Large wood storage in streams of the Eastern Italian Alps and the relevance of hillslope processes

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[1] An understanding of the dynamics of large wood (LW) in mountain channels provides the basis for evaluating natural morphological patterns as well as managing potentially hazardous wood transport during flood events. Few studies have investigated the distribution of LW in managed streams of the Alps across a wide spatial scale. This paper presents extensive field measurements of LW storage and channel morphology carried out in 13 channels of the Eastern Italian Alps with drainage areas ranging from 1.2 to 70 km^2, mean bed slope between 0.03 and 0.38, and channel width between 2 and 20 m. More than 9000 LW elements were measured in the 33 reaches surveyed. A geostatistical, geographic information system (GIS)-based model for wood recruitment from hillslope instabilities was also developed and applied to the study basin. LW storage in the study channels results as being much lower than in seminatural basins of comparable size and climate, and only basins characterized by extensive mass wasting processes contain high wood loads with relevant morphological consequences. The statistical analysis of LW storage at the reach scale indicates that unit stream power is apparently the most significant hydromorphological factor influencing LW storage, in agreement with studies in other world regions. However, we argue that the effect of unit stream power on LW storage is not only linked to flow transport capacity but also derives from its association with LW supply and valley morphology. Both the GIS model and statistical tests on field data indicate that hillslope instabilities connected to the channel network dominate the LW recruitment volume and the distribution of in-channel wood storage.

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1. Introduction

[2] In-channel large wood (LW) directly influences the physical, chemical, and biological aspects of aquatic ecosystems [see, e.g., *Montgomery and Piégay*, 2003; *Tockner et al.*, 2003; *Seo et al.*, 2008] and as such is now recognized by ecologists and geomorphologists to be a key component in river systems, if not generally by society as a whole [*Piégay et al.*, 2005; *Florsheim et al.*, 2008; *Chin et al.*, 2008, 2009; *Dufor and Piégay*, 2009]. This is because floating LW elements can represent a hazard during intense flood events [*Fischer*, 2006; *Waldner et al.*, 2007; *Comiti et al.*, 2008b]. LW may increase flood risk by a variety of processes, such as flow and sediment surges following the collapse of temporary wood dams [*Castiglioni*, 1974], inclusion in debris flows [*Ishikawa*, 1990; *Lancaster et al.*, 2003; *Lenzi*, 2006], clogging of bridges and other structures [*Diehl*, 1997; *Bezzola et al.*, 2002; *Lyn et al.*, 2007; *Mao and Comiti*, 2010; *Mazzorana et al.*, 2011], and local bank erosion [*Daniels and Rhoads*, 2004].

[3] LW recruitment processes vary spatially and temporally within river basins [*Bilby and Bisson*, 1998; *Piégay et al.*, 1999; *Gurnell et al.*, 2002; *Benda and Sias*, 2003], including physical (e.g., landslide, debris flow, bank erosion, snow-, and windthrow) and biological (e.g., tree senescence, insects, and fungal diseases) processes, as well as human activities (e.g., harvesting). It has long been noticed that bank erosion input predominates in higher-order, lowland streams, whereas colluvial processes (landslides and debris flows) are responsible for most LW recruitment in lower-order mountain streams [see *Keller and Swanson*, 1979; *Nakamura and Swanson*, 1993; *Gurnell and Sweet*, 1998; *Hassan et al.*, 2005; *Comiti et al.*, 2008a; *Cadol et al.*, 2009; *Iroumè et al.*, 2010]. However, such a distinction remains somewhat vague and highly dependent on basin characteristics.

[4] Focusing here on mountain river basins where natural LW transfer dynamics must be managed in order to reduce flood hazards (i.e., in the densely populated mountain areas such as the European and Japanese Alps), a better understanding of LW input processes and the localization of LW sources is of great value, along with transport distance, for managing wood storage/transport volumes. In fact, the identification of wood input, transport, and deposition reaches within a channel network for different flood scenarios is needed to estimate probable LW volume and characteristics (i.e., distribution of log length and diameter),

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which in turn provides information for the location and design of suitable countermeasures (e.g., vegetation management, bridge design, retention structures [see *Bezzola et al.* 2002; *Rimböck*, 2004; *Mazzalai et al.*, 2006; *Conesa-Garcia and Lenzi*, 2010]). Unfortunately, the extreme complexity and stochasticity inherent in the array of processes entailing wood recruitment, transport, and deposition render the implementation of deterministic models unsuitable or at least not feasible for the prediction of wood transport volume at relatively short timescales (e.g., flood event scale). Instead, a simpler wood budget approach can be a viable and more reliable solution in mountain basins. In particular, conceptual models for LW routing may benefit from the use of geometric and morphological reach characteristics (e.g., width and depth relative to log size, bedforms, abundance of boulders) for modeling LW transfer in the system; whereas the identification of unstable areas on basin hillsides should help model LW input from landslides and debris flows, which are the dominant sources in mountain basins.

[5] Such conceptual models for LW transfer can be spatially distributed with their implementation in a raster-based geographic information system (GIS) model [*Rigon*, 2009; *Mazzorana et al.*, 2009, 2010], and thus able to predict the location of recruitment sites, LW transport, and depositional reaches. However, as in all modeling efforts, calibration and validation against field data within the channel network is crucial.

[6] Currently, most of the information regarding LW input rates, storage, and distribution in mountain rivers is derived from investigations in unmanaged watersheds (e.g., with old-growth forests, quasi-pristine riparian corridors [e.g., *Martin and Benda*, 2001; *Gomi et al.*, 2001; *Hassan et al.*, 2005; *Comiti et al.*, 2008a; *Mao et al.*, 2008a, 2008b; *Seo et al.*, 2008; *Wohl and Goode*, 2008; *Seo and Nakamura*, 2009; *Wohl and Jaeger*, 2009; *Bathurst et al.*, 2010]). Although several publications on LW storage and transfer during flood events from human-impacted mountain basins are available in German [e.g., *Bänzinger*, 1989; *Rickenmann*, 1997], only a few can be found in the international literature.

[7] This paper is intended as a continuation and broadening of the research started by *Comiti et al.* [2006] in managed forested basins of the Eastern Italian Alps. Two main hypotheses will be specifically addressed: the degree of hillslope instability connected to the channel network dictates the amount of wood stored in the channels and is thus the dominant recruitment process to be modeled in such steep basins; and as occurs in sediment dynamics, different limiting conditions for the transfer of wood downstream (supply versus transport) exist at different basin scales, in the range 1–100 km^2 of drainage area. The main aim of the paper is thus to test the extent to which these two hypotheses are verified in mountain basins of the Italian Alps. The relationship between LW storage and its geomorphic role will be also investigated.

[8] The study is based on field surveys conducted in 13 watersheds (drainage area A = 1.2–70 km^2) all belonging to the upper Cordevole basin within the Dolomites region. A statistical analysis is used to identify which hillslope and channel factors control LW storage at both basin and reach scale.

2. Study Area

[9] The 13 analyzed mountain rivers (Table 1) are located in the Cordevole catchment, Dolomites (Province of Belluno, Italy, Figures 1 and 2), upstream of the Alleghe Lake. Five of these 13 basins (Fiorentina, Pettorina, Cordon, Code, and Molini) had already been analyzed by *Comiti et al.* [2006]. The Cordevole basin features high relief, rugged terrain, and complex morphology. There are three main valleys: Pettorina to the west, Fiorentina to the east, and upper Cordevole to the north, which converge at the village of Caprile. This village has been severely affected by floods in the past, in particular the November 1966 flood transported huge amounts of LW down the Fiorentina River [see *Comiti et al.*, 2006].

[10] The geology of the area is very complex. The higher parts of the basins are generally composed of dolomite, limestone, and volcanic rocks forming subvertical cliffs, whereas the lower slopes, deeply incised by rivers, are formed by highly erodible sedimentary rocks and quaternary deposits, with diffuse mass wasting processes.

[11] In these valleys, the annual average temperature is ~5°C and annual precipitation is ~1100 mm, with maximum rainfall occurring in spring and autumn, and snowfalls from late November to early April. Short, intense summer thunderstorms often generate flash floods and debris flows in the smaller basins.

[12] Forests have been managed for timber production and firewood since Roman times, and probably most intensively during the 19th century. The forest area started to expand after World War I as a result of land abandonment due to emigration, and this process is still ongoing. Nowadays, woodlands cover 43% of the territory, and are mainly spruce (*Picea abies*) at lower elevations (<1500–1600 mean annual sea level [MASL]), mixed with larch (*Larix decidua*) and stone pine *Pinus cembrae* higher up. The average standing volume of spruce woods is 259 m^3 ha^{-1}, with an average tree height of 28 m with an average diameter of 35 cm. There are no old-growth stands in the basins, with most of the forests being relatively young (<150–200 years). Only small areas (<100 m^2) are now logged contiguously due to soil protection regulations. Nonetheless, the ruggedness of the terrain is such that most of the forested area is no longer harvested because it is either unprofitable or classified as protection forest. Riparian vegetation is composed of broadleaves at the lowest elevations (<1400–1500 MASL): mostly alder (*Alnus incana*) with some ash (*Fraxinus excelsior*), maple (*Acer pseudoplatanus*), and willow (*Salix spp.*), with spruce and larch in the upper part of the channels.

[13] Debris flows dominate sediment and wood transport in the smaller basins (<2.5 km^2). These streams are very steep (>25%), with a bed morphology of alternating bedrock, colluvial, and cascade reaches (Figure 2a). Channels draining larger areas (3–30 km^2) have progressively lower gradients (ranging from 10% to 20%), can be classed as semialluvial and are characterized by stable bed forms (cascade and step pool). Finally, larger basins (50–70 km^2) have channels with bed slope <3%–6% and mostly plane-bed morphologies, but here the alteration due to grade-control structures is determinant. The main characteristics of the study basins are reported in Table 1.

Table 1. General Characteristics of the Study Basins[a]

Basin	Stream Order	Basin Area (km^2)	DI (−)	Mean Elevation (Mean Annual Sea Level)	Mean Basin Slope (%)	Mean Channel Slope (%)	Length Surveyed (km)	Length Surveyed Reaches	Bed Morphology	Survey Year
Bianco[b]	1	1.2	1	1724	72	38	0.35	5	cs/br	2007
Della Miniera[b]	1	1.5	2	1886	75	28	0.2	3	cs/br	2007
Code[b]	2	2.2	3	1776	41	26	1.6	24	cs/br	2003
Molini	2	2.9	1	1609	51	16	2.1	35	sp/br	2004
Valbona	2	3.8	3	1888	76	21	0.35	5	cs	2007
Ornella	2	6.7	2	1961	54	18	0.4	6	cs	2007
Cordon	3	7.7	3	2075	47	10	2.7	41	sp	2003
Davedino	2	8.7	3	1961	60	16	2.9	37	cs	2006
Codalunga	4	13.5	1	1930	55	10	4.2	43	cs/sp	2005
Andraz	4	27.2	2	1950	49	13	0.7	7	cs/sp	2007
Pettorina	4	51	1	1944	65	6	8.8	46	Pb[c]	2004
Fiorentina	5	58	1	1838	55	4	5.4	51	pb[c]	2003
Alto Cordevole	4	70	1	1194	51	3	3.3	34	pb[c]	2007

[a]DI is the basin scale dissection index (see text). For bed morphology, cs is cascade, bk is bedrock, sp is step pool; pb is plane bed [sensu *Montgomery and Buffington*, 1997].
[b]Evidence of debris flows along the main channel.
[c]Bed morphology altered by sequences of check dams.

