling city of Ushuaia, and hosts a small glacier that imparts a glacionival regime to the stream. The climate is cold temperate humid with a mean annual temperature of 5·5 °C at sea level. Precipitation is of low intensity and high frequency, evenly distributed throughout the year but with a strong altitudinal gradient. Annual precipitation in the Buena Esperanza (Urciolo *et al.*, 2006) ranges from 530 mm (sea level) to 1300 mm (watershed divide).

Only 34% of the drainage area is covered by forest; the rest is above the timberline. Forest cover is characterized by the relatively simple 'magellanic mixed forest', dominated by *Nothofagus pumilio* ('lenga') in association with *Nothofagus antarctica* ('ñirre') and *Nothofagus betuloides* ('coigüe de Magallanes'). Tree growth in Tierra del Fuego is much lower than in the Araucania region, and consequently tree diameters are generally smaller, such that old-growth stands (>200–250 years) may have diameters at breast height as small as 30 cm (Rebertus *et al.*, 1997; Barrera *et al.*, 2000), in contrast to approximately 40 cm for *N. dombeyi* in the Valdivian Andes (Veblen *et al.*, 1981). In addition, the forest structure of *N. pumilio*, whose maximum lifespan is between 300 and 400 years, in Tierra del Fuego is governed by periodic wind blowdowns associated with low-pressure systems originating in Antarctica (Rebertus *et al.*, 1997). As a consequence, trees having diameters greater than 0·5 m are very uncommon in the Buena Esperanza basin.

At present, no forest harvesting is allowed in the Buena Esperanza, whereas some occasional logging was conducted in the past, especially during the 1940s. Stream flow has been monitored since 2000 by Subsecretaría de Recursos Naturales Provincia de Tierra del Fuego, and for the period 2000–2006 the annual peak discharge ranged approximately from 2·5 to 4 $m^3 s^{-1}$ (Urciolo *et al.*, 2006).

Survey of channel morphology, wood characteristics and wood mobility

The study channels (Figure 3) were surveyed in March–April 2005 (Tres Arroyos, TA), January 2006 (Toro, TO) and February–March 2006 (Buena Esperanza, BE). The total channel lengths investigated are reported in Table I. In the Buena Esperanza, an intermediate, 230 m long reach within a gorge was not included because it was inaccessible. The longitudinal profiles of the study sections were surveyed using a laser distance meter with inclinometer. Individual reaches were defined based on uniformity of either slope, channel width or abundance of debris. The following characteristics were measured at each single reach: mean channel slope, mean bank-full and fluvial corridor (i.e. bank-full channel plus adjacent active floodplain) width, mean bank-full water depth and number of steps. Drainage area at each reach was determined from a digital elevation model using GIS software.

Wood pieces greater than 10 cm in diameter and 1 m in length were measured both in the active channel and in the adjacent active floodplain, as in the work of Andreoli *et al.* (in press). Where the floodplain was absent, as in many confined reaches, a maximum flood level was estimated and served as the upper elevation limit for LW to be included in the records at each location. More than 5500 elements were recorded over all of the study segments.

The length and mid-diameter of each element were measured with a tape and a tree caliper, respectively. The precision is estimated to be ~1 cm for diameter and ~5 cm for piece length. All the pieces forming log jams (i.e. accumulations of at least two elements) were measured, and the geometrical dimensions of jams (length, width and height) were also taken in the Tres Arroyos and in the Buena Esperanza.

Several additional data were recorded for each wood piece during the field survey (Andreoli *et al.*, in press): type (log, rootwad, log with rootwads attached), tree species (*Nothofagus*/*Araucaria*/conifers), orientation to flow (parallel, orthogonal, oblique), delivery mechanism into any given reach (bank erosion, landslide, natural mortality, transported from upstream) and position (log step, in channel, bank-full line, channel bridging, channel margins). In-channel pieces were defined as all the wood elements lying at least partially at a lower elevation than bank-full height, but excluding log steps (which form a different class). For log steps, drop height and pool depth were also measured. The LW elements found at an elevation corresponding to the bank-full stage were combined into a separate group. Wood elements spanning the channel at an elevation higher than bank-full stage were classified as channel bridging, and channel margin pieces were defined as those located on the area adjacent to and higher than the bank-full channel, thus subject to inundation during low-frequency floods. In the case of long logs stretching across different portions of the channel, their prevalent location was assigned. For pieces lying partly above the maximum inundation level, no estimation of the reduced log volume actually located within the flow was made, so that the total piece length was recorded. This procedure might lead to a slight overestimation of the total LW volume.

The volume of each wood element was calculated from its mid-diameter D_{log} and length L_{log}, assuming a solid cylindrical shape, as commonly done in LW studies. Spatial density of LW, in terms of both volume and number of elements, on the active channel and the fluvial corridor was calculated based on bank-full and corridor widths, respectively. Correlations between channel properties and wood variables were carried out using (log + 1) transformed values in the software STATISTICA 7.1 (StatSoft, 2006).

