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Dynamics of large wood during a flash flood in two mountain catchments

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Abstract

Understanding and modelling the dynamics of large wood (LW) in rivers during flood events has spurred a great deal of research in recent years. However, few studies have documented the effect of high-magnitude flash floods on LW recruitment, transport and deposition. On 25 October 2011, the Magra river basin (north-western Italy) was hit by an intense rainstorm, with hourly rainfall rates up to 130 mm h^{-1} and event rain accumulations up to 540 mm in 8 h. Such large rainfall intensities originated flash floods in the main river channels and in several tributaries, causing severe damages and loss of lives. Numerous bridges were partly or fully clogged by LW jams. A post-flood survey was carried out along the channels of two catchments that were severely and similarly affected by this event, the Gravegnola (34.6 km^2) and Pogliaschina (25.1 km^2). The analysis highlighted a very relevant channel widening in many channel reaches, which was more marked in the Gravegnola basin. Large wood recruitment rates were very high, up to 1270 $m^3 km^{-1}$, and most of it (70–80 %) was eroded from the floodplains as a consequence of channel widening processes, while the rest came from hillslopes processes. Overall, drainage area and channel slope are the most relevant controlling variables in explaining the reach-scale variability of LW recruitment, whereas LW deposition appears to be more complex, as correlation analysis did not evidence any statistically significant relationship with the tested controlling variables. Indeed, in-channel LW displacement during the flood has been mostly limited by the presence of bridges, given the relatively large width attained by channels after the event.

1 Introduction

Floods are the natural hazard which affects the largest number of people at the world scale (Jonkman, 2005), and within these events, flash floods are cause of the highest mortality (Doocy et al., 2013). Flash floods are defined as sudden events with high peak discharges, produced by severe thunderstorms that are generally of limited areal extent

(IAHS-UNESCO-WMO, 1974). Despite their relevance, these phenomena are poorly understood, mainly because they cannot be extensively monitored (Borga et al., 2014). Therefore, it has been stated the need of a systematic post-event monitoring of flash floods in order to improve their understanding and the assessment of both hazard and vulnerability (Gaume and Borga, 2008; Borga et al., 2014). The intense precipitations originating the rapid and large increase in discharge in the channel network frequently trigger slope instabilities, such as landslides and debris flows, during the same event (Borga et al., 2014). These colluvial processes, coupled to the fluvial dynamics, supply large volumes of both sediments and large wood (LW) to the channels in forested catchments (Comiti et al., 2008).

The presence of LW in river systems has been demonstrated to have very positive effects, as it enhances the hydromorphological diversity of riverine habitats and it represents both a source and a retention mean of organic matter within channels (Gregory et al., 2003; Wohl, 2013; Beckman and Wohl, 2014). On the other hand, LW can increase flood hazards by clogging narrow cross-sections. These are typically represented by undersized or pier-type bridges (Diehl, 1997; Schmocker and Hager, 2011). Indeed, following bridge clogging, backwater effects onset is often associated with bed aggradation, bank erosion and avulsion. As a result, bridge failure and/or large unexpected flooded areas are observed (Mazzorana et al., 2009; Ruiz-Villanueva et al., 2013b). However, wood can clog also natural sections forming “debris dams” or “valley jams” (Lancaster and Grant, 2006). These may determine increased water levels upstream of them, and could lead to dam-break flows in case of large impounded water volumes and sudden breaching (Castiglioni, 1974; Comiti et al., 2008), similarly to the temporary dams created by landslide deposits (Davies and Scott, 1997).

In-channel LW storage and its morphological effects have been studied quite extensively in the recent decades (see for a summary Gurnell, 2014; Wohl, 2014). As to LW transport (i.e. incipient motion thresholds, travel distances, controlling variables), several field investigations have been carried especially in mountain rivers (Faustini and Jones, 2003; Gurnell, 2003; Andreoli et al., 2007; Mao et al., 2008; Wohl and Goode, 2008; Iroumé et al., 2014), but none of these included LW transport associated to extreme events.