3. Survey Methodology and Data Analysis

[14] The methods deployed in the field are the same as those used by *Comiti et al.* [2006] during the above-mentioned field surveys of the five basins (i.e., Fiorentina, Pettorina, Cordon, Code, and Molini) in 2003–2004. The other channels analyzed in this paper were surveyed in 2004, 2006, and 2007. Over this period there have been only ordinary flood events in the channel network (apart from the Fiorentina River, see Table 2 for the available peak discharge data), and LW recruitment and transfer have been at a low level, also based on repeated visual observations.

[15] The streams were divided into reaches of varying length based on bed morphology and geometry (mostly slope and width). Surveys were carried out along the main channels from the downstream end stretches up to the tree line or insurmountable obstacles (e.g., waterfalls). A continuous investigation was performed along most of the streams (Figure 1), whereas in some channels (Bianco,

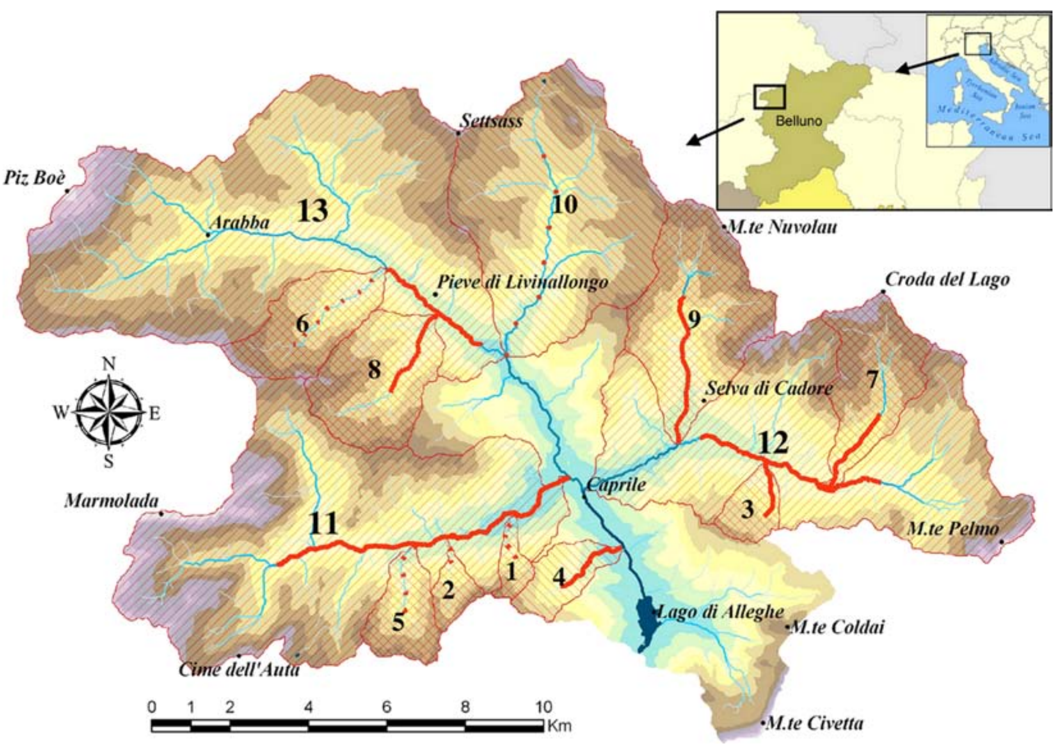

Figure 1. Map of the study basins (northeastern Italy). Numbers refer to Table 1, the surveyed reaches are marked in red.

Figure 2. Photos of the study channels: (a) Rio Bianco, (b) depositional reach in the Rio Code, (c) view of the Fiorentina, (d) debris flow fan deposited in the Alto Cordevole, (e) log step in the Rio Andraz, (f) wood-rich stretch in the Rio Davedino.

Della Miniera, Valbona, Ornella, and Andraz) a systematic sampling procedure was adopted by previously identifying discontinuous reaches on the map, together covering $\geq$10% of the total stream length from the lower to the higher elevations. A total of 337 reaches were surveyed. In every reach the following geometric characteristics were measured by a laser distance meter and a clinometer: bankfull channel width (W_{bf}), mean bankfull depth (h_{bf}), and mean channel slope (S_c). Mean bankfull depth (h_{bf}) was measured by a stadia rod at three representative cross sections along each reach. The identification of the bankfull stage was carried out by analyzing cross-sectional characteristics such as abrupt variations in transversal slope, changes in sediment composition, levels of stable vegetation, and unvegetated bars. Undoubtedly, a large degree of uncertainty affects this type of analysis, especially for the bankfull water depth in bedrock-dominated reaches. In the post-2004 field surveys carried out in eight basins, the sediment clasts with an average diameter of $>h_{bf}$ were also counted in each reach.

[16] All wood pieces lying in the channel and along its banks were measured by a tree caliper and a meter tape, provided they were >5 cm in diameter and >0.5 m in length. This definition of LW (smaller than the typically used >10 cm in diameter and >1 m in length) is due to the small dimensions (particularly in terms of diameter, see results in section 5) of wood elements in our study basins, i.e., we aimed to have large samples for each channel. The volume of each piece was then calculated assuming a cylindrical shape, a very reasonable assumption for the dominant LW type (i.e., relatively short conifer boles) found in the study basins. Reach LW volume was determined by summing all LW pieces found in a given reach.

[17] Other LW characteristics were also recorded, such as tree species (conifer/broadleaved), channel location (in-channel, log-step, bridging, banks), and the estimated recruitment mechanism (bank erosion, landslide/debris flow, harvest residue, natural mortality, transported from upstream, as in the work of *Mao et al.* [2008a]), but only for the post-2004 surveys. It is important to point out that for this purpose bank erosion includes all of the small (<2 m high) landslides adjacent to channels, only occasionally linked to floodplain surfaces that are of limited expanse in all the study basins (highly confined channels, see also below).

[18] In order to quantify the possible role of slope instabilities (i.e., landslides, bank erosions, and debris flow confluences) in supplying LW to the channels, their linear extent (i.e., adjacent to the channel, for both banks) in each reach was measured during the field surveys by a laser distance meter. A dissection index (DI), a categorical variable featuring three classes, was then introduced at the reach scale. It was calculated by summing the linear extent of channel-connected instabilities (and dividing this by the total surveyed stream length for each basin. Each channel was therefore assigned one of three classes (1–3) of DI with increasing levels of dissection, i.e., the extent of mass wasting processes connected to the channels. The first class (DI = 1) is attributed to channels with unstable banks/slopes adjacent to the main channel for <33% of the channel length, DI = 2 identifies channels with instabilities between 33% and 66%, and DI = 3 refers to basins whose main channel is bordered by landslides/bank erosion/debris flows for more than 66% of the length.

[19] Further observations were made in the Davedino basin to determine the relationship between jam type (following the classification by *Abbe and Montgomery* [2003], slightly modified by *Mao et al.* [2008a]), jam size, and their

Table 2. Available Data on Annual Maximum Discharge for Three of the Study Rivers ($m^3\ s^{-1}$)[a]

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cordon	0.9	4.0	2.9	4.3	**10.4**	2.7	3.0	1.5	**4.7**	3.7	3.3	2.0	2.8	1.0	2.2	1.7	1.3				
Fiorentina				**19.3**	14.5	6.5	9.5	6.4	14.6	9.1	**17.6**	9.5	**31.1**	8.0	11.7	**21.3**	4.5	5.5	14.6	7.7	**17.7**
Cordevole	4.3	9.0	15.4	12.5	20.9	13.2	13.0	18.6	18.2	**32.2**	19.0	**26.5**	13.2	**35.5**	9.9	9.2	16.0	8.3	7.7	**24.4**	17.0

[a]Cordon (A is 5 km^2), Fiorentina (A is 56 km^2), Cordevole (A is 110 km^2). Discharges higher than Q_5 (i.e., discharge with recurrence interval of 5 years, calculated by a frequency analysis based on the lognormal distribution) are marked in bold. Data source: ARPA Veneto (http://www.arpa.veneto.it/datirete.htm).

morphological consequences, similarly to the work done in Tierra del Fuego by *Mao et al.* [2008a]. In particular, jam key elements [sensu *Abbe and Montgomery*, 2003] were identified and measured, all LW pieces within the jam were counted and measured, the gross sediment volume (i.e., neglecting porosity) trapped upstream of each jam was estimated based on the size of the sediment wedge [as also by *Andreoli et al.*, 2007], and finally the morphological and sedimentological effects of each accumulation were qualitatively interpreted [see *Rigon*, 2009 for details].

[20] The spatial and hydrological analysis was conducted with ESRI ArcGis 9.1 software using digital Regional Technical Maps (CTR Veneto Region). A raster digital elevation model DEM (10 m cell) was obtained, which provided the basis for all of the morphometric analyses on the study basins. The stream reaches surveyed were geo-referenced and digitized in order to derive their drainage area and mean hillslope gradient (i.e., the slope of their valley sides averaged over a 100 m wide buffer across the stream course) from the DEM. Land use, forest management, and geolithological maps (Italian geological map, sheets 11 and 12; available at http://www.apat.gov.it/Media/carta_geologica_italia/default.htm) were also digitized.

[21] Besides the geometric and morphological characteristics, a parameter probably related to LW transfer is stream power [*Seo and Nakamura*, 2009; *Wohl and Jaeger*, 2009]. In our study we calculated the reach unit stream power (ω) at the bankfull stage by assuming critical (Fr $\sim$1) flow conditions, as suggested by previous measurements in steep channels [*Grant*, 1997; *Comiti et al.*, 2007], as well as by a visual estimation based on water surface patterns during ordinary events in some of the study channels. Such an assumption clearly introduces a certain error in the determination of unit stream power, but it can provide a reasonable approximation in the study channels. The equation is as follows (with γ being the specific weight of water in Nm^{-3}):

$$\omega = \frac{\gamma \times Q \times S_c}{W_{bf}} = \frac{\gamma \times V_{bf} \times A_{bf} \times S_c}{W_{bf}} = \frac{\gamma(\sqrt{g h_{bf}})(h_{bf} W_{bf}) S_c}{W_{bf}}. \tag{1}$$

[22] Data relative to LW storage and dimensions were subsequently analyzed at both basin and reach scale, in order to identify which morphological and hydraulic variables are more relevant in determining LW distribution along the drainage network. Statistical analyses were performed on log-transformed data to stabilize variance and thus match the assumptions of normally distributed data needed for the parametric analysis with the software STATISTICA 6 [*StatSoft*, 2004]. A significance level $p = 0.05$ was adopted for discriminating significant correlation and differences.