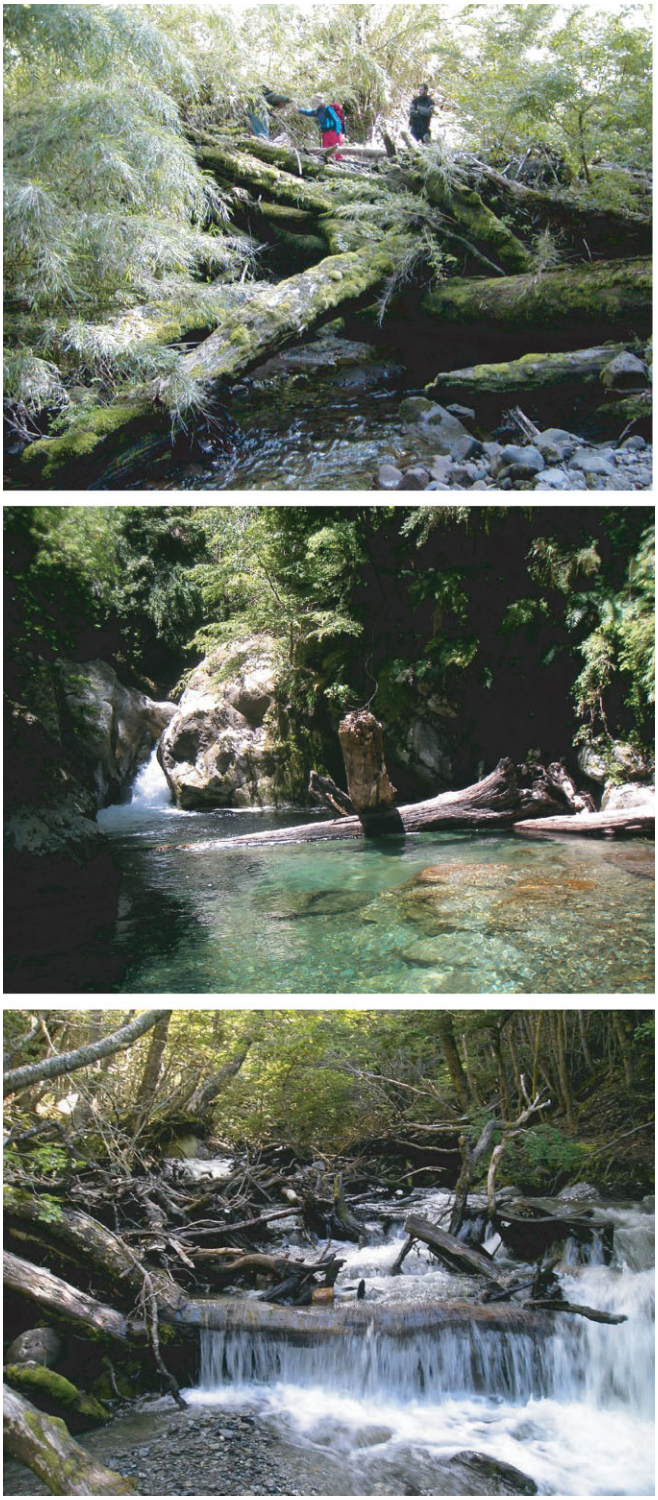

Figure 3. Views of the Tres Arroyos (top), Rio Toro (middle) and Buena Esperanza (bottom) main channels. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Table II. Characteristics of the channel reaches and units considered for flow resistance

	Reach/unit	LW	Morphology	Length (m)	Slope (m m^{-1})	D_{84} (m)	*H* (m)	*L* (m)
Buena Esperanza	A		low step-pools	21·5	0·022	0·223	0·25	2·4
	C		riffle-glide	17·2	0·023	0·113	0·22	1·9
	E		cascade	23·4	0·076	0·260	0·42	6·0
	G		step-pool	17·0	0·103	0·336	0·61	3·4
	B	×	two valley jams	22·8	0·097	0·083	0·99	3·6
	D	×	log step & big pool	4·1	0·105	0·172	1·00	2·7
	F	×	valley jam	13·7	0·092	0·208	1·02	2·3
	DEF	×	log step & valley jam	41·3	0·084	0·219	0·72	4·3
	GH	×	valley jam & step-pool	22·6	0·132	0·285	0·78	3·9
	H	×	valley jam	5·6	0·223	0·153	1·28	5·3
Tres Arroyos	15		riffle/step-pools	36·9	0·028	0·151	0·37	13·7
	1		low step-pools	23·9	0·057	0·378	0·21	9·7
	14		step-pool/cascade	50·5	0·072	0·341	0·53	4·8
	8		riffle/step-pool	42·1	0·036	0·385	0·63	5·8
	10	×	sequence of log steps	32·1	0·153	0·143	1·89	10·6

The volume of sediment stored behind log steps and valley jams was estimated as a solid wedge, whose geometrical dimensions (i.e. streamwise length, upstream and downstream width, height) were measured by a tape. Sediment porosity was not measured. H and L indicate mean step height and step length, respectively.

Determination of LW effects on streambed characteristics and flow hydraulics

In order to determine whether LW significantly increases the overall roughness of the study channels, several field measurements were carried out to evaluate flow resistance in reaches with and without significant wood influence in the Tres Arroyos and in the Buena Esperanza. The main characteristics of the selected reaches are summarized in Table II.

Field measurements of reach-averaged flow velocity were carried out using the salt tracer method. Portable conductivity meters (Campbell CR510 with probe CS547) storing data every second were placed at the upstream and downstream ends of each study reach, and the distance and elevation change between the probes was surveyed as part of the longitudinal-profile surveys. As a tracer, a variable quantity (0·1–0·5 kg) of salt (NaCl) was mixed into a plastic bin filled with stream water, avoiding saturation. The salt mixture was then injected into the main stream at a distance of at least 10 channel widths upstream from the upper probe to promote adequate lateral mixing (Elder *et al.*, 1991). The time lag between the conductivity peaks recorded by the upstream and downstream instruments gives information on the average travel time of the flow, following the methods of Curran and Wohl (2003) and MacFarlane and Wohl (2003). Travel distance between the probes (thalweg length derived from longitudinal profile survey) was divided by travel time to determine mean flow velocity. At least three velocity measurements were carried out at each reach, in order to obtain average values. Only one discharge (measured by the salt dilution method) was measured for each reach, and low-flow conditions were measured both in the Tres Arroyos and in the Buena Esperanza.

Flow resistance, expressed in terms of the Darcy-Weisbach friction factor (f), was determined by the following expression:

$$f = 8ghS/V^2 \tag{1}$$

where g is gravitational acceleration (9·8 m s^{-1}), h is the reach-averaged flow depth (m), S is the reach slope (m m^{-1}) and V is the reach-average velocity (m s^{-1}). Bed slope (S) used in Equation (1) was calculated from detailed longitudinal profiles carried out at each velocity reach. Reach-averaged flow depths (h) – derived from the continuity equation, using discharge, velocity and the average of cross-section flow widths – were used in Equation (1) instead of cross-sectional hydraulic radii, as done by Curran and Wohl (2003).

The reach-averaged values of step height (H) and step spacing (L) were then calculated (Table II), along with the standard deviation of the longitudinal profile (σ), which Aberle and Smart (2003) indicated as a good predictor of bed macroroughness. Bed surface grain size distribution of each reach was characterized by a grid-by-number survey of the intermediate axis of at least 100 clasts. The clasts measured in steps and pools were analysed together to derive a composite grain size distribution.

In order to assess the partitioning of flow resistance between the different sources of roughness (see the introduction), grain resistance f_g was calculated for each reach using a modified version (Millar and Quick, 1994) of Keulegan's traditional equation, as done by MacFarlane and Wohl (2003). The equation is the following:

$$f_g = \left[2{\cdot}03\log\left(\frac{12{\cdot}2h}{k_s}\right)\right]^{-2}. \qquad (2)$$

Average flow depth is used instead of the hydraulic radius, as in Equation (1), and the D_{50} of the surface grain size distribution as the roughness height k_s, following MacFarlane and Wohl (2003).

