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Characteristics, distribution and geomorphic role of large woody debris in a mountain stream of the Chilean Andes

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Abstract

The paper presents an analysis of amounts, characteristics and morphological impact of large woody debris (LWD) in the Tres Arroyos stream, draining an old-growth forested basin (9·1 km²) of the Chilean Southern Andes. Large woody debris has been surveyed along a 1·5 km long channel section with an average slope of 0·07 and a general step–pool/cascade morphology. Specific wood storage is very high (656–710 m³ ha⁻¹), comparable to that recorded in old-growth forested basins in the Pacific Northwest. Half of the LWD elements were located on the active floodplain, and around two-thirds of LWD elements were found in accumulations. Different types of log jam were observed, some heavily altering channel morphology (log-steps and valley jams), while others just line the channel edges (bankfull bench jams). Log-steps represent approximately 22% of all steps, whereas the elevation loss due to LWD (log-steps and valley jams) results in 27% loss of the total stream potential energy. About 1600 m³ of sediment is stored in the main channel behind LWD structures, corresponding to approximately 150% of the annual sediment yield. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: large woody debris; channel morphology; valley jams; log-steps; Andes

Introduction

Once being characteristic of all drainage networks in forested basins worldwide (Montgomery *et al.*, 2003), in-channel large woody debris (LWD, i.e. pieces of wood at least 10 cm in diameter and 1 m long) is now abundant only in relatively undisturbed mountain streams. In fact, the massive deforestation that has been pursued in the lower part of watersheds for centuries, and is now particularly active in the developing countries, has mostly left forests in the upper part of the basins. In addition, 'cleaning' larger, lowland channels from woody debris has long been carried out to reduce flood risk and improve navigation, and because LWD represents an available source of fuel for local people (Williams, 2000; Montgomery *et al.*, 2003).

Large pieces of wood resting within channels have strong consequences for river hydraulics, sediment transport, channel morphology and river ecology, as summarized by Gurnell *et al.* (2002), Montgomery *et al.* (2003) and Montgomery and Piégay (2003). In particular, the morphology of mountain streams running through old-growth forests and their potential for sediment storage are largely controlled by LWD, which causes a forced morphology to establish (e.g. log-steps, log jams and valley jams with the associated forced pools) as defined by Montgomery and Buffington (1997). Although LWD represents a serious concern for the conveyance of flood flow (Shields and Gippel, 1995; Darby and Thorne, 1995; Dudley *et al.*, 1998), the environmental benefits of abundant LWD in channels are such that now natural or engineered woody debris is placed within the channels to enhance the quality of stream ecosystems (see e.g. Hilderbrand *et al.*, 1997; Lacey and Millar, 2004; Shields *et al.*, 2004).

Most geomorphological research on LWD has been carried out in the Pacific Northwest region of North America, with some in Europe (see the summary reported by Comiti *et al.*, 2006), and, to the authors' knowledge, very few papers on the subject have been published about the other continents (e.g. Jacobson *et al.*, 1999, for Africa; Baillie and Davies, 2002, and Webb and Erskine, 2003, for Oceania). Among the parts of the world lacking studies on LWD, the humid temperate and tropical regions of the Latin American continent are characterized by thousands of streams

flowing through both pristine and managed forests featuring very large trees, where consequently LWD is expected to affect stream morphology significantly; however, to date no investigations have been performed in such a huge area. Narrowing down the perspective, the Southern Andes represent an ideal location for studying LWD in mountain streams draining forested basins.

Native forests are becoming progressively less abundant in the Southern Andes and neighbouring piedmont areas (within the territories of Chile and Argentina) due to deforestation for agricultural production and for the more profitable industrial plantations of fast-growing species, mostly *Eucalyptus spp.*, Douglas fir (*Pseudotsuga menziesii*) and Monterey Pine (*Pinus radiata*). In particular, the Chilean native temperate rainforest – the so-called Valdivian forest, very similar to the Pacific Northwest forests along the Coastal Range – has been largely eliminated from the piedmont valleys of central and southern Chile.

However, in the upper Andean environments, portions of native, old-growth forest dominated by southern beech (*Nothofagus spp.*) and araucaria (*Araucaria araucana*) are still present within national parks and reserves. These locations thereby provide excellent investigation areas for analysing the influence of large woody debris on the morphology and dynamics of mountain rivers in an almost pristine environment other than North American basins, especially because forest trees growing in the southern Andes differ considerably – in terms of tree size, shape and growth habit – from the well studied basins covered with old-growth coniferous forest typical of the US Pacific Northwest.

The objectives of this paper are (i) to report some basic data on the quantity and characteristics of LWD recorded in a mountain stream of the Chilean Andes, (ii) to describe the impact of LWD on channel morphology and sediment yield at the basin scale and (iii) to compare the results with similar basins located in other regions of the world.

Field Setting

Study basin

The study area is the small 'Tres Arroyos' experimental basin, located within the Malacahuello-Nalcas National Reserve, in the province of Malleco, between the small towns of Curacautin and Lonquimay (IX Chilean Region 'Araucania', Figure 1). The basin area (9·1 km²) is delimited to the north by the southern flanks of the Lonquimay volcano (2865 m a.s.l.) and to the south by the Cautin River, which receives the Tres Arroyos near the town of Malalcahuello (950 m a.s.l.). The main physiographic and climatic characteristics of the watershed are reported in Table I.

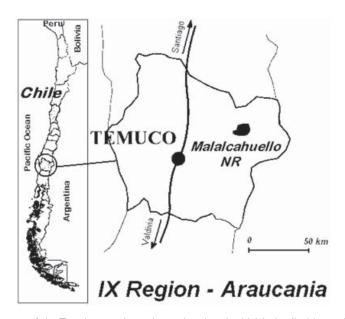


Figure 1. Geographical location of the Tres Arroyos basin, located within the Malalcahuello National Reserve.