4. LW Recruitment From Hillslopes: A Geostatistical Modeling Approach

[23] As mentioned in the introduction, one of the working hypotheses of the paper is that the extent of lateral instabilities connected to the channels should provide information about the level of LW storage. The dominance of LW input from mass wasting processes is thought to stem from the low natural mortality in the relatively young, managed forests covering the study area, and the fact that these channels are highly confined, so LW input from floodplain erosion is very limited. Furthermore, the capacity and timing of water flows to flush wood out of these basins (especially in first- to third-order streams) is assumed to be insufficient to cancel out the different level of LW input [see *Comiti et al.*, 2006]. For example, LW storage is expected to be constantly higher in the more dissected basins until a very intense flood event (or debris flow) sweeps the channel.

[24] The dissection index quantifies the instabilities (i.e., landslides, bank erosions, and debris flow confluences) adjacent to the main channel at the time of the survey, but provides no information on the dissection of the entire basin or for the past (e.g., previous 50–100 years). Regarding the latter, aerial photos of sufficient resolution to detect small landslides are unfortunately available only for the most recent years, and are thus of limited use because LW residence time in small mountain channels can be $>$100 years [*Hyatt and Naiman*, 2001]. Therefore, the ability to model the recruitment from hillslope instabilities would be highly useful for predicting LW transport volumes during future flood events as well as for ranking basins based on their potential to supply LW to the channel network (see section 1), and also for comparing the modeled LW input against the LW storage measured in the field. This latter objective is addressed in this paper.

[25] A model for LW recruitment from hillslope instabilities to the channel network needs to: predict unstable areas over the entire basin, determine the LW volume and characteristics (e.g., tree size) on these unstable areas, simulate the transfer of such LW downhill, and determine how much of the original unstable LW reaches the channel network (through mass wasting processes). Once LW is within the channel network, the further modeling of its transfer downstream can be of great value to predict LW redistribution along the channels as well as possible hazards arising from wood accumulations [*Lancaster et al.*, 2003; *Rigon*, 2009; *Mazzorana et al.*, 2010]. On the other hand, the prediction of location and the magnitude of the LW supply from mass wasting processes alone (i.e., without the channel transfer) would be a great achievement for flood mitigation purposes as well as for determining one of the most significant input components for in-channel wood budgeting.

[26] Deterministic models for slope stability (e.g., SHALSTAB [*Montgomery and Dietrich*, 1994]) are not applicable in the study basins because of the extremely wide variability in soil and substrate characteristics, for which information is lacking. An alternative geostatistical approach has therefore been adopted in this research, following the work by *Campana et al.* [2007] in the same area.

[27] Landslides and debris flow susceptibility maps were obtained through a geostatistical bivariate analysis ("WofE," weight of evidence method [*Bonham-Carter et al.*, 1989]), based on a comparison between the density of landslides and several potential factors (i.e., elevation, slope, aspect, concavity, geolithology, and land use). In the WofE method, positive weight values indicate that there are more "unstable" cells belonging to a given class of a certain potential factor than would occur randomly; conversely, negative values indicate fewer unstable cells than expected for that

factor class. Subsequently, the weighted factors have been combined according to posterior probability theory to obtain a value ranging from 0 to 1 (susceptibility), which is directly related to the likelihood of the instabilities occurrence. More details can be found in the work of *Sawatzky et al.* [2009]. Three different levels of estimated likelihood of occurrence (high, scenario 1; medium, scenario 2; and low, scenario 3) were then chosen based on susceptibility values, i.e., 0.5–1, 0.25–0.5, and 0.05–0.25, respectively. It must be pointed out that there is no formal relationship between such likelihood of occurrence and the recurrence interval of rainfall events triggering instabilities.

[28] The raster-based WofE analysis was conducted using ArcGIS software and the ArcSDM application package [*Sawatzky et al.*, 2009], using the information layers described in section 3. The inventory of landslides and debris flows needed to calculate the weights for each instability factor were obtained from the "IFFI Project" (Inventory of landslides in Italy [*Amanti et al.*, 2001]) integrated by the detailed study in the Upper Cordevole Basin presented by *Campana et al.* [2007], and by new field mapping, especially for small mass wasting adjacent to the channels.

[29] Once the unstable cells within the raster grid are identified for each of the three scenarios of instability, the "unstable LW" in m^3 for every scenario is easily calculated using the digitized forest maps, which give the forest stand mass in m^3 ha^{-1} for each cell (surveyed in 2003–2007). The subsequent transfer of such unstable LW volume toward the channel network was modeled using the "slope decay" function featured in "TauDEM" [*Tarboton*, 2002], whereby the initial LW mass undergoes a progressive decrease depending on the distance, along the flowpath, from the unstable area to the channel, and steepness of the slope, i.e., the steeper the slope and shorter the distance, the larger the fraction of LW volume delivered into the network. Therefore, each cell of the channel network is characterized by a value of LW input from the hillslopes, expressed in m^3. By summing up the LW input values in all of the channel network cells within each basin we could obtain the simulated LW input from mass wasting processes for the three scenarios to be compared with the LW storage resulting from the field surveys. A summary of the entire model is presented in Figure 3. The in-channel transport downstream from recruited LW was modeled by *Rigon* [2009] using a "stream decay function," but results are still preliminary so they are not presented here. More details about the model are provided by *Rigon* [2009], and model sensitivity with respect to the parameters used in the slope decay function will be addressed in a later paper.

5. Results

5.1. LW Storage and Dimensions at the Basin Scale

[30] Overall, more than 9000 LW elements were measured in the 337 reaches surveyed in the 13 channels. LW storage or load, defined throughout the paper as LW pieces

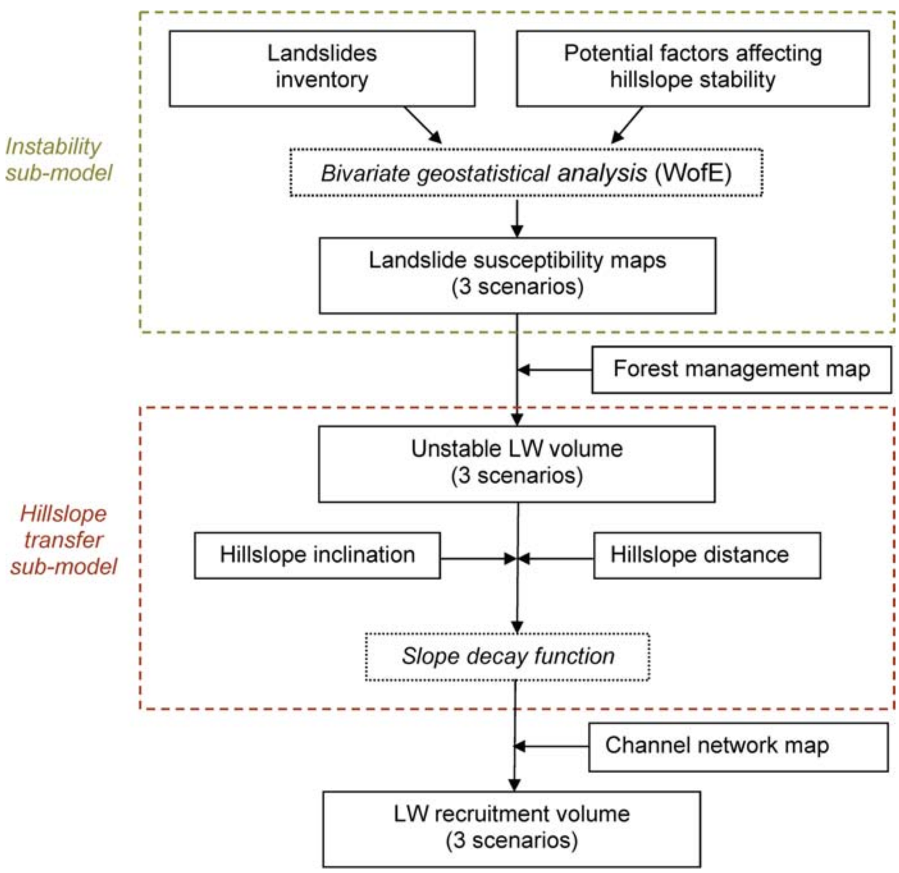

Figure 3. Flowchart describing the LW recruitment model developed for GIS systems and applied to the study basins.

Table 3. In-Channel LW: Quantity and Size at the Channel Scale[a]

Basin	LW_n (ha^{-1})	LW_v (m^3 ha^{-1})	D_{l50} (m)	D_{l84} (m)	L_{l50} (m)	L_{l84} (m)	$D_{l84}\, h_{bf}^{-1}$	$L_{l84}\, W_{bf}^{-1}$
Alto Cordevole	590	18	0.09	0.17	1.7	3.8	0.13	0.49
Andraz	2503	73	0.13	0.25	3.5	10.0	0.26	1.25
Bianco	1028	71	0.11	0.23	1.2	3.7	0.34	1.34
Codalonga	956	16	0.07	0.14	2.9	6.4	0.17	0.79
Code	209	73	0.10	0.22	1.8	5.1	0.22	1.17
Cordon	647	31	0.11	0.18	2.1	5.8	0.15	1.05
Davedino	418	106	0.12	0.22	2.0	5.0	0.16	0.86
Della Miniera	1112	93	0.10	0.20	1.2	3.2	0.23	0.97
Fiorentina	313	16	0.10	0.19	1.7	3.9	0.18	0.41
Molini	311	59	0.10	0.20	1.6	4.0	0.24	1.15
Ornella	203	24	0.07	0.12	1.7	3.9	0.24	0.85
Pettorina	255	8	0.08	0.14	0.8	1.6	0.13	0.20
Valbona	267	27	0.11	0.18	2.8	5.1	0.23	0.76

[a]LW_n and LW_v are wood storage in number of elements and volume, respectively, per unit bed area; D_{lx} and L_{lx} are the xth quantile of the distribution of log diameter and length, respectively; h_{bf} and W_{bf} are the bankfull depth and width, respectively.