Results

Spatial density of wood

Figure 4 reports the average LW load in terms of numerical and volumetric spatial density in the study basins, for both the active channel (i.e. within the bank-full width) and the entire fluvial corridor. Data referring to the fluvial corridor

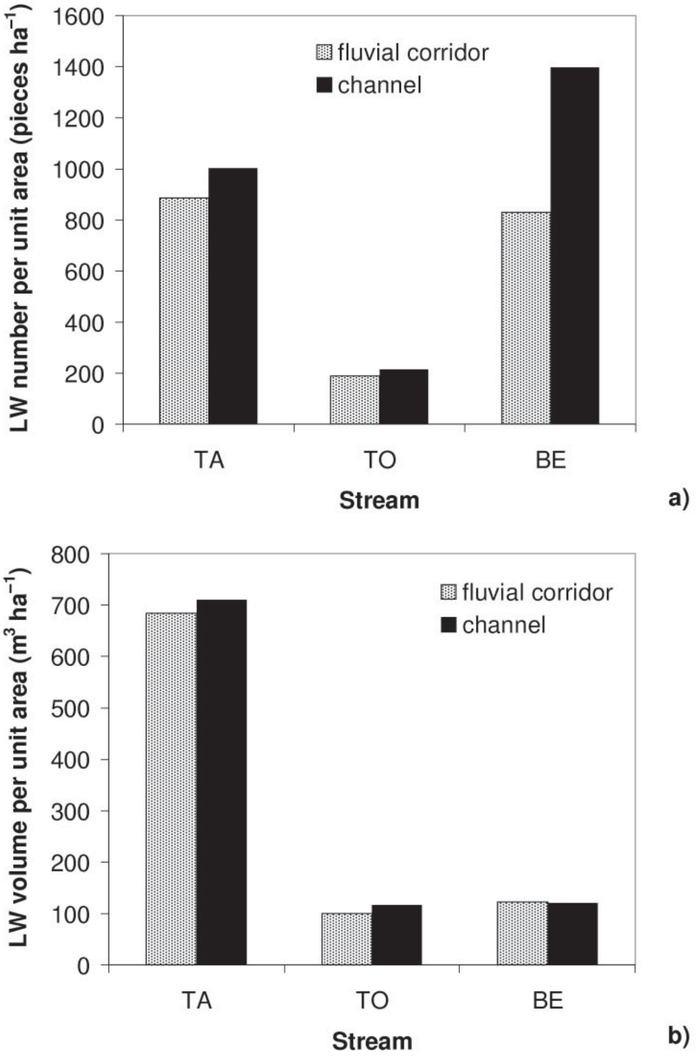

Figure 4. Large wood storage in terms of total piece number (a) and total volume (b) in the active channel (i.e. within the bankfull width) and in the entire fluvial corridor of the three study basins (TA Tres Arroyos; TO Rio Toro, BE Buena Esperanza).

should be viewed as indicative, because measurement of all LW pieces in the floodplain was not always feasible because of the dense vegetation growing in the Araucanian basins.

Average values are obtained by dividing the total piece number/piece volume by the total reference bed area, i.e. bank-full channel area and fluvial corridor area (in hectares), of the surveyed channel segments. Based on LW number the Buena Esperanza shows the highest load in the channel (1400 pieces ha^{-1}), whereas if volume is considered the Tres Arroyos features the largest value, as much as 700 $\text{m}^3\ \text{ha}^{-1}$. The Rio Toro has the lowest LW loads both in terms of piece number and volume (215 pieces ha^{-1} and 117 $\text{m}^3\ \text{ha}^{-1}$, respectively), but this value is very similar to the Buena Esperanza when LW volume is considered. The large discrepancy in the Buena Esperanza number/volume data depends on LW dimensions, as will be analysed in the next section. Figure 4 also shows that LW spatial density is generally lower in the fluvial corridor than in the active channel, although this difference is small except for the Buena Esperanza.

Characteristics of wood elements

Marginal pieces of LW (i.e. lying on the floodplain) constitute about half the total number in the Tres Arroyos, but represent a minor fraction (about 20%) in the other channels. LW found at bank-full elevation was rather common in the Buena Esperanza and in the Tres Arroyos (9 and 22%, respectively), but not so in the Rio Toro (<1%). Both log steps and channel-spanning elements are less than 2% in all of the streams. In the Rio Toro, no log steps were found. In order to facilitate a more significant comparison among the study channels, all the subsequent analyses, where not specified, will exclude LW pieces found at channel margins.

In the Tres Arroyos and the Rio Toro, a very low fraction of the wood pieces derive from *Araucaria* trees (6 and 1%, respectively), the vast majority being from *Nothofagus*. In the Fueginan basin, all the LW is from *Nothofagus*, and distinction among species (i.e. lenga, ñirre, guindo) was not possible. A rather consistent fraction of total LW forms log jams among the three streams, i.e. 68% in both Toro and Tres Arroyos, and 60% in the Buena Esperanza.

The vast majority of logs appear to have been subject to some transport (i.e. were not immobile pieces fallen into that location of the channel), ranging from 68% (TO) to 75% (BE), up to 88% (TA). The actual travel distance could not be assessed, however, and these pieces may have come from upstream locations of the same reach, whereas many pieces classified as 'transported' in the Tres Arroyos may derive from debris flow rather than fluvial transport (Andreoli *et al.*, in press). Only a small percentage of the measured LW has rootwads still attached (2·1, 4 and 6·4% for TO, TA and BE, respectively), and detached rootwads are even fewer (0·3, 0·6 and 1% for TO, BE and TA, respectively). Wood clearly coming from nearby eroding banks is of importance only in the Buena Esperanza (11%), whereas natural mortality, which includes dead trees sliding down from adjacent hillslopes, is highest in the Toro (27%). Wood pieces found at the toe of landslides inside the channel account for 5% in the Toro, 1% in the Tres Arroyos and only 0·1% in the Buena Esperanza.

Log orientation with respect to flow shows a rather similar pattern between the Tres Arroyos and the Buena Esperanza (i.e. approximately one-third in each class). In contrast, the Rio Toro presents a higher number of orthogonal elements (51%).

Wood dimensions

Some characteristics parameters of wood piece dimensions (i.e. diameter, length and volume) are summarized in Table III. Figure 5(a) and (b) illustrates the frequency distribution of log diameter (truncated at 1 m) and length (truncated at 15 m), respectively.

It is evident that the Fueginan stream (BE) differs substantially from the Araucarian channels in having much smaller wood diameters, whereas piece length values and their distribution are similar to the other two basins. In the Buena Esperanza, in fact, as many as 57% of all wood pieces in the active channel are in the 10–20 cm class, and few logs are larger than 30 cm. By contrast, in the Tres Arroyos, wood larger than 50 cm (i.e. approximately the average bank-full water depth) is relatively common. The best-fit distribution for both log diameter and length is log normal for all the streams, but – based on the Kolmogorov–Smirnov coefficient D – this is not statistically significant ($p < 0{\cdot}01$). The average length of pieces classified as log steps matches the 87th and 89th percentiles of the cumulative length distribution in the Tres Arroyos and Buena Esperanza, respectively, whereas the average log-step diameter corresponds to 59 and 73% of the cumulative diameter distributions. No log steps were found in the Rio Toro.

