INCO-CT2004-510739

EPIC FORCE

Evidence-based Policy for Integrated Control of Forested River Catchments in Extreme Rainfall and Snowmelt

Instrument: Specific Targeted Research Project

Thematic Priority: Specific Measures in Support of International Cooperation, Developing Countries, A.2 Rational Use of Natural resources, A.2.1 Managing humid and semi-humid ecosystems

Deliverable D20

Functional relationships for LWD volume, mobility and impact on channel hydraulics

Authors: Andreoli A., Comiti F., Lenzi M.A., Mao L., Picco L., Rigon E., Pecorari E.

University of Padova (UNIPD)
Department of Land and Agroforest Environments

Due date of deliverable: Month 30
Actual submission date: Month 30

Start date of project: 1 February 2005 Duration: 36 months

Organisation name of lead contractor for this deliverable: University of Padova

Revision [final]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

SUMMARY

The document is a report on storage, mobility and effects of woody debris in Alpine and Andean study basins. The aim is to provide scientific knowledge on a component of river systems overlooked until recently, but which can be very relevant for the dynamics of streams in the Southern Andes, as well as for flood risk mitigation in such regions.

Five mountain rivers with channel slopes ranging from 0.04 to 0.26 (basin area 2.2 – 51 km^2) were surveyed in the Italian Alps to test and calibrate the field methods, then applied to three third-order mountain basins (mean channel slope 0.05 – 0.08, drainage area 9 – 12 km^2), ranging from the temperate warm Chilean Andean Cordillera to the subantarctic Tierra del Fuego (Argentina).

Channels were divided into uniform reaches and their mean gradient, bankfull width and flow depth were measured, along with number of steps, number of boulders and other morphological features. Amount, characteristics and dimensions of wood pieces were recorded, as well as their effects on stream morphology, hydraulics and on sediment storage. Wood jam type were classified based on a system developed for temperate rainforest basins in the U.S. Pacific Northwest. Also, wood transport over a 1 year time period was assessed by means of metal tags repeatedly surveyed in two Andean basins.

Results show that very large variations in the volume of woody debris per unit of streambed area occur even within single streams, and that massive inputs may result from slope instabilities adjacent to the channels. In the Alps, wood storage is low (i.e., 10 – 100 m^3ha^{-1}) compared to most previous data published from different world regions, mostly for the relatively young age of forest stands (previously heavily harvested or replaced altogether by crops and pastures) and for the periodic channel cleaning. A strong negative correlation is here observed between basin area and wood storage.

In the Andes, major differences in wood abundance exist even between adjacent basins, due to the basins' disturbance history (fire). Massive wood volumes (i.e., > 1,000 m^3ha^{-1}) can be reached in basins disturbed by fires followed by mass movements and debris flows. Wood mobility at bankfull conditions appears quite scarce (<4% of the logs moved), and it seems likely that only infrequent events (> 20-30 yr) may lead to a substantial wood transport, with consequent flooding hazards. On

the other hand, positive impacts of wood on stream morphology and dynamics are impressive in the Andes. Potential energy dissipation due to wood dams is about a quarter of the total elevation drop in two streams, with a sediment volume stored of around 1,000 m^3km^{-1}, of the same order of the annual sediment yield. A quarter of the streambed length is influenced in slope and grain size by the presence of wood dams, which may increase flow resistance up to one order of magnitude. Therefore, in-channel wood in Andean basins is a precious resource for stream stability and ecological status which must be preserved, and only in case of high flood risk levels wood-trapping structures might be worth to be installed upstream of sensitive locations.

A flow chart for assisting decisions on where and how to manage wood for flood prevention is presented at the end of the document. This tool aims at helping local agencies to optimize structural and non-structural efforts in controlling possible flood risks deriving from floating wood.

TABLE OF CONTENTS

1. INTRODUCTION

This report summarize the LWD relationships founded on 2005-2006 field work in northern Italy and south America. Furthermore LWD impact for different forest types and management are discussed.

Data has been collected from basins in the Alps and from two of the focus areas in Latin America. The European basins was included to provide a convenience test sites close to participant 2 which used it to test methodologies and collect data for developing the functional relationships. The Latin American sites allow the validation of the relationships and extension to different conditions (such as forest type and management). The final relationships can be used to show the impacts of different land covers and management on LWD mobility and volume and to assist in evaluating the flood risk and potential damage to infrastructure from LWD.

Using field data, relationships has been developed for predicting LWD volume and mobility during flood events as a function of catchment and stream characteristics, forest cover, water discharge and land use. Techniques deployed include dividing the study streams into reaches with specific characteristics, mapping of large logs and log jams, tagging to monitor mobility and surveying sediment wedges stored behind LWD accumulations (e.g. Faustini, 2000; May , 2001, 2002; CFER, 2002; Faustini and Jones, 2003).

2. FIELD SETTINGS

2.1 Italian study sites

The Italian study sites are represented by six basins located in the southeastern alps (Figure 2.1). Figure 2.2 shows some images of the surveyed channels. They drain calcareous and sedimentary mountain catchments within the administrative boundaries of the Province of Belluno. A summary of the most important characteristics of the study basins is reported in Table 2.1. The basins' relief are very high (>2,000 m) with very steep hillslopes and diffused dissection due to the prevalence of sedimentary rocks. In particular, the channels investigated are part of the Cordevole basin (tributary to the Piave River flowing into the Adriatic sea), which suffered enormous damages in 1966 during an extraordinary flood event (recurrence interval estimated > 200 yr). Much of the destruction was attributed to large woody debris derived from bank erosion and landslides causing obstructions and flood pulses from debris-dam collapse (Castiglioni, 1974).

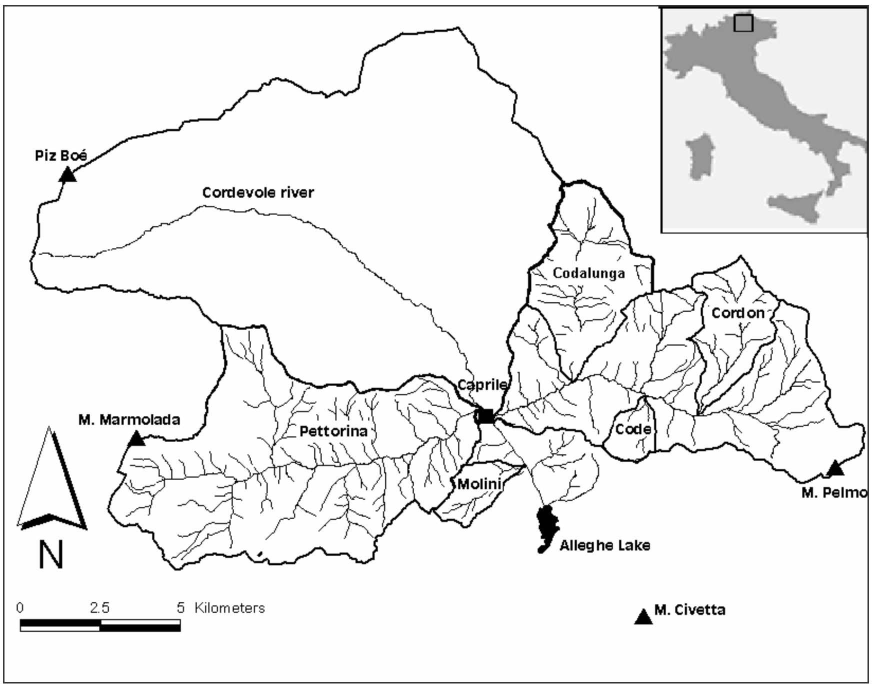


Figure 2.1 – Location map of the italian study basins (Northeastern Italy). Triangles indicate the major peaks of the area, and the town of Caprile is also marked (black square).

Figure 2.2 – Some pictures of the italian study channels: a) debris accumulation upstream of a check-dam in the Fiorentina; b) alders falling into the Codalunga; c) log-step in the Rio Cordon; d) depositional reach in the Rio Code; e) image of the Rio Molini; f) narrow deep gorge in the Pettorina.

Basin	Area (km^2)	Forested area (%)	Stream order	Mean elevation (m a.s.l.)	Mean basin slope (%)	Channel length (km)	Mean channel slope (%)	Dominant bed morphology
Fiorentina	58.1*	51	5**	1838	55	12.0	6	Artificial****/Riffles
Cordon	7.7	32	3	2075	47	5.5	12	Step-pool
Code	2.2	89	2	1776	41	1.7	26	Cascade / Bedrock
Codalunga	13.51	38	4	1930	55	6.3	17	Step-pool
Pettorina	51.0	41	4	1944	65	12.9	9	Artificial**** / Riffles
Molini	2.9	91	2	1609	51	3.6	26***	Step-pool/Bedrock

Table 2.1 – General characteristics of the italian study basins. (*Actual drainage area at the downstream end section surveyed is 37 km^2, **Actual stream order at the downstream end section surveyed is 4, ***100 m-high waterfall in the channel, ****Sequences of concrete check-dams.)

Precipitation (1100 mm annual average) falls mainly in spring and autumn as cyclonic, long-duration rainfalls, and as snowfall from December through April. Short-duration, intense summer rainstorms cause flash floods in the smaller basins (generally < 2-3 km^2), where debris flow phenomena are frequent. Sediment sources in the form of talus slopes, shallow landslides, bank erosion and slow mass movements are widespread but their abundance differs considerably according to the geology of each basin.

Forest cover (Tab.2.1) of the basins – the upper tree limit is around 2000-2100 m a.s.l. – is mostly represented by conifers: spruce (*Picea abies*, (L.) H.Karst. 1881) within the elevation range 1000 – 1600 m a.s.l., whereas the upper zone (1600 – 2000 m a.s.l.) features mixed spruce-larch (*Larix decidua*, Mill. 1768) stands. No old-growth stands exist in the basins. Most of the forest stands covering the study basins are classified as "protection forests", meaning that their main function is to prevent mass movements, snow avalanches and soil erosion. In such a category, only the selective cut (e.g. single mature trees) is allowed. Nonetheless, the ruggedness of the terrain is such that most of the forested area is not harvested anyway because unprofitable. Therefore, effects of logging slash on in-channel woody debris is expected to be small or negligible.

Riparian vegetation is constituted by broadleaves at the lowest elevations (<1400-1500 m a.s.l.) – mostly alder (*Alnus incana* L.) with minor presence of ash (*Fraxinus excelsior* L.), maple (*Acer pseudoplatanus* L.), and willow (*Salix* spp) – and by spruce and larch in the upper part of the channels. Conifer trees typically have diameters on average around 0.3 - 0.4 m, while riparian broadleaves feature smaller sizes (< 0.3 m). Mean tree height is around 20 – 30 m for conifers and 5 – 10 m for broadleaves.

Clearing of woody debris and cut of riparian vegetation has certainly affected some reaches of the three larger channels, i.e. segments of the Pettorina and Fiorentina closer to towns and roads. As a consequence, LWD density and dimensions in these two channels have been heavily lowered – locally at least – by direct human interventions. On the contrary, clearing of woody debris in the other smaller streams (Code, Molini, Cordon) is not commonly practiced, but stream restoration operations immediately following the disastrous 1966 flood event have approximately “set to zero” the amount of woody debris in all the six study channels, thus making the three steeper creeks examples of “quasi-undisturbed” conditions lasting for more than three decades (1967-2003).

Channel morphological types of the study streams – following the classification by Montgomery and Buffington (1997) – are summarized in Table 2.1. The Rio Code is the only channel out of the six under study where debris flow processes are likely to dominate sediment transport and dictate channel morphology (see its relatively large channel width in Table 2.2 and Figure 2.2). However, debris flows and/or hyper-concentrated flows may occur less frequently (approximately every 50-100 yr) in the Rio Cordon and Rio Molini. Along with natural morphologies, Fiorentina Pettorina and Codalunga feature several “artificial” reaches where the local bed gradient is determined by prevailing deposition upstream of check-dams. These low-slope (≈1-3%) streambed lengths, often also unnaturally wide, typically show lateral and median bars with riffles and transverse ribs in the low-flow channels.

Channel	Surveyed length (km)	N reaches	Mean slope (%)	Mean bankfull width (m)	N pieces	N jams	N rootwads	N log-steps
Fiorentina	5.4	65	4	11.4	1557	76	180	39
Cordon	2.7	60	10	5.4	602	34	90	35
Code	1.6	37	26	4.8	767	49	152	55
Codalunga	4.1	43	15	5.7	818	20	33	11
Pettorina	8.8	50	6	7.4	1320	108	77	11
Molini	2.1	48	16	3.6	655	15	41	41

Table 2.2 – Summary of the Italian LWD field survey.

Concrete check-dams were built in most streams of the area after the exceptional 1966 flood, even if some control structure was already present. Of the six study channels, the Fiorentina main channel is the most impacted by control structures (several check-dams, two open check-dam and many ripraps). The Pettorina is also heavily “artificial” (weirs, check-dams, ripraps and concrete banks within villages), while the Rio Cordon presents just a staircase-like sequence of concrete check-dams upstream of its confluence with the Fiorentina. Also, the upper Cordon is monitored since 1987 by an automatic measuring station which has provided valuable insights into the sediment dynamics of steep mountain rivers (see Lenzi, 2001; Lenzi et al., 2003, 2004; Mao et al., 2005). The station potentially traps all the woody debris coming from the upper 5 km^2 of the basin, but the forest cover of such area is very small (~7%). The Rio Code and the Codalunga have few high check-dams in their mid section, whereas the Rio Molini can be seen as the more "natural", featuring just one tall gabions check-dam.

2.2 Chilean study sites

The location of the two basins investigated in the Southern Chilean Andes (Tres Arroyos in the Malalcahuello National Reserve and Rio Toro within the Malleco Natural Reserve) is shown in Figure 2.3. The main physiographic characteristics of the two basins are resumed in table 2.3.
The region where the Rio Toro and the Tres Arroyos lie is characterized by the presence of large and high volcanoes that strongly influences the climate and the geology of the area. Moreover, together with lightning, volcanoes are priming factors of fire, 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 actually lie within the range of the historic fire regimes that have shaped this forested landscape.

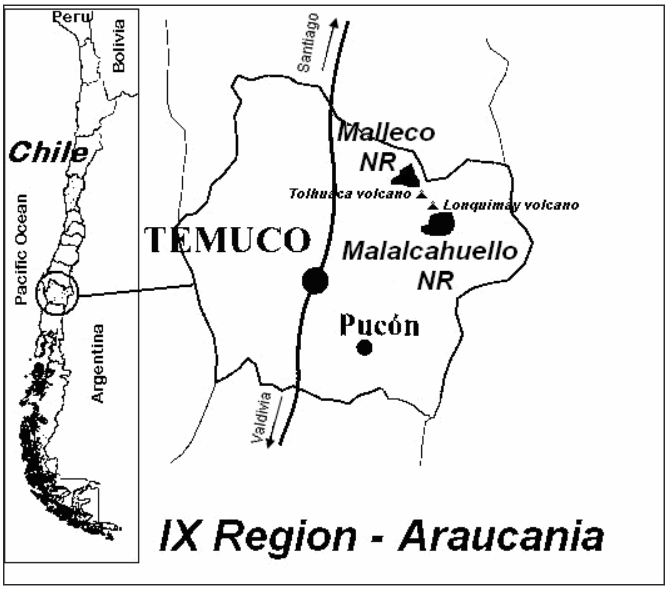


Figure 2.3 – Location map of the two chilean study basins: the Tres Arroyos lies in the Malalcahuello National Reserve and the Rio Toro is within the Malleco Natural Reserve.

The basin area (9.1 km^2) of the small experimental basin "Tres Arroyos" is delimited to the north by the southern flanks of the Lonquimay volcano (2,865 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 characteristics of the watershed are reported in Table 2.3.

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 piroclastic 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 piroclastic layers. In the Malalcahuello area only a type of intrusive rock is found, comprised mostly of monzonites and granodiorites (*Plutónico Melipeuco* group).