(number) and volume (in m^3) divided by streambed area (in ha), the latter in turn derived from the mean bankfull width times channel length, calculated at the entire channel scale (i.e., total LW/total streambed area surveyed in each channel) displays wide variability both in number (LW_n, 200–2500 pieces ha^{-1}) and volume (LW_v, 8–106 m^3 ha^{-1}), as can be seen in Table 3. The Davedino and Andraz basins featured the greatest LW storage, in volume and number respectively, whereas the lowest LW storage was found in the Pettorina. Figure 4 shows how channel-averaged LW storage generally tends to decrease for increasing basin areas, but with some notable exceptions (i.e., see Davedino and Andraz). Furthermore, LW load within each channel (Figure 5) is quite variable in some basins, especially for the lower order channels featuring relatively large LW storage (e.g., Davedino, Code, and Della Miniera).

[31] Log dimensions (i.e., mid-diameter D_l and length L_l) in the 13 channels are shown in Figure 6. Log length appears to be much more variable among basins than diameter. In fact, the median diameter is ~10 cm in all of the streams, whereas median length ranges from 0.79 m (Pettorina) up to 3.5 m (Andraz). The longest logs (up to 18 m) were found in this latter channel, whereas the largest diameter logs were encountered in the Rio Bianco (0.6 m). LW diameter is apparently related to basin ruggedness, i.e., steeper, more remote, and thus less managed (in terms of

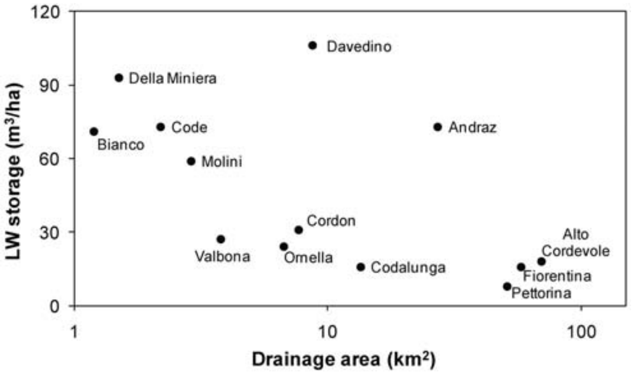

Figure 4. Scatterplot of LW storage at the channel scale (in terms of volume, LW_v) versus the respective basin area.

forests) basins (i.e., Rio Bianco, Davedino, and Andraz) are the ones with the largest logs. In all of the study channels, the larger logs and the vast majority (>80% in all the channels) of LW had originated from conifer trees growing on the hillslopes; whereas LW from riparian broadleaved trees were only a small fraction of the total storage.

5.2. Factors Controlling LW Distribution at the Reach Scale

[32] In order to determine which morphological and hydraulic variables control the amount of LW storage (LW_n and LW_v), reach values of LW quantity were analyzed with the channel variables described in the previous section 5.1, i.e., drainage area, bankfull channel width and depth, bed slope, hillslope gradient, and unit stream power. A simple preliminary Pearson's correlation analysis was done first (Table 4), because LW and several morphological variables (e.g., channel width, depth, and slope) are potentially linked to one another in complex ways, i.e., dependent and independent variables cannot be identified a priori. The analysis was performed on log-transformed variables for the reasons explained in section 3; a check was made that the use of untransformed data did not substantially change the results, but correlation coefficients in this case were lower.

[33] The correlation matrix shows that channel depth is the only variable that does not significantly relate to LW storage. Drainage area and channel width are inversely related to LW storage, whereas channel slope and unit stream power are positively correlated with it. However, correlation coefficients are quite low even if significant, and LW expressed in number (LW_n) exhibits a stronger dependence upon the variables than LW_v.

[34] Unit stream power (see equation (1)) is the variable associated with the highest correlation with LW both in number and volume (although still quite low at 0.46 and 0.36, respectively), followed by very similar coefficients for drainage area and channel bed slope. In addition, the hillslope gradient appears to be more influential than channel width. However, in Figure 7, no monotonicity (or linearity) of the relationships between LW storage and several variables (drainage area, bed slope, hillslope gradients, and unit stream power) is apparent. Indeed, nonlinear, parabolic-like patterns may actually better characterize the relationship between LW storage and those variables. In fact,

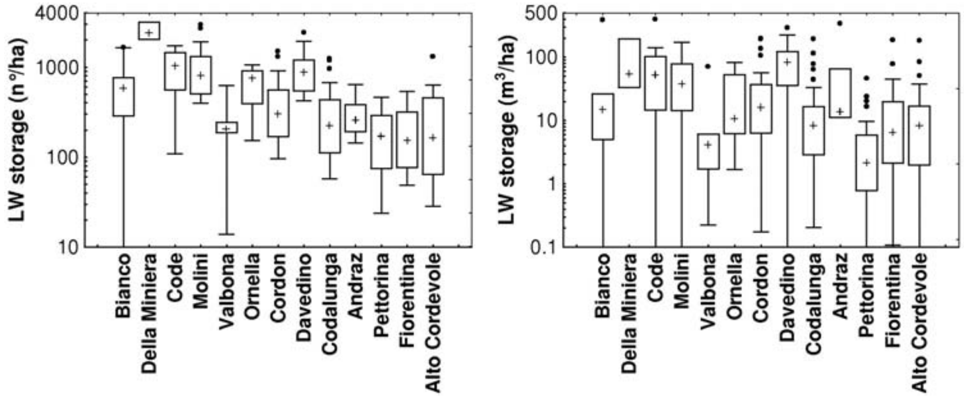

Figure 5. Variation of LW storage in number (LW_n, left) and volume (LW_v, right) within each channel. Boxes are arranged in order of increasing drainage area from left to right. The cross within each box indicates the median value, box ends are 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and dots are outliers.

maximum LW storage is found to occur in drainage areas between 1 and 10 km^2, bed slope between 0.15–0.25 m m^{-1}, hillslope gradient between 0.5 and 1 m m^{-1}, and unit stream power between 2000 and 4000 Wm^{-2}. Unfortunately, the data set does not allow definitive statistical conclusions to be drawn about these trends because the scatter is considerable and there are few reaches with small drainage areas, steep channels, and high unit stream power. Nonetheless, the likely rationale behind these trends is quite plausible and will be described in the discussion (section 6). In contrast, a negative trend between LW storage and channel width is rather evident (Figure 7b), indicating that LW load markedly decreases for increasing channel size (note the sharp drop between 5 and 15 m width). Note also that 10 m represents a channel size larger than the 84th quantile of the distribution of LW piece length for all of the channels (Table 3).

[35] In order to more thoroughly investigate the data set, a covariance analysis (ANCOVA [*Zar*, 1999]) was conducted assuming LW storage as a dependent variable and the fact that channel variables are cross-correlated in the study basins (Tables 5 and 6, respectively), in order to isolate the role of each channel variable on LW storage. The analysis shows that the significant variables are unit stream power, drainage area, and, rather surprisingly, channel bankfull depth, which exhibited no significant correlation in terms of Pearson's R (Table 4). The differences between the channels (included as a categorical variable in the ANCOVA) also turned out to be highly significant, indicating that the magnitude of LW storage cannot be linked solely to morphological and hydraulic variables, but also to other factors specific to each basin (e.g., the degree of dissection, see the discussion in section 6).

5.3. LW Storage and Potential Mobility

[36] No data about LW mobility (e.g., discharge level for initiating transport, transfer distance at different discharges) are available for the study channels. However, conceptual [*Braudrick and Grant*, 2000; *Gurnell et al.*, 2002] as well as laboratory and field investigations [*Braudrick et al.*, 1997; *Braudrick and Grant*, 2001; *Haga et al.*,

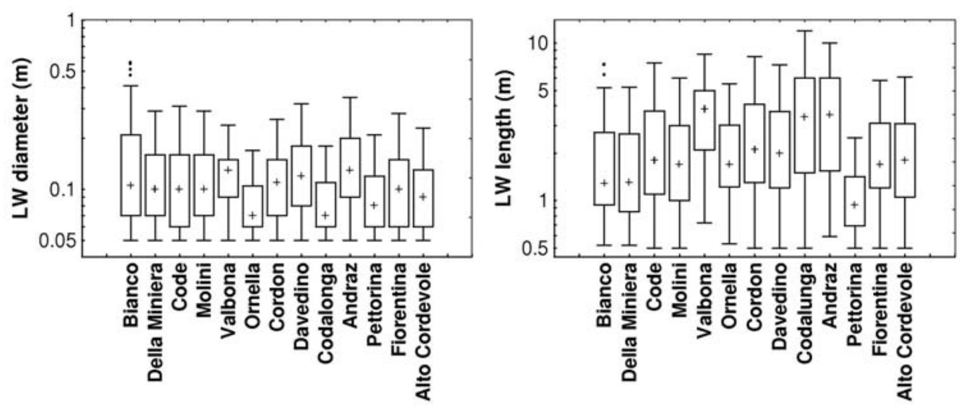

Figure 6. Box plots of LW diameter (left) and length (right) in the different channels. Boxes are arranged in order of increasing drainage area from left to right. The cross within each box indicates the median value, box ends are 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and dots are outliers.

Table 4. Matrix Correlation (Pearson's R) Between LW Storage (in Number, LW_n, and Volume, LW_v) and Morphological/Hydraulic Channel Reach Variables ($N = 334$)[a]

	A	W_{bf}	h_{bf}	S_c	S_s	ω
LW_n	**−0.39**	**−0.24**	0.07	**0.39**	**0.31**	**0.46**
LW_v	**−0.31**	**−0.22**	0.03	**0.31**	**0.24**	**0.36**

[a]The correlation was done in log-transformed variables. Significant ($p <$ 0.05) correlations are in bold. A is drainage area, W_{bf} is bankfull width, h_{bf} is bankfull depth, S_c is channel slope, S_s is hillslope gradient, and ω is unit stream power.

2002; *Gurnell*, 2003; *Mao et al.*, 2008b] indicated that log mobility in nonsinuous channels should be fundamentally related to two parameters, L_l/W_{bf} (lateral mobility) and 0.5 D_l/h_{bf} (buoyancy mobility [*Abbe*, 2000; *Abbe and Montgomery*, 2003]). Herein, we refer to these parameters as LW stability indices, i.e., the larger their values above unity, the less likely a log will pass through a reach of given geometry. Nonetheless, other factors may concur to determine LW mobility, such as wood density and the presence and size of rootwads. Figure 8a shows how stability indices vary with the drainage area of single reaches, using as log dimensions the 84th quantile of their D_l and L_l distributions. The rationale for this choice lies in the fact that even a few immobile logs in a reach could act as traps for floating LW, thus triggering possible jam formation.