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Unit **Values** Basin area km^2 9.1 1487 Average elevation m asl 1000 Minimum elevation m a.s.l. Maximum elevation 1850 m a.s.l. 4.89 Length of the main channel km Mean gradient of the main channel % 18 Mean bankfull width 7.8 m Mean bankfull depth 0.45 m Stream order 3 Annual precipitation 2217 Maximum water discharge recorded* $m^3 s^{-1}$ 14

Table I. Main characteristics of the Tres Arroyos basin

The climatic classification (Fuenzalida, 1965) identifies the area as 'temperate warm with winter precipitations'. The presence of large and high volcanoes strongly influences the climate of the region. The mean annual precipitation is 2217 mm; the most rainy month is June with 402 mm whilst January is the driest with 57 mm. Although snowfall occurs in winter, the hydrological regime is dominated by rainfall. The average time of concentration of the basin is estimated as 1·1 hours (DGA, 2000). The mean annual temperature is 8·5 °C; the warmest month is January with an average temperature of 14·3 °C whilst the coldest month is July with 3·3 °C.

The geology of the area is characterized by pyroclastic rocks such as andesite breccias, tuffs and ignimbrites, lavas and sedimentary layers, all belonging to the Miocenic *Cura Mallin* formation (Emparan *et al.*, 1992). Two more recent volcanic units associated with the Lonquimay volcano date from the Pleistocene and Holocene. The Quaternary sediments have not been differentiated and are described as unconsolidated sediments with pyroclastic layers. In the Malalcahuello area only a type of intrusive rock is found, comprised mostly of monzonites and granodiorites (*Plutónico Melipeuco* group).

The basin is 72% forested (Figure 2), with 61% represented by native old-growth stands having trees up to 40–50 m tall and 1–2 m in diameter, and 6% by much smaller and younger (<50 yr) conifers planted to reduce soil erosion following the large wildfires that occurred during the first half of the last century. The remaining area is characterized by unvegetated sandy volcanic ashes (around the watershed divide, 6%) and herbaceous-shrub cover (near the tree limit, 22%).

The native forests in the Tres Arroyos basin are of two types: the araucaria forest (*Araucaria araucana*) and roble–raulí–coigüe forest (respectively, *Nothofagus obliqua*, *Nothofagus alpina* and *Nothofagus dombeyi*). The araucaria type is found only in the upper part of the basin, above 1200–1300 m a.s.l., with the remaining lower area covered by the mixed southern beech type (DGA, 1998). The understorey of the old-growth nothofagus forest is completely dominated by a very invasive autochthonous bamboo plant, the southern quila (*Chusquea* spp.).

Tres Arroyos main channel

The main channel (third order) from the source to the outlet is almost 5 km long with a mean gradient of 18%. However, the gradient is locally very variable because local controls such as landslides, large valley jams (debris dams) and high log-steps impart to the longitudinal profile a stepped pattern at the stream segment scale (see below). Reach morphology (following the classification by Montgomery and Buffington (1997)) thus covers the range from steep cascade and step–pool to pool–riffle types, but with a high degree of forced morphologies associated with LWD. The channel is mostly well confined within steep rocky slopes, with a narrow active floodplain widening in the lower section of the stream (downstream of the confluence described at the end of this subsection). Terraces whose formation is presumably linked to valley jams (as reported for the Queets River, Washington State, by Abbe and Montgomery, 2003) are commonly evident along the main channel.

The hydrology and sediment transport in the Tres Arroyos have been monitored since 1997 (Iroumé, 1997). The water-gauge station is located at 1080 m a.s.l. and controls a 5.9 km² watershed area (Iroumé, 1997). Preliminary relationships between suspended sediment concentration, bed load rates and water discharge have already been determined (Iroumé, 2003; Lenzi *et al.*, 2004; Uyttendaele, 2005).

^{*}The value refers to the gauging station controlling the upper part of the basin, 5.9 km² in area, as shown in Figure 4.

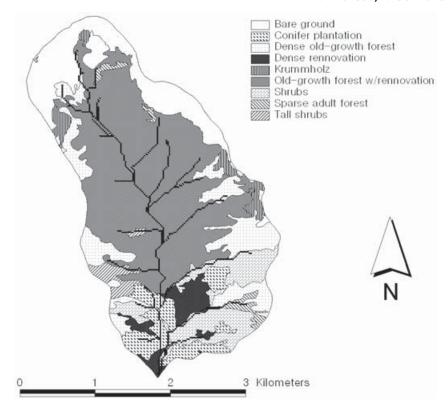


Figure 2. Vegetation map of the Tres Arroyos basin.

Intense flood events occurred in 1972 and 1992, with damage to the road at the outlet of the basin. Local people living on the alluvial fan of the Tres Arroyos claim that LWD was crucial for the dynamics of the 1992 flooding, and report that huge quantities of LWD were deposited on the alluvial fan, not reaching the confluence with the Cautin River. The alluvial fan is characterized by a great deal of LWD spread all over the surface, particularly on unvegetated bars and wooded terraces (Figure 3). Importantly, the Tres Arroyos is heavily affected by debris flows coming from



Figure 3. View of the alluvial fan created by the Tres Arroyos at the exit of its valley. Thousands of wood pieces are spread on the fan surface and buried within the sediments. This figure is available in colour online at www.interscience.wiley.com/journal/espl

the steep tributaries, which deliver huge amounts of sediment and LWD into the main channel. The 1992 flood is estimated (Uyttendaele, 2005) to have transported 5300 m³ of sediment to the alluvial fan, most of which derived from a steep tributary channel where debris flow events are very frequent due to naturally unstable hillslopes and as a consequence of the above mentioned wildfire (Figure 4). An enormous accumulation of LWD (gross geometrical volume ~ 600 m³, Figure 5), formed by 100–150 wood pieces 0.5 m in diameter and 4–5 m long on average, lies at the confluence of this debris flow channel with the main Tres Arroyos channel (another smaller channel also enters the main stream a few meters upstream, as shown in Figure 4). Figure 6 shows two images of the channel: Figure 6(a) depicts the stream upstream of the confluence through the old-growth stands, whilst the lower, wider segment is illustrated in Figure 6(b).