Indeed, modelling the dynamics of large wood in rivers during floods spurred a great deal of research in recent years (Benda et al., 2003; Mazzorana et al., 2009, 2011; Rigon et al., 2012; Ruiz-Villanueva et al., 2013a, 2014a, b). However, few studies have actually documented the effect of high-magnitude flash floods on LW dynamics collecting data on recruitment, transport and deposition rates, all information required in order to validate or develop new models on LW transport. Fischer (2006) and Waldner et al. (2007) presented an inventory of the LW deposited after the catastrophic 2005 flood event occurred in different Swiss catchments, following the previous work by Rickenmann (1997) in the same country. These studies reported a very large scatter in the relationship between drainage area and LW volume, and a predominance of LW recruitment from the floodplains. Comiti et al. (2008) and Marchi et al. (2009) analyzed a 2007 flash flood in a relatively small catchment of the Slovenian Alps. Although a detailed LW budget was not carried out, it was assessed that both colluvial processes and floodplain erosion were similarly responsible for LW recruitment, and highlighted how bridge clogging had been key in favoring hazardous channel avulsions. More recently, Ruiz-Villanueva et al. (2013a) described the LW deposits during a flash flood event occurred in 1977 in Central Spain, and compared them to the results obtained from a numerical LW transport model.

Indeed, several relevant scientific questions – and of great applicative importance for a correct river management – regarding LW dynamics during flash floods are still unclear, such as: (i) what are the most likely LW sources within a catchment? (ii) how does channel morphology affect LW dynamics (transfer vs. deposition)? and (iii) what are the key variables (geomorphological and hydraulic alike) determining LW volumes transported at a given river section?

These issues were investigated in two catchments belonging to the Magra river basin (north-western Italy), where a flash flood occurred on 25 October 2011, causing major geomorphic changes in the channel network, severe economic damage, the destruction of infrastructures and loss of nine lives (Nardi and Rinaldi, 2014). LW played an important role during this event along the basin channel network, mostly by clogging numerous bridges (Fig. 1; Lucía et al., 2015a).

2 Study area

The Magra river basin is located in the Tosco-Ligurian Apennines, Italy (Fig. 2), and features a drainage area of 1717 km^2, ranging from a maximum elevation of 1901 m a.s.l. to the sea level (Ligurian Sea). The average gradient of the basin is 43 %. The catchment is delimitated by aligned ridges with direction NW–SE that also divides the area in two main basins with similar patterns, the main, larger (1146 km^2) Magra basin in the east, and the Vara basin in the west (571 km^2). The climate is temperate with a summer dry season. The mean annual precipitation in the basin is about 1700 mm. For more information on the Magra basin, see Nardi and Rinaldi (2014).

On 25 October 2011, rainfall intensities up to 130 mm h^{-1} and cumulated values up to 540 mm in 8 h were locally registered within the Magra basin, with estimated return periods up to 300 yr. In the channel network, such high-intensity precipitation led to unit peak discharges > 20 $m^3 s^{-1} km^{-2}$ in some tributaries of 10–20 km^2 drainage area. More information on the event can be found in the work by Nardi and Rinaldi (2014) where its morphological effects on the Magra river channel are analysed in detail.

LW dynamics during the October 2011 event were studied in two tributaries of the Vara River, i.e. the Gravegnola (drainage area 34.6 km^2) and the Pogliaschina (25.1 km^2) creeks (Fig. 2). These two catchments were selected because they were similarly affected by the event, featuring basin-average cumulated precipitation of 350 and 380 mm for Pogliaschina and Gravegnola, respectively, and max unit peak discharges in the range 15–25 $m^3 s^{-1} km^{-2}$ (Rinaldi et al., 2015). On the other hand, they differ considerably geologically and geomorphologically. The Pogliaschina is mostly underlain by two types of sandstones (Macigno and Monte Gottero formations; Mondini et al., 2014), whereas the Gravegnola features a higher lithological diversity, including sandstones, claystones, flysch deposits and metamorphic rocks such as ophiolites. Its tectonic structure is also more complex, and the relevance of inactive landslides deposits is more significant (21.1 % of the area vs. 2.8 % in the Pogliaschina).