[37] It appears that almost all reaches draining >10 km^2 feature *virtually* mobile LW elements (i.e., neglecting other factors such as rootwads), whereas for smaller drainage areas quite a number of reaches are characterized by a stability index $L_l/W_{bf} > 1$. The buoyancy parameter is only in one case >1, thus suggesting that channel width is the main controlling or limiting factor for LW transport, at least at the bankfull stage. Of course, at lower flow rates or in the case of rootwads, water depth would also become relevant

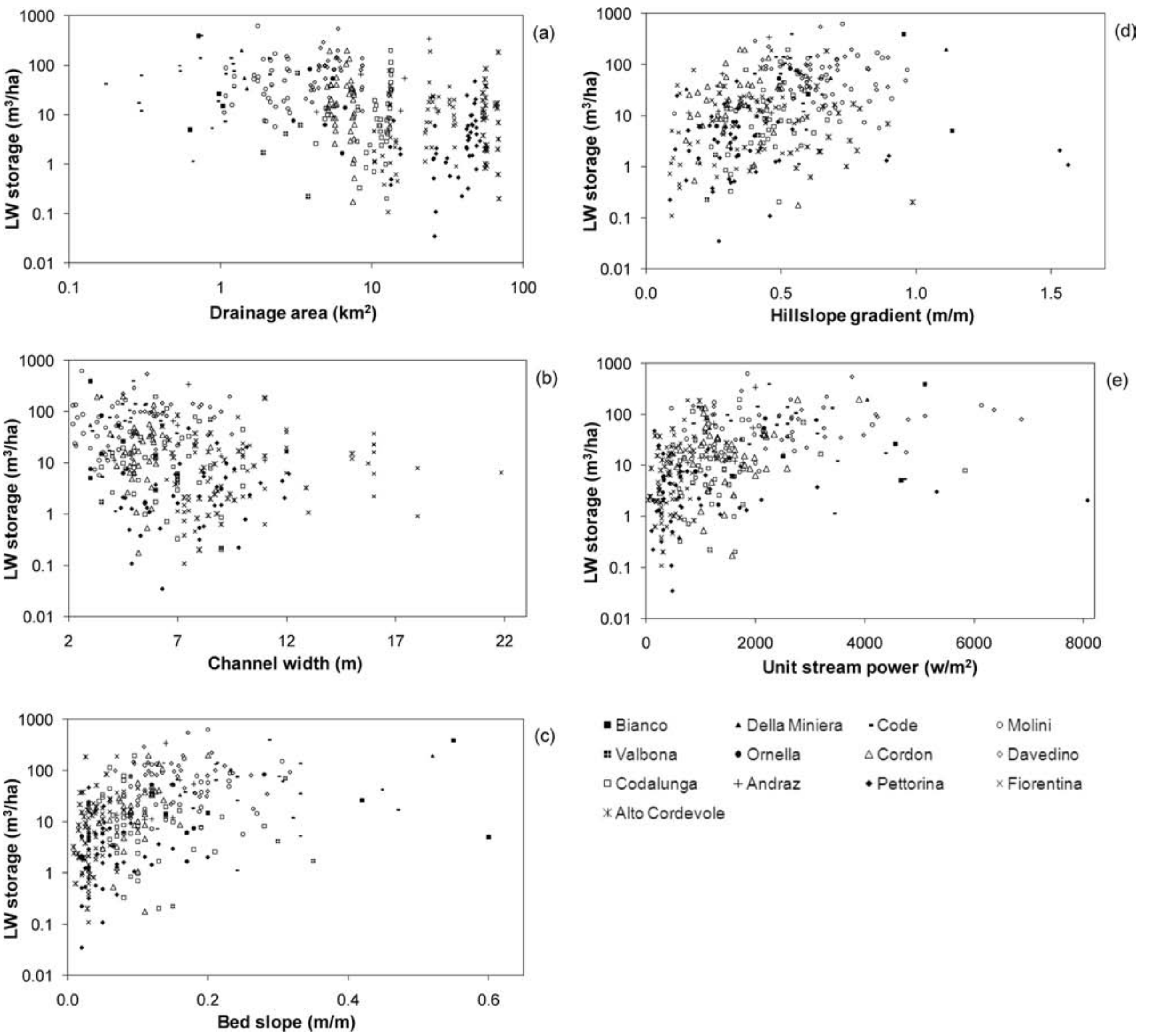

Figure 7. LW storage (in volume, LW_v) at the reach scale in relation to (a) drainage area, (b) channel width, (c) mean bed slope, (d) hillslope gradient, and (e) unit stream power.

Table 5. Results of the Covariance Test Between LW Storage in Number of Elements (LW_n) and Morphological/Hydraulic Reach Variables ($N = 334$)[a]

Effect	SS	DF	MS	F	P
Intercept	2.71	1	2.71	1.62	0.20
A	**12.64**	**1**	**12.64**	**7.55**	**0.006**
W_{bf}	0.4	1	0.41	0.23	0.61
$\boldsymbol{h_{bf}}$	**11.28**	**1**	**11.28**	**6.74**	**0.009**
S_c	2.74	1	2.74	1.64	0.20
S_s	0.11	1	0.11	0.07	0.80
ω	**15.40**	**1**	**15.40**	**9.20**	**0.003**
Channel	**56.55**	**12**	**4.71**	**2.82**	**0.001**
Error	530.60	317	1.67		

[a]For variable symbols see Table 4. "Channel" is a categorical variable formed by the 13 surveyed streams. SS is the sum of squares, DF are the degrees of freedom, MS is mean square; F is Fischer's statistics, p is the level of significance. Variables having $p < 0.05$ are in bold.

if not dominant. The larger percentage of reaches with potentially stable LW are in the Rio Bianco and Molini (50% and 46%, respectively), whereas in the Pettorina, all logs have smaller dimensions (diameter and length) than bankfull channel size (depth and width, respectively). Again, the presence of rootwads reduces LW mobility in terms of buoyancy [*Braudrick and Grant*, 2000] and thus Figure 8a should be interpreted as just an approximate indication of how log mobility tends to vary with drainage area.

[38] Reaches with higher stability indices should be deposition sites either for LW coming from upstream and/or for locally recruited stable LW. A positive correlation can therefore be expected between LW storage and L_l/W_{bf}. Figure 8b displays such a relationship, but nonetheless features a great deal of scatter ($R^2 = 0.29$, $p << 0.001$).

[39] Beside channel width and depth, channel roughness elements such as large boulders may play a determinant role in trapping LW in low-order channels [*Faustini and Jones*, 2003]. We tested this hypothesis by performing a correlation analysis between LW storage and the spatial density of large rocks (i.e., the number of rocks with diameter > mean bankfull depth divided by streambed area, see section 3). The analysis revealed a lack of significant correlation both with number (LW_n, $R = -0.09$, $p = 0.31$) and

Table 6. Results of the Covariance Test Between LW Storage in Volume (LW_v) and Morphological/Hydraulic Reach Variables ($N = 334$)[a]

Effect	SS	DF	MS	F	p
Intercept	10.91	1	10.91	7.77	0.005
A	**10.69**	**1**	**10.69**	**7.61**	**0.006**
W_{bf}	0.11	1	0.11	0.079	0.78
$\boldsymbol{h_{bf}}$	**9.77**	**1**	**9.77**	**6.96**	**0.009**
S_c	1.47	1	1.47	1.048	0.31
S_s	0.40	1	0.40	0.29	0.59
ω	**15.26**	**1**	**15.26**	**10.86**	**0.001**
Channel	**95.14**	**12**	**7.93**	**5.65**	**0.001**
Error	445.19	317	1.40		

[a]For variable symbols see Table 4. "Channel" is a categorical variable formed by the 13 surveyed streams. SS is the sum of squares, DF are the degrees of freedom, MS is the mean square, F is Fischer's statistics, and p is the level of significance. Variables having $p < 0.05$ are in bold.

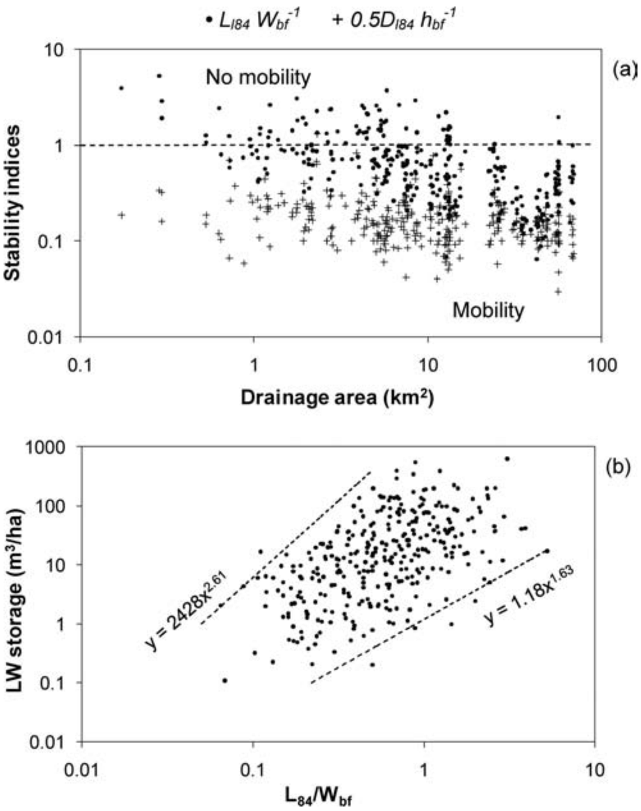

Figure 8. (a) Stability indices (lateral and buoyancy) at the reach scale in relation to drainage area, and (b) relationship between the lateral stability index and LW storage. Envelope lines enclose 95% of the data.

volume (LW_v, $R = -0.14$, $p = 0.11$) of wood stored in the channels.