Study methods

The study channel was surveyed for LWD in March–April 2005, on a length of 1540 m, from the alluvial fan apex – the outlet of the basin in Figure 4 – moving upstream. However, an additional 1 km long stretch was also inspected upstream, up to a high waterfall located close to the lower limit of the Araucaria forest. This channel stretch features a morphology and a woody debris density very similar to the upper part of the segment surveyed in detail (i.e. upstream of the confluence with the debris flow channels; see Figure 4).

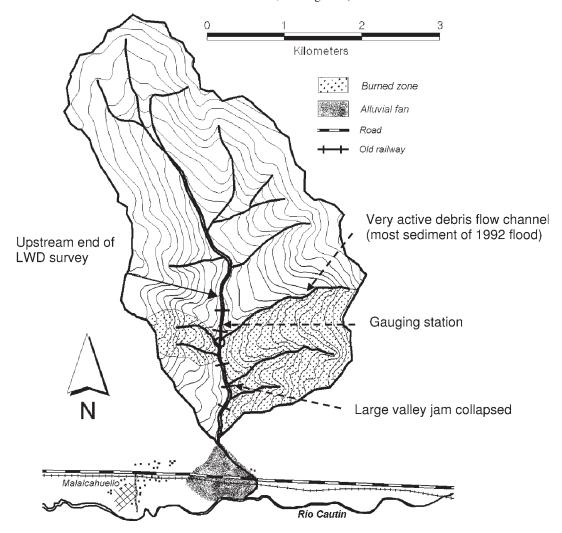


Figure 4. Sketch of the Tres Arroyos basin illustrating the channel network, the extent of the surveyed stream section and the location of the intact valley jams (solid lines transversal to the channel) and of the 'nodal' point (white circle) at the confluence with two debris flow channels. The location of the gauging station operating since 1997 is also shown.



Figure 5. Downstream (a) and upstream (b) view of the large wood jam occurring at the 'nodal' point (see Figure 4 for location) of the Tres Arroyos channel. In (a), the surface underneath the woody debris pile is bedrock. Two persons are indicated for scaling in (b), where the 3 m thick sediment deposit is visible on the left, along with logs protruding from the deposit. This figure is available in colour online at www.interscience.wiley.com/journal/espl

The longitudinal profile of the study section (Figure 7) was surveyed using a laser distance meter with inclinometer. Seventeen individual reaches were defined based on uniformity of either slope, channel width or abundance of debris (Table II). Reach numbering starts from upstream (Reach 1) to downstream (Reach 17). The following characteristics were measured at each single reach: mean channel slope (S), mean bankfull and floodplain (or fluvial corridor) width (W_{bf} and W_{fp} respectively), mean bankfull depth (h_{bf}), number of steps (N_{st}) and number of boulders (N_{b}) respectively higher and larger than h_{bf} . Reach slopes range from 3 to 15% and bankfull width varies from 5.5 to 15.5 m, with average values of 7% and 7.8 m, respectively. Basin area drained at each reach, A_{rp} , was determined from a digital elevation model using GIS software and ranges from 5.5 to 9.1 km².

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. Where the floodplain was absent – as in many confined reaches – a maximum flood level was estimated and served as the upper elevation limit for LWD to be included in the records at each location. A total of 2391 elements were recorded over the entire study segment. In order to quantify the wood storage on the alluvial fan, LWD elements were also measured within a sample area of 2100 m² considered representative of the average wood spatial density on the fan.

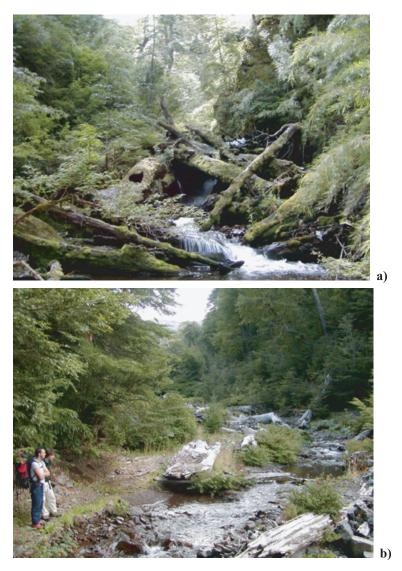


Figure 6. Views of the Tres Arroyos channel: (a) upstream of the nodal point, where the stream is narrower and the largest LWD elements are covered with thick mosses; (b) downstream of the nodal point, where the channel and the valley floor are wider. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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 for a subset of log jams. For detached rootwads, both the minimum diameter (i.e. on the trunk side) and the maximum diameter (i.e. distal root distance) were recorded beside the length of the near-cylindrical part (i.e. the trunk remains, the most relevant as to wood volume).

Several additional data about each wood piece were recorded during the field survey: type (log, rootwad, log with rootwads attached), tree species (nothofagus, araucaria, conifers), orientation to flow (parallel, orthogonal, oblique), state of decay (low, medium, high, based on visual estimation), delivery mechanism into any given reach (bank erosion, landslide, natural mortality, transported from upstream) and position (log-step, in-channel, bankfull line, channel bridging, channel margins). In-channel pieces were defined as all the wood elements lying – at least partially – at a lower elevation than bankfull height, but excluding log-steps (which form a different class). For log-steps, drop height and pool depth were also measured. The LWD elements found at an elevation corresponding to the bankfull stage were combined into a separate group. Wood elements spanning the channel at an elevation higher than bankfull

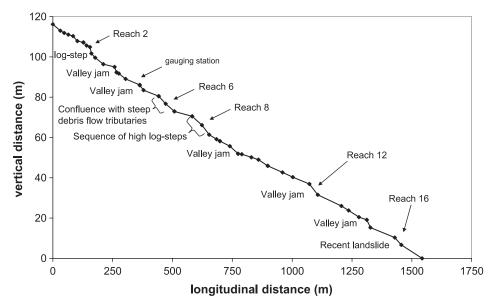


Figure 7. Longitudinal profile of the surveyed section of the Tres Arroyos. The main LWD-related features and external forcings are indicated along with the location of the most relevant reaches.