Basin and channel characteristics	Unit	Tres Arroyos (TA)	Toro (TO)
Basin Area	km^2	9.1	11.1
Average elevation	m a.s.l.		
Minimum elevation	m a.s.l.	1000	750
Maximum elevation	m a.s.l.	1850	1750
Mean basin slope	%	43	20
Hydrological regime	-	pluvial/nival	pluvial/nival
Forest cover	%	74	95 (98% burned)
Forest type	-	Native	Native
Dominant forest species	-	*Nothofagus dombeyi Araucaria araucana*	*Nothofagus dombeyi Araucaria araucana*
Forest disturbance	-	Wildfire (1920's)	Wildfire (2002)
Channel order	-	3	3
Channel length	km	4.98	7
Channel morphology	-	Step-pool / Cascade	Plane-bed/Step-pool
Average channel slope	m/m	0.08	0.05
Average channel width	m	7.7	11.9
Investigated channel length	km	1.54	2.17
Annual precipitation	mm	2217	2480
Climate	-	Temperate warm humid	Temperate warm humid
Geology	-	Volcanic / pyroclastic	Volcanic / pyroclastic

Table 2.3 - Main characteristics of the Chilean basins.

The basin is 74% forested (Figure 2.4), with 61% represented by native old-growth stands having trees up to 40-50 m tall and 1-2 m large, 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 characterised by unvegetated sandy volcanic ashes (around the watershed contour, 6%) and herbaceous-shrubs cover (near the tree limit, 22%).

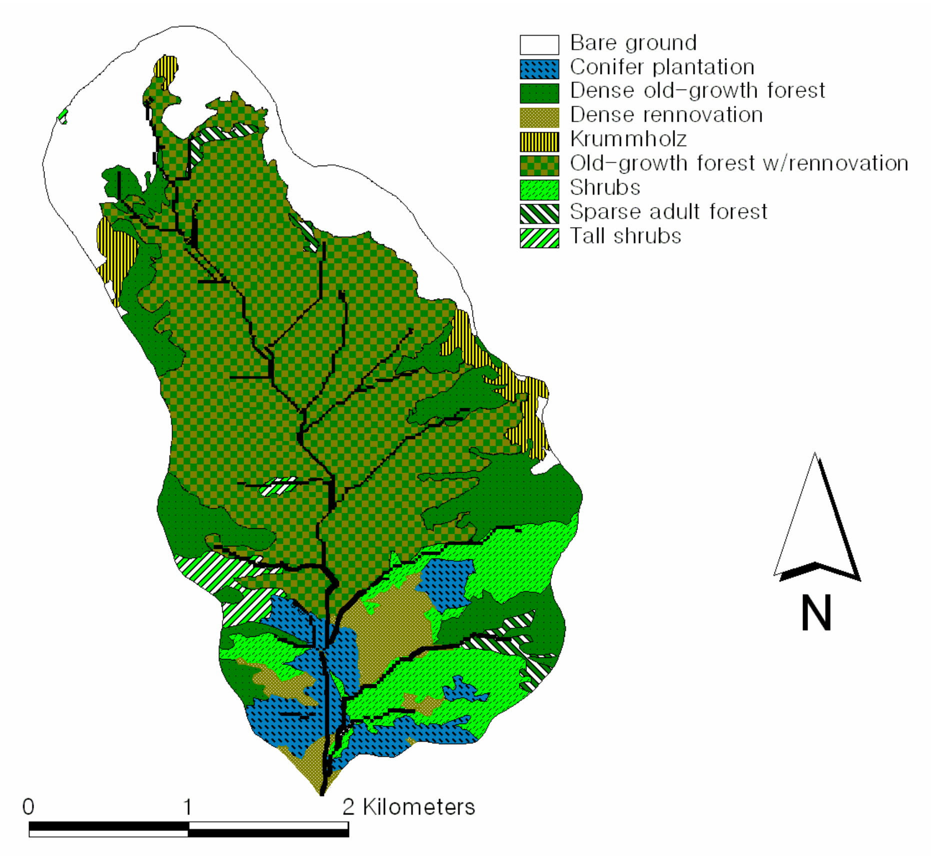


Figure 2.4 – Vegetation map of the Tres Arroyos basin

The native forests in the Tres Arroyos basin are of two types: the araucaria forest (*Araucaria araucana* (Mol.) K. Koch) and roble-raulí-coigüe forest (respectively, *Nothofagus obliqua* (Mirb.) Oerst., *Nothofagus alpina* (P. et E.) Oerst., and *Nothofagus dombeyi* (Mirb.) Oerst.). 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.).

The main channel (3^{rd} order) from the source to the outlet is almost 5 km long with a mean gradient of 18%. (Table 2.3). 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 scale (see below). Reach morphology (following Montgomery and Buffington's, 1997, classification) covers the range from steep cascade and step-pool to pool-riffle types, but with a high degree of forced morphologies associated to 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 km^2 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; Mao et al., 2007).

Intense flood events occurred in 1972 and 1992, with damages 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 characterised by a great deal of LWD at different state of decay spread all over the surface, particularly on unvegetated bars and wooded terraces (Figure 2.5).

Figure 2.5 – 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.

The Tres Arroyos is also heavily affected by debris flows coming from the steep tributaries, that deliver huge amounts of sediment and LWD into the main channel. The 1992 flood is estimated (Uyttendaele, 2005) to have transported 5,300 m^3 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 2.6). An enormous accumulation of LWD (gross geometrical volume ~ 600 m^3, Figure 2.7), formed by 100-150 wood pieces 0.5 m large and 4-5 m long on average, lies at the confluence of this debris flow channel with the main Tres Arroyos channel (also another smaller channel enters the main stream a few meters upstream, as shown in Figure 2.6).

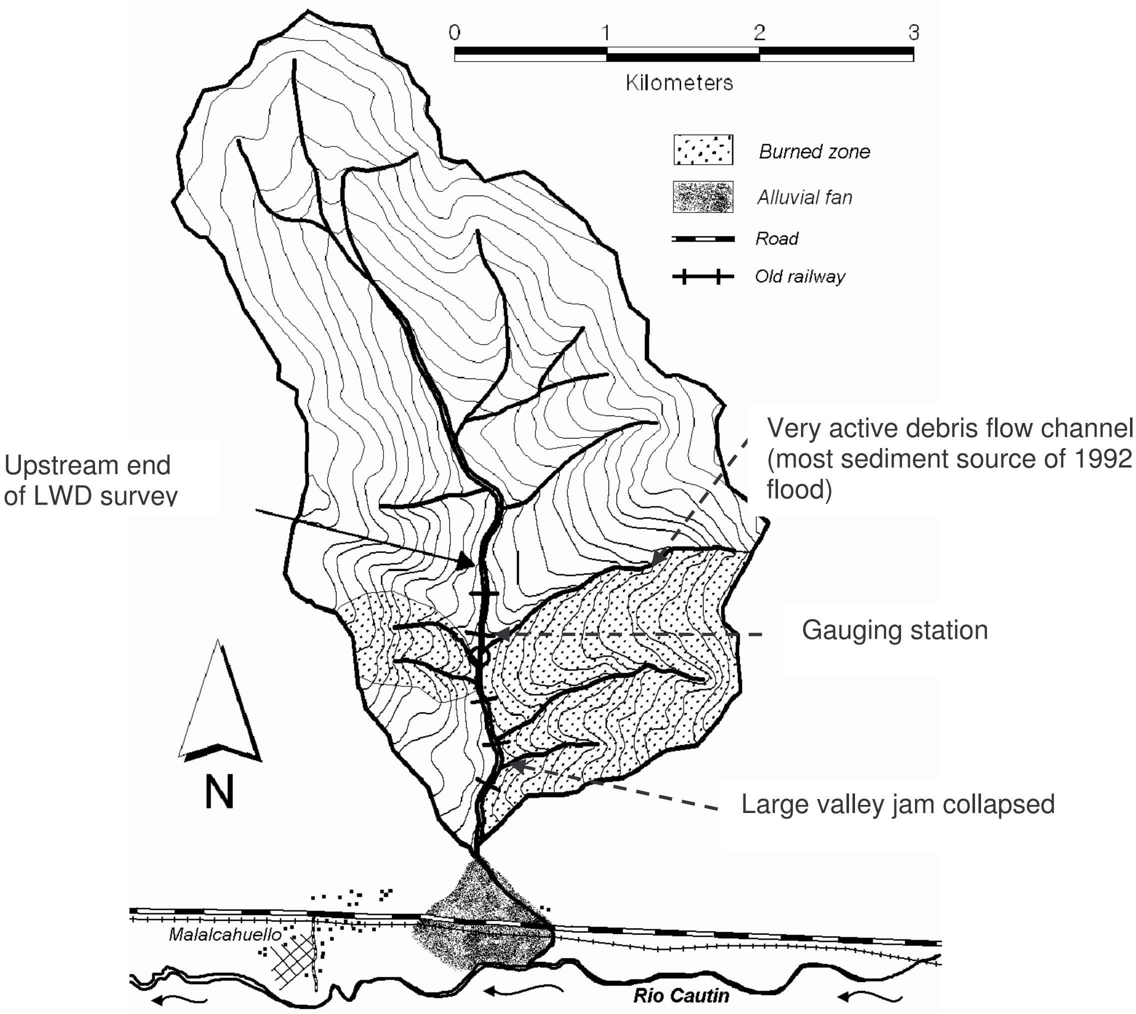


Figure 2.6 – Sketch of the Tres Arroyos basin illustrating the channel network, the extent of the surveyed stream section, the location of the intact valley jams (solid lines transversal to the channel) and of the "nodal" point (white circle) at the confluence with two debris flow channels. The location of the gauging station operating since 1997 is also shown.


a)

Figure 2.7 – Downstream view of the large wood jam occurring at the "nodal" point of the Tres Arroyos channel. The surface underneath the woody debris pile is bedrock.

The Rio Toro basin (Figure 2.8) present a drainage area 11.1 km^2. The main physiographic characteristics of the watershed are reported in Table 2.3.

According to the classification of Köeppen, the climate is tempered rainy, with a relative summer drought (less than four months dry) (Ramirez, 1978); Amigo and Ramirez (1998) classify the study area as temperate warm. The nearest weather station (Los Guindos, 38°03' lat. S., 71°49' long. W, 440 m a.s.l.), recorded an annual average precipitation of 2,482 mm, with an annual average temperature of 12°C, and 1 to 2 months with precipitations less than 30 mm.

The basin is 94% forested (Figure 2.8), with 75% represented by native, old-growth stands having trees up to 40-50 m tall and 1-2 m large, and 19% by forest renovation. The remaining area is characterised by herbaceous-shrubs cover (near the tree limit, 5%) and rocky outcrops (less then 1%).

A huge wildfires that occurred in 2002 burned almost all the vegetated surface (98%) (Figure 2.9) with a grade of damage from 1 to 4 (light damage to serious damage) as show in figure 2.10. At the moment of the field works a strong recolonization by the southern quila was observed.

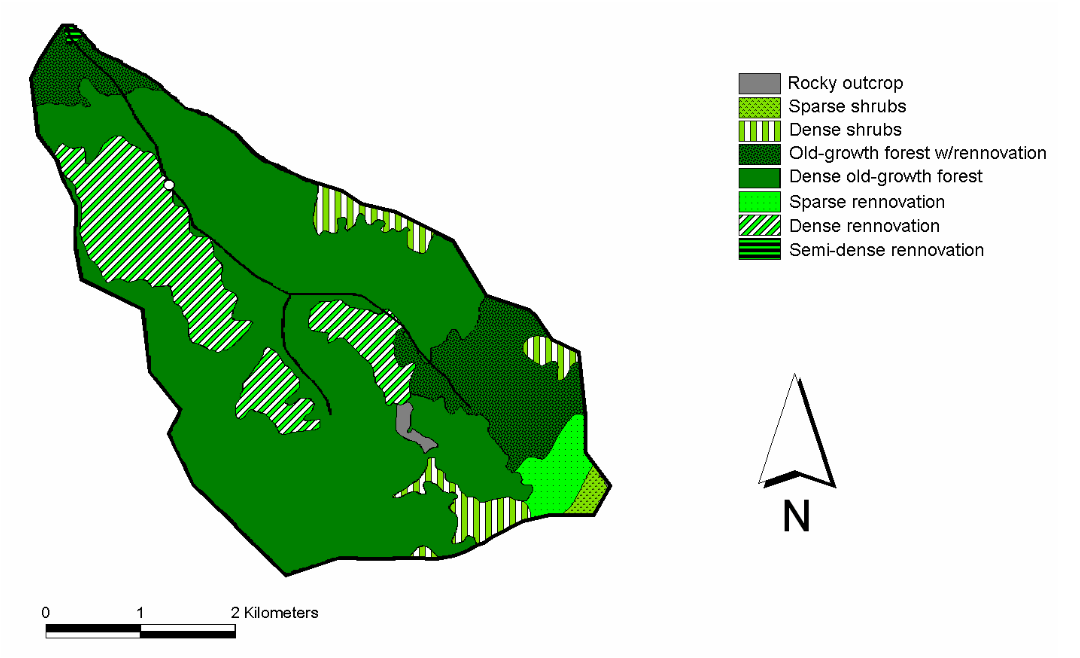


Figure 2.8 – Vegetation map of the Rio Toro basin.

Figure 2.9 – General view of the Rio Toro Basin: it's well visibile the burned area.

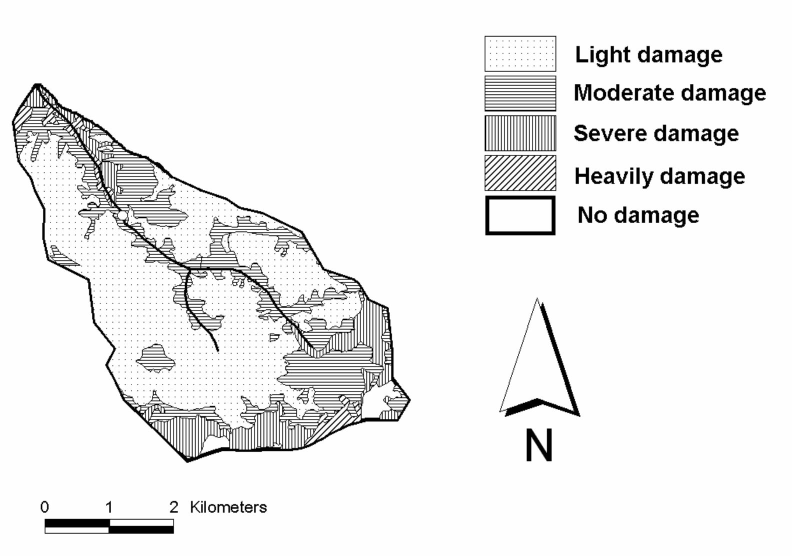


Figure 2.10 – Grade of vegetation damage due to wildfire occurred in 2002 in the Rio Toro basin.

The main channel of Rio Toro (3rd order) is 7 km long from the source to the outlet with a mean gradient of 7% (table 2.3). Reach morphology (following Montgomery and Buffington's, 1997, classification) covers the range from plane bed to steep cascade and step-pool, with apparent no forced morphologies associated to LWD and no presence of debris-flow signs. The channel is overall well-confined within steep rocky slopes, and presents a very narrow active floodplain. No antecedent hydrological studies are known for this stream.

2.3 Argentinean study site

The field work was carried out in the Buena Esperanza basin (Ushuaia, Tierra del Fuego Argentina, Figure 2.11) from 9th February to 13th March 2006.

In the Tierra del Fuego, the vast majority of river basins (98%) are heavily impacted by the damming activity of beavers (*Castor canadensis* Kuhl) after their artificial introduction in the 1946 (Lizarralde, 1993; Coronato et al., 2002), and the selected study basin – the Buena Esperanza – represents one of few channels not impacted by these mammals.