5.4. Relevance and Effect of LW Jams

[40] In the study channels, the number of LW elements organized in jams, the accumulation of >2 wood elements, ranged from 18% (Rio della Miniera) to 62% (Andraz). If we consider the volume of LW in jams, the percentages are higher (50% Rio della Miniera and 87% Andraz) because the average size of jam-forming LW is larger. The type and effects of LW were analyzed in the Rio Davedino, the channel with the greatest amount of LW jams (a total of 87 m^3). Figure 9a illustrates the morphodynamic effects caused by LW jams. Local lateral erosion is associated with flow deflection jams and downstream from debris dams, whereas banks appear reinforced against erosion by bench and landslide jams. The most important effect is definitely related to sediment retention, which occurs for all types of accumulation but with very different magnitudes. Figure 9b reports the relationship between wood volume (the sum of all pieces forming the jam) and gross sediment volume (i.e., neglecting porosity as explained in section 3) for each jam found in the Davedino. The jam types more efficient in trapping sediment are landslide jams, debris dams, and log steps. The latter have the highest ratio of sediment-to-wood volume, i.e., small log steps can stabilize a large amount of sediment, up to 20 times their wood volume. However, the largest sediment volume was retained

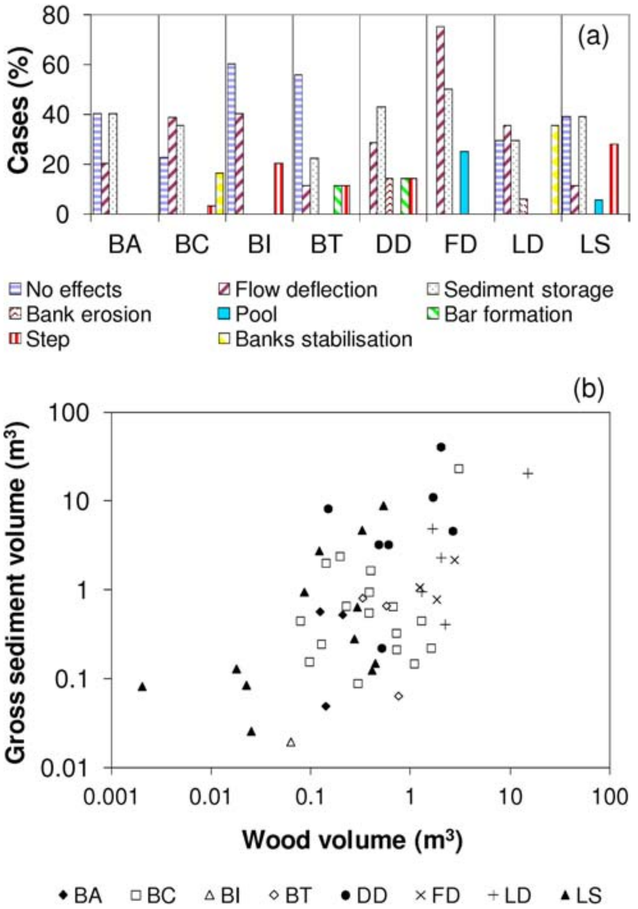

Figure 9. Morphological effects of wood jams in the Rio Davedino. (a) The occurrence of effects for the different jam types, classified according to *Abbe and Montgomery* [2003], modified by *Mao et al.* [2008a]. BA is the bar apex, BCis the bench, BI is bank input, BT is bar top, DD is debris dam, FD is flow deflection, LD is landslide jam, LS is log step. (b) The relationship between wood volume and gross (geometric, i.e., not accounting for porosity) sediment volume stored by each jam.

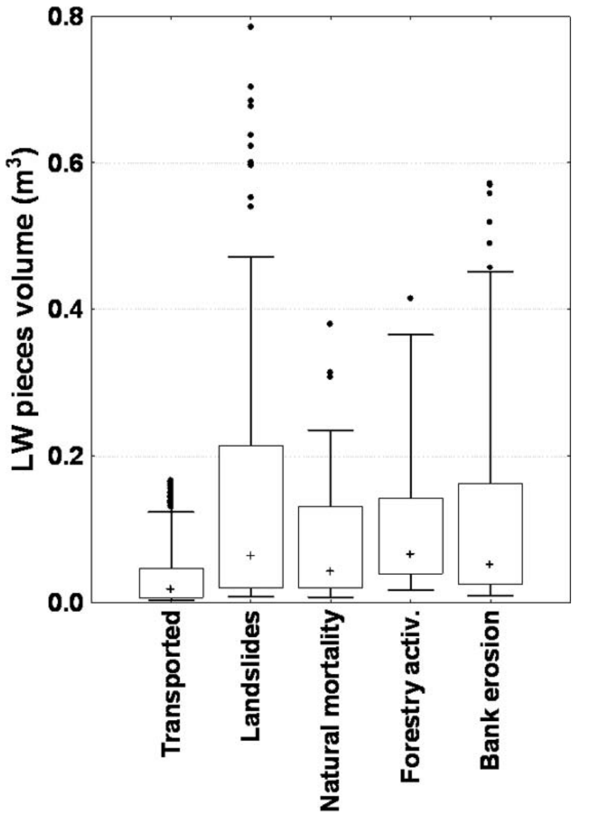

Figure 10. Volume of single LW pieces in the Rio Andraz and Davedino. The cross within each box indicates the median value, box ends are 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and dots are outliers.

by a debris dam (41.5 m^3 of sediment by 2 m^3 of wood). In the Davedino, LW retains a total of 167 m^3 (equivalent to 58.6 m^3 km^{-1}).

5.5. Relevance of LW Input From the Hillslopes

[41] An analysis of the volume of each LW piece in relation to its estimated input to a given reach (Figure 10) reveals that the largest LW elements are delivered by landslides whereas, as expected, transported logs (i.e., from upstream reaches) are the smallest (Figure 10). Indeed, the LW elements judged to have arrived in a reach directly from natural instability processes on the adjacent hillslopes (i.e., landslides, debris flows, and bank erosion), as opposed to those transported from upstream reaches, comprise a large proportion of the total LW load in terms of number, i.e., an average of 33% of the LW elements taking all of the channels (from 11% in the Alto Cordevole to 53% in the Andraz), and as much as 57% in terms of LW volume (from 32% in the Alto Cordevole to 88% in the Andraz).

[42] Considering all of the channels where input mechanism was estimated (post-2004 surveys, see methods in section 3), 56% of LW pieces were estimated to be transported logs (although the distance traveled is unknown), 6% of the LW elements were from natural mortality, and 5% were derived from harvesting operations (residues of tree felling). Clearly, the transported logs were originally recruited to the channel network by either natural mortality (probably mainly because of windthrow in the study basins) or by mass wasting processes. From the fact that natural mortality appears to be a minor contributor at the reach scale, we can infer that the vast majority of LW stored in the channels was recruited from landslides, bank erosion, and debris flows.

[43] In order to more fully understand the role of basin instability in supplying LW to the channels, a one-way ANOVA was performed on LW storage (in m^3 ha^{-1}) at the reach scale using the extent of lateral instabilities adjacent to the main channels as the category predicting variable (see the definition of dissection index in section 3). The analysis reveals that the longer the proportion of channel bordered by mass wasting processes (i.e., increasing DI) the higher is the LW storage (Figure 11). Therefore, the hypothesized role of hillslopes in strongly determining LW storage at the reach scale seems to be confirmed based on the quantification of channel-connected instabilities in the field.

[44] As a consequence, if a model could adequately predict LW recruitment from the hillslopes, it would become

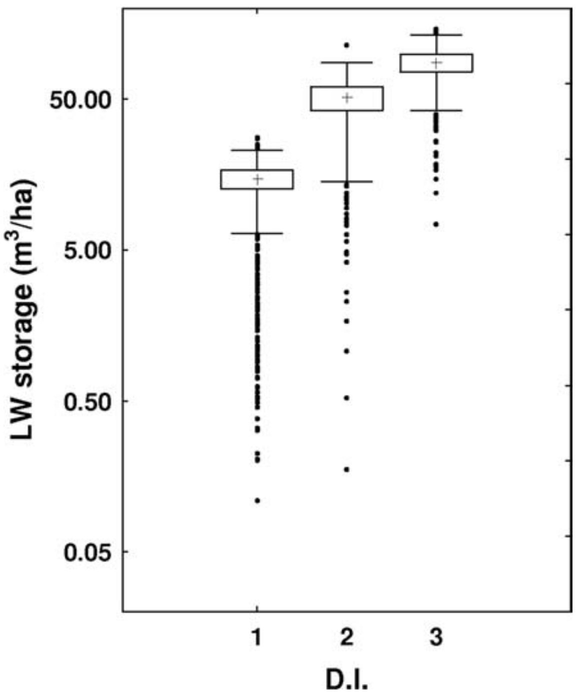

Figure 11. Variation of LW storage (in volume, LW_v) in relation to the dissection index (DI), where 1 is low dissection (<33% of channel length is bordered by mass wasting processes), 2 is medium (33%–66%), and 3 is high (>66%). The cross within each box indicates the median value, box ends are 25th and 75th percentiles, whiskers are the 10th and 90th percentiles, and dots are outliers. The difference among the three levels of DI is highly significant ($p < 0.05$, based on one-way ANOVA).

possible to characterize different basins (and reaches) with respect to their most likely level of LW storage. With this aim, the GIS model for LW recruitment described in section 4 has been applied to the entire Cordevole basin (Figure 1) adopting the three different probabilistic levels (scenarios) of instabilities, from 1 (very likely, high frequency of occurrence) to 3 (unlikely, low frequency of occurrence).

[45] Figure 12 illustrates the graphical output of the model on a small area of one study basin. Unstable forested areas were first identified for the different scenarios applying the WofE algorithm, followed by the transfer on the hillslopes using the slope decay function (Figure 12a). Each cell of the raster grid is characterized by a value of LW expressed in m^3 ha^{-1}. Figure 12b displays only the channel-forming cells with their total value of LW in m^3 ha^{-1}. The sum of these values for all of the cells comprising the main channel in each basin, and the subsequent multiplication by their total area (in hectares) provide the simulated LW storage for the main channel assuming no LW is transported out through the streams (see discussion in section 6).

[46] In order to compare the survey-based versus model-simulated in-channel LW volumes (in m^3) at the channel scale, the former were calculated assuming that the LW storage measured in the surveyed segments (m^3 ha^{-1} in Table 3) applies to the entire main channel defined for the model, i.e., to the same streambed area used to derive the simulated LW. Figure 13 shows the result of the comparison for the 13 study basins, ranked according to their total LW volume estimated from the field surveys. The graph illustrates that for about half of the study channels (Valbona, Molini, Bianco, Code, Davedino, Fiorentina, Andraz) the modeled scenario 1 (i.e., the most probable level of landslide occurrence) gives estimates of LW recruitment relatively close to the LW volume estimated by field measurements. Only for the Rio della Miniera is the measured LW volume more similar to the modeled scenario 2. It is relevant to point out that none of the study basins have been affected by major, diffuse landslide and flooding events since 1966, even if prolonged, intense rainfall events in November 2002 (estimated as having a recurrence interval of around 10–15 years in the study area) caused localized hillslope instabilities and some wood input at least in the larger study basins (see Table 1).