Table II. Characteristics of the 17 investigated reaches of Tres Arroyos

Reach	Length (m)	Slope (m m ^{-l})	Bankfull width (m)	Floodplain width (m)	Channel morphology*	Adjacent forest type**	Notes	LWD-related features***
-	128	0.07	7.0	11.7	SP, RP	ON	landslide	steps, jam
2	49	0.15	5.5	8.0	SP	ON	tributary fan, landslide	high step, broken VJ
3	90	0.08	6.2	13.7	RP	ON	bank erosion	VJ
4	97	0.07	5.6	8.0	SP, CA	ON	bedrock	jam
5	79	0.06	6.8	17.7	SP, RP	ON	_	steps, VJ
6	65	0.12	8.0	16.0	SP, CA	CP	confluence debris flow channels	steps, huge LWD pile
7	74	0.03	15.5	22.0	RP	ON, CP	deposition area	broken VJ
8	116	0.11	8.0	20.0	SP	ON, YN	confluence dissected sub-basin	Steps, abandoned channel
9	76	0.08	7-8	20.5	SP, RP	ON, YN	bank erosion	VJ
10	124	0.05	7.2	20.4	CA, SP	YN, CP	large terrace	Bend, broken VJ
П	105	0.05	7.1	23.8	SP, CA	YN, CP	large terrace	_
12	69	0.05	7.6	30.2	SP, RP	YN, CP	tributary fan	VJ, broken VJ, jams
13	134	0.07	5.8	27.3	SP, RP	YN, CP	_	steps, jams
14	106	0.07	7-1	21.3	SP, RP	YN, CP	landslide, confluence with steep tributary	jams, broken VJ
15	117	0.08	8.2	11.6	SP, CA	YN, CP	landslide	VJ
16	32	0.11	9-1	16.7	CA	YN, CP	recent landslide	jams, broken VJ
17	82	0.08	7.6	17.3	SP, CA	YN, CP	_	broken VJ

^{*} SP = step-pool, CA = cascade, RP = riffle-pool.

stage were classified as channel bridging, and channel margins pieces were defined as those located on the area adjacent to and higher than the bankfull channel, thus subject to inundation during low-frequency flood events. 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

^{**} YN = young nothofagus; CP = conifer plantation; ON = old nothofagus.

^{***} VJ = valley jam (as in Abbe and Montgomery, 2003).

flow was made, so the total piece length was recorded. This procedure might lead to a slight overestimation of the total LWD 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 LWD studies. Rootwads' volume was approximated to the stem section only – again as a cylinder, neglecting the actual root mass. The spatial density of LWD – in terms of both volume and number of elements – on the active channel and the fluvial corridor will be calculated based on bankfull and corridor widths, respectively.

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. The total instream sediment storage due to LWD will then be compared to the Tres Arroyos basin sediment yield (bedload and total load), as evaluated by Lenzi *et al.* (2004) at the gauging station whose location is shown in Figure 4.

Results

LWD volume, spatial density and characteristics

The average LWD volume stored within the entire fluvial corridor (i.e. including channel margins) of the Tres Arroyos is rather impressive. Based on channel length, it turns out to be 1198 m³ per km of channel length, whereas if normalized by the fluvial corridor extension it is equal to 656 m³ per hectare of fluvial corridor area. The average number of pieces amounts to 1550 km⁻¹ and 848 ha⁻¹. If only pieces within the bankfull channel are considered (i.e. excluding channel margin elements and using bankfull channel area as the reference extension), the volume becomes 556 m³ km⁻¹ or 710 m³ ha⁻¹, with an average spatial density of woods elements of 786 pieces km⁻¹ or 1004 pieces ha⁻¹. LWD storage on the alluvial fan (see Figure 3) downstream of the study channel segment is about 330 m³ ha⁻¹, with 1069 pieces per hectare.

Figure 8 shows the variation of the LWD spatial density along the study channel, with average values of LWD for each individual reach. The variation between reaches is considerable, both considering the active channel, where it ranges from 100 m³ ha⁻¹ (Reach 15) up to more than 4000 m³ ha⁻¹ (Reach 2), and the fluvial corridor, within the interval 350 (Reach 11)–3200 m³ ha⁻¹ (Reach 2).

Maximum and mean dimensions of LWD elements are shown in Table III, where it can be seen that they are slightly different between active channel and fluvial corridor only with respect to maximum values of diameter and

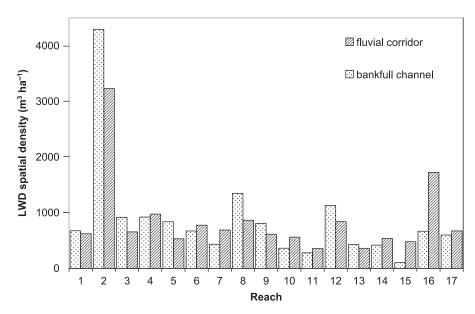


Figure 8. Variation of LWD spatial density between individual reaches. The huge debris flow jam depicted in Figure 5 (located at Reach 6) is not included in the analysis. The extremely high values in Reach 2 are due to a combination of landslide and confluence with a steep tributary.