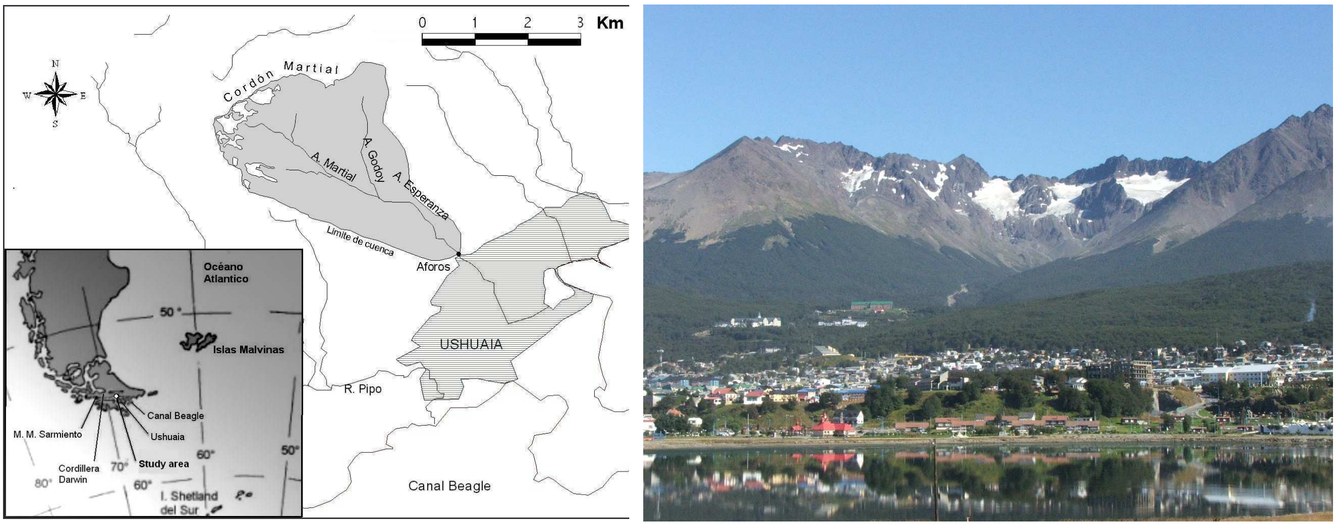


Figure 2.11 – Location map and view of the Buena Esperanza basin (Ushuaia, Tierra del Fuego, Argentina).

The basin of Arroyo Buena Esperanza is located in the Fuegian Andes with slope to Beagle Channel and outlet in Ushuaia city and present a drainage area of about 13 km^2. The main physiographic characteristics of the watershed are reported in table 2.4. The investigated part of the basin may be divided in two characteristic zones: the upper one characterized by the Martial Glacier and the lower that rappresent the turistic zone north of Ushuaia.

The climate of the zone is subantartic, cold and humid without dry season. The mean annual temperature at sea level is 5.5 °C (1.0 °C in the coldest and 9.6 °C in the warmest months). Strong winds are often present, mainly from the southwest.

Precipitation range from 530 mm at sea level to 1300 mm in the upper part of the basin (Tuhkanen, 1992) and are evenly spread over the year.

The Buena Esperanza catchment is placed over sedimentary marine rocks dating from Inferior Cretacic of Yahgan Formation.

The vegetation is rapresented by Nothofagus forest till the altitude of 550 m, and sphagnum mires (Figure 2.12). Three types of Nothofagus tree are recognizable: lenga (*Nothofagus pumilio* Poepp. et Endl.), ñire (*Nothofagus antártica* (G. Forst.) Oerst.) and guindo o coihue de magallanes (*Nothofagus betuloides* (Mirb.) Oerst.), but the predominant vegetal cover of the basin is mainly in two variants: lenga homogenous forest and mixed forests, where they mix foot by foot, of lenga and guindo.

Lenga is the dominant species, over which is based the forestry economy of the island. In good conditions lenga mature individuals may reach mean highs of 20-25 meters and mean diameter of 0.40-0.60 m. The Guindo, commonly called coihue in Tierra Del Fuego, is the only species with perennial leaf; it appears associated with lenga in humid sectors. It's possible to find it associated to "canelo" (*Drymis winterii* J.R. et Forster) in the southeast of the island. The ñire is the species of higher plasticity of the 3 fagaceas. There is a little portion of this species in the study zone. The basin does not present forest activities at the present while there were some log activities in the past century, mainly in the forties.

Basin and channel characteristics	Unit	Buena Esperanza
Basin Area	km^2	12.89
Average elevation	m a.s.l.	666
Minimum elevation	m a.s.l.	133
Maximum elevation	m a.s.l.	1275
Mean basin slope	%	23
Hydrological regime	-	Glacionival
Forest cover	%	34
Forest type	-	Native
Dominant forest species	-	*Nothofagus pumilio*, *Nothofagus antarctica*
Forest disturbance	-	Roads, skitrails
Channel order	-	3
Channel length	km	5
Channel morphology	-	Cascade / Step-pool
Average channel slope	m/m	0.065
Average channel width	M	6.3
Investigated channel length	km	1.85
Annual precipitation	mm	530/1300
Climate	-	Temperate cold humid
Geology	-	Sedimentary/Metamorphic

Table 2.4 - Main characteristics of the Buena Esperanza basin.

Sphagnum magellanicum Brid. moss associated with juncacea *Marsippospermum grandiflorum* (L.f.) Hook represent the vegetated part without trees of the basin, and in less order it's possible to find another type of covers such as grasslands and peat bogs of ciperaceas.

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 yr) 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 however between 300 and 400 yr – in Tierra del Fuego is governed by periodic wind bloLWDowns associated to low-pressure systems originating in Antarctica (Rebertus et al., 1997). As a consequence, trees having diameters > 0.4 m are very uncommon in the Buena Esperanza basin.

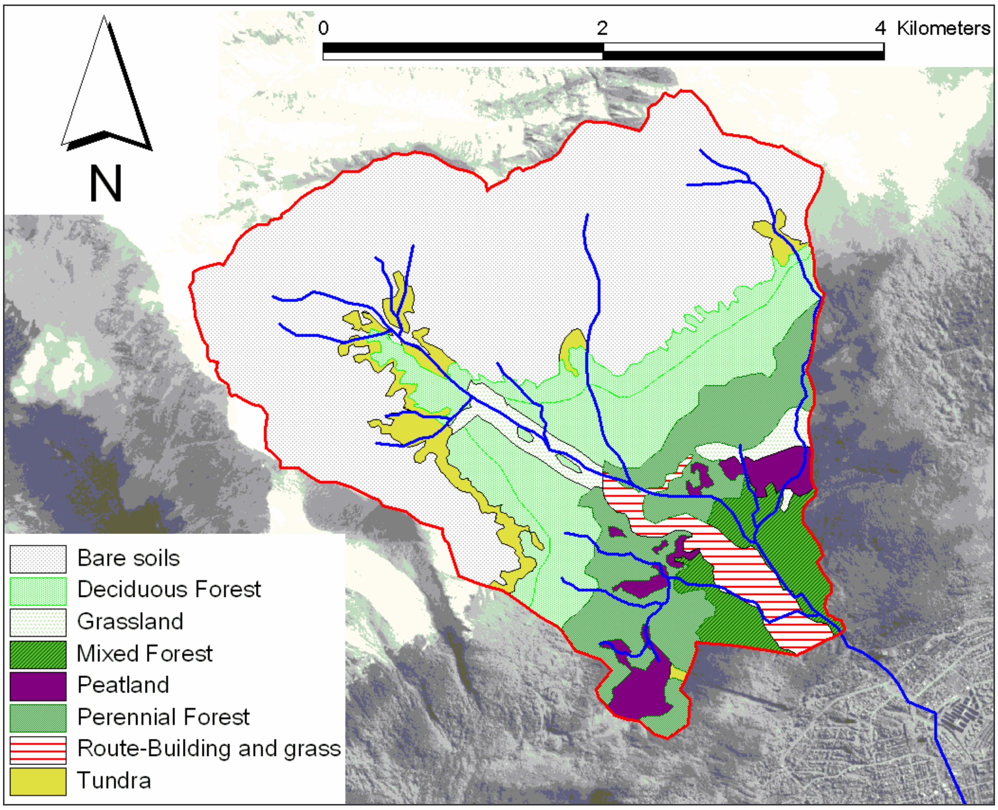


Figure 2.12 – Vegetation map of the Arroyo Buena Esperanza basin.

The main channel of the Arroyo Buena Esperanza is 5 km long from the source, at the Martial Glacier slopes, to the outlet in the Beagle Channel (Table 2.4). Runoff has a snow-glacier origin with small cirque glaciers at the catchment head, a periglacier zone with discontinuous permafrost and associate geoforms, a fluvial proglacial which alternate with morenic arcs corresponding from the Small Ice Age to the Late-Neoglacial o Late glacial (Strelin and Iturraspe, 2001), the last ones coming into forest zone. The mean water discharge is 300 l/sec. Few meters after receiving its tributary, Godoy stream, channel bed is confined in an old glacier geoform parallel to Beagle channel. Runoff is mainly regulated by seasonal snow, mountain range detritus storages and contributing glaciers that causes a high turbidity during spring season.

After the potable water plant (basin end section) the stream goes down to the lower sector in which is situated Ushuaia city. At this section water present signs of contamination probably due to the turistic activity that affect the middle part of the basin.

3. SURVEY METHODS

3.1 Italian basins study methods

The six study channels were surveyed for large woody debris (LWD) dimensions in summer 2003 (Fiorentina, Cordon, and Code) and 2004 (Codalunga, Molini and Pettorina). Measured LWD were wood pieces > 5 cm in diameter and > 0.3 m in length both in the active channel and in the adjacent active floodplain, which was however rather narrow (1-10m at each side). Such dimensional criteria are therefore less strict than those commonly used to define LWD (diameter >10 cm and/or length > 1 m), in order to "capture" as much as possible all the woody debris present, which must not be necessarily large to cause hydraulic and geomorphic consequences (see e.g. Jackson and Sturm, 2002). Of each piece, its length and its mid-diameter were measured by a tape meter and a tree caliber, respectively. The precision was ~1 cm for diameters and ~5 cm for piece lengths. Pieces forming debris and log jams (i.e. accumulations of >2 wood elements) were all measured in the 2003 survey (Fiorentina, Cordon and Code), whereas in the subsequent year only the geometrical dimensions of jams (length, width and height) were taken, along with a visual assessment of the air-wood ratio for each accumulation. For detached rootwads, both the minimum diameter (i.e. trunk side) and the maximum diameter (distal roots distance) were recorded beside the length of the near-cylindrical part (i.e. the trunk remains, the most relevant as to wood volume).

Channels were surveyed for a considerable length (see Table 2.2) from their downstream-most section moving upstream. An exception is the Fiorentina, whose first 2.5 km upstream of Caprile (see Figure 2.1) were excluded from the analyzed segments because LLWD complete clearing was carried out just before the survey. Reaches were defined based on uniformity of either slope, channel width or abundance of debris. All LWD pieces within the above dimensional criteria were measured and recorded for each reach.

Overall, measured pieces ranged between 600 (Cordon) and 1600 (Fiorentina, see Table 2.2). The following characteristics were measured at each single reach: mean channel slope (S, by a hand clinometer), mean bankfull and floodplain width (B_{bf} and B_{fp} respectively, by a tape meter), and mean bankfull depth (h_{bf}, by a stadia rod). Basin area drained at each reach, Ar, was calculated from a 5m x 5m Digital Elevation Model by a GIS software. Several additional information relative to each LWD piece were recorded during the field survey, namely: type (log, rootwad, log with rootwads attached), species (broadleaves/conifers, when detectable), orientation to flow (parallel, transversal, oblique), visually-estimated permanence time (i.e. decay state: low, medium, high), origin (natural/human, i.e. harvesting residuals based on saw-cuts) and position (log-step, in-channel, channel-bridging, channel margins). In-channel pieces were defined as all the elements at least partially at a lower elevation than bankfull height, but excluded log-steps which form a different class. Channel-bridging elements are those spanning the channel at an elevation higher than bankfull stage. Finally, pieces at channel margins were defined as those located on the area adjacent to the bankfull channel subject to inundation during low-frequency flood events.

Volume of each element was calculated from its mid-diameter D_{log} and length L_{log} assuming a solid cylindrical shape, as commonly done for LWD studies. Rootwads' volume was approximated to the stem section only – again as a cylinder – neglecting the actual roots mass. Spatial density of LW – 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. LWD accumulations posed relevant doubts as to a proper and fast quantification. Such a problem led to two different approaches. The detailed method used in 2003 (Fiorentina, Cordon, Code; see above) provided precise volume estimates plus the number of elements for each jam, but is very time-consuming. Conversely, the "gross jam dimensions" method adopted for Codalunga, Pettorina and Molini had the advantage to be much faster, but its reliability becomes well reduced. So, for the following campaign of survey in Latin America, the detailed method was adopted. In order to assign values to the air-wood ratios of each jam, the work by Thevenet et al. (1998) was taken as a reference (air volume in jams ~ 90%).

Finally, correlations between channel properties and wood variables were carried out using (log+1) transformed values in the software STATISTICA 7.0 (StatSoft, 2005).

3.2 South American basins study methods

The Tres Arroyos channel was surveyed for LWD in March-April 2005, on a length of 1,540 m, from the alluvial fan apex – the outlet the of the basin in Figure 2.7 – 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 2.7).

The longitudinal profile of the study section (Figure 3.1) 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 3.1). Reach numbering starts from downstream (reach 1) to upsteam (reach 17). The following characteristics were measured at each single reach: mean channel slope (S), mean bankfull and floodplain (or fluvial corridor) width (B_{bf} and B_{fp} respectively), mean bankfull depth (h_{bf}), number of steps (N_{st}) and of 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, Ar, was determined from a Digital Elevation Model using a GIS software and ranges from 5.5 to 9.1 km^2.

Moreover, 500 metal tags were inserted into 322 wood elements of different size and location, in order to track their movements over time using some stakes as reference points. The availability of flow and sediment rates can allow (after repeated surveys) to correlate log displacement to the characteristics of flood events. The metal tags are numbered and placed progressively from downstream to upstream in logs chosen randomly, nailing from 1 to 3 tags based on the length of the logs (approximately 1 tags in logs from 1 to 3 meter long, 2 tags in logs of 3-6 m, 3 tags in logs longer than 6m). To assign the position of the log, the distance and direction from a stake was measured, additionally the in-stream position (left, right or central) and grade of blockage was noted.

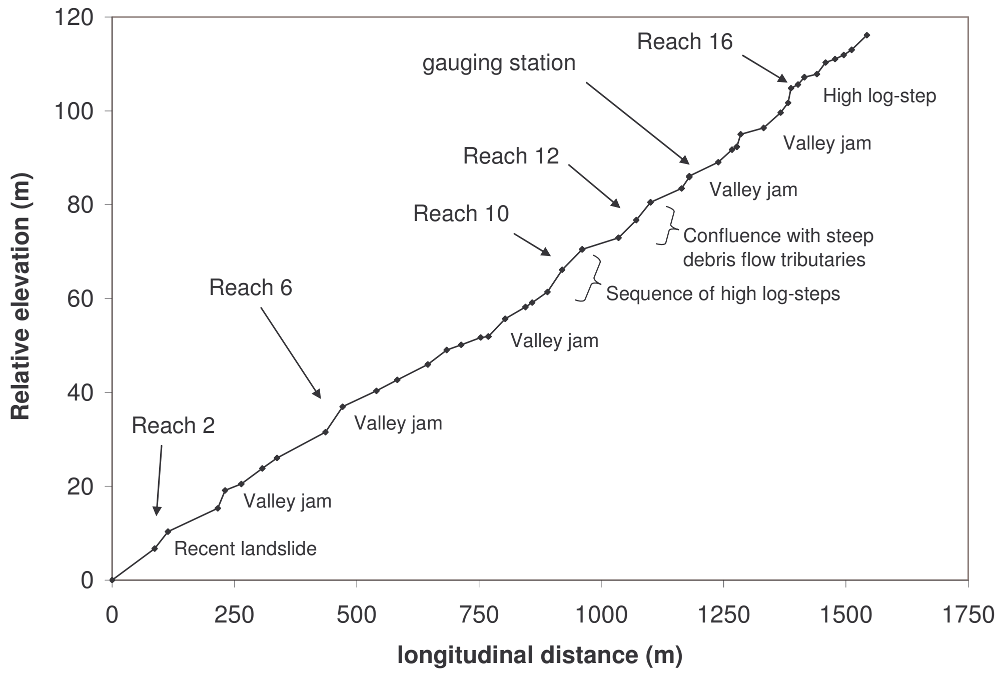


Figure 3.1 – Longitudinal profile of the surveyed section of the Tres Arroyos. The main LWD-related features and external forcings are indicated along with location of the most relevant reaches.