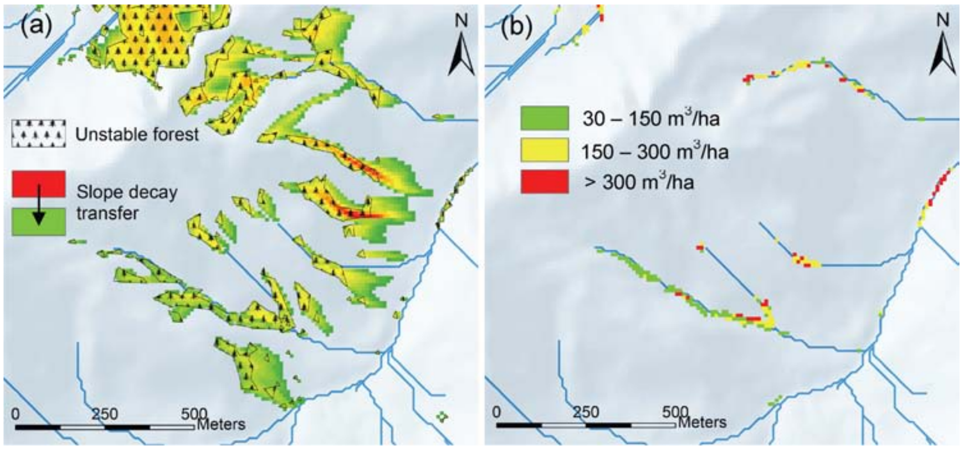

Figure 12. GIS output of the LW recruitment model. (a) Once the unstable forested hillslopes (unstable forest) are identified based on the geostatistical method (for the three instability scenarios, see text), the slope decay transfer function is applied on the hillslope. (b) The intersection between the channel network map and the slope-transferred LW volumes provides the recruited in-channel volume for each cell.

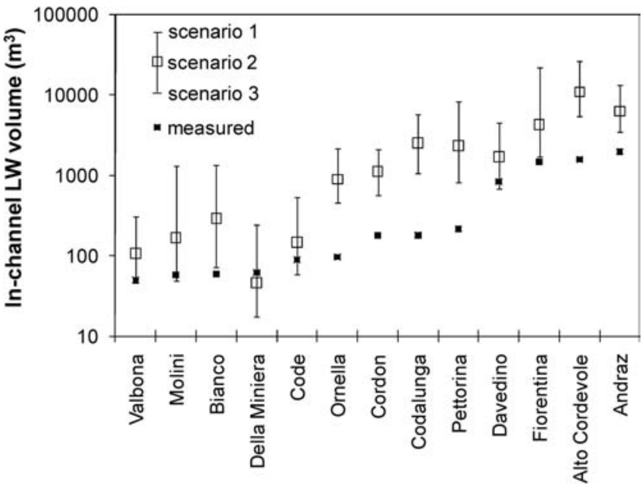

Figure 13. Comparison between recruited LW volumes as predicted by the GIS model (Figure 12) and LW volumes measured during the field surveys for the same channel length.

[47] However, overall, the measured LW storage (surveys took place in 2003–2007) is thought to reflect a rather long (~40 years) period of relatively high hillslope stability, apparently adequately simulated by scenario 1 in the model. In fact, although there are few data for performing statistical analysis, the simulated LW input for scenario 1 is significantly correlated to the measured LW storage ($R^2 = 0.72$, $p < 0.05$). Intermediate and severe instability scenarios (i.e., levels 2 and 3, associated to less frequent rainfall events, probably having a recurrence interval of >30–50 years) predict much higher LW storage, and the increase is greater for the smaller, steeper basins (e.g., Molini, Bianco, Della Miniera). On average, the LW input from scenario 3 is one order of magnitude larger than scenario 1.

[48] It is notable that channels where the difference between simulated and measured LW volume is considerable are those characterized by higher accessibility (e.g., the presence of adjacent roads), and thus likely to be subject to more intense river management (vegetation and wood removal). However, data about removed volumes are unfortunately not available. The ratio between simulated (scenario 1) and measured LW varies between 0.3 (Rio della Miniera) and 6 (Codalunga), but is 2.2 on average, suggesting that the model tends to provide higher LW recruitment volumes than those found in the channels (LW storage). The fact that simulated LW recruitment is generally higher than measured LW storage is not surprising, because a fraction of LW could have been transported downstream, thus exiting the channel. However, we believe that most of the discrepancy between simulated LW input and LW storage measured in the Ornella, Cordevole, Pettorina, and Codalunga channels can be attributed to their greater "artificiality" in terms of wood removal.

[49] The inclusion of LW transfer along the channel network [see, e.g., *Rigon*, 2009; *Mazzorana et al.*, 2010] would make the GIS-based model more complete but, in order to have useful outputs, channel width should be accurately extracted at small spatial scales to allow for the automatic detection of narrow stretches possibly prone to LW clogging. Such automatic channel-width extraction would benefit from high-resolution, LiDAR-derived Digital Terrain Models (DTMs) [e.g., *Trevisani et al.*, 2009; *Pirotti and Tarolli*, 2010], which were not available for the study basins. The size of recruited LW should also be included in the model for a more accurate prediction of its transport distance.

6. Discussion

[50] As previously described by *Comiti et al.* [2006], LW storage in historically managed (i.e., management of forests and channels) mountain basins such as those of the European Alps is much lower than that characterizing more natural sites of comparable watershed size (i.e., 1–100 km^2) and potential forest tree size. For example, average values in the range 100–200 m^3 ha^{-1} are reported for basins in the Rocky Mountains,United States, [*Richmond and Fausch*, 1995; *Wohl and Goode*, 2008], Tierra del Fuego, Argentina [*Mao et al.*, 2008a], and the Southern New Zealand Alps [*Meleason et al.*, 2005, 2007], and relevant geomorphic effects are described in such situations. In our study channels, channel-averaged LW storage ranges between 10 and 100 m^3 ha^{-1}, and its morphological and sedimentation consequences are rather minor (mostly associated with occasional small log steps), because LW elements are small in size compared to channel dimensions and therefore quite mobile (Figure 8) and likely prone to breaking up during relatively frequent flood events. Unfortunately, field data on log breaking up (as well as on wood decay) are not yet available, but a LW tagging project aiming to monitor LW dynamics was started in the some of the study basins in 2007, similar to what has been done in South America [*Mao et al.*, 2008b; *Iroumè et al.*, 2010]. Indeed, a relationship between log size, decay status, and the hydrodynamic force required for breakage would greatly improve the understanding of the geomorphic potential of LW, plus the ability to model its transfer along the channel network.

[51] We demonstrated through the significant effect of the dissection index on LW storage, the dominant fraction of LW volume originated by landslide/bank erosion/debris flow, and by comparing model-simulated LW input against measured LW storage, how significant the role of hillslope instabilities is in supplying LW to the study channels. Given the low natural tree mortality in the relatively young (<150–200 years) forest stands covering most of the area, LW recruitment in these confined mountain basins is highly dependent on mass wasting processes, which are nonetheless intimately linked to bed/bank dynamics (incision and lateral erosion) that often represent their triggering agent. In fact, the contribution of floodplain erosion is minor due to the confined nature of the channels, and wildfires are not a problem in the area. However, episodic inputs from windthrow and snowstorms can be substantial, as happened in 2009.

[52] These circumstances lead to several consequences: With similar morphological and hydraulic reach characteristics, LW storage differs significantly among channels (see ANCOVA results, Tables 5 and 6); the spatial LW distribution within single channels is highly random and associated with the location of debris flow confluences and landslide deposits, as previously pointed out by *Comiti et al.* [2006] for some of the study basins and by *Benda et al.* [2002] in

quasi-natural basins of the Pacific Northwest; and the variation over time of LW storage is likely very pronounced and correlated with the timing of hillslope disturbances and occurrence of large flood/debris flows, similar to what happens with wildfires input in other regions [see *Benda et al.*, 2003; *Comiti et al.*, 2008a], but in this case without lag time between the disturbance and the increase in wood storage.

[53] Despite such complex spatial-temporal wood dynamics, some general trends are apparent. Looking at LW storage at the basin scale (drainage area roughly between 1 km^2 and 70 km^2), an inverse correlation with drainage area is evident within the study area, even with some outliers. Previous studies in North American streams have shown the same negative correlation [*Keller and Swanson*, 1979; *Keller and Tally*, 1979; *Montgomery et al.*, 1995; *Wohl and Jaeger*, 2009], whereas others have not [*Martin and Benda*, 2001; *Benda et al.*, 2002; *Fox and Bolton*, 2007]. In particular, our trend contrasts with the results and the conceptual model proposed by *Seo and Nakamura* [2009] for Japanese river systems, which predicts increasing LW storage for increasing drainage area.

[54] Unit stream power is apparently the most statistically significant hydromorphological factor influencing wood abundance in the analyzed streams. Overall, unit stream power decreases with drainage area (Figure 14) and, excluding some outlier reaches, is maximum for first-order, steep (mean channel slope S = 0.25) stretches with drainage areas 0.1–2 km^2 (on average ω = 2400 W m^{-2}). Reaches draining 2–10 km^2 (i.e., second- and third-order stretches, S = 0.14) are characterized on average by ω = 1950 W m^{-2}, and finally reaches with A = 10–70 km^2 (S = 0.05) present a mean ω = 840 W m^{-2}. It must be noted that in this paper we use the stream power per unit of channel bed area (i.e., unit stream power) because it can provide a better characterization of transport flow capacity (in analogy with sediment transport) and not the total stream power as previously used in LW studies by *Seo and Nakamura* [2009] and *Wohl and Jaeger* [2009].

[55] Although the relationship between LW storage and unit stream power is apparently monotonic in a log-log plot (Figure 7e), the actual maximum LW loads appears to occur at intermediate stream power values. Relatively lower LW storage at high-stream power values (ω > 4000 W m^{-2}, mostly steep, headwater bedrock channels, A < 1–2 km^2) can mainly be explained by the low wood supply derived both from the high elevation of these headwater reaches (i.e., only part of their drainage basin is below the tree line in the study area) and by the diffuse presence of bedrock hillslopes with fewer and more spindly trees due to limited growth on such a poor substrate. Furthermore, the geostatistical WofE model indicates that hillslopes with a gradient of 1 m m^{-1} (>45° inclination) are less prone to instabilities than those in the range 0.25–1 [*Rigon*, 2009]. The reason is the more stable rocky substrate of the former. The scarcity of wood in these headwater reaches may also derive from the occurrence of frequent debris flows that can transport LW downstream. Overall, LW flux in these stretches can be identified as supply-limited, in the sense that the limiting factor in LW transport at relatively short timescales is not represented by the capacity of flows to convey LW downstream, but rather by the supply of LW to the channel. For these headwater channels, the capacity is high mostly because the steep bed slopes determine frequent debris flows able to flush the accumulated LW out notwithstanding the relative stability of LW pieces in such narrow channels (Figure 8).

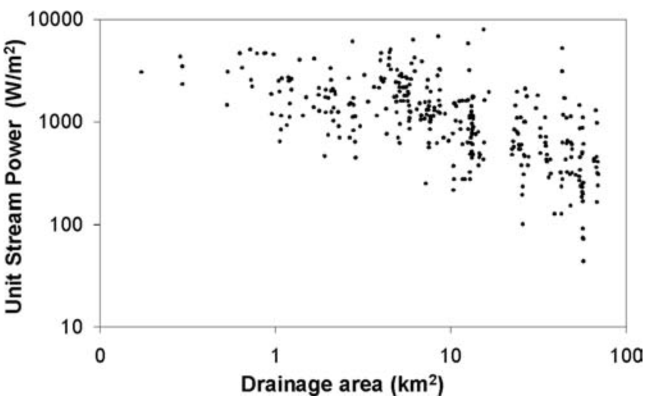

Figure 14. Relationship between unit stream power at bankfull stage and drainage area for all the surveyed reaches.