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Table III. Maximum and average dimensions of wood pieces, differentiated between bankfull channel, fluvial corridor and alluvial fan

	Bankfull channel	Fluvial corridor	Alluvial fan
Maximum diameter (m)	1.2	2.2	1.0
Mean diameter (m)	0.50	0.41	0.38
Maximum length (m)	25.7	26.0	6.0
Mean length (m)	3.0	3.2	2.0
Maximum volume (m³)	24.86	36.85	3.40
Mean volume (m³)	0.70	0.77	0.31

Table IV. Decay rate of wood elements, differentiated between bankfull channel and fluvial corridor (i.e. including LW D at channel margins). 'Low' indicates that leaves or most of the bark was still attached, 'High' refers to porous, low density elements and 'Medium' to an intermediate state (absence of bark and leaves, but solid wood)

	Bankfull channel	Fluvial corridor	Alluvial fan
Low (%)	2	2	0
Medium (%)	83	71	97
High (%)	15	27	3

piece volume. In contrast, wood elements found on the alluvial fan are considerably shorter and much smaller in terms of piece volume.

The proportion of nothofagus and araucaria is the same both considering 'marginal' elements and not: 94 and 6%, respectively. In contrast, in the alluvial fan as many as 11% were pieces of araucaria trees, and the remainder 89% of nothofagus, possibly indicating that the former can move through the channel more easily. Very few, small pieces of conifers (pine, Douglas fir) derived from plantations were found in the channel, and are negligible altogether, also in lower reaches where the old-growth nothofagus forest is absent. As to the decay rate (Table IV), elements having a low degree of decay were very uncommon, and an intermediate state (i.e. solid wood but no bark) dominates. In the fluvial corridor as a whole, a higher percentage of LWD exhibits an advanced decay state, possibly due to more favourable conditions for decomposition such as a long exposure to the atmosphere in a humid environment, shaded by the riparian trees. In contrast, almost all the wood pieces on the alluvial fan featured an intermediate state of decay (drier conditions due to the absence of tree cover).

Approximately two-thirds of LWD elements were found in accumulations, and only one-third as single pieces. No large differences are present between the whole fluvial corridor and the bankfull channel: the number of elements categorized as jam forming is in fact very similar in both situations, amounting to 66 and 68%, respectively, whereas they amount to only 44% on the alluvial fan.

Similarly, no discrepancies are apparent with respect either to the type of LWD element (Table V) or to the orientation of wood pieces to the flow (almost equally distributed among oblique, orthogonal and parallel categories, with a weak dominance of oblique pieces, 37%). The orientation of pieces on the alluvial fan was not assigned, given the difficulties in evaluating the actual flow direction relevant to each wood element.

Looking at the presumed origin of the LWD within each given reach (Figure 9), as many as 88% of the pieces within the bankfull channel appeared to have been transported from upstream, around 10% were associated with local

Table V. Composition of woody debris in terms of the type of wood element, differentiated between bankfull channel, fluvial corridor and alluvial fan

	Bankfull channel	Fluvial corridor	Alluvial fan
Rootwad (%)	I	I	2
Logs with rootwad (%)	4	3	5
Logs without rootwad (%)	95	96	93

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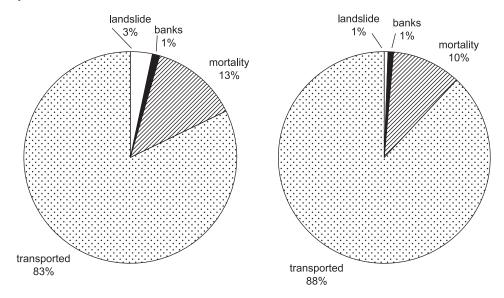


Figure 9. Presumed cause of delivery of LWD to any reach. Left, within the whole fluvial corridor; right, within the bankfull channel.

natural tree falls and the remainder with landslides and bank erosion occurring within the reach. Input from debris flow channels is included in the 'transported' category. LWD found on the alluvial fan was all transported from upstream.

Dimensions and characteristics of wood jams

In the surveyed reaches a total of 123 accumulations of LWD pieces were found within the entire fluvial corridor, which corresponds to the spatial density of 80 jams per km of channel length. If only jams at least partly located within the bankfull channel are considered (i.e. those likely to affect bed morphology), the total number of jams amounts to 78, corresponding to 51 jams per km of channel length, with an average jam spacing of about 20 m. As to the LWD volume, half of the total volume of wood stored in jams belongs to accumulations located outside the channel. The main log-jam characteristics are reported in Table VI.

Different types of log jam (following the classification of Abbe and Montgomery, 2003) were observed in the Tres Arroyos channel, varying from *in situ* to combination and transport jams (Figure 10). *In situ* and combination types are mostly represented by log-steps and valley jams (or large debris dams) that will be analysed in detail in the following sections. The dominant transport jam-type is bankfull bench jams lining the channel edges, with fewer

Table VI. Average characteristics of the log jams in the Tres Arroyos. Figures in brackets represent the range of variation of the parameters. Jam dimensions refer to a subset of 53 jams (total jam number = 123)

Jam characteristic	Value
Number of pieces	13 (2–93)
Wood volume (m³)	9 (0·2–68)
Piece diameter (m)	0.4 (0.10-2.2)
Piece length (m)	3.0 (1.0–25.7)
Jam length (m)	6.2 (1.0–17.5)
Jam width (m)	4.2 (1.0-17.0)
Jam height (m)	1.1 (0.3–2.5)
Geometric volume (m³)	45 (0.8–315)
Wood/air ratio	0.2

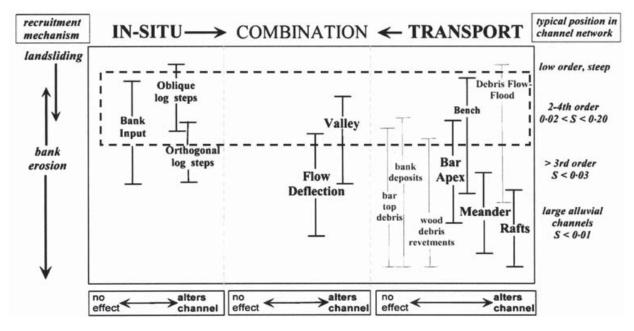


Figure 10. The types of log jam found in the Tres Arroyos (within the dashed rectangle), shown on the background of the classification of Abbe and Montgomery (2003). The jam types in the Tres Arroyos (third order channel, 0.03 < S < 0.15) match those previously described for the Queets River (Washington State, US).

occurrences of unstable jams located also on the floodplain (bank deposits and revetments). Few debris flow jams occur but these represent the largest accumulations, mostly lying outside the channel at confluences with steep tributaries (see Table II and Figures 5 and 10).