Reach	Length (m)	Slope (m/m)	Bankfull width (m)	Floodplain width (m)	Channel morphology*	Adjacent forest type**	Notes	LWD-related features***
1	82	0.08	7.6	17.3	SP, CA	YN, CP	-	broken DD
2	32	0.11	9.1	16.7	CA	YN, CP	Recent landslide	jams, broken DD
3	117	0.08	8.2	11.6	SP, CA	YN, CP	Landslide	DD
4	106	0.07	7.1	21.3	SP, RP	YN, CP	Landslide, confluence with steep tributary	jams, broken DD
5	134	0.07	5.8	27.3	SP, RP	YN, CP	-	steps, jams
6	69	0.05	7.6	30.2	SP, RP	YN, CP	Tributary fan	DD, broken DD, jams
7	105	0.05	7.1	23.8	SP, CA	YN, CP	Large terrace	-
8	124	0.05	7.2	20.4	CA, SP	YN, CP	Large terrace	Bend, broken DD
9	76	0.08	7.8	20.5	SP, RP	ON, YN	Bank erosion	DD
10	116	0.11	8.0	20.0	SP	ON, YN	Confluence dissected sub-basin	Steps, abandoned channel
11	74	0.03	15.5	22.0	RP	ON, CP	Deposition area	broken DD
12	65	0.12	8.0	16.0	SP, CA	CP	Confluence debris flow channels	steps, huge LWD pile
13	79	0.06	6.8	17.7	SP, RP	ON	-	steps, DD
14	97	0.07	5.6	8.0	SP, CA	ON	Bedrock	Jam
15	90	0.08	6.2	13.7	RP	ON	Bank erosion	DD
16	49	0.15	5.5	8.0	SP	ON	Tributary fan, Landslide	High step, broken DD
17	128	0.07	7.0	11.7	SP, RP	ON	Landslide	steps, jam

Table 3.1 - Characteristics of the 17 investigated reaches of Tres Arroyos (* SP = step-pool, CA = cascade, RP = riffle-pool; ** YN = young nothofagus, CP = conifer plantation, ON = old nothofagus; * DD = debris-dam (valley jam).**

The Rio Toro channel was surveyed for LWD in January 2006, on a length of 2,170 m, from the confluence with Niblinto river – the outlet of the basin in Figure 2.10 – moving upstream. Seventeen individual reaches were defined based on uniformity of either slope, channel width or abundance of debris (Table 3.2). Reach numbering starts from downstream (reach 1) to upsteam (reach 17). As to the Tres Arroyos channel at each single reach were measured mean channel slope (S), mean bankfull and floodplain (or fluvial corridor) width (B_{bf} and B_{fp}), mean bankfull depth

(h_{bf}), number of steps (N_{st}) and of number of boulders (N_b) higher and larger than h_{bf}. In the Rio Toro slopes range from 1.5% to 11% and bankfull width varies from 7.5 to 15.5 m, with average values of 5.3% and 11.9 m, respectively. The longitudinal profile of the study section (Figure 3.2) was surveyed using a laser distance meter with inclinometer.

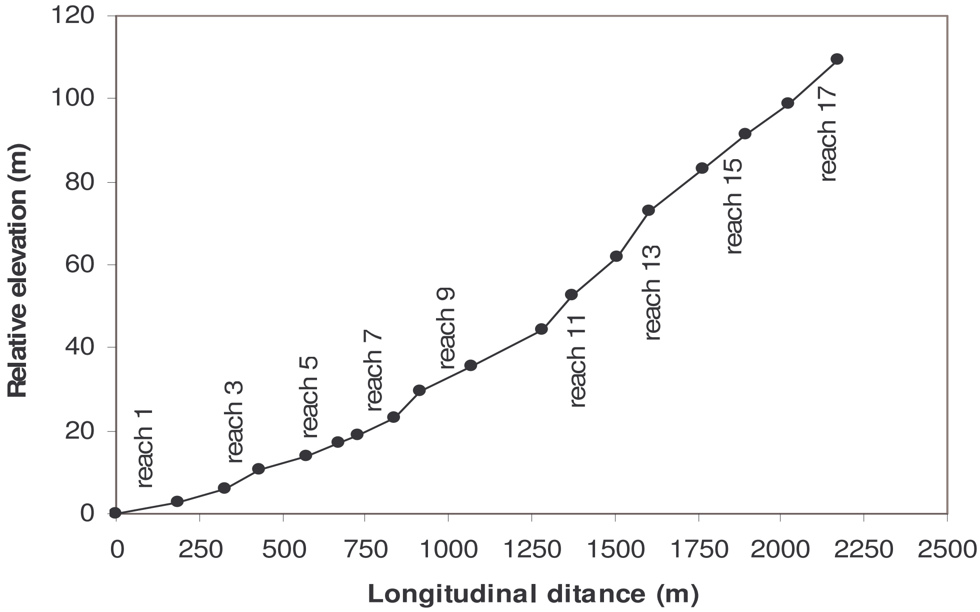


Figure 3.2 - The longitudinal profiles of the Rio Toro.

Reach	Length (m)	Slope (m/m)	Bankfull width (m)	Floodplain width (m)	Channel morphology*	Adjacent forest type**	Notes	LWD-related features***
1	185	0.02	15	21	PB	YN	Large terrace	Jams
2	143	0.02	13	19	RP	YN, ON	-	-
3	104	0.04	13	13	SP	YN,ON	-	-
4	139	0.02	11	16	RP	ON	-	-
5	98	0.03	12.5	12.5	SP	ON	Confined pools	-
6	61	0.03	11	20	SP	ON	-	-
7	110	0.04	8	8	SP	ON	-	-
8	76	0.08	7.5	7.5	CA	ON	Big boulders/ confined	-
9	155	0.04	12	16	RP	ON	-	-
10	211	0.04	12	20	RP	ON	-	-
11	88	0.10	8	8	CA	ON	Confined	-
12	136	0.06	15	22	SP	ON	-	-
13	101	0.11	8	8	SP	ON	Confined	-
14	156	0.07	11.5	22	SP	ON	-	-
15	130	0.06	14.5	25	SP, RP	ON	-	-
16	129	0.06	15.5	30	SP, RP	ON	-	Jams/burned pieces in channel margins
17	145	0.07	15	30	SP	ON	-	-

Table 3.2 - Characteristics of the 17 investigated reaches of Rio Toro (* SP = step-pool, CA = cascade, RP = riffle-pool, PB = plane bed; ** YN = young nothofagus, ON = old nothofagus; * DD = debris-dam (valley jam).**

An intermediate reach within a gorge was impossible to walk and to measure due to the inaccessibility caused by vertical cliffs and high rock steps along the channel, so two segments have been separated (Figure 3.3). Basing on uniformity of either slope, channel width or abundance of debris thirty three individual reaches were defined (not comprising the one were was no possible carry on the survey). Like in the other investigation fields, reach was numbered starts from downstream (reach 1) to upstream (reach 33).

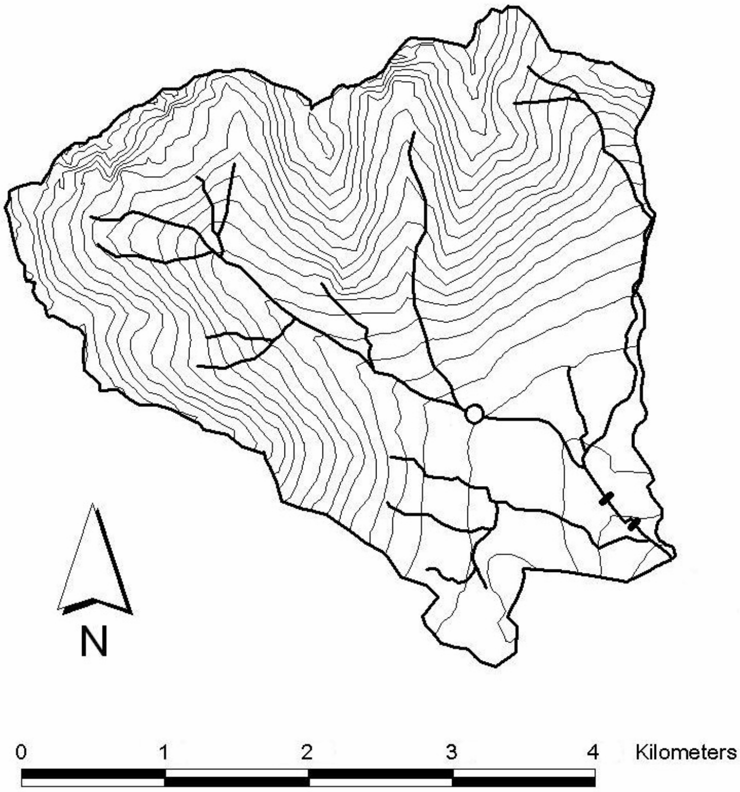
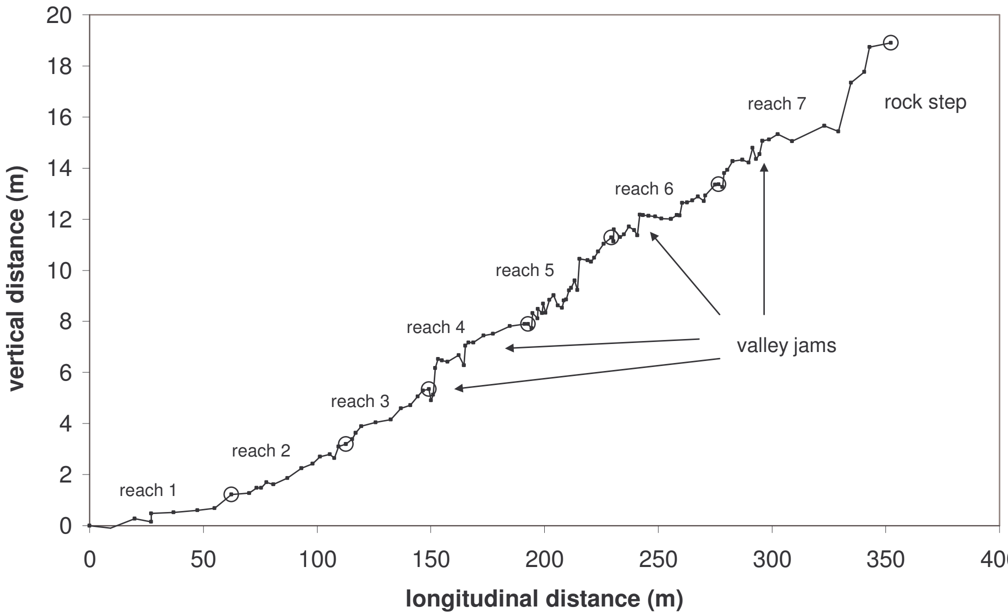


Figure 3.3 – Channel network of the Buena Esperanza. The circle represents the upstream end section of the survey. The short stream segment within the two thick solid lines is a narrow, rough gorge which was not feasible to survey.

The topographic survey of channel longitudinal profiles (Figure 3.4) and cross-sections was performed by a laser distance meter with inclinometer, coupled to a prisma rod. Reaches were defined based on uniformity of either slope, channel width or abundance of woody debris. The end sections of each reach were fixed by wood stakes on channel banks. Bankfull width and depth, and floodplain width, were measured for each reach (Table 3.3). Additionally, for each reach the number of boulders and steps (larger than bankfull depth) was noted.



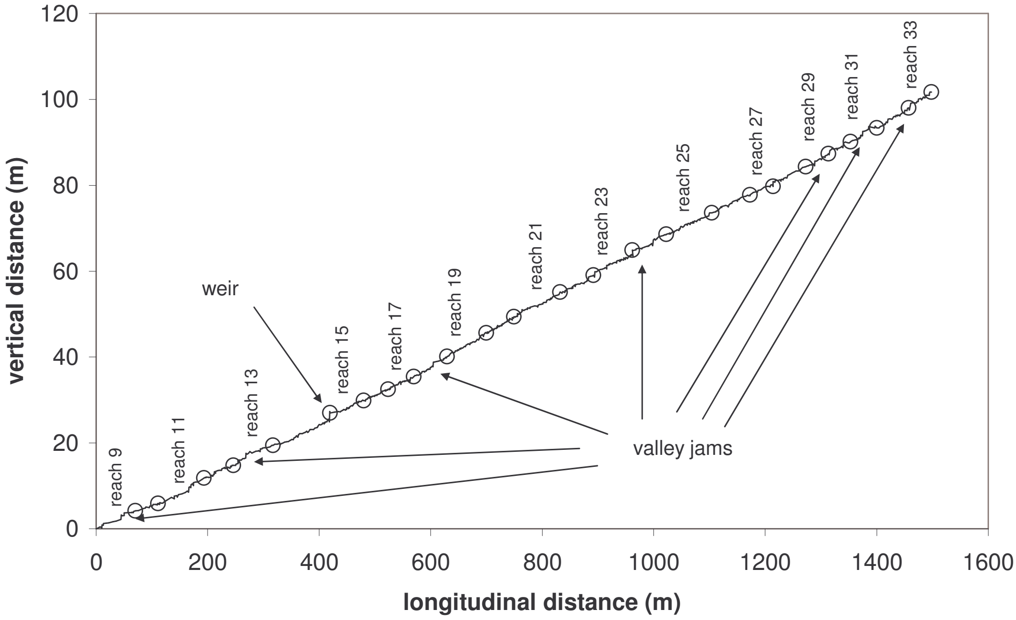


Figure 3.4 – Longitudinal profiles of the segment downstream (above) and upstream (below) of the gorge marked in Figure 3.3.

Following the methodology already explicated for the Tres Arroyos, 620 metal tags were inserted into 381 wood elements, and a survey of logs displacement has been carried out after 1 year (February 2007).

Reach	Length (m)	Slope (m/m)	Bankfull width (m)	Floodplain width (m)	Channel morphology*	Adjacent forest type**	LWD-related features***
1	102,74	0,01	7,5	18,3	RP	ON	DD
2	60,04	0,04	4,7	12,0	SP, CA	ON	
3	44,12	0,06	4,2	13,0	SP,CA	ON	
4	46,73	0,06	5,1	16,0	SP	ON	DD
5	59,27	0,09	5,5	7,3	BR, SP	ON	
6	70,77	0,05	5,4	12,5	RP, SP	ON	DD
7	49,34	0,03	5,9	7,6	BR, RP, SP	ON	DD
9	83,17	0,06	5,8	34,0	CA	ON	DD
10	59,43	0,04	5,2	20,0	CA	ON	broken DD
11	71,68	0,07	8,3	19,2	CA	ON	DD
12	61,35	0,06	7,0	20,1	CA, PB	ON	
13	81,37	0,07	4,7	21,0	CA. PB	ON	DD
14	68,93	0,07	5,2	19,5	SP, PB	ON	DD
15	40,93	0,05	4,6	14,4	SP	ON	
16	58,36	0,06	4,9	17,4	CA, SP	ON	
17	41,25	0,06	5,2	23,5	SP, CA	ON	
18	39,34	0,08	5,6	21,5	CA	ON	DD
19	47,35	0,08	6,1	15,4	SP	ON	
20	57,21	0,08	5,8	17,3	SP	ON	Broken DD
21	40,51	0,07	4,9	16,3	SP	ON	
22	102,74	0,07	7,5	16,8	SP	ON	
23	60,04	0,09	4,7	15,5	SP	ON	
24	44,12	0,06	4,2	12,0	CA	ON	DD
25	46,73	0,06	5,1	10,0	SP	ON	
26	59,27	0,06	5,5	9,5	SP, CA	ON	
27	70,77	0,05	5,4	8,2	SP, CA	ON	
28	49,34	0,08	5,9	7,1	CA, PB	ON	
29	83,17	0,07	5,8	8,7	SP	ON	DD
30	59,43	0,07	5,2	13,0	CA,SP	ON	
31	71,68	0,08	8,3	11,8	CA	ON	DD
32	61,35	0,08	7,0	12,2	SP	ON	DD
33	81,37	0,09	4,7	9,7	SP	ON	

Table 3.3 - Characteristics of the 32 investigated reaches of Arroyo Buena Esperanza (* SP = step-pool, CA = cascade, RP = riffle-pool, BR = bed rock, PB = plane-bed; ** YN = young nothofagus, ON = old nothofagus; * DD = debris-dam (valley jam).**

In the three channels investigated in Argentina and Chile the survey of the Large Woody Debris follow the methodology here reported: 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 used as the upper elevation limit for LWD to be included in the records at each location. A total of 5,738 elements were recorded over the entire study segments of the three investigated channels. The length and mid-diameter of each element were measured with a tape and a tree caliber, 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 2 elements) were measured, and the geometrical dimensions of jams (length, width and height) were also taken for subset of log jams. For detached rootwads, both the minimum diameter (i.e. on the trunk side) and the maximum diameter (i.e. distal roots 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 and 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 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 flow was made, so that 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 roots mass. 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.