The Pogliaschina catchment is more forested than the Gravegnola (92 % vs. 71 % of basin area, respectively). Around 50 % of the Pogliaschina catchment is covered by hardwood forests (mostly composed of chestnut, *Castanea sativa*), with a smaller presence of coniferous (maritime pine, *Pinus pinaster*), and mixed woodlands. Agricultural areas occupy approximately 10 % of the catchment. In the Gravegnola catchment, pine, chestnut and mixed forests have similar distributions. In both catchments urban areas are small and mostly located at low elevations.

The confluences of the two creeks with the Vara River lie almost at the same location (at ∼ 94 m a.s.l., see Fig. 2). The Pogliaschina and Gravegnola basins are characterized by maximum elevations of 721 and 1205 m a.s.l., and by average gradients of 56 and 39 %, respectively. The average channel slope of the studied reaches is higher in the Gravegnola (5.6 vs. 2.6 %), and the drainage density is slightly higher in the Pogliaschina (6.31 vs. 5.15 km km^{-2}). Several channels were analysed in the two creek basins (Fig. 2).

3 Methods

Both GIS analysis and field surveys were carried out to investigate flood magnitude and LW dynamics in the study basins. Peak discharge was estimated after the post-flood surveys carried out in February and November 2012, following the methodology described in Gaume and Borga (2008). Two and six cross sections were surveyed in the Gravegnola and in the Pogliaschina creeks, respectively. The estimated peak discharges were validated through the application of a rainfall–runoff model (Gaume et al., 2004; Borga et al., 2007; Gaume and Borga, 2008). The peak discharge was then used for calculating stream power, as explained below.

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Field surveys aimed to assess morphological variations and LW-related processes were made in November 2011, February 2012 and November 2012 (Fig. 3). The channels were subdivided into reaches, 21 in the Gravegnola and 34 in the Pogliaschina – whose limits were mapped by a GPS – as homogenous as possible in terms of width, slope and LW abundance. Reach length is on average 634 and 568 m in the Gravegnola and Pogliaschina catchment, respectively. The post-flood width and the average slope of the channels were measured by a rangefinder with inclinometer to validate the calculations made with the orthophoto. In each reach, evidences of bed incision or aggradation were noted, and when possible, their magnitude (i.e. the vertical elevation change) was estimated.

The lateral inputs of sediment and large wood, such as landslides or debris flows, were also mapped. Moreover, it was noted whether LW from these processes actually reached the channel, as the slope-channel LW coupling is quite difficult to be determined from aerial photos. In the reaches featuring LW jams, their average height was measured in the field for the subsequent computation of LW jam volume through the jam areas determined from aerial photos, as will be described later in the text. Where LW deposits could not be detected from the aerial photos (i.e., covered by the canopy of remaining trees or for the shadows as in most of the Pogliaschina channel network) their size was assessed in the field by measuring the different dimensions of a geometric form (generally with a parallelepiped form) that enclosed the LW jam (Thevenet et al., 1998). Breast-height diameter and height of dominant (in terms of area) standing trees at channel margins and islands were also measured by tree calliper and range finder for each reach, and numerous pictures were taken to document in detail the channel conditions.

The field surveys were integrated by a GIS analysis on the comparison of pre- and post-flood orthophotos (Fig. 4). The post event photos were taken ad hoc in the study area by the Liguria Region on 28 October 2011 (0.1 m resolution) and 28 November 2011, taken by the Civil Protection of Friuli Venezia Giulia (0.15 m resolution). The pre-event orthophotos which were used this work date to 2006 (0.5 m pixel resolution, contracted by the Italian Ministry for the Environment). Despite 5 years passed before the flood event occurred, these orthophotos were verified to be representative of the pre-event situation thanks to the images taken in July 2011 available in Google Earth. Indeed, the latter are the last areal images before the event, but their resolution is coarser than for the 2006 orthophotos. The pre- and post-event channel banks were digitized, and channel width was calculated dividing channel area by its length (measured along the centreline) using ESRI ArcGIS 10.1. In some reaches the channel was not well visible from the aerial photos due to the thick and continuous forest cover associated to narrow width, which were in these cases based on field observations. Channel widening for each reach was then calculated as the ratio (α) between the post-event width and the pre-event width.