Analysing the origin of the LWD elements found in jams, the vast majority appear to have been transported from upstream (86%), and represent racked or loose pieces. Key pieces derive from landslides (4%), bank erosion (1%) and natural mortality (9%). Such a distribution closely resembles that depicted in Figure 9 for the total population of LWD pieces (single and in accumulations together). Conversely, within the jams there is a dominant element orientation, which is the oblique category (42%), with fewer orthogonal elements (29%).

Position and morphological role of LWD in the Tres Arroyos

Floodplain. Slightly more than half of the LWD pieces measured in the Tres Arroyos lie outside the bankfull channel (Figure 11) and are represented either by transport, debris flow jams formed at the outlet of the tributaries, by single pieces and unstable jams deposited at the flood peak along the main channel or by stable valley jams. No significant

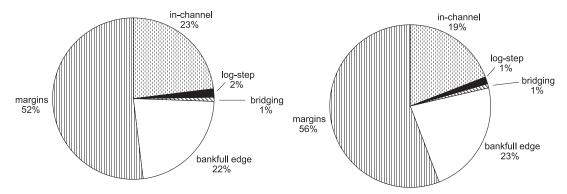


Figure 11. Position of the wood pieces in the Tres Arroyos shown for the single and jam-forming elements together (left) and for the single elements only (right).

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differences emerge when comparing the positions of all wood pieces (single and in jam, Figure 11(a)) with those of the single pieces only (Figure 11(b)). Unstable jams or single loose pieces deposited on the channel margin have a small influence on the channel or floodplain morphology, even though they alter the establishment of vegetation on the floodplain and may limit bed degradation and promote sediment deposition, elevating the channel bed (cf. Kochel et al., 1987). On the other hand, stable LWD pieces at channel margins in the Tres Arroyos were either part of complex jam structures blocking the channel and extending into the floodplain (i.e. valley jams) or gave evidence of the former existence of similar structures now collapsed (see below), tightly associated with terraces a few meters higher than the present active floodplain.

Bankfull channel. Of the LWD in the bankfull channel, the majority is equally split between in-channel (i.e. resting on the channel bed) and bankfull (i.e. lining the channel edges) pieces (Figure 11). Very few pieces actually constitute log-steps (i.e. form step crests) or bridge the channel. Bankfull elements, mostly oriented parallel to the flow, did not clearly show large influences on bed morphology, but are likely to shelter the banks from the direct action of the main flow, thereby limiting bank erosion as long as they are not mobilized. We rarely observed bed deformations (e.g. pools or bars) directly linked to the presence of LWD, suggesting that most of them may be rather mobile or at least that they have not had the time to produce major changes since they were deposited during the last flood event. However, bed surface grain size was locally altered by the presence of LWD (e.g. patches of finer gravel behind large logs).

Log-steps. Even though step-forming elements represent just a tiny proportion of the total LWD population, they, along with valley jams, exert a major influence on the channel morphology and flow energy expenditure in the Tres Arroyos (Table VII). Twenty-seven log-steps, excluding those forming parts of valley jams, were identified, corresponding to an average density of 1·7 log-steps per 100 m of stream length. The total number of steps (clast steps, log-steps and mixed ones) along the surveyed stream section is 122, and thus the proportion of log-steps is equal to around 22%.

In order to compare the sediment stored behind log-steps with the basin sediment yield (see discussion), the total geometric sediment storage of 1000 m^3 (Table VII) must be reduced accounting for porosity. Assuming that interstices between pebbles and cobbles are at least partially filled by gravel and sand, a value for porosity ≈ 0.20 can be assumed (Carling and Reader, 1982; Lisle and Lewis, 1992; Barrash and Reboulet, 2004). In this way, the total sediment stored behind log-steps becomes 800 m^3 .

Valley jams (large debris dams). Five intact large debris dams (valley jams as defined by Abbe and Montgomery, 2003) extending across the channel and into the present banks were observed in the Tres Arroyos (Figure 4), and seven more, now collapsed, were identified based on the terraces associated with orthogonal key-logs protruding out of the banks, as well as on the residual loose and racked elements lying on the terraces.

Valley jams in the Tres Arroyos are formed by a variable number of wood pieces (17–63), mostly transported from upstream, but key elements may derive from bank erosion, natural tree mortality or debris flows. The intact valley jams present a cumulative elevation drop of 10 m. Combining this value with the cumulative elevation drop due to log-steps (23·5 m) gives the total loss of the elevation due to LWD at 33·5 m, which corresponds to dissipation of 27% of the potential stream energy in the surveyed channel section (Table VII).

The total volume of sediment stored behind valley jams (Table VII) is almost identical to the cumulative sediment volume trapped behind log-steps. Therefore, an overall estimation of about $1600 \, \text{m}^3$ of sediment (accounting for porosity ≈ 0.20 , as mentioned above) stored in the main channel due to LWD can be made. However, some smaller sediment deposits stabilized by wood pieces are not included in this calculation and, moreover, the sediment stored on

Table VII. Average characteristics of log-steps and valley jams in the Tres Arroyos. Figures in brackets represent the range of variation of the parameters. Sediment storage values do not account for porosity (see text for details)