[56] On the other hand, low LW storage in reaches of lower unit stream power (ω < 1000 W m^{-2}, mostly plane-bed or artificially grade-controlled reaches, for A > 10 km^2) is likely due to a combination of relatively high mobility of LW elements (see Figure 8), greater channel stability reducing lateral LW recruitments, and frequent channel clearings, which also removed large key pieces potentially able to form log jams [*Comiti et al.*, 2006; *Wohl and Jaeger*, 2009]. Unfortunately, the lack of data on removed wood volumes hinders any further analysis. However, LW flux here is again supply-limited because the flow capacity to transport LW is quite high due to the high mobility of LW pieces (Figure 8) in such comparatively wide and deep channels, even though unit stream power is relatively low. In fact, in contrast to sediment transport, LW transport does not require a critical stream power for motion as long as the minimum flow depth for floating is attained and logs are not trapped by obstructions. As a consequence, when occasional LW inputs occur, e.g., from toe-scouring landslides or steep debris flow tributaries, LW transport can reach very high rates (see, e.g., the Fiorentina River during the 1966 flood event [*Comiti et al.*, 2006]), thus posing considerable flood hazards from bridge clogging.

[57] Finally, intermediate unit stream power values (1000 < ω < 4000, drainage area 2–10 km^2) in the study area are typical of relatively narrow step pool and cascade reaches. In these stretches, lateral instabilities delivering LW to channels are diffuse due both to the tendency of channels to incise during intense floods and the steepness of the hillsides favoring frequent mass movements. The large supply of wood is not balanced by the ability of streams, mainly because of the low channel width-to-log length ratio (see Figure 8) to transport wood downstream, thereby LW storage is higher and the reaches can be classed as having limited transport capacities, because ordinary flood flows are not able to break up or dislodge LW elements anchored against banks and bed obstructions. Only during high-magnitude events, flow momentum attains the threshold to mobilize/break such stable logs, likely helped

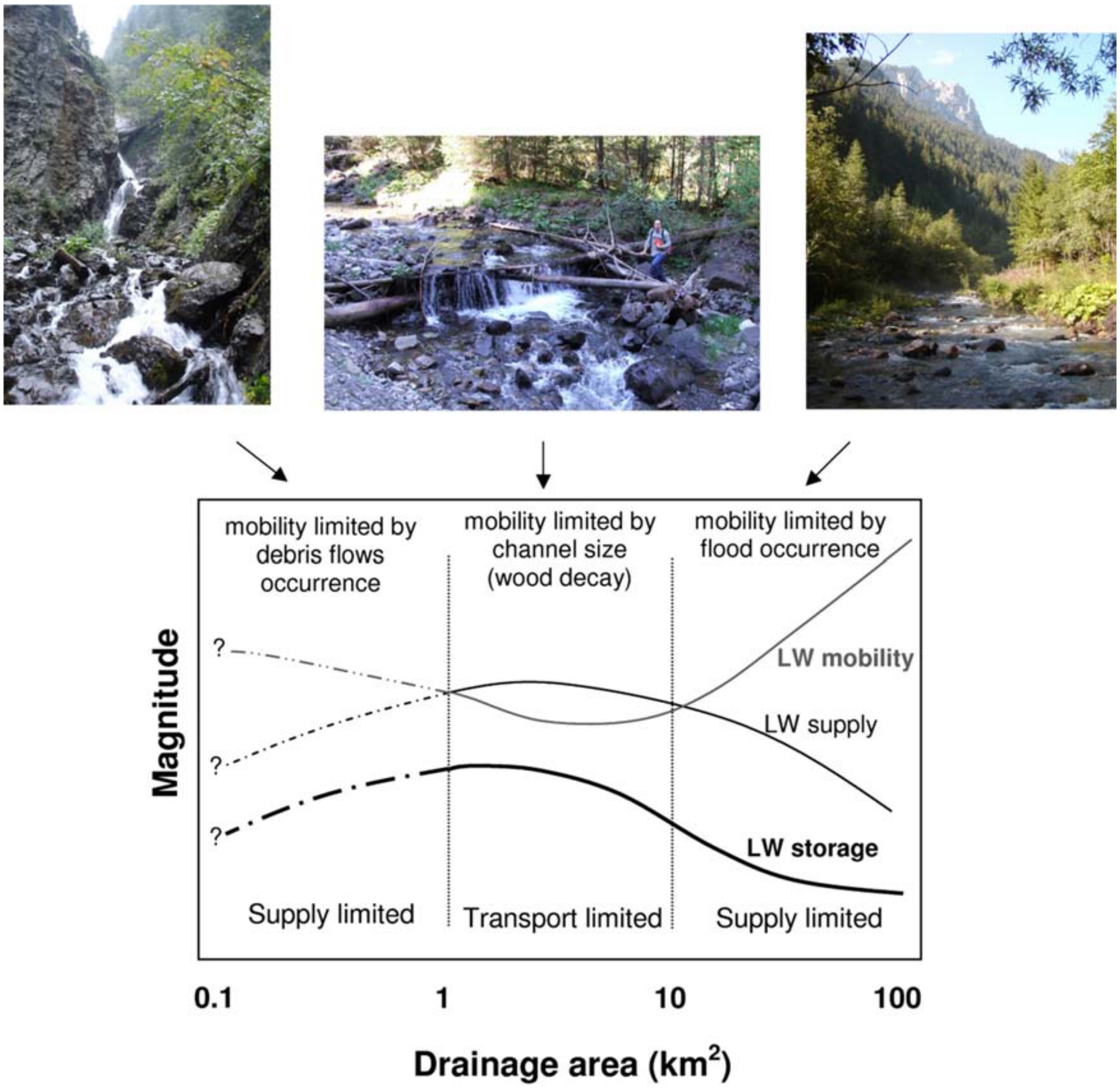

Figure 15. Sketch showing the hypothesized pattern (conceptual model) of LW supply, mobility, and storage in mountain basins (<100 km^2) of the Eastern Alps. The trends for drainage areas <1 km^2 are more speculative and so are represented by dotted lines.

by the concomitant coarse bed load transport as well as by bank and bed erosion. Wood decay processes causing weaker and thus breakable logs are possibly the most important limiting factor for wood mobility in these stretches [*Abbe*, 2000], leading to a probable lag time (possibly of a few decades) between LW input and LW transport.

[58] Figure 15 illustrates the conceptual model for LW storage, supply, and mobility described in the previous paragraphs. The model extends the one put forward by *Comiti et al.* [2006], *Wohl and Jaeger* [2009], and *Fremier et al.* [2009] inasmuch it includes two possible types of supply-limited sections, both upstream and downstream from reaches with limited transport capacities, and builds on the results presented above as well as on unpublished field observations in several similar basins of the Eastern Alps. However, there is a need to more fully investigate LW storage and dynamics especially in the smaller basins (<1 km^2), i.e., those for which there are fewer data and so the hypothesized trend of LW storage versus drainage area is more speculative, as highlighted in Figure 15. Indeed, headwater reaches in different regions may present varying situations, depending on basin geology/geomorphology as well as elevation, entailing conditions of low supply (high-altitude or bedrock-dominated basins) as is the case in the study area, as well as conditions of higher LW supply whereby LW transport can be limited by the occurrence of debris flows.

7. Conclusions

[59] Despite the increased efforts to establish statistical models to reasonably predict LW storage in mountain streams, the wide spatial and temporal variability associated with recruitment processes, coupled with the complex transport mechanics in narrow, rough channels render such a goal still distant at the reach scale. Furthermore, each basin with different hydrological, geological, and geomorphological settings and flood history features different relationships

between LW recruitment and hillslope/channel variables. The statistical analysis of LW storage at the reach scale in the study basins pointed out, in accordance with previous studies in other world regions, that unit stream power is the most significant factor influencing LW storage. However, we propose that the significance of unit stream power in explaining the amount of LW stored in mountain channels is not solely linked to flow transport capacity but derives from the relationship between LW supply and channel morphology with channel slope and drainage area, which are the variables determining stream power.

[60] The conceptual model presented here for mountain basins <100 km^2, and in particular the sizes of the catchment areas (i.e., $\sim$1 km^2 and 10 km^2) at which the limiting LW transfer conditions (supply versus transport) are anticipated to change, is believed to apply only to mountain landscapes similar to that analyzed here, e.g., to the Eastern Alps. In fact, both the relationship between drainage area and forest vegetation influenced by local climate and geomorphology, and that linking drainage area and channel confinement, width, and slope affected by tectonics, glaciation history, hydrological regime, and rock substrate determine the shift between LW supply to LW transport conditions and vice versa. For example, mountain basins, where forest cover extends up to the divide and hillslopes, are not too steep for forest growth, and there may be no supply-limited stretch at the headwaters. On the other hand, other regions may have basins in the 50–100 km^2 range containing extensive floodplains with mature woodlands (unlike the study site), which could provide a substantial LW supply from bank erosion and thus determine a higher level of LW storage and limited transport capacity.

[61] For applied purposes (e.g., prediction of LW potential for flood hazard mitigation measures), we believe that with the current state of the art, the magnitude of LW fluxes and storage is more reliably estimated following conceptual routing models (i.e., LW budgets at the flood event scale) adapted to each basin rather than by using general statistical models. The LW geostatistical recruitment model presented here focused on hillslope instability as this is the main recruitment mechanism in the study region; it has the potential to assist in the identification of the most likely LW source areas and to estimate LW input into the channel network. This type of modeling can be useful for prioritizing management actions (e.g., installation of wood retention structures) and locating the most suitable intervention sites.

Notation

A drainage area (km^2)
A_{bf} flow area at bankfull stage (m^2)
Di dissection index ($-$)
D_l diameter of LW elements at midlength (m)
D_{lx} xth quantile of LW diameter distribution (m)
g acceleration due to gravity (m s^{-2})
h_{bf} mean bankfull channel depth (m)
J_v LW jam volume (m^3)
L_l length of LW elements (m)
L_{lx} xth quantile of LW length distribution (m)
Lw_n LW storage in number of elements per unit bed area (pieces ha^{-1})
LW_v LW storage in volume per unit bed area (m^3 ha^{-1})
S_c mean bed gradient (m m^{-1})
S_s mean hillslope gradient (m m^{-1})
V_{bf} mean flow velocity at bankfull stage (m s^{-1})
W_{bf} mean bankfull channel width (m)
ω unit stream power (W m^{-2})
γ specific weight of water (N m^{-3})

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