The areas affected by landslides as well as by debris flows that delivered LW to the channel were digitized on the post-event orthophotos. The portions of slopes and channels without forest vegetation in the 2006 photos were also delineated, in order to obtain by subtraction the forest-covered areas which were eroded on the slopes and in the floodplains during the 2011 event. The forest stand volumes present on these areas before the event were assigned based on the land use maps available for the study area and on the information provided by the National Forest Service, La Spezia Province district. On the floodplains, mostly composed of mature alder woodland, an average value of 200 $m^3 ha^{-1}$ was used, whereas on the slopes, pine (150 $m^3 ha^{-1}$) and chestnut (250 $m^3 ha^{-1}$) forests were distinguished. In the case the vegetation was classified as mixed forest, a value of 200 $m^3 ha^{-1}$ was applied. LW recruitment (i.e. wood eroded and connected to the channel) for each reach was calculated as the surface where forest resulted to have been eroded – by colluvial and fluvial processes – multiplied by the relative stand volumes.

LW elements and jams were identified and digitized using the post-event orthophotos in the Gravegnola Creek only. The wood volume of each jam was calculated geometrically through its area and height (measured in the field), considering a 80–90 % range in porosity. The lower value in this range was observed in LW jams in Chilean creeks

(Andreoli et al., 2007), whereas the higher one in French piedmont rivers (Thevenet et al., 1998). In case of single LW elements visible in the orthophotos, each of them was digitized as a line, and log length was associated to the projected line length. Each log was also assigned a class relative to its mid-length diameter, i.e. class 1 < 20 cm, class 2 20–40 cm, and class 3 > 40 cm. Log volume were calculated as if they were solid cylinders (Cordova et al., 2007) using as diameters 10, 30 and 50 cm for class 1, 2 and 3, respectively. In the Pogliaschina basin, due to the shadows covering most of channel bed in the orthophotos, deposited LW volume could only be derived from field measurements. In addition to LW storage measured in the field and mapped from the orthophotos, we have acquired information on LW volumes cleaned out of the channels– mostly obstructions at the bridges – by the Province of La Spezia in the hours after the flood. Such transported LW portion would have not been measurable in the orthophotos, taken three days after the event.

Several morphological and hydraulic parameters were calculated at the reach scale in order to investigate their possible role to explain the variability in LW dynamics (i.e. recruitment, deposition, export) observed at both reach and basin scale. These parameters are the average longitudinal slope (S), the drainage area (A) at the upper limit of the reach, the stream power (Ω), and the stream power index (SPI). The DEM available for the catchments (10 m resolution) was used to obtain morphological parameters such as drainage area and channel slopes. Stream power was calculated as $\Omega = \rho g Q S$, being ρ the fluid density (kg m^{-3}), g is the acceleration due to gravity (m s^{-2}), Q is the peak discharge (m^3 s^{-1}), and S the channel slope. The stream power index (Marchi and Dalla Fontana, 2005) was calculated as the product of the channel slope and the square root of the drainage area ($\mathrm{SPI} = S \cdot A^{0.5}$).

Variables related to channel width, e.g., unit stream power or unit stream power index (Rigon et al., 2012), were not taken into account for the analysis. In fact, the width of the studied channels greatly varied during the event, making the selection of the appropriate (pre- vs. post-event) width highly disputable. Indeed, pre-event widths ranged in most reaches between 3 and 5 m, but accurate estimations were hindered

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by the dense forest canopy overhanging on channels. Therefore, if the pre-event width was used to calculate the unit stream power, correlations with LW variables would not differ from those obtained by using the stream power, actually higher uncertainty would be added. On the other hand, as channel widening and LW recruitment from the fluvial corridor are directly related to the eroded areas that mostly determine the post-event width, spurious correlations between these variables and unit stream power would enter the analysis if post-event width was adopted.