Correlations between channel properties and wood variables were carried out using (log+1) transformed values in the software STATISTICA 7.0.

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. In the case of study of Tres Arroyos basin, the total in-stream sediment storage due to LWD will then be compared to the basin sediment yield (bedload and total load), as evaluated by Lenzi et al. (2004) at the gauging station whose location is shown in Figure 2.6. Moreover, in order to quantify the wood storage on the alluvial fan of this basin, LWD elements were also measured within a sample area of 2,100 m^2 reckoned representative of the average wood spatial density on the fan.

4. LWD VOLUME, MOBILITY AND IMPACT ON CHANNEL HYDRAULICS

4.1 Italian Basins

4.1.1 Channel-averaged LWD abundance

Basin area seems to be significant to differentiate total LWD volume (Fig. 4.1). The best-fit equation turns out (R^2=0.98, p<0.005):

$$V_a = 1.15A^{-0.65} \quad (1),$$

where V_a is the woody debris volume (m^3) per 100m^2 of streambed area, including log-jams.

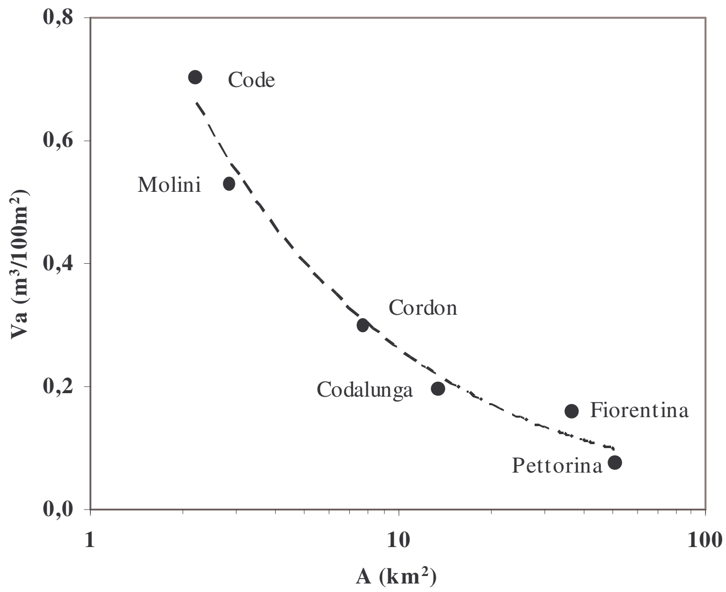


Figure 4.1 - Semi-log graph illustrating the relationship between basin drainage area, A, and LWD total volume per 100m^2 of streambed area, Va.

LWD jam volume normalized to streambed area, V_{jam}, is shown in Figure 4.2 plotted against basin drainage area, A. The graph indicates that larger basins feature overall smaller volumes of LWD jams, following what observed for non-jam LWD, whereas if the proportion of LWD in jams relative to the total LWD amount (Va) is considered, an opposite trend appears (Fig. 4.2): higher-order channels draining larger areas have more LWD stored in jams, up to around 50% for Fiorentina and Pettorina. However, the Rio Molini presents an anomalous low value of LWD jam volume (3% of the total) despite its small size, whereas its total LWD volume fits in the general trend.

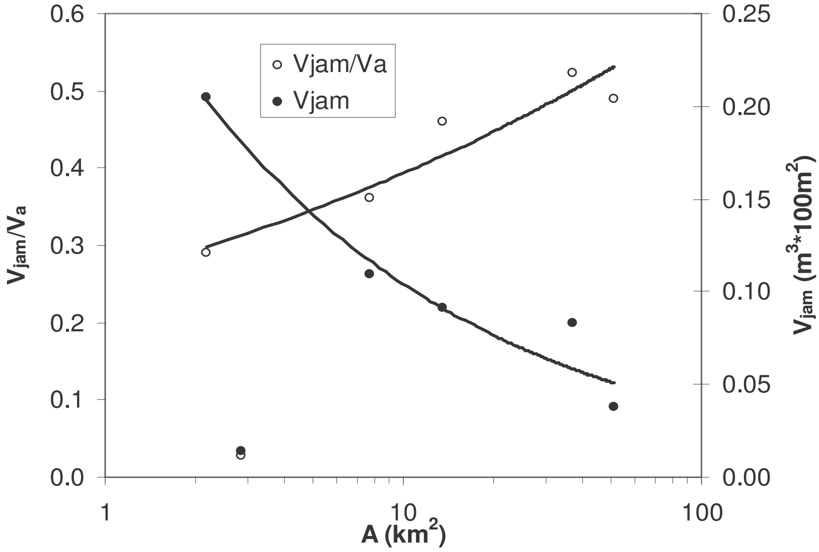


Figure 4.2 - Semi-log plot illustrating the correlation of LWD jam volume per 100m^2 of streambed area, V_{jam}, and of its proportion to the total LWD volume, V_{jam}/V_a, with basin drainage area, A.

4.1.2 Channel-averaged LWD dimensions

With regard to LWD dimensions relative to channel and flow dimensions – which are crucial for piece mobility (Braudrick and Grant, 2000, 2001) – and taking bankfull conditions (i.e. bankfull width B_{bf} and mean water depth h_{bf}) as reference values, results show that mean values of both L_{log}/B_{bf} and D_{log}/h_{bf} are overall well below unity. Ratios were calculated for each piece (not in jams), using its dimensions and reach characteristics, and then averaged. Looking at relative length, Fiorentina and Pettorina appear to have much more mobile LWD, whereas Molini, Cordon and Code present high percentages of pieces that are virtually immobile at bankfull flows ($L_{log}>B_{bf}$). Considering relative diameters instead, the Fiorentina would feature more immobile elements, and the Molini and Cordon would have relatively more mobile LWD pieces.

Figure 4.3 shows that a strong negative correlation between basin size and mean values of the ratio L_{log}/B_{bf} is present, whilst the ratio D_{log}/h_{bf} exhibits a minor dependence on drainage area. The different degree of "connection" with basin size occurring between piece length and diameter (Fig. 4.3) can be explained as the fact that long LWD elements tend to break-up in the upper, narrower channels, creating shorter pieces that will characterize higher-order streams. On the contrary, piece diameter cannot be affected by breakage processes but only by much less effective abrasion phenomena.

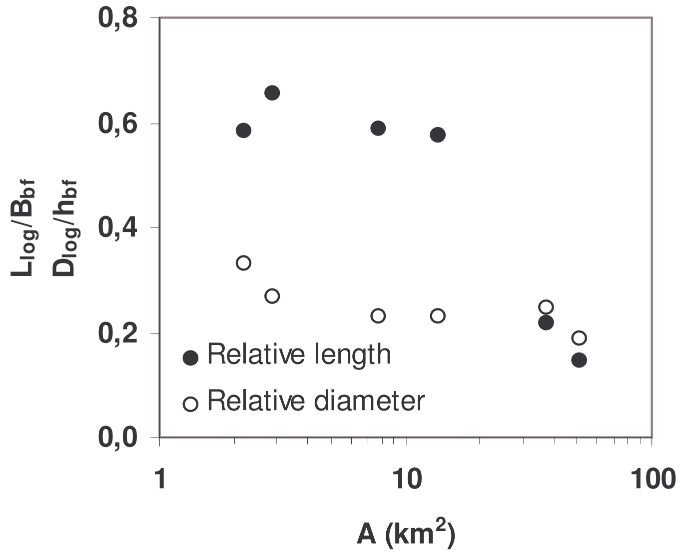


Figure 4.3 – Relationships between piece dimensions (length, L_{log}, and diameter, D_{log}) relative to channel size (bankfull width, B_{bf}, and bankfull mean water depth, h_{bf}) and drainage area, A.

4.1.3 Log-steps frequency

A consistent pattern seems to exist between basin size and presence of log-steps. The average number of log-steps per 100m of channel length results well correlated with drainage area, varying from 3.5/100 m in the Rio Code to 1-2/100 m for Molini and Cordon, down to values well below 1/100 m for Fiorentina, Pettorina and Codalunga (Fig. 4.4). The best-fit relationship is the following (R^2=0.90, p=0.05):

$$N_{ls} = 6.45A^{-0.92} \quad (2),$$

where N_{ls} is the number of log-steps per 100m of channel length. A strong positive correlation is also observed between log-step frequency and LWD volume per unit streambed area, V_a:

$$N_{ls} = 4.91V_a^{\ 1.25} \quad (3),$$

with R^2=0.98 and p<0.05.

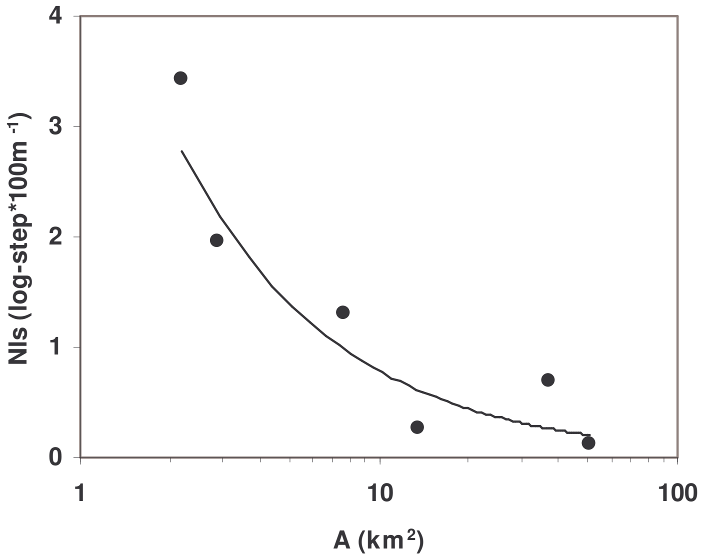


Figure 4.4 – Relationships between density of log steps and drainage area, A in the six italian streams.

Analysing mean values of the ratios L_{log}/B_{bf} for the pieces forming log-steps in the six channels, it results that smaller basins (Code, Molini, Cordon and Codalunga) present log-steps whose elements are long between 0.7-0.8 times the bankfull width (i.e. log-steps span almost the entire channel), whereas larger channels (Fiorentina and Pettorina) have log-steps characterized by relatively shorter elements, i.e. 0.3-0.4 B_{bf} (i.e. log-steps span only part of the channel cross-section). By looking at the distribution of piece length and diameters, the average dimensions of pieces forming log-steps match with the higher percentiles of the cumulative distributions of piece dimensions for each stream.

A certain consistency is present as to LWD dimensions required for log-step stability, with a slight positive trend related to channel size.

4.1.4 Reach-scale analysis of LWD volume

It was clearly evident during the field survey that the vast majority of woody debris was linked to small or large hillslope instabilities present at the same location, and LWD transport did not cause a substantial redistribution of the localized input (Fig. 4.5). In order to test whether drainage area at each reach A_r and reach geometry (namely bankfull width B_{bf}, depth h_{bf}, and channel slope S) may affect the quantity and characteristics of woody debris for each of the study channels, matrixes of Pearson's correlation coefficient R were computed using reach values for debris volumes per unit streambed area (total, V_a, rootwads, V_{rw}, and jams, V_{jam}), number of pieces per unit streambed area, N_a, and number of log-steps per unit channel length, N_{ls}. Only correlations that are significant at the level $p<0.05$ are discussed hereafter.

Reach drainage area has very little relevance for LWD volume, and only in the Pettorina and Codalunga a significant correlation is observed (with V_a, R=0.460 and R=0.353 respectively). Bankfull width, B_{bf}, does not present any significant correlation in the Codalunga and Rio Code, while in the two other "small" channels, i.e. Molini and Cordon, a rather weak (R=-0.410 and R=-0.269, respectively) negative correlation is present with the number of pieces per unit streambed area, N_a. In the Fiorentina, on the contrary, channel width is positively correlated with N_a (R=0.274), whereas the Pettorina shows significant positive correlations of B_{bf} with V_a (R=0.371) and V_{jam} (R=0.423). As to bankfull mean flow depth, it gives a significant correlation only with V_{jam} and N_a in the Codalunga (R=0.348 and R=0.332 respectively). On the other hand, reach slope seems to be effective, especially in the Fiorentina, where it correlates with V_a (R=0.384), V_{rw} (R=0.320), and N_a (R=0.408). Conversely, in the Pettorina and Molini no significant correlations turned out with channel slope, whilst rootwad volume V_{rw} results to be inversely related to S in the Code (R=-0.350). Finally, total LWD volume V_a and piece density N_a are correlated with reach slope in the Rio Cordon (R=0.261 and R=0.352, respectively).

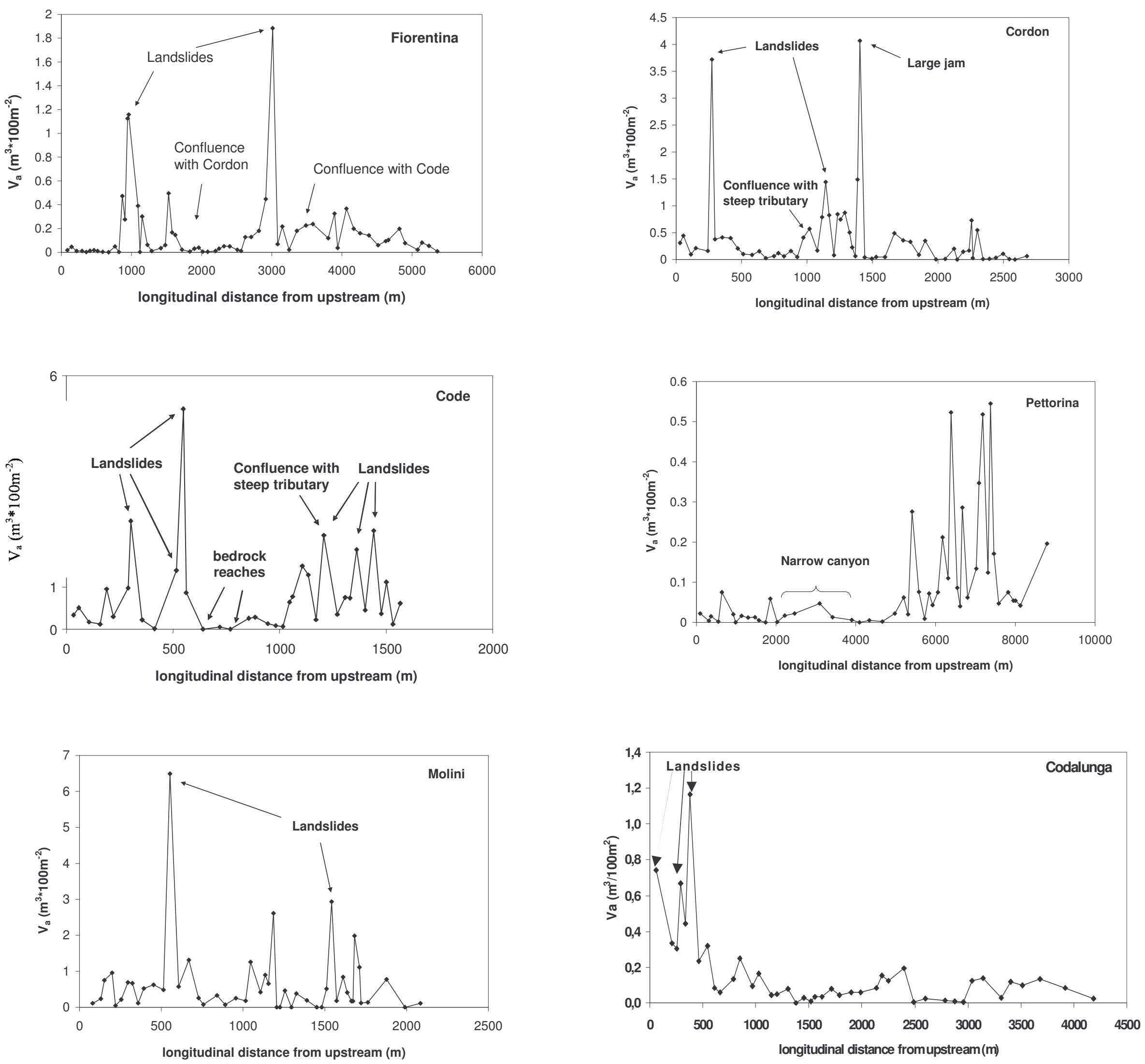


Figure 4.5 – Variation of LWD spatial density Va along the six Italian channels.