	Log-steps	Valley jams
Frequency	1·7 per 100 m	0·33 per 100 m
Drop height (m)	0.87 (0.15-3.00)	2 (1.5–2.7)
Cumulative elevation loss (% of total)	19	8
LWD piece diameter (m)	0.47 (0.20-1.10)	0.36 (0.10-1.00)
LWD piece length (m)	6.11 (1.25-25.70)	3.20 (1.00-12.00)
LWD total volume (m³)	2.1 (0.1–24.4)	19.6 (9.69–33.00)
Sediment stored behind each structure (m³)	37 (0.5–175)	191 (52–308)
Total sediment stored (m³)	1000	956
Total sediment stored per unit channel length (m³ km ⁻¹)	648	620

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Figure 12. View from downstream (above) and upstream (below) of the large collapsed valley jam (indicated in Figure 4) at the confluence with a debris flow channel delivering huge amounts of LWD into the main stream. Two persons are circled for scaling in (b). The large amount of sediment once stored behind this LWD structure can be inferred from the sediment layers on the left of the picture. This figure is available in colour online at www.interscience.wiley.com/journal/espl

the floodplain is completely overlooked, so that the total amount of sediment retained in the stream due to LWD is presumably much higher.

The biggest collapsed valley jam (Figure 12) was estimated to be 3.5 m high and 22 m wide, and to have stored approximately 1700 m³ of sediment (wedge volume), causing deposition and widening of the channel bed for 60 m upstream. This collapsed dam is located between Reaches 11 and 12 (Table II), a few meters upstream of an intact dam at the confluence with a steep tributary delivering huge amounts of LWD. A large fan forcing the main channel has been built over time by the tributary stream in which recent debris flow events certainly occurred, and probably increased in frequency after the wildfire (Figure 4). Furthermore, Reach 11 (located just upstream of this failed debris dam) is characterized by wide terraces at different elevations and having different tree ages, presumably linked both to the tributary fan evolution and to former valley jams.

Also, the 'nodal' point, i.e. the multiple confluence with the two debris flow channels (Figure 4) which now 'hosts' the large LWD accumulation described in the previous section, once was probably the location of another large debris dam. This is indicated by the presence of a 3 m-thick layer of fine sediment and logs sticking out from the banks (Figure 5(b)).

Other types of morphological influence of LWD. As indicated in Figure 10, flow-deflection jams could also be expected to occur in a relatively steep, low-order channel such as the Tres Arroyos (Abbe and Montgomery, 2003). In fact, some examples of such jams were observed; however, their impact on the channel morphology was generally limited, apart from an unusually abrupt bend (Reach 10), and a case of log jam that had caused an avulsion, leaving a 30 m long abandoned channel beside the present stream course (Reach 8).

Discussion

LWD storage in the Tres Arroyos channel is extremely abundant (on average 710 m³ ha⁻¹ within the bankfull channel). Higher values have been reported only for old-growth forests in the Pacific Northwest, where wood storage up to 1000 m³ ha⁻¹ can be reached (Gurnell, 2003). For example, in the Mack Creek, a third-order stream (9 m wide, thus comparable to the Tres Arroyos, see Table I) that flows through a 500-year-old coniferous forest, the average wood storage is 812 m³ ha⁻¹ (reported by Gurnell *et al.*, 2002).

However, LWD storage both in the active channel and in fluvial corridor of the Tres Arroyos varies considerably between reaches (Figure 8). Indeed, the extreme value featured by Reach 2 is heavily determined only by the presence of three huge logs (>1 m in diameter and >20 m long). Peaks of LWD spatial density are primarily associated with steep debris flow tributaries (Reaches 12, 8 and partly 2) and with landslides (Reaches 16 and partly 2), paralleling what is commonly observed in other environments (see Comiti *et al.*, 2006), with valley jams and high log-steps typically forming in these LWD-rich channel sections (see below). It is important to recognize, however, that single reach values of spatial density are strongly dependent on the way in which the subdivision into reaches was made, this not being at fixed channel length intervals (see Table II).

Most of the surveyed channel (from Reach 6 to 17) lies adjacent to the area that experienced wildfires in the past century (Figure 4). Different LWD spatial densities could then be expected (see, e.g., Zelt and Wohl, 2004) between this lower stream section and the reaches located upstream (1–5). A comparison (by the Mann–Whitney U test) of the respective specific wood storage values reveals no statistical difference when considering all the LWD elements within the fluvial corridor, whereas for the pieces within the bankfull channel only, a significant (p < 0.05) discrepancy is shown. The upstream reaches feature, on average, twice as much LWD volume as the downstream section affected by the wildfire. Unfortunately, such an outcome cannot be reliably attributed to the wildfire because exactly the same stream sections differ with respect to other important geomorphological features such as valley width and hillslope gradient.

Wood pieces - mostly deriving from large, mature nothofagus trees - in the Tres Arroyos active channel are relatively quite large when compared in terms of bankfull depth, but much smaller based on channel width. In fact, the average ratio between piece diameter and bankfull depth is close to unity, whereas the ratio between piece length and bankfull channel width is around 0.40 and only 6% of the elements are longer than mean bankfull width (i.e. stable pieces). Furthermore, only the 95th percentile of the cumulative distribution of piece length is equal to the mean bankfull width, whereas just the 70th percentile of piece diameter distribution is needed to match mean bankfull depth. As a comparison, in the Mack Creek (see above), the mean channel width is approximately equal to the 75th percentile of the piece length distribution (reported by Gurnell et al., 2002). In the Rio Cordon, a third-order channel of the Dolomites (managed conifer forest), the average ratio between piece length and bankfull width is 0.66, and 19% of the LWD elements are longer than the channel width (Comiti et al., 2006). Following Bilby and Ward (1989) and Braudrick and Grant (2001) concerning the dominant role of piece length/channel width for wood transport in small streams, the differences reported above suggest that wood mobility in the Tres Arroyos might be higher than in streams draining coniferous-forested basins, possibly due to mature nothofagus trees that deliver many relatively short - yet large - branches into the channel. Furthermore, LWD on the alluvial fan - which was certainly transported from upstream – is much shorter than wood elements along the channel, and presents a maximum length (Table III) 25% smaller than the average channel width, whereas mean and maximum diameter do not differ so much from values recorded in the channel. Indeed, LWD transport in the study stream seems to be quite active as inferred from the occurrence of large pieces of araucaria - probably easier to transport given their straight cylindrical shape without branches – and nothofagus well downstream from their possible input locations, the scarce presence of logs with rootwads, the relatively high percentage of wood elements parallel to the flow and the high degree of wood 'jamming' (see Gurnell, 2003).