4 Results

4.1 Flood magnitude and frequency

Flood magnitude resulted to be very high in both catchments (Fig. 5). In the Gravegnola basin, unit peak discharges of 17.7 and 15.9 $m^3 s^{-1} km^{-2}$ were estimated in the Veppo Creek (11.8 km^2) and in the main Gravegnola channel (30.2 km^2). In the Pogliaschina catchment, unit peak discharges appear to be quite variable among the different sub-basins due to large differences in rainfall inputs. In the Redarena Creek a value of 21.2 $m^3 s^{-1} km^{-2}$ (at 1.7 km^2) was estimated, exceeded only in the Cassana catchment with 28.2 $m^3 s^{-1} km^{-2}$ (at 5.7 km^2). The lower unit peak discharges were 17.2 and 8.7 $m^3 s^{-1} km^{-2}$, in the Pogliasca (3.8 km^2) and Pogliaschina (3.4 km^2) creeks, respectively. The large variability in peak flows observed within the Pogliaschina catchment determines strong differences in the estimated flood return period, from < 30 yr in the upper Pogliaschina Creek to about 100 yr in the Pogliasca and > 200–500 yr in the Cassana.

The same peak discharge was attributed to the entire channel length represented by measured cross-section. In channels where cross-sections were not surveyed (i.e. Ginepro, Redovego and Sottano; Fig. 2), we applied the average of the unit peak discharge measured in the Redarena, Cassana and Pogliasca to calculate their peak discharges.

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4.2 LW budget

The LW budget during the October 2011 event for the analysed sub-catchments of Gravegnola and Pogliaschina basins (i.e. cumulating all LW recruitment and deposition observed upstream of each section) is illustrated graphically in Fig. 6. During the event, large quantities of LW were mobilized from both river corridors and hillslopes. The amount of LW recruited in the whole Gravegnola basin results to be about 9400 m^3, twice as much of the Pogliaschina (4800 m^3). In both basins, most of the recruited LW stemmed from floodplain erosion (79 % in the Gravegnola and 68 % in the Pogliaschina), with a lesser but still relevant proportion from colluvial processes, predominantly landslides. However, Fig. 6 shows that in some small sub-basins, LW recruitment from the hillslopes (landslides) has been dominant. Out of the total LW volume recruited, 96 and 74 % remained stored in the channels of the Gravegnola and Pogliaschina, respectively, trapped by natural obstacles (i.e. standing vegetation) but mostly clogged at bridges. Overall, only 360 and 1270 m^3 were exported to the Vara River, respectively. It is evident from Fig. 6 how LW recruitment and deposition are more balanced approaching the outlet of the two main catchments, whereas recruitment tended to exceed deposition in the smaller upstream sub-catchments.

The characteristics of LW budget varies not only among sub-catchments, as shown in Fig. 6, but also within them, at the reach scale. In order to identify the response of the different reaches in terms of LW recruitment and deposition, the analysis of non-cumulative values at reach level is shown in Fig. 7, basically illustrating only the LW processes taking place in each reach, thus excluding the upstream drainage area. From this analysis, it is evident how both LW erosion and deposition featured a higher magnitude in the Gravegnola, where also more marked differences are present among the different reaches. Also, the deposition does not only occur at the lower part of the catchments. Depositional reaches are evidenced in the upper part of the Gravegnola main channel and after the confluence of the Cassana and Redarena creeks due to the presence of bridges and islands.

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4.3 Comparison between the two study basins

The two study catchments had quite different responses in terms of morphological changes. Therefore a statistical comparison between the two catchments has been done in order to understand the possible controlling factors determining these differences.

The main statistics of the variables investigated in order to link LW dynamics to channel characteristics at the reach scale are reported in Table 1, where all the reaches belonging to the two basins (Gravegnola and Pogliaschina) are included. The application of the Shapiro–Wilk test indicated that none of the variables presented a normal distribution, and thus a non-parametric approach was required. In order to assess whether the two study basins differ with respect to these variables, their medians were compared through the Mann–Whitney (Wilcoxon) test. The significance p values from this test are presented at the bottom of the Table 1, and values < 0.05 evidence statistically significant differences between the two catchments at the 95 % confidence level.