With regard to log-steps frequency N_{ls}, i.e. number per 100m of channel length, important differences emerge among the study streams. In the Code and Codalunga no parameter gives significant correlations with N_{ls}, whereas in the Pettorina only LWD density N_a (R=0.607) appears important. More factors are interrelated with log-steps in the other channels: V_a and V_{jam} for the Molini (R=0.521 and R=0.411, respectively), V_{rw}, V_{jam} and N_a in the Cordon (R=0.445, R=0.538 and R=0.688), and finally V_a (R=0.576) and N_a (R=0.407) in the Fiorentina. This latter channel is the only one where reach geometry – namely channel slope – is significantly correlated, even though very weakly (R=0.255), with log-step frequency. Reach drainage area is not correlated with N_{ls} in none of the six study channels but is correlated with the number of pieces N_a in the Codalunga (R=0.496). However, when all the 303 reaches from the six streams are analyzed together, drainage area does show a significant – yet very weak – negative correlation with woody debris volume V_a (R=-0.18, p<0.005) and log-step frequency (R=-0.200, p=0.001). The extent to which such a trend may be viewed as "real" will be discussed in the next section. Finally, the hypothesis that channel width at the reach scale might be influenced by LWD amount (as found for example by Jackson and Sturm, 2002) was tested by multiple linear and non-linear regressions, but with no success: only drainage area and channel slope resulted statistically important.

4.2 South American Basins

In-channel wood quantity in old-growth forested mountain basins of Southern Andes can vary considerably both between and within channels. 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 redwood forests in the Pacific Northwest, where average wood storage of up to 1,000 m^3 ha^{-1} were recorded (Gurnell, 2003). For example, in the 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 in Gurnell et al., 2002). The relatively low LW volume stored in the Buena Esperanza (120 m^3 ha^{-1}, 76 m^3 km^{-1}) is determined by small log diameters, in turn deriving from the extremely slow growth of nothofagus in the Tierra del Fuego, notwithstanding the extremely high abundance of wood pieces. The Rio Toro is instead characterised by a relatively low supply of large wood that overall makes its LW storage comparable to the Buena Esperanza (117 m^3 ha^{-1}, 144 m^3 km^{-1}).

4.2.1 Wood and log jams dimensions

Fueginan stream (BE) differentiates substantially from the Araucarian channels in terms of much smaller wood diameters, whereas piece length values and their distribution are similar to the other two basins (Table 4.1).

In terms relative to reach-scale channel size (i.e. bankfull width for piece length and bankfull water depth for piece diameter, Braudrick and Grant 2001), all the three streams are statistically different based on piece length/channel width ratios (one-way ANOVA and *t*-tests, $p < 0.05$).

	TA		TO		BE	
	Bankfull channel	**Fluvial corridor**	**Bankfull channel**	**Fluvial corridor**	**Bankfull 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}	0.55	0.60	0.50	0.5	0.25	0.25
D_{50}	0.30	0.35	0.30	0.29	0.15	0.15
D_{16}	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	2.90	3.17
L_{84}	5.0	4.9	4.0	4.0	4.8	5.5
L_{50}	2.2	2.5	2.2	2.2	2.0	2.1
L_{16}	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
Length / Bankfull witdh	0.40 (0.35)	-	0.30 (0.22)	-	0.48 (0.36)	-
Diameter / Banfull depth	0.95 (0.46)	-	0.41 (0.23)	-	0.43 (0.21)	-

Table 4.1. Summary of main wood dimensions. For the relative dimensions, average values and standard deviation (in brackets) are reported.

4.2.2 Potential energy dissipation and sediment storage due to LWD

Even if LWD 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 (24%). This is due to the lower dam height in the latter channel.

Rio Toro is not included because no LW dams were found along its investigated segment.Upstream of LWD dams, an impoundment forms where deposition takes place and bed slope is lower than the average in the channel.

Sediment storage due to wood dams are, in terms of volume normalized by the surveyed channel length and not accounting for porosity, 1,270 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 lead to the lack of wood-related sediment storage.

4.2.3 Reach-scale analysis of wood characteristics

A Pearson correlation matrix obtained on the (log_{10}+1) transformed variables – putting together all reaches from the three channels – was performed (Table 4.2) and larger number of variables were tested. Correlations coefficients are generally low, even though significant. Wood spatial density normalised by channel area (AN) feature higher correlations than by using channel length (LN). The most important channel variables correlated with LW numeral abundance appear to be bankfull channel width and depth.

Wood spatial density is significantly correlated with reach slope (R=0.56, p=0.018) and drainage area (R=-0.502, p=0.040) in the Tres Arroyos, but not in the other streams. Boulders spatial density appear to correlate positively with jam frequency in the Buena Esperanza (R=0.366, p=0.039), but negatively with log step frequency in the Tres Arroyos (R=-0.574, p=0.016).

Variable	LLT	LN	AN	AV	LV	MD	ML	ML/BFW	MD/BFH
S	0,2233	,3030	,3384	,3151	,2412	,0354	-,2802	,0305	,1817
	p=,072	**p=,013**	**p=,005**	**p=,010**	p=,051	p=,778	**p=,023**	p=,808	p=,144
BFW	-,1566	-,2961	-,6442	-,0883	,2299	,4100	,2352	-,8067	,0145
	p=,209	p=,016	**p<,001**	p=,481	p=,063	**p=,001**	p=,057	**p<,001**	p=,908
BFH	-,2784	-,5489	-,6458	-,2389	-,0770	,2933	,3637	-,2721	-,4692
	p=0,024	**p<,001**	**p<,001**	p=,053	p=,539	**p=,017**	**p=,003**	**p=,027**	**p<,001**
DA	-,2318	-,3579	-,4732	-,3116	-,1567	,1036	,3065	-,2558	-,3600
	p=0,061	**p=,003**	**p<,001**	**p=,011**	p=,209	p=,408	**p=,012**	**p=,038**	**p=,003**
FA/DA	-,2544	-,5937	-,7645	,1349	,3535	,7829	,4061	-,4200	,2093
	p=,039	**p=,000**	**p=,000**	p=,280	**p=,004**	**p=,000**	**p=,001**	**p=,000**	p=,092
RW	,4493	,7141	,8229	,3912	,1954	-,3640	-,1556	,4451	,1182
	p=,000	**p=,000**	**p=,000**	**p=,001**	p=,116	**p=,003**	p=,212	**p=,000**	p=,345
BO	-,0100	,0176	,0809	,3408	,2793	,2675	,0693	,2294	,4332
	p=,936	p=,888	p=,518	**p=,005**	**p=,023**	**p=,030**	p=,580	p=,064	**p=,000**
ST	,0662	,0014	,0021	,2622	,2640	,2535	,1235	,1037	,3125
	p=,598	p=,991	p=,987	**p=,033**	**p=,032**	**p=,040**	p=,323	p=,407	**p=,011**

Table 4.2. Pearson's R coefficient correlation matrix between reach variables in South American channels. S slope, BFW bankfull channel width, BFH bankfull water depth, DA drainage area, FA/DA forested/drainage area, RW spatial density of rootwads, BO spatial density of boulders (having diameter >DFH), ST frequency of steps, LLT frequency of log steps, LN number of LW pieces per km-1, AN number of LW pieces per ha-1, AV volume of wood per ha-1, LV volume of wood per km-1, MD mean wood diameter, ML mean wood length, ML/BFM mean relative length, MD/BFH mean relative diameter. Values significant at p<0.05 level are in bold.

4.2.4 Wood mobility

The survey of log displacement in the Tres Arroyos in 2006 allows to get some insights into wood mobility. After a spring runoff (peak discharge of 4.2 m^3s^{-1}, around bankfull stage), only 8 pieces out of 322 (2.5%) were found to have moved, whereas 7 elements could not be recovered, possibly because flow at the time of survey was quite high thus preventing a perfect underwater vision. The dimensions of the transported logs are comprised between 0.15 – 0.45 in diameter and 1.00 – 5.30 in length. When travel distance is normalized by log diameter, a power relationship – yet weak and non-significant, R^2=0.23 – with the log length/bankfull width ratio is apparent (fig. 4.6).

It is noteworthy that the majority of transported pieces (62%) were single logs (i.e. not in jams), had a parallel orientation and were defined as “free” elements, i.e. not “anchored” by other wood pieces, boulders or by the banks. As to original piece location, 6 pieces out of 8 had initially been classified as “in-channel”, whereas 2 as “bankfull edge”.

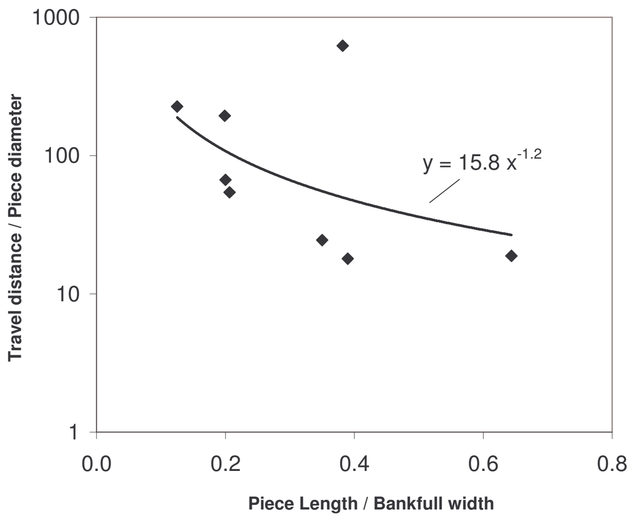


Figure 4.6. Log travel distance in the Tres Arroyos; relationship between non-dimensional travel length and non-dimensional log length. The best-fit power equation is also reported, though not statistically significant.

After 1 year of tags positioning in the Buena Esperanza , a survey of log displacement was done. 39 pieces out of 381 tagged (10%) were found to have moved and the dimensions of the transported logs are comprised between 0.10 – 0.60 in diameter and 1.00 – 4.50 in length. As in the Tres Arroyos, the majorities of transported pieces had originally a parallel orientation and were defined as “free” elements, i.e. not “anchored” by other wood pieces, boulders or by the banks. As to original piece location, 33 pieces out of 38 had initially been classified as “in-channel”, whereas 3 as "bankfull edge" and 1 lied on the channel margins. The transported pieces are equally distributed between single logs and in jams.

Plotting the travel distance normalized by log diameter, with the log length/bankfull width ratio a relation similar to what founded in the Tres Arroyos appear, but the significance is still lower (fig. 4.7).

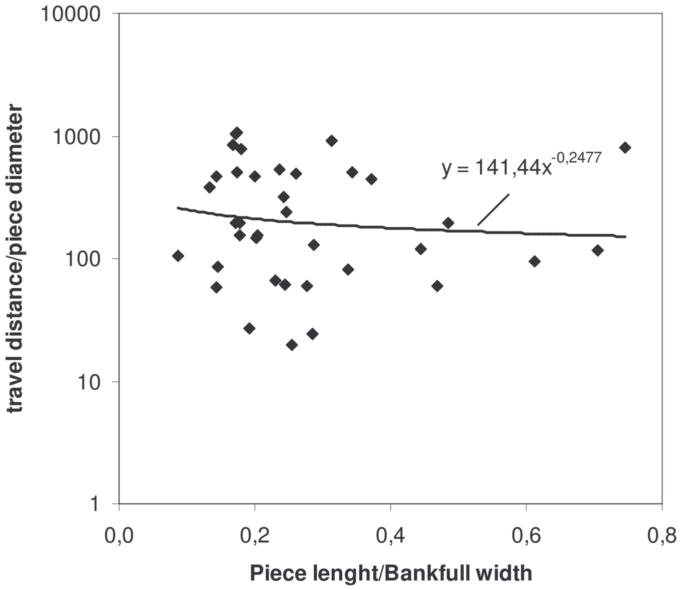


Figure 4.7. Log travel distance in the Buena Esperanza; relationship between non-dimensional travel length and non-dimensional log length. The best-fit power equation is also reported, though not statistically significant.

4.2.5 LWD influence on grain size distribution 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. Analyses of grain size distribution of the stream reaches show that both D_{50} and D_{84} are significantly larger in non-wood reaches than in wood-loaded ones ($p<0.05$).

The geometry of the longitudinal bed profile is also significantly different between the two groups. In fact, the reach-averaged drop height Z (calculated as step height minus pool depth) is considerably higher in LW reaches ($p<0.001$), as well as the ratio between average step height and step spacing (H/L, $p=0.001$). 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 ($p<0.001$).

Flow resistance shows a decreasing trend and non-LW reaches features lower friction factors (up to one order of magnitude) than LW reaches for similar values of q^* (fig. 4.8).

When channel slope is included in a general liner model along with q^* - after a log-transformation of the variables – the friction factor *f* results to be not significantly affected (p>0.10) by the presence or absence of LW. In other words, the dominant effect of wood accumulations in the measured reaches is likely the creation of steeper gradients associated to drops such as log steps and valley jams.

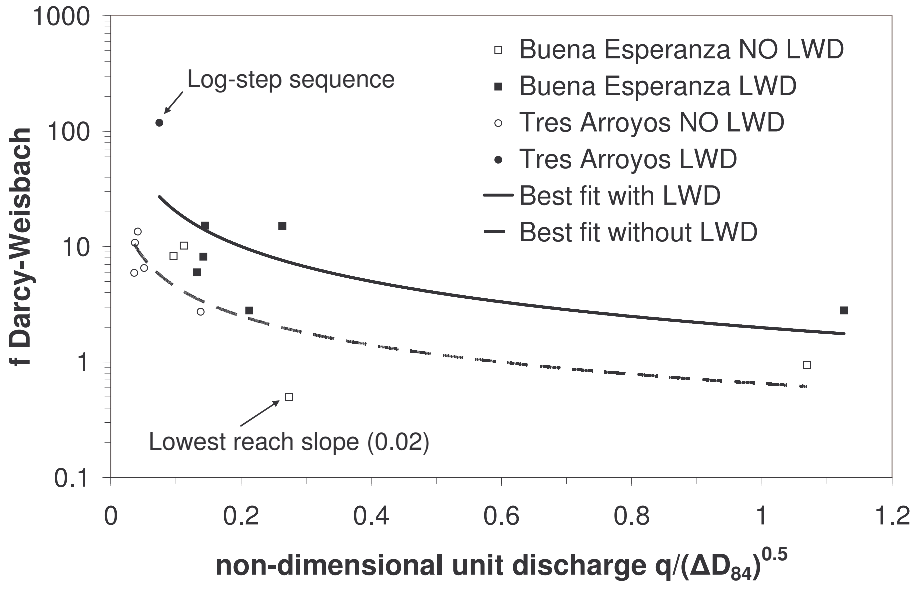


Figure 4.8. The Darcy-Weisbach friction factor f calculated for the investigated channel reaches (with and without LW) plotted versus the non-dimensional unit discharge $q/(\Delta D_{84})^{0.5}$.

5. LWD IMPACT FOR DIFFERENT FOREST TYPES

In Italian basins, there seems to exist a very clear trend between basin size and LWD abundance in the main channel. However, the strong inverse relationship between basin drainage area and average LWD volume (Eq.1), may – at least to some extent – be an "artifact" due to high degree of human alteration to the two larger channels, i.e. Fiorentina and Pettorina, where LWD removal and cuts of riparian vegetation are commonly practiced. More indicative of natural processes are data from the smaller basins (Code, Molini and Cordon), which nonetheless exhibit the inverse relationship between basin/reach drainage area and LWD volume per unit streambed area. An upper threshold size of approximately 10 km^2 (stream order ≤ 3) characterizes – in the Italian study area – basins where LWD is relatively abundant and following "quasi-natural" dynamics of LWD input and storage at present times.