Jam frequency values conform well to the mean number of jams per unit channel length described for the Queets River by Abbe and Montgomery (2003), whereas they are generally smaller than values (25–50 m) found by Martin and Benda (2001) for similar drainage areas (5–10 km²) in the Game Creek basin, Alaska. However, Martin and Benda (2001) defined as jams only such log accumulations which block at least 20% of the bankfull channel width. In the Tres Arroyos, only 14 jams reduced as much the cross-sectional width, with an average blocking factor for each of

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these jams amounting to 40%. It is noteworthy that the average jam wood/air volume ratio of about 20% is very similar to that observed in the Tagliamento, a large gravel-bed river in Italy (Gurnell *et al.*, 2000), assuming for that site an average wood density of 500 kg m⁻³ (Harmon *et al.*, 1986). However, this wood/air ratio is twice that found by Thévenet *et al.* (1998) in French piedmont rivers.

The distribution of the jam types in the Tres Arroyos closely resembles that described by Abbe and Montgomery (2003) for the steepest (second–fourth order channels, with the gradient steeper than 0·02) segments of the Queets River. This reflects the abundance of large trees in the adjacent forest delivering to the channel both several stable key pieces and several smaller fragments able to build up impressive valley jams as well as more unstable accumulations at the channel edges and on the banks.

However, in the Tres Arroyos, log-steps (Table VII) appear to be less frequent than in the Queets basin – considering streams draining areas less than $10 \, \mathrm{km^2}$ – where Montgomery *et al.* (2003) found log-step frequency in the range 5–10 per 100 m. A similar frequency was observed in the Mack Creek (see above), for which Faustini and Jones (2003) reported about 1·7 log-steps per 100 m of channel length. Considering other third-order channels worldwide, smaller log-step frequencies were instead observed in the Oregon Coast Range (0·4 per 100 m; Marston, 1982) and in the Dolomites (1·3 per 100 m in the Rio Cordon; Comiti *et al.*, 2006). Valley-jam frequency in the Tres Arroyos is very similar to that encountered in the Queets River for similar basin areas. Unfortunately, the sample size of these accumulations in the study channel is too small to analyse their distance from a geostatistical perspective, as recently done by some authors (Wing *et al.*, 1999; Keim *et al.*, 2000; Kraft and Warren, 2003).

The location of the valley jams is clearly linked (Table II and Figure 4) to external forcings such as landslides, actively eroded banks and the confluences with debris flow channels, which provide the main channel with large, stable wood pieces able to build up a large transversal jam structure by trapping smaller wood pieces (cf. Abbe and Montgomery, 2003). Similar valley jams with similar spacings were also observed during a preliminary inspection undertaken upstream of the surveyed channel section, where the channel is confined within a thick old-growth forest, analogous to Reaches 1–5 (Table II, Figure 6). Along this upper section of the stream, the delivery of wood by debris flows is much less important, whereas rock outcrops narrowing the channel provide favourable locations for valley jams to establish, possibly with smaller key elements.

In the Tres Arroyos, the overall 27% of channel elevation loss due to LWD-induced steps (log-steps and valley jams, Table VII) is very similar to the percentage reported by Faustini and Jones (2003) for the third-order Mack Creek channel (30%) and for other headwater streams in the Pacific Northwest (Keller and Swanson, 1979; Keller and Tally, 1979), but much higher than the value (6%) reported by Marston (1982) for third-order channels in the Oregon Coast Range. As reported in the previous section, 1600 m³ of sediments are stored in the Tres Arroyos behind log-steps and valley jams, whereas the annual bedload and total sediment yield can be estimated – extending the estimated areal value presented by Lenzi *et al.* (2004) to the whole basin and assuming a specific sediment weight of 2·7 t m⁻³ – to be 856 and 1334 m³ yr⁻¹, respectively. Therefore, LWD can be considered responsible for the in-channel sediment storage of about 187% and 119% of the mean annual bedload yield and total sediment yield, respectively, very similarly to that found (123% of the mean annual sediment yield) for streams of the Oregon Coast Range by Marston (1982). However, other authors report that LWD creates storage sites able to accumulate volumes of 10–15 times the annual sediment yield in mountain streams (e.g. Mehagan, 1982; Swanson and Fredriksen, 1982), whereas Keller *et al.* (1995) found, for third-order Californian streams, that sediment storage due to LWD was equivalent to the 100–150 years bedload yield. Such a discrepancy is likely to depend – at least partially – on the large interannual variations in basin sediment yield occurring in mountain rivers (Lenzi *et al.*, 2004), which give a high degree of uncertainty to this reference value.

Conclusions

Large woody debris in the third-order Tres Arroyos stream is very abundant. In fact, the amount of wood storage is comparable only to channels in the old-growth conifer forests of the US Pacific Northwest. In contrast, wood dimensions relative to channel dimensions appear to be smaller, probably as a consequence of the different type of wood element produced by the surrounding tree species. Natural tree mortality appears to be an important input mechanism, more than landslides or bank erosion, but massive inputs from debris flow channels represent critical locations of channel forcing. Such large quantities of woody debris exert a considerable influence on the stream functioning, with large valley jams and high log-steps imparting a macro-scale stepped profile to the channel, dissipating more than one-fourth of the potential stream energy and storing a volume of sediment of at least the same order of magnitude as the annual sediment yield. Finally, this is probably the first study on woody debris in Andean basins, thus further investigations on the topic are absolutely necessary to validate the results presented here and to analyse the wood dynamics at different basin scales.

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