The two catchments present significant differences in terms of channel slope, drainage area, stream power and stream power index, with the Gravegnola featuring higher values for all these variables. Regarding the channel changes occurred during the event, the widening ratio results statistically significantly larger in the Gravegnola Creek (median of 8 vs. 2.9 in the Pogliaschina).

As to the variables describing LW dynamics during the event, they turn out significantly larger in the Gravegnola basin (Table 1), with the exception of the LW export ratio ($LW_{ex\ R}$), which does not present significant differences. As already observed above at the basin scale, LW volume recruited in the fluvial corridor per unit of channel length ($LW_{r\ F}$) is higher than LW originated from the slopes ($LW_{r\ S}$) in both creek basins.

4.4 Control factors and LW dynamics at the reach scale

In order to investigate the potential factors controlling LW dynamics (recruitment, deposition and net export) at the reach scale, a correlation analysis was carried out.

Because the variables do not present a normal distribution, the non-parametric Spearman correlation was adopted and calculated (Table 2, where statistically significant correlations $p < 0.05$ are in bold). Some correlations result to be statistically significant, although they are rather weak and often show opposite signs in the two datasets (Pogliaschina and Gravegnola basins). For example, the widening ratio shows a positive correlation with drainage area in both catchments and negative with the reach slope, but only in the Pogliaschina this correlation is significant.

Within the Pogliaschina, fluvial LW erosion correlates significantly also with drainage area (positively) and reach slope (negatively). On the other hand, LW recruited from the slope does not show any statistically significant correlation with any of the control factors for the Pogliaschina dataset, but it does so in the Gravegnola basin, where it is correlated negatively with drainage area and positively with reach slope and stream power index.

Relatively surprising is the fact that LW deposition does not present statistically significant correlation with any of the control variables in both catchments. Instead, LW export from a reach is significantly and negatively correlated with the reach slope, whereas it is positive correlated with drainage area in both catchments. Finally, the LW export ratio is not significantly correlated with any of the tested control variables.

Summarizing the correlation analysis results, LW dynamics are poorly correlated with any of the hydraulic variables. The graphs in Fig. 8 display clearly how LW variables (as well as widening ratio) in the Gravegnola plot higher than for the Pogliaschina, notwithstanding the comparable range in the tested controlling variables. The graphs illustrate the large variability inherent in the analysed datasets, which determines the low coefficients of correlation.

4.5 Size of LW deposited in the Gravegnola basin

As described in the methods section, the size of all LW jams and single elements could be measured within the GIS system for the Gravegnola basin only, thanks to quality of the orthophotos taken there after the event. A total of 1747 logs and 654 jams were

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digitized, and a summary of their characteristics is reported in Table 3. Log length varies between 1 and 18 m, plus an outlier (a single tree) of 38 m. Jam area features a high variability, ranging from 1 to 1700 m^2.

The Shapiro–Wilk test was carried out on the distributions of the log length in the different channels, indicating that they do not follow a normal distribution, and neither do their logarithms. Therefore, the non-parametric Kruskal–Wallis test was adopted to determine whether significant ($p < 0.05$) differences among the channels of the Gravegnola basin exist. Logs in the Gravegnola Creek result to be shorter than in the other channels, whereas there is no significant difference between the two reaches of the Casserola and the Veppo creeks. On the other hand, the Suvero creek presents the longer logs. These differences could be due to the fragmentation of LW pieces during the transport to the downstream reaches. Because the log diameter – differently from log length – was assigned based on three classes (see methods), its distribution for the different channel is shown as histograms (Fig. 9). Diameter distributions are also non-normal, a median value is the same in all the Gravegnola channels.

The distribution of jam areas does not follow a normal distribution, but in this case their logarithms do, thus permitting the use of ANOVA to the log-transformed variable to determine differences in the Gravegnola channels. The Multiple Range Test using the Fisher's least significance (LSD) procedure was used for this analysis. This test indicates the Casserola 1 as the channel in which jams are significantly smaller, then intermediate size jams are present in the Veppo, Suvero and Casserola 2 creeks, and the larger jams are found in the Suvero, Casserola 2 and Gravegnola.

5 Discussion

The magnitude of LW recruitment and deposition occurred during the October 2011 flash flood in the study basins was characterized by a very high variability at different spatial scales, i.e. both at the catchment, sub-catchment and reach scale. An interpretation of the observed evidence is provided below.

5.1 LW recruitment and channel widening

At the basin scale, most LW recruitment (about 70–80 %) took place in the fluvial corridors and not on the slopes, similarly to what observed during the 2005 flood events in Switzerland (Waldner et al., 2007). Therefore, channel widening was more important than slope instability in "collecting" wood from forested surfaces. The relevance of floodplain erosion was greater in the Gravegnola than in the Pogliaschina basin. Indeed, channels in the former catchment widened – in both absolute and relative terms – more than in the latter (median of widening ratio approximately 8 vs. 3, respectively). The range in the widening ratio is similar to what observed after the severe 2005 floods in the Austrian Alps (Krapesch et al., 2011) but no significant differences among catchments were evidenced.

The stream power does differ considerably between the two catchments, mostly for the steeper slopes characterizing the Gravegnola channel network. Therefore, the results at the large (basin) scale seems to indicate that channel widening could be related to the total power of the flow. However, the results at the reach scale (Table 2) do not support the hypothesis that channel widening and thus LW recruitment from the floodplain correlates with stream power. As discussed in the methods section, a strong degree of spurious correlation is present when analysing such a ratio against unit stream power, whereas the pre-event width is of little relevance for our relatively small range of channel size. Therefore the role of unit stream power cannot be addressed here, unlike in Krapesch et al. (2011) who analysed a dataset comprising both small relatively large channels (based on the before the event width).

The drainage area only resulted to be significantly correlated with the widening ratio for the two basins separately (Table 2). Channel slope seems also relevant, but its correlation coefficients are slightly smaller. Negative correlation between widening ratio and channel slope can be ascribed to the higher confinement of upstream channels. In these reaches, which are more confined and steeper, vertical variations (incision) are more likely to occur rather than horizontal variations (widening). On the con-

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trary, horizontal variations are more likely to occur in the low gradient and unconfined downstream reaches. Overall, drainage area and channel slope (which are strongly and negatively correlated, $R^2 = 0.78$ and 0.46 in the power function of the Gravegnola and Pogliaschina, respectively) perform better than stream power or SPI in explaining the variability of widening ratio and LW recruitment (both from the floodplain and hillslopes). This indicates that the lower, milder reaches in both catchments underwent larger widening, but the physical process/reason for its occurrence remain unclear, as well as the fact that Gravegnola reaches featured much larger widening and thus larger LW floodplain recruitment than those in the Pogliaschina, despite the partial overlap in drainage area and channel slope (Fig. 8).

A factor potentially responsible for these differences could be the degree of channel confinement, i.e. the ratio between valley floor width and channel width. This is an obvious boundary condition for rivers with a narrow fluvial corridor, but it could not be assessed with accuracy in the study basins due to the inadequate geological map scale/DEM resolution. We believe sediment supply and bedload deposition during the event to have played a major role in determining channel widening and thus floodplain recruitment. Indeed, the total surface affected by landslides connected to the channel network (Fig. 10) was 10.5 ha in the Gravegnola basin but only 1.39 ha in the Pogliaschina. Also, landslide sediment volumes were probably higher in the Gravegnola due to their greater thickness, but these were estimated only visually and a quantitative assessment is not possible. The higher amount of sediment supplied to the channels of the Gravegnola catchment could have triggered widespread avulsions and increased lateral mobility processes within this basin, and as these processes are more intense where strong deposition tends to occur (Bryant et al., 1995), widening increases moving downstream in the fluvial network, at lower slopes and larger drainage areas.