Earlier works on LWD in North American streams had identified a similar trend between debris storage and channel/basin size (Keller and Swanson, 1979; Keller and Tally, 1979; Montgomery et al., 1995) whereas more recent studies do not clearly support such a relationship (e.g. Martin and Benda, 2001; Benda et al., 2002), although comparisons are made quite complex by the use of different LWD metrics (i.e. volume/pieces normalized by channel length, width or streambed area, Jackson and Sturm, 2002). In the six study channels, LWD jam size and mean number of pieces per jam were found to increase with drainage area, as described by Martin and Benda (2001) along an Alaskan river. Jam frequency indicated instead an overall negative trend with basin size, again matching the findings of Martin and Benda (2001).

All the channel-averaged LWD volumes of the mountain rivers here analyzed appear very low compared to most published data from world rivers (see Gippel, 1995, and Gurnell et al., 2002), expressed as cubic meter per hectar of streambed area.

The six study channels feature, in fact, between 8 and 73 m^{3}ha^{-1}, including LWD pieces smaller than most common definitions of LWD, and also elements at channel margins and overhanging the streambed. When, for example, pieces having D_{log}<0.10 m are taken out from the present dataset, the range becomes 6.8 m^{3}ha^{-1} (Pettorina) – 69 m^{3}ha^{-1} (Code). A comparison with data from the western U.S. (Harmon et al., 1986; Lisle, 1995; Martin and Benda, 2001; Montgomery et al., 2003) gives large differences: reported LWD amounts for American coniferous forests range from 200 to 1000 m^{3}ha^{-1}. Studies from an Australian stream (Webb and Erskine, 2003) also exhibit large debris volumes (576 m^{3}ha^{-1}), whereas three small (order 1st-4th) streams in UK feature LWD volumes between 44 and 88 m^{3}ha^{-1} (Gurnell et al., 2002), thus in the same order of magnitude of the results presented here. Other larger European rivers show even lower LWD densities, down to <10 m^{3}ha^{-1}

(Gurnell et al., 2002). In New Zealand (Baillie and Davies, 2002), small first and second streams featured on average 127 m^3ha^{-1} (pine plantation) and 94 m^3ha^{-1} (native forest). Linear LWD volumes do conform well, instead, to values (1.5-7.8 m^3 per 100 m of channel length) found by Degetto (2000) in several small mountain rivers of the Trentino Province (Italy), very near the present study area, and also with other European streams as some 2nd-4th order streams of the UK Highland Waters investigated by Gurnell et al., 2002 (44 – 88 m^3 ha^{-1}), in relatively undisturbed 2nd-4th channels in Central Europe (20 – 85 m^3 km^{-1}; Kaczka 2003), and in an Iberian third order stream (0.4 – 4.8 m^3 ha^{-1}; Diez et al., 2001). Forest management seems to 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.

In contrast to pristine basins worldwide, an LW dam frequency of 13 km^{-1} measured in the Rio Cordon channel, is comparable with a similar value (around 15 km^{-1}) found in a third-order channel of the Bavarian Alps (Kaczka, 2003) and the absence of dams observed in several third-order channels in northern Spain (Diez et al., 2001). Interestingly, in second–third order Italian basins here analyzed, 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.

As stated above, the LWD removal policy is most likely the main responsible for the very low amounts of woody debris found in the two larger streams (Fiorentina and Pettorina). However, LWD amounts are relatively low even for the smaller, now “untouched” streams (Molini, Code and Cordon). In these cases several reasons can be envisaged. First, these streams were subject to stream maintenance and control works following the 1966 flood. Secondly, forests in these basins are only now recovering from the intense exploitation occurred for centuries, now featuring low forest biomass (150-300 m^3/ha) and small tree dimensions. Furthermore, these forest stands are characterized by lower fertility – due to steep slopes, thin soils, low precipitations – compared to many other investigated sites for LWD, so that tree dimensions and forest biomass would be smaller even under pristine conditions.

Absolute LWD dimensions in the study channels are relatively small compared to other environments where trees reach much larger dimensions for several reason (climate, species, stand age, forest management history). LWD “virtual” mobility is accordingly high and only the longer and larger elements can stabilize and form log-steps. Such a low relative dimension, together with the scarce amount of LWD in the study channels, renders the geomorphic relevance of woody debris rather small, especially in the larger rivers.

Averaging along the whole channel length, log-steps are in fact quite few (1.3-3.5 log-steps per 100m of channel length for the smaller (<10 km^2) basins, but as low as 0.1-0.7 for the larger (4th order) channels, and comprise only a small fraction (~10%) of the total step number in the step-pool/cascade streams analyzed here. Log-step frequency depends on LWD spatial density, and given the inverse relationship between this latter variable and basin size, log-steps become more frequent in streams draining smaller basins. Such trend between basin area and log-step frequency – and log-jams frequency too – had already been observed in the Queets River (Washington State, US, Montgomery et al., 2003), , with values in the range 5-10 log-steps per 100m for basin areas <10 km^2. Conversely, Marston (1982) observed that third-order channels in the Oregon Coast Range presented the highest frequency of log-steps (0.4 per 100m). Gomi et al. (2003) reported – for Alaskan headwater streams draining areas of 0.12-0.35 km^2 – frequencies of steps formed by either large and fine woody debris up to 35 per 100m, with LWD-formed steps accounting for an average of 51% of the total number of steps. A similar percentage (45%, comprising both large and fine woody debris steps) was found by Curran and Wohl (2003) in basins (< 10 km^2) of the Cascade Range (Washington, US). An even higher relevance of "organic" steps was found by Jackson and Sturm (2002) in first- and second-order streams in the Coast Range (Washington, US) where "inorganic" steps accounted for only 19% of the total number of steps. Previously, the percent of steps formed by LWD had been correlated by Wohl et al. (1997) to basin/channel size in streams of Montana (US), with values ranging from 50% (area 1-2 km^2) to 10% (area > 6 km^2).

Apart from log-step formation, the influence of LWD on channel morphology is mostly due to debris jams which – although rather small and infrequent – may determine local flow obstructions and deviation, but only minor consequences were observed. Instead, isolated in-channel pieces are generally too small to cause substantial alteration of the flow field and subsequent bed deformation, whereas suspended and marginal LWD elements – accounting for a considerable proportion of the total amount surveyed – do not bring about any morphological/hydraulic effect during ordinary flood events.

Woody debris represents a component of mountain rivers whose dynamics, abundance and geomorphic influence are very difficult to model (Benda and Sias, 2003), even to a greater extent than sediments. Characteristics of forest stands (e.g. age, diameter, height, occurrence of disease and wildfires) along with local instability processes such as bank erosions, landslides and debris flows contribute to render very chaotic the pattern of LWD presence along watercourses that are tightly coupled to adjacent slopes such as mountain streams. Such a behaviour becomes absolutely evident in the six channels analyzed here, where inputs of LWD into the streams largely rely on point sources rather than on more continuous – both spatially and temporally – processes (i.e. senescence and mortality) given the relative young age of stands and the low relevance of windstorms and wild fires in the study basins. Peaks of LWD volume are in fact clearly related to reaches affected by landslides and/or confluences with steeper tributaries, as also found by Grant and Swanson (1995) and Benda et al. (2003).

The morphological and geological characteristics of the study basins (i.e. steep gradients, widespread faulting, erodible sedimentary rocks and quaternary deposits) are the main factors imparting such an irregular woody debris input pattern. In fact, the Pettorina – which features the most regular LWD distribution as well as the lowest LWD density – lacks important landslides close to the main channel, unlike the Fiorentina which has a similar size but a much more dissected basin due to lithological reasons (Slongo, 2004).

Disasters linked to LWD such as that occurred in the 1966 at Caprile (see introduction) likely depend on local, massive inputs of whole portions of forested slopes adjacent to the channels due to mass wasting processes (Castiglioni, 1974). The monitoring and the enhancement of hillslope stability thus becomes a critical aspect of flood risk mitigation also in relation with woody debris, possibly more effective than frequent, anti-ecological cuts of the riparian vegetation.

In-channel wood quantity in old-growth forested mountain basins of Southern Andes can vary considerably both between and within channels. 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 redwood forests in the Pacific Northwest, where average wood storage of up to 1,000 m^3 ha^{-1} were recorded (Gurnell, 2003). For example, in the 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 in Gurnell et al., 2002).

The relatively low LW volume stored in the Buena Esperanza (120 m^3 ha^{-1}, 76 m^3 km^{-1}) is determined by small log diameters, in turn deriving from the extremely slow growth of nothofagus in the Tierra del Fuego, notwithstanding the extremely high abundance of wood pieces. The Rio Toro is instead characterized by a relatively low supply of large wood that overall makes its LW storage comparable to the Buena Esperanza (117 m^3 ha^{-1}, 144 m^3 km^{-1}).

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, similarly low percentage of wood pieces (2·5–4%) is mobilized each year by ordinary floods, while a greater fraction of logs are transported by flow in the Buena Esperanza (10%) probably due, once again, to the smaller dimensions of the logs, so easier to be moved.

The strong longitudinal variation of LW quantity in the Tres Arroyos and in the Buena Esperanza, as well as its link to "external" factors (occasional large trees fallen into the channel, debris flows confluences and landslides) rather than to channel properties, reflects what observed in 2^{nd} – 4^{th} order channels of the Italian Dolomites.

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. bankfull width) featured by the three south American third order streams.

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 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 vs. windblown moving southward), but notwithstanding different log size and log number the net effect on channel morphology is apparently very similar. In the subanctartic climate of Tierra del Fuego, wood rarely reach large dimensions but its abundant supply by wind-caused mortality make streams prone to be locally grade-controlled by valley jams and log steps composed of floated debris trapped by occasional fallen trees. In the warmer climate of the Araucania, fires command forest regeneration and thus probably wood supply to channels. However, in-channel wood loading does not respond immediately to wildfire but a certain 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 occurred almost a century ago. Of course, basin geology and topography plays a fundamental role in delivering burned dead wood from the hillslope to the main channel. In the Tres Arroyos, the destruction of the forest cover caused severe slope instability that in turn resulted in debris flow phenomena 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.

The Tres Arroyos and the Buena Esperanza features 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 but are very similar to the percentage reported by Faustini and Jones (2003) for the third-order

Mack Creek channel (Oregon, U.S.) 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 mountain rivers of the Alps.

Moreover the present study confirms that wood-rich reaches present finer sediments, smaller steps and higher flow resistance than non-wooded segments , as previously found by MacFarlane and Wohl (2003). Higher flow resistance appear to occur mostly as a consequence of the steeper and rougher profile that wood jams induce by creating higher steps.

Wood storage and its morphological effects vary considerably as a function of forest disturbance history (Figure 5.1). In the Araucania region, wildfires – already acknowledged as the main factor driving forest rejuvenation – seems to play a major role in supplying the channel network with large wood, at least in relatively steep basins. In the southernmost Andean regions, wind would naturally take over as the main forest “timer”, but the colder climate due to the difference of latitude, influence the log size. Despite of this the net effect on channel morphology is very similar.

In Italian streams, clearing of woody debris and cut of riparian vegetation has certainly affected the quantity and characteristics of woody elements, especially in those segments closer to towns and roads. Moreover the management in these zones is active from ancient times, with different reasons over the centuries.

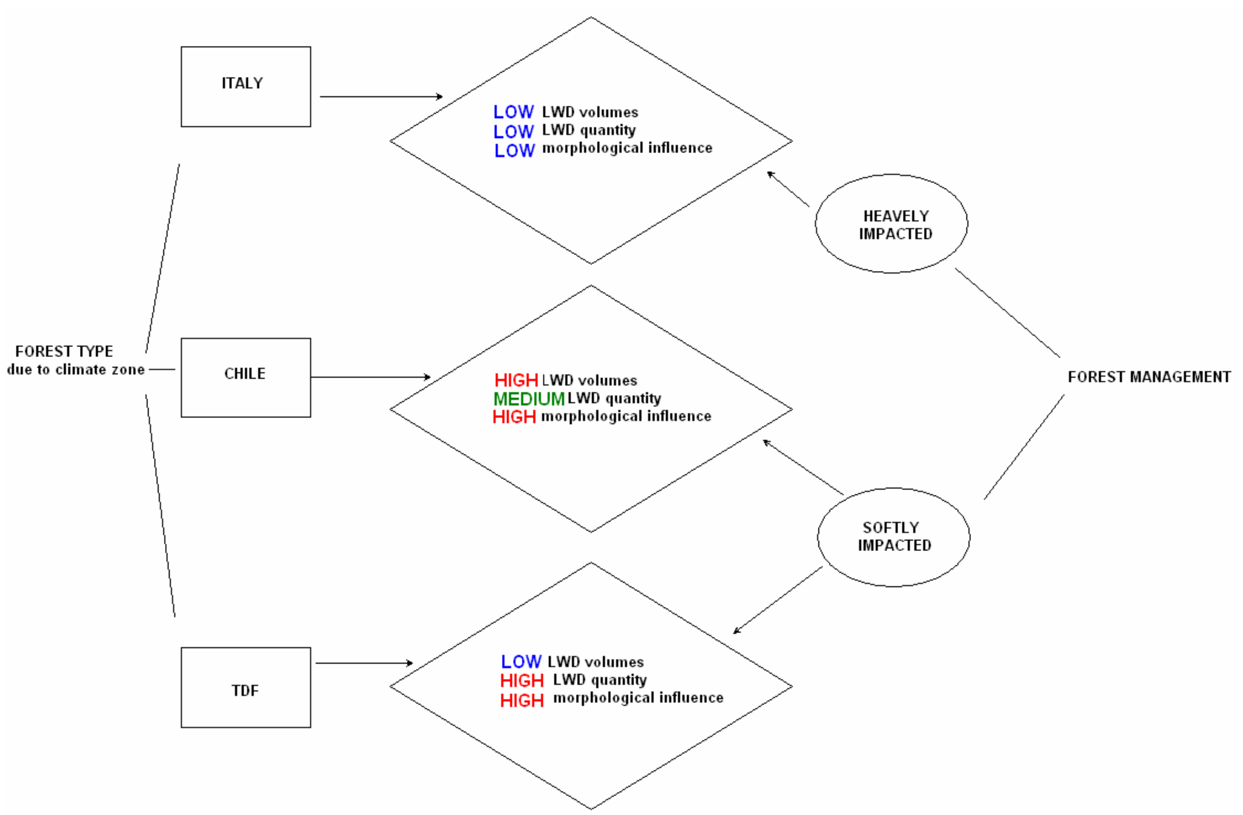


Figure 5.1. Relations between LWD characteristics in stream channels and forest disturbance history and forest characteristics.

6. MANAGEMENT OPTIONS FOR LWD IN MOUNTAIN BASINS

The previous chapters have illustrated how in-channel woody debris represents a fundamental component of the upland channel networks in the Southern Andes. In contrast to European basins, much of the original geomorphological and ecological richness deriving from an abundant presence of wood in the stream network can still be found in many parts of the temperate Andes. At the same time, the human presence is there rapidly encroaching pristine or semi-pristine basins, thus increasing flood risk by building infrastructures and residential structures within fluvial corridors (i.e. active floodplains and channels) and on alluvial fans, parts of the landscape which are naturally subject to potentially dangerous transport of sediment and wood during major flood events (i.e., recurrence interval > 20-30 yr).

Therefore, the first management option against flood risk – not only due to floating wood – is avoid building any valuable structure in flood-prone areas, i.e. the adoption of a careful land use planning. However, if something is already located in the fluvial corridor because of ill-advised decisions of the past, priority should be given to assess whether its removal (i.e relocation) is feasible, because this option is often the most sustainable in the long run. For minor infrastructure, some solutions as debris sweepers at bridge piers and racks at culverts (Bradley et al., 2005) might be sufficient. A change in typology could also be a good strategy (e.g., a suspension bridge instead of having piers).

In the case buildings and/or infrastructures of major relevance cannot be relocated and wood is recognized to represent a significant hazard during major floods (20-100 yr return interval), the adoption of structural countermeasures is needed, after an evaluation of where and how much wood will enter the network, as well as where critical cross-sections for obstructions are situated. Because these control works (e.g., filter concrete check dams, rope net, cable filters) can be expensive, their construction must be justified by a cost-benefit analysis.