In terms relative to reach-scale channel size (i.e. bank-full width for piece length and bank-full water depth for piece diameter, Braudrick and Grant, 2001), all three streams (Table III) are statistically different based on piece length/channel width ratios (one-way ANOVA and *t*-tests, $p < 0{\cdot}05$). Based on the piece diameter/channel depth ratio, the Tres Arroyos has significantly (*t*-test, $p < 0{\cdot}05$) larger logs than the other two streams, which do not differ from each other (*t*-test, $p > 0{\cdot}05$).

Table III. Summary of main wood dimensions. For relative dimensions, average values and standard deviation (in brackets) are reported

	TA		**TO**		**BE**	
	Bank-full channel	**Fluvial corridor**	**Bank-full channel**	**Fluvial corridor**	**Bank-full channel**	**Fluvial corridor**
Maximum diameter (m)	1·2	2·2	1·2	1·2	0·90	0·90
Mean diameter (m)	0·50	0·41	0·33	0·33	0·18	0·19
D_{84} (m)	0·55	0·60	0·50	0·5	0·25	0·25
D_{50} (m)	0·30	0·35	0·30	0·29	0·15	0·15
D_{16} (m)	0·20	0·20	0·20	0·15	0·10	0·1
Maximum length (m)	25·7	26·0	15	15	17	17
Mean length (m)	3·0	3·2	3·62	3·56	0·50	3·17
L_{84} (m)	5·0	4·9	4·0	4·0	4·8	5·5
L_{50} (m)	2·2	2·5	2·2	2·2	2·0	2·1
L_{16} (m)	1·2	1·2	1·5	1·4	1·0	1·1
Maximum volume (m^3)	24·86	36·85	12·43	12·43	6·68	6·68
Mean volume (m^3)	0·70	0·77	0·56	0·53	0·13	0·15
Log length/bank-full width	0·40 (0·35)	–	0·30 (0·22)	–	0·46 (0·36)	–
% logs longer than bank-full width	5·9	–	1·5	–	8·8	–
Log diameter/bank-full depth	0·95 (0·46)	–	0·41 (0·23)	–	0·43 (0·21)	–
% logs larger than bank-full depth	33·3	–	1·9	–	1·7	–

Table IV. Summary of main jam dimensions. Average values and ranges (in brackets). For the Rio Toro geometrical dimensions of jams are not available (n/a)

	TA	**TO**	**BE**
Number of jams per km	51	19	55
Number of pieces	15 (2–93)	12 (3–47)	11 (3–57)
Wood volume (m^3)	9 (0·2–68)	6·5 (0·2–20)	1·4 (0·06–8·09)
Piece diameter (m)	0·4 (0·21–0·65)	0·33 (0·10–1·15)	0·2 (0·1–0·8)
Piece length (m)	3·0 (1·2–6·4)	3·55 (1·0–14)	2·8 (0·6–17·0)
Jam length (m)	5·6 (1·2–14·1)	n/a	7·3 (3·3–12·5)
Jam width (m)	3·3 (1·2–12·0)	n/a	2·1 (0·5–7)
Jam height (m)	1·0 (0·5–2·5)	n/a	1·3 (0·5–2·3)
Geometric volume (m^3)	24 (2·1–143)	n/a	23·8 (2·1–177)

Log-jam dimensions are reported in Table IV. Tres Arroyos and Buena Esperanza have similar jam frequency values and jam geometrical dimensions, and the number of logs forming each jam seems to be relatively constant in all the basins (non-significant one-way ANOVA, $p > 0·10$). Average jam wood volume is significantly smaller (one-way ANOVA, $p < 0·01$) in the Fueginan channel, however, because of the smaller diameters of wood pieces (Table IV). It is important to bear in mind that only wood elements of over 10 cm were measured in all the channels, therefore a direct comparison of the ratio between jam wood volume and jam geometrical dimensions (the wood/air ratio, Andreoli *et al.*, in press) between the two basins has little physical meaning.

Potential energy dissipation and sediment storage due to LW

For each study channel, the elevation drop associated with log steps and valley jams (the ensemble of these two natural structures will be hereafter referred to as 'LW dams') was calculated summing all LW structure drops, and this value was then divided by the total elevation drop in the surveyed segment. The results are presented in Table V. Rio Toro is not included because no LW dams were found along the segment investigated.

Even if LW dams occur more frequently in the Buena Esperanza, the largest effect of wood on the longitudinal profile (i.e. on potential energy dissipation mechanisms) is in the Tres Arroyos, where 27% of the total drop is dissipated locally at LW dams. The Buena Esperanza shows a slightly lower value. This results from the lower dam

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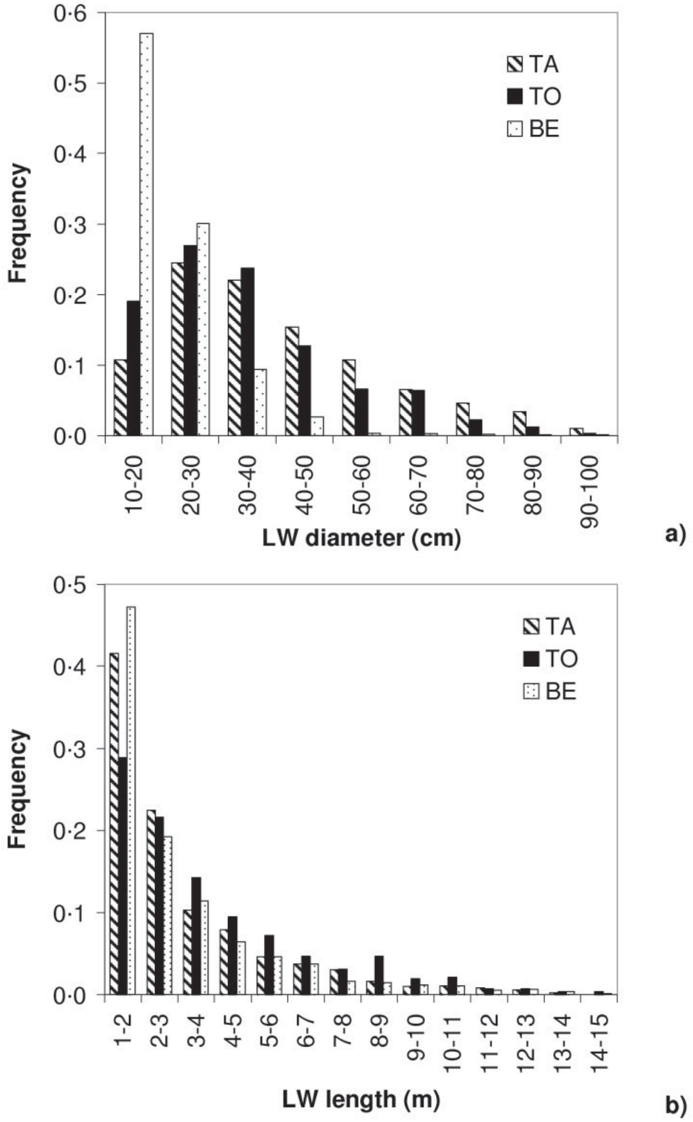

Figure 5. Frequency distribution of LW diameter (a) and length (b) in the three study channels. LW outside the channel is not included.

Table V. Characteristics of log steps and valley jams

	TA	BE
Frequency of LW dam (number km^{-1})	20	32
Frequency of log steps (number km^{-1})	17	17
Frequency of valley jams (number km^{-1})	3	15
Fraction of LW dams on total number of steps (%)	22	19
Maximum dam height (m)	3·5	1·3
Mean LW dam height (m)	1·12	0·54
Mean LW dam pool depth (m)	–	0·33
Mean LW dam pool length (m)	–	1·65
Channel length occupied by LW dam pools (%)	–	4
Channel length occupied by LW dam impoundments (%)	24	22·3
Channel elevation loss due to LW dams (%)	27	23·6
Sediment stored behind LW dams (m^3 km^{-1})	1270	872

height in the latter channel (Table V). Overall, 20% of all steps (i.e. drops larger than the average bank-full water depth in each reach) are represented by LW dams in both channels. On average, valley jams are higher than log steps in both streams.

Upstream of LW dams, an impoundment forms, where deposition takes place and bed slope is lower than the average in the channel. A wedge of deposited sediment can thus be attributed to each wood dam. Summing up all the impoundment lengths, as much as 24 and 22·3% of the total channel length is grade (and sediment) controlled by wood in the Tres Arroyos and Buena Esperanza, respectively (Table V). In contrast, the Rio Toro does not exhibit any significant grade control exerted by wood.

Sediment storage associated with wood dams is also reported in Table V. The total volumes (not accounting for porosity and normalized by the surveyed channel length) are 1270 $m^3 km^{-1}$ and 872 $m^3 km^{-1}$ for the Tres Arroyos and the Buena Esperanza, respectively. In the Rio Toro, the absence of substantial impoundments basically leads to the lack of wood-related sediment storage.

Reach-scale analysis of wood characteristics

The linkage between basin and channel characteristics and LW amount and type, as well as interrelationships between different wood characteristics, was explored using reach-based values for the three study streams. Seventeen reaches were identified both in the Tres Arroyos and the Toro, and 33 in the Buena Esperanza. Wood data used for this analysis, as for most previous analyses, refer to the active channel only. Figure 6 shows the high magnitude of reach-scale variability in LW loading within all the study channels. Median values reflect what was already observed for channel-averaged LW quantities. The longitudinal pattern of wood loading in terms of wood pieces per hectare of streambed area in the three study channels is illustrated in Figure 7, where longitudinal distances are normalized by the total investigated length.

Two different patterns are evident. A very jagged, irregular pattern characterizes the Tres Arroyos and the Buena Esperanza, whereas the Rio Toro features a more uniform distribution of wood along its course. Peaks of LW in the former streams are associated with reaches characterized by LW dams which may act as 'trap' locations for incoming floating logs, or with dams triggered either by fallen trees from eroding banks (Buena Esperanza) or by debris flow tributaries (Tres Arroyos, see Andreoli *et al.*, in press). In contrast, the absence of LW dams in the Rio Toro make its wood distribution – at least until now – dependent more on chronic natural mortality from the hillslopes.

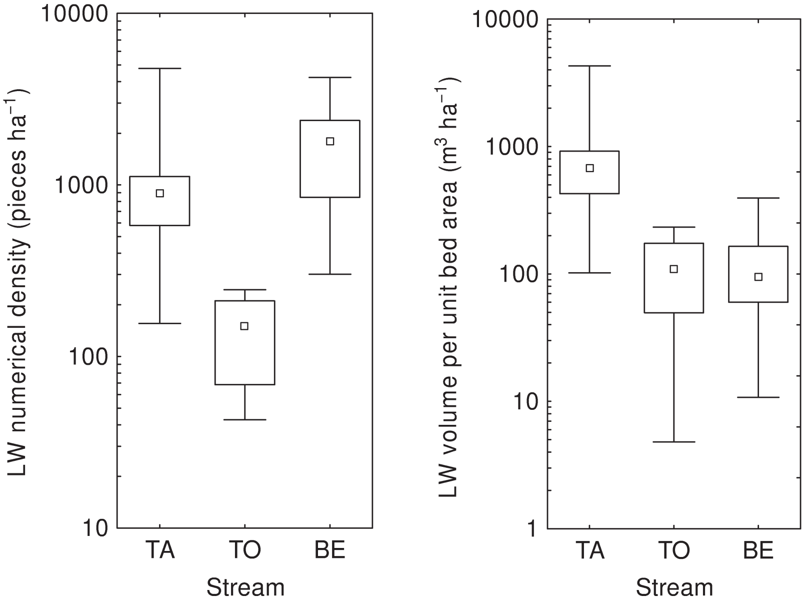

Figure 6. Reach-scale overall variation of LW storage in the active channel in terms of piece number per hectare (left) and volume per hectare (right) for the three study channels. For each box plot, the solid box indicates the range between the 25th and 75th percentiles, the square icon indicates the median and the whiskers indicate the maximum and minimum values.

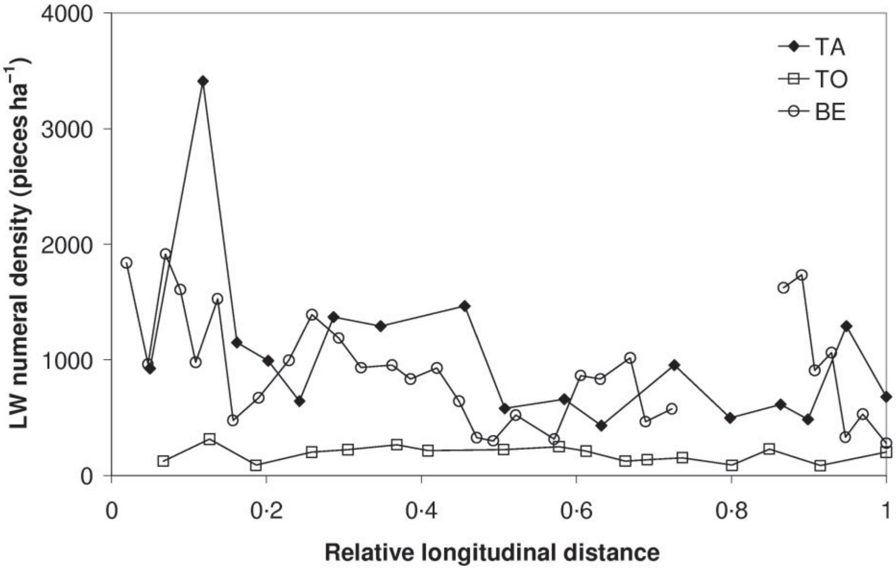

Figure 7. Longitudinal reach-scale variation in LW storage (pieces per hectare) for the three study channels. The gap present in the Buena Esperanza results from the unsurveyed reach (see the text).

A Pearson correlation matrix obtained on reach-scale, log-transformed variables describing channel geometry (slope, bank-full channel width and depth, number of boulders and steps larger than bank-full depth) and wood characteristics (spatial density of wood pieces, rootwads and volume, log-step and jam frequency, wood dimensions relative to channel width and depth) was performed using all reaches from the three channels. Unfortunately, correlation coefficients are generally low, and relationships in terms of LW volume are strongly biased because of the large differences in wood diameter and wood supply among the three basins. However, an interesting outcome is the high correlation ($R^2 = 0{\cdot}64$, $p < 0{\cdot}001$) between abundance of wood and number of wood pieces longer than bank-full width (number per ha of streambed area for both variables). In contrast, a much smaller correlation ($R^2 = 0{\cdot}20$, $p < 0{\cdot}001$) is observed when considering the number of wood pieces larger than bank-full depth.

Analysing each stream separately, only a few significant correlations can be observed. Wood spatial density is significantly correlated with reach slope ($R^2 = 0{\cdot}310$, $p = 0{\cdot}018$) and drainage area ($R^2 = -0{\cdot}250$, $p = 0{\cdot}040$) in the Tres Arroyos, but not in the other streams. Bank-full width and depth do not correlate with wood density in any channel. A linkage between abundance (i.e. spatial density) of rootwads and wood loading seems instead to exist in all the channels ($R^2 = 0{\cdot}25$–$0{\cdot}36$, $p < 0{\cdot}05$).

LW influence on grain size distribution, bed roughness and flow resistance

The key parameters describing the roughness characteristics of the reaches analysed through the salt tracer measurements were compared in order to assess dissimilarity between LW and non-LW reaches (see above). Analyses of grain size distribution in the stream reaches show that the composite D_{84} of the non-LWD reaches ranges from 0·113 to 0·385 m, whereas in LW-influenced reaches the values range from 0·083 to 0·285 m. Figure 8 shows that both D_{50} and D_{84} are significantly larger in non-wood reaches than in wood-loaded ones ($p < 0{\cdot}05$). The geometry of the longitudinal bed profile is also significantly different between the two groups (Figure 9). The reach-averaged drop height Z (calculated as step height minus pool depth) is considerably higher in LW reaches ($p < 0{\cdot}001$), as well as the ratio between average step height and step spacing (H/L, $p = 0{\cdot}001$). Together, the two variables indicate higher steps and deeper pools in the LW-loaded reaches. Furthermore, the comparison in terms of the standard deviation of the longitudinal profile (σ) shows significantly larger roughness in LW reaches ($p < 0{\cdot}001$).

Figure 10 illustrates the variation of the Darcy–Weisbach friction factor f – calculated using Equation (1) – with the dimensionless unit discharge (i.e. $q/(gD_{84}{}^3)^{0.5}$, as in the work of Comiti *et al.*, 2007). The investigated q^* ranges from 0·036 to 1·126 and calculated friction factor f from 0·3 to 97·5. The field-based curve derived by Comiti *et al.* for step-pool streams is also reported. Despite the large scatter, flow resistance shows a decreasing trend and, most notably, non-LW reaches feature lower friction factors (up to one order of magnitude) than LW reaches for similar

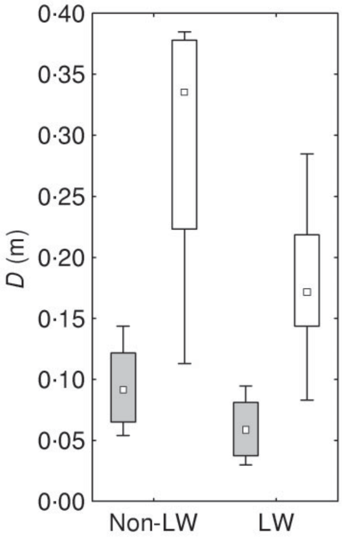

Figure 8. Grain size comparisons between non-LW and LW-loaded reaches. Shaded boxes represent D_{50} and the empty boxes represent D_{84}. For each box plot, the solid box indicates the range between the 25th and 75th percentiles, the square icon indicates the median, the whiskers indicate the non-outlier maximum and minimum values.

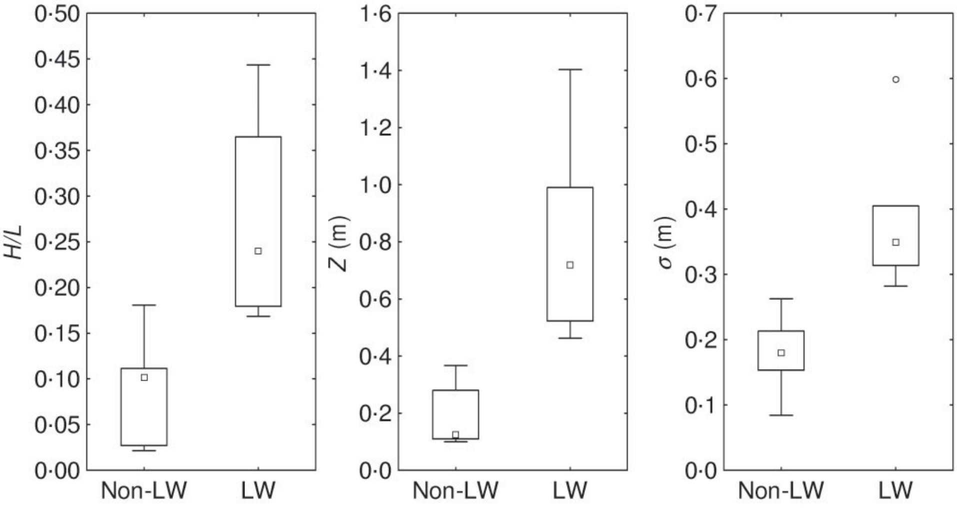

Figure 9. Step-pool geometry comparison between non-LW and LW-loaded reaches. For each box plot, the solid box indicates the range between the 25th and 75th percentiles, the square icon indicates the median, the whiskers indicate the non-outlier maximum and minimum values and the void circles indicate outliers.

values of q^*. The highest f (around 100) is associated with Tres Arroyos reach 10 – one of the steepest reaches (Table II) – where a sequence of high log steps with large intervening pools provides substantial spill resistance. Interestingly, non-LW flow resistance values are generally lower than the empirical curve previously obtained for step-pool channels. This might reflect the poorly developed step-pool geometry exhibited by the measured reaches, which have a low channel slope relative to the streams analysed by Comiti *et al.* (2007). It is important to bear in mind, however, that Figure 10 neglects the strong effect of channel slope on flow resistance (Comiti *et al.*, 2007), and provides only a means to compare flow resistance in reaches having different relative roughnesses. In fact, when channel slope is included in a general linear model along with q^*, the friction factor f is not significantly affected ($p > 0{\cdot}10$) by the presence or absence of LW. In other words, the dominant effect of wood accumulations in the measured reaches is probably the creation of steeper gradients associated with drops such as log steps and valley jams.

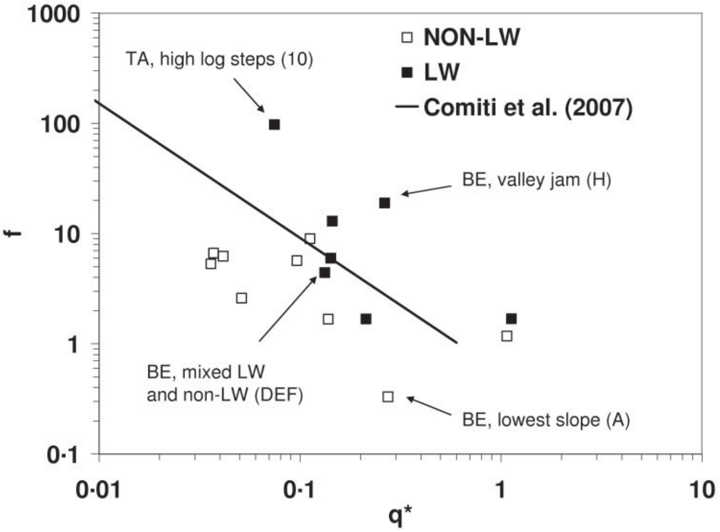

Figure 10. The Darcy–Weisbach friction factor *f* calculated for the investigated channel reaches (with and without LW) plotted versus the non-dimensional unit discharge q^*. The equation for high-gradient streams mostly without wood derived by Comiti *et al.* (2007, Equation (14)) is also reported, and several reaches are marked (Tres Arroyos TA, Buena Esperanza BE; see Table II).

Analysis of the ratio between grain resistance f_g (estimated by Equation (2)) and the measured total friction factors indicates that grain roughness is able to explain only a small fraction of the total flow resistance (<10%), apart from reach A in the Buena Esperanza, which is characterized by a low channel slope and by a smooth profile. Overall, LW reaches feature the lowest ratios – on average 2·8% – compared with the mean value of reaches without wood (5·4%, excluding reach A). However, a Mann–Whitney *U* test did not reveal a strong statistical difference ($p = 0{\cdot}08$) between the two groups.

Discussion

In-channel wood quantity in old-growth forested mountain basins of the Southern Andes can vary considerably both between and within channels. The strong longitudinal variation of LW quantity in the Tres Arroyos and in the Buena Esperanza as well as its link to 'external' factors rather than to channel properties – shown by the low correlations with stream variables – reflects what Comiti *et al.* (2006) observed in second–fourth order channels of the Italian Dolomites.

Basically, wood location in such confined, relatively small mountain streams (i.e. relative to wood size) is not primarily determined by stream hydraulics, such as deposition on bars as found in wider, lower gradient rivers (Gurnell *et al.*, 2000; Wzyga and Zawiejska, 2005), but by complex bank/hillslope processes (e.g. falling of large trees, debris flows, landslides). These latter processes are the main sources of stable (i.e. relatively long, with rootwads attached) pieces, which can subsequently trap mobile woody debris floating from upstream. In other words, wood storage is mostly related to the availability of stable wood pieces locally delivered by banks and hillslopes rather than coming from upstream reaches.

However, similarities in log length distribution, orientation to flow, number and fraction of pieces within jams and jam dimensions are probably determined by the similar channel size (i.e. bank-full width) of the three third-order streams.

LW storage in the Tres Arroyos (around 700 $m^3 ha^{-1}$ in the active channel, or 556 $m^3 km^{-1}$ based on channel length) is extremely abundant. Comparably high values have been reported only for old-growth conifer forests in the Pacific Northwest, where average wood storage of up to 1000 $m^3 ha^{-1}$ is recorded (Gurnell, 2003). For example, in Mack Creek, a third-order stream (9 m wide, thus comparable to the Tres Arroyos) that flows through a 500-year-old coniferous forest, the average wood storage is 812 $m^3 ha^{-1}$ (reported by Gurnell *et al.*, 2002). Such high LW storage can be partly attributed to the small fraction of wood pieces moved by 'ordinary' floods (<1% in the Mack Creek, Gurnell *et al.*, 2002). In the Tres Arroyos, current investigations using metal tags indicate that a similarly low percentage of wood pieces (2·5–4%; Andreoli, 2007) is mobilized each year by ordinary floods.

The relatively low LW volume stored in the Buena Esperanza (120 m^3 ha^{-1}, 76 m^3 km^{-1}) is determined by its small log diameters, which derive from the extremely slow growth of *Nothofagus* in the Tierra del Fuego, despite the extremely high abundance of wood pieces. The Rio Toro is instead characterized by a low supply of large wood that makes its LW storage comparable to the Buena Esperanza (117 m^3 ha^{-1}, 144 m^3 km^{-1}). Similar values (100–200 m^3 ha^{-1}) are, however, typical of unmanaged mature hardwood forests (Harmon *et al.*, 1986; Hering *et al.*, 2000; Gurnell, 2003), and, most notably, of second order streams in *Nothofagus* native forest in New Zealand (94–101 m^3 ha^{-1}, Evans *et al.*, 1993; Baillie and Davies, 2002). Higher (85–470 m^3 ha^{-1}) wood storage is reported by Meleason *et al.* (2005) for small (3–6 m wide) channels in pristine New Zealand basins. Overall, a reference minimum wood storage between 100 and 120 m^3 ha^{-1} can be envisioned for mountain streams flowing in pristine *Nothofagus* forests in both South America and New Zealand.

Much smaller LW volumes characterize second–third order channels in long managed montane territories such as the Italian Alps (30–70 m^3 ha^{-1}; Comiti *et al.*, 2006), UK Highland Waters (44–88 m^3 ha^{-1}; Gurnell *et al.*, 2002) and northern Spain (0·4–4·8 m^3 ha^{-1}; Diez *et al.*, 2001). Forest management drastically reduces the supply of large logs, which typically dominate wood volume budget (Meleason *et al.*, 2005), and which also represent potential key pieces able to trap finer wood in channels.

Along with spatial density, wood morphological effects may range from almost negligible (as in the case of Rio Toro) up to controlling more than a quarter of the total elevation drop and bed surface characteristics along a quarter of the channel length. Interestingly, differences may be substantial even in adjacent basins, and less pronounced between different climates and forest type (i.e. latitudes). Latitude surely acts on tree growth (i.e. wood diameter) and on natural forest disturbance processes (i.e. wildfire versus windblown moving southward), but, notwithstanding different log size and log number, the net effects on channel morphology are apparently very similar. In the sub-Antarctic climate of Tierra del Fuego, wood rarely reaches large dimensions but the abundant supply associated with wind-caused mortality makes streams prone to local grade-control by valley jams and log steps composed of floated debris trapped by occasional fallen trees. In the warmer climate of the Araucania, fires control forest regeneration and thus probably wood supply to channels. In-channel wood loading does not respond immediately to wildfire, however; a lag time of several decades exists (Benda *et al.*, 2003; Zelt and Wohl, 2004). This may explain why wood volumes are so different between the Rio Toro, where almost all the basin forests burned in 2002, and the Tres Arroyos, which is now heavily dissected as a consequence of fires that occurred almost a century ago. Of course, basin geology and topography play a fundamental role in delivering burned dead wood from hillslopes to the main channel. In the Tres Arroyos, the destruction by fire of the forest cover and of the root network caused severe slope instability, which in turn resulted in debris flows able to transport many huge pieces of wood into the stream, prompting the formation of massive valley jams.

In contrast, in the Rio Toro the burned trees are still standing, and no landslides have taken place yet in the basin, possibly as a consequence of the smaller basin slope (Table I). Wood quantity in this 'wood-limited supply' basin is low, especially when measured as number of pieces per hectare of bed area. Wood volumes are comparable to the Fueginan channel only because *Nothofagus* trees are much bigger in the Rio Toro than in the cold, wind-battered Buena Esperanza. Also, relative wood dimensions in the Rio Toro are smaller than in the other two channels (Table III), possibly favouring wood transport and thus limiting wood storage. However, we may expect Rio Toro to become much enriched in wood within a few decades (10–30 years), once basin hillslopes lose the stabilizing effect of tree roots, and trees themselves decay, fall to the ground and eventually reach the channel network. Whether the degree of basin dissection, frequency of debris flows and in turn wood storage will attain a level comparable to the Tres Arroyos is difficult to predict given the effect of other topographic and lithologic factors.

The Tres Arroyos and the Buena Esperanza have very similar values (27 and 24%, respectively) of channel elevation loss due to LW dams, as well as of percentage of LW-related steps (22 and 19%, respectively). These values are generally lower than in the Pacific Northwest (see the introduction), but are very similar to the percentage reported by Faustini and Jones (2003) for the third-order Mack Creek channel (Oregon, US) and for other headwater streams in the Pacific Northwest (Keller and Swanson, 1979; Keller and Tally, 1979). Much lower relative numbers and drops caused by LW dams were observed in managed mountain rivers of the Alps (Comiti *et al.*, 2006).

The present study confirms that wood-rich reaches, especially those characterized by wood dams, have finer sediments, higher steps and higher flow resistance than non-wooded segments, as previously found by MacFarlane and Wohl (2003). Higher flow resistance appears to occur mostly as a consequence of the steeper and rougher profile that wood jams induce by creating higher steps. However, MacFarlane and Wohl (2003) found that the relative contribution of grain roughness to the total flow resistance – also negligible in most of our reaches – was significantly lower in LW reaches, whereas in the present study the difference is less pronounced.

The longitudinal frequency of LW dams (Table V) in the Buena Esperanza and the Tres Arroyos (32 and 20 dams per km, respectively) appears somewhat lower than in catchments of similar size within the Queets basin (Washington

State, US; Montgomery *et al.*, 2003). However, this reflects the smaller number of log steps for both studied channels; valley jam frequencies are very similar to or even higher than (as in the Buena Esperanza) in the Pacific NW basin. Nonetheless, an identical log-step frequency was observed in the Mack Creek (Faustini and Jones, 2003), and less frequent log steps were observed in the Oregon Coast Range (4 km^{-1}; Marston, 1982). Pristine third order streams in New England were found to have 10–60 dams km^{-1} (Bilby, 1979), therefore encompassing the frequency observed in the Tres Arroyos and Buena Esperanza.

In contrast to pristine basins worldwide, an LW dam frequency of 13 km^{-1} was measured in the third-order Rio Cordon channel (Italian Alps, Comiti *et al.*, 2006), a similar value (around 15 km^{-1}) was found in a third-order channel of the Bavarian Alps (Kaczka, 2003) and the absence of dams was observed in several third-order channels in northern Spain (Diez *et al.*, 2001). Interestingly, in second–third order Italian basins (Comiti *et al.*, 2006), average log-step lengths relative to the cumulative length distribution of wood pieces is smaller (74th–76th percentile) than that found for Tres Arroyos and Buena Esperanza (87th and 89th). In contrast, average log-step diameters are larger (68–83% of the cumulative distribution) in the Alps than in the Andean basins (59 and 73%). This comparison suggests that the lower frequency of LW dams observed in the Alpine streams, and possibly elsewhere in managed basins, is primarily due to the limited availability of large logs in these channels.

Finally, as reported by Andreoli *et al.* (in press), LW can be considered responsible for in-channel sediment storage of about 187 and 119% of the mean annual bedload yield and total sediment yield, respectively. Unfortunately, the lower sediment storage per unit of channel length (Table V) recorded in the Buena Esperanza cannot be compared to measured sediment yield data. Considering the basin's hydrological regime and the scarcity of sediment sources, however, sediment yield in the Buena Esperanza is probably lower than in the Tres Arroyos, and the quantity of sediment stored in its channel by wood is probably 100–200% of the annual sediment yield. These results agree with the value (123% of the mean annual sediment yield) found by Marston (1982) for streams of the Oregon Coast Range.

Conclusions

Old-growth forested basins in the Southern Andes may feature extremely high quantities of large wood (up to 700 m^3 ha^{-1}, and to 1400 pieces ha^{-1}), which exerts a strong control on fluvial processes, composing up to a quarter of the potential energy drop, 'impounding' a similar fraction of channel length, increasing flow resistance by up to one order of magnitude and storing a volume of sediments larger than the annual sediment yield. Wood storage and its morphological effects vary considerably, however, as a function of forest disturbance history and associated degree of basin dissection. In the Araucania region, wildfires – already acknowledged as the main factor driving forest rejuvenation – seem to play a major role in supplying the channel network with large wood, at least in relatively steep basins. More research is thus needed to understand the time lag between fire occurrence and wood storage response, ideally via monitoring of wood abundance in the Rio Toro, which was affected in the 2002 by a severe wildfire but after 4 years still did not show relevant large wood effects in its streambed. Conversely, in Tierra del Fuego, the extent of transformation in channel morphology brought about by the introduction of beavers could be assessed by using the Buena Esperanza as a reference site that has wood dams not created by beavers.

Acknowledgments

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