The different landslide activity during the event in the Gravegnola basin compared to the Pogliaschina likely depends its geological characteristics. In fact, 21.6 % of the Gravegnola catchment was mapped – before the 2011 event – as landslide deposits, and almost half (47 %) of the hillslope areas which contributed LW to the channels during the event was mapped as paleolandslides. In contrast, in the Pogliaschina catchment only 2.8 % was mapped as landslide deposit, and nearly half of the basin area is underlain by the Macigno fm., which is quite stable and featured quite few landslides in comparison with the Gottero fm. (Mondini et al., 2014).

5.2 LW deposition

LW deposition appears to be even more difficult to explain than recruitment, as correlation analysis did not evidence any statistically significant relationship with the tested controlling variables. Nonetheless, deposition seems to have been more pronounced in the wider, milder reaches, typically located in the lower river sections. This contrasts to what observed in mountain catchments in the Italian Alps where LW storage was analysed long after extreme events occurred (Comiti et al., 2006; Rigon et al., 2012), but matches observations carried out after the 2005 flood events in Switzerland (Waldner et al., 2007). In our study basins, LW deposition was severely affected by the presence of newly-formed islands (from floodplain dissection) or even of single standing trees, which – similarly to bridges – were key in promoting wood trapping. The lower values of reach-scale LW export (Fig. 8) actually characterize reaches where bridges were clogged or where standing vegetation (islands) trapped large amount of wood (as in the Redarena and Veppo creeks). Indeed, these elements, in particular bridges, should be considered as the first order factors controlling wood transport during flood events.

Volumes per unit of channel area of LW deposited during the flood, taking into account the entire channel width active during the flood, result to be on average 126 $m^3 ha^{-1}$, ranging from 0 to 361 $m^3 ha^{-1}$ in the different reaches of the Gravegnola basin and 98 $m^3 ha^{-1}$ (from 0 to 1203 $m^3 ha^{-1}$) in the Pogliaschina catchment. These values are slightly higher than LW storage reported for European mountains rivers, but assessed long time after extreme flood events occurred (Gurnell, 2003; Comiti et al., 2012). Also, they are similar to LW storage in different channels of Chile (Iroumé et al., 2014) and headwater streams in the Colorado Rocky Mountains (Wohl and Goode, 2008), but definitely smaller than in rivers flowing in regions like the Pacific northwest (Gurnell, 2003).

Also, LW sizes measured in detail in the Gravegnola basin are small compared to such peculiar – but well investigated – geographical area, where old-growth conifer forests supply channels with very large wood elements. On the other hand, deposited logs in the Gravegnola are on average longer – and larger – than those measured in mountain catchments of the Italian Alps (Comiti et al., 2006; Rigon et al., 2012), but are quite similar to LW surveyed in Switzerland after the 2005 floods (Waldner et al., 2007). In fact, nearly all LW measured in the Gravegnola after the flood derived from freshly recruited trees – as estimated from wood characteristics, see MacVicar et al. (2009) – which were not subject to breaking up processes over the years, as also reported for the Swiss study case (Waldner et al., 2007).

6 Conclusions

This study highlights the high complexity of wood dynamics in mountainous catchments during flash floods, and thus the difficulties in predicting LW budgets and LW-related hazards. The large uncertainties in forecasting a reliable flood event LW budget lie in the prediction of both LW recruitment and deposition. Indeed, rivers featuring similar flood severity responded quite differently in terms of channel widening and thus of wood recruitment from the floodplains, which was the dominant process in partly-confined channels. More post-event investigations are thus needed to understand the factors responsible for channel widening during extreme events, which is a key aspect for the definition of the morphological dynamics river corridors (Rinaldi et al., 2014), in turn a precious tool for a sound river management planning. Nevertheless, wood recruited by hillslope processes was quantitatively relevant as well, but also in this case its prediction would encounter the large uncertainties inherent in the prediction of slope instabilities, elevated by the necessity to assess their connectivity with the channel network. To this aim, the GIS-based model developed by Lucía et al. (2015b) – which

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extends to LW dynamics the Cavalli et al. (2013) approach for sediment connectivity – is a first attempt to address such an issue. LW deposition – and thus LW export – at the reach scale was observed to be a very complex process too, poorly related to any hydro-morphological variable and highly influenced by the presence of standing