Removal of wood and of riparian trees from the channel, typically viewed as “ordinary maintenance” of the entire stream network, should be adopted only locally where it is clear that a dangerous jam is being formed at a critical cross-section. Furthermore, such operation is an expensive, mostly useless activity, with negative effects on stream morphology, stability and ecological status.

These considerations are organised as a flow chart in Fig. 5.2, developed for basins < 200-300 km^2.

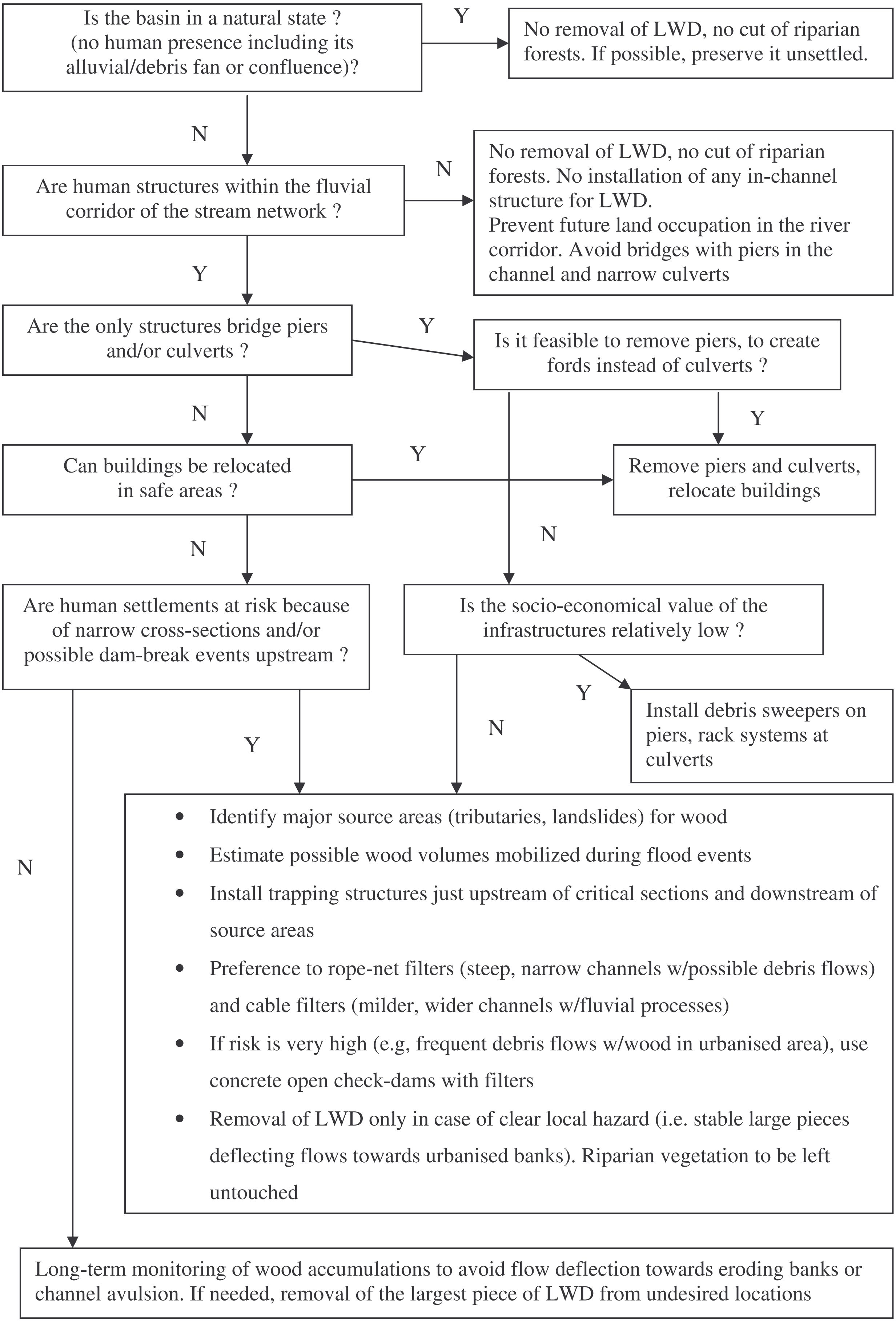


Figure 5.2. Flow chart illustrating the management options for LWD in small to medium basins.

7. REFERENCES

ABBE T.B., MONTGOMERY D.R. 2003. Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology* 51: 81-107.

AMIGO, J., RAMIREZ, C., 1998. A bioclimatic classification of Chile: woodland communities in the temperate zone. *Plant Ecology (Holanda)*, vol. 136, 1, 9-26.

ANDREOLI A., 2007. Volume and Characteristics of Woody Debris in Mountain Rivers of Italian Dolomites and Southern Andes. PhD dissertation, University of Padova – Universidad Austral de Chile (available online at: www.tesaf.unipd.it/people/andreoli/index.htm).

BARRERA, M.D., FRANGI, J.L., RICHTER, L.L., PEDROMO, M.H., PINEDO, L.B.ET AL., 2000. Structural and functional changes in Nothofagus pumilio forests along an altitudinal gradient in Tierra del Fuego, Argentina. *Journal of Vegetation Science*, vol. 11, 2, 179-188.

BAILLIE, B.R., DAVIES, T.R., 2002. Influence of large woody debris on channel morphology in native forest and pine plantation streams in the Nelson region, New Zealand. *New Zealand J. of Marine and Freshwater Research* 36, 763-774.

BENDA L., MILLER D., SIAS J., MARTIN D., BILBY R., VELDHUISEN C., DUNNE T. 2003. Wood rectruiment processes and wood budgeting. In *The ecology and management of wood in world rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society, Bethesda, Maryland: 49-73.

BENDA, L., BIGELOW, P., WORSLEY, T.M., 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, USA. *Canadian Journal of Forest Research* 32, 1460-1477.

BENDA, L., SIAS, J., 2003. A quantitative framework for evaluating the mass balance of in-stream organic debris. *Forest Ecology and Management* 172, 1-16.

BRADLEY J.B., RICHARDS, D.L., BAHNER, C.D. Debris Control Structures – Evaluation and Countermeasures. Hydraulic Engineering Circular 9. Third Edition. Report No. FHWA-IF-04-016. U.S. Department of Transportation, Federal Highway Administration, pp. 181.

BRAUDRICK, C.A., GRANT G.E. 2001. Transport and deposition of large woody debris in streams: a flume experiment. *Geomorphology* **41**: 263-283.

BRAUDRICK, C.A., GRANT, G.E. 2000. When do logs move in rivers? *Water Resources Research* 36, 571-583.

BURNS, B.R., 1993. Fire-Induced dynamics of Araucaria araucana-Nothofagus antartica forest in the southern andes. *Journal of Biogeography*, vol. 20, 6, 669-685.

CASTIGLIONI, G.B., 1974. Le calamità naturali nelle Alpi. Proc. XXI Congresso Geografico Italiano, Istituto di Geografia, Università di Padova, pp. 335.

COMITI F., ANDREOLI A., LENZI M. A., MAO L. (2006) Spatial density and characteristics of woody debris in five forested streams of the Dolomites (Italian Alps), *Geomorphology 78, 44-63.*

CORONATO, A., ROIG, C., MIR, X., 2002. Geoformas glaciarias de la región oriental de lago Fagnano, Tierra del Fuego. Actas del Decimo Quinto Congreso Geológico Argentino, El Calafate, abril 2002.AGA, 2, pp463.

DEGETTO M., 2000. Dinamica del legname in alveo e modellazione del suo comportamento in presenza di briglie filtranti. *M.S. Thesis*, University of Padova, Italy.

DGA Dirección General de Aguas. 2000. Cuenca experimental representativa, Reserva Forestal Malalcahuello, Cuenca Río Imperial, IX Región de la Araucanía. Ministerio de Obras Publicas, Departamento de estudios de planificación y Universidad Austral de Chile (Valdivia). Vol. 1-2.

DGA Dirección General de Aguas. 1998. Cuenca Experimental Representativa Reserva Forestal Malalcahuello, cuenca Río Imperial, IX Región de la Araucanía. Ministerio de Obras Publicas, Departamento de estudios de planificación y Universidad Austral de Chile (Valdivia). Volumen Nº1: 120 pp.

DIEZ , J.R., ELOSEGI, A., POZO, J., 2001. Woody debris in north Iberian streams: influence of geomorphology, Vegetation , and management. *Environmental Management*, vol. 28, 5, 687-698.

EMPARAN C, SUÁREZ M, MUÑOZ J. 1992. Curacautín, Carta Geológica de Chile. Sernageomin, Chile.

FAUSTINI JM, JONES JA. 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology* 51: 187-205.

FUENZALIDA H. 1965. Geografía económica de Chile. CORFO: 130-267.

GIPPEL, C.J., 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering* 121, 388-395.

GOMI, T., SIDLE, R.C., WOODSMITH, R.D., BRYANT, M.D., 2003. Characterstics of channel steps and reach morphology in headwater streams, southeast Alaska. *Geomorphology* 51, 225-242.

GONZALEZ ME, VEBLEN TT, SIBOLD JS. 2005. Fire history of Araucaria-Nothofagus forests in Villarica National Park, Chile. *J. Biogeogr* 32: 1187-1202.

GRANT, G. E., SWANSON, F.J., 1995. Morphology and processes of valley floors in mountain streams, Western Cascades, Oregon. In: Costa, E., Miller, A.J., Potter, K.W., Wilcox, P.R., *Natural and anthropogenic influences in fluvial geomorphology*. American Geophysical Union, Geophysical Monograph 89, Washington, D.C..

GURNELL AM. 2003. Wood storage and mobility. In *The ecology and management of wood in world rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society, Bethesda, Maryland: 75-91

GURNELL, A.M., PIEGAY, H., GREGORY, S.V., SWANSON, F.J., 2002. Large wood and fluvial processes. *Freshwater Biology* 47, 601-619.

HARMON, M.E., FRANKLIN, J.F., SWANSON, F.J., SOLLINS, P., GREGORY, S.V., LATTIN, J.D., ANDERSON, N.H., CLINE, S.P., AUMEN, N.G., SEDELL, J.R., LIENKAEMPER, G.W., CROMACK JR., K., CUMMINS, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. In: MacFadyen, A., Ford, E.D. (Eds), *Advances in Ecological Research*, Academic Press, New York, 15, pp. 133-302.

IROUMÉ A. 1997. Estudio de los procesos hidrológicos en una cuenca experimental andina de la IX Región, Chile. *Bosque* 18(1): 73-81.

IROUMÉ A. 2003. Transporte de sedimentos en una cuenca de montaña en la Cordillera de los Andes de la Novena Región de Chile. *Bosque* 24(1): 125-136.

JACKSON, C.R, STURM, C.A., 2002. Woody debris and channel morphology in first- and second-order forested channels in Washington's Coast Ranges. *Water Resources Research* 38(9), 1177, doi:10.1029/2001WR001138.

KACZKA, R.J., 2003. The coarse woody debris dams in mountain streams of central Europe, structure and distribution. *Studia Geomorphologica Carpatho-Balcanica*, vol XXXVII, 111-127.

KELLER, E.A., SWANSON, F.J., 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* 4, 361-380.

KELLER, E.A., TALLY, T., 1979. Effects of large organic debris on channel form and fluvial processes in the coastal Redwood environment. In: Rhodes, D.D., Williams, G.P. (Eds.), *Adjustments of the Fluvial System*. Kendal-Hunt, Dubuque, IA, pp. 169–197.

LENZI, M.A., 2001. Step-pool evolution in the Rio Cordon, Northeastern Italy. *Earth Surface Processes and Landforms* 26, 991-1008.

LENZI, M.A., MAO, L., COMITI, F., 2003. Interannual variation of sediment yield in an alpine catchment. *Hydrological Sciences Journal* 48 (6), 899-915.

LENZI MA, IROUME A, MAO L, PALACIOS H. 2004. Analysis of sediment transport in experimental alpine and Andean catchments. In *Proceedings of the 10° International Symposium Interpraevent*. Riva del Garda, Italy; vol 2: 77-88.

LISLE, T.E., 1995. Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research* 31, 7, 1797-1808.

LIZARRALDE, M.S., 1993. Current status of the beaver (*Castor canadensis*) introduced in Tierra del Fuego (Argentina). *AMBIO*, 22: 351-358.

MACFARLANE W.A., WOHL E.E. 2003. Influence of step composition on step geometry and flow resistance in step-pool streams of the Washington Cascades. *Water Resources Research* **39**(2), W1037, doi:10.1029/2001WR001238.

MAO L., UYTTENDAELE G.P., IROUMÉ A., LENZI M.A., 2007. Field based analysis of sediment entrainment in two high gradient streams located in Alpine and Andine environments. Geomorphology (2007), doi:10.1016/j.geomorph.2007.03.008

MAO, L., COMITI, F., ANDREOLI, A., LENZI, M.A., SCUSSEL, G.R., 2005. Bankfull and bed load effective discharges in a steep boulder-bed channel. In Walling, D.E., Horowitz, A.J. (eds), *Sediment budget I*, IAHS Publ. N°291, 189-195.

MARTIN, D.J., BENDA, L.E., 2001. Patterns of instream wood recruitment and transport at the watershed scale. *Transaction of the American Fisheries Society* 130, 940-958.

MARSTON, R.A., 1982. The geomorphic significance of log steps in forest streams. *Annals of the Association of American Geographers* 72 (1), 99-108.

MELEASON MA, DAVIES-COLLEY R, WRIGHT-STOW A, HORROX J, COSTLEY K. 2005. Characteristics and geomorphic effect of wood in New Zealand's native forest streams. International Review of Hydrobiology 90(5/6): 466– 485.

MONTGOMERY, D.R., BUFFINGTON, J.M., SMITH, R.D., SCHIMDT, K.M., PESS, G., 1995. Pool spacing in forest channels. *Water Resources Research* 31, 1097-1105.

MONTGOMERY, D.R., BUFFINGTON, J.M., 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109, 596-611.

MONTGOMERY D.R., COLLINS B.D., BUFFINGTON K.M., ABBE T.B. 2003. Geomorphic effects of wood in rivers. In *The ecology and management of wood in world rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society, Bethesda, Maryland: 21-47.

RAMIREZ, C., 1978. Estudio florístico y vegetacional del Parque Nacional Tolhuaca. Santiago: Museo Nacional de Historia Natural (Chile), Publicación Ocasional n° 24, 3-23.

REBERTUS, A.J., KITZBERGER, T., VEBLEN, T.T., ROOVERS, L.M., 1997. BloLWDown history and landscape patterns in the andes of Tierra del Fuego, Argentina. *Ecology*, vol. 78, 3, 678-692.

SLONGO, M., 2004. Tipologia dimensione e quantità del legname in alveo presente in tre collettori montani (bacino del T. Fiorentina, Belluno). *M.S. Thesis*, University of Padova, Italy.

STATSOFT, 2006. Statistica, version 7.1, Tulsa, Oklahoma.

THEVENET, A., 1998. Interet des debris ligneux grossiers pour les processus dans les grands cours d'eau. Pour une prise en compte de la dimension cologique des debris ligneux dans la gestion des cours d'eau. *Ph.D. Thesis*, Université Lyon I, France.

UYTTENDAELE GP. 2005. Procesos de transporte de sedimentos en áreas de montaña, comparación entre la cuenca del Río Cordón (Alpes, Italia) y el Estero los Tres Arroyos (Andes, Chile). *PhD thesis*, Universidad Austral de Chile, Valdivia and Università di Padova.

VELBEN, T.T., DONOSO, C.Z., SCHLEGEL, F.M., ESCOBAR, B.R., 1981. Forest dynamics in south-central Chile. *Journal of Biogeography*, vol. 8, 3, 211-247.

WEBB, A.A., ERSKINE, W.D., 2003. Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. *Geomorphology* 51, 109-126.

WOHL, E., MADSEN, S., MACDONALD, L., 1997. Characteristics of log and clast bed-steps in step-pool streams of northwestern Montana, USA. *Geomorphology* 20, 1-10.

ZELT R.B., WOHL E.E. 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. *Geomorphology* **57**(3): 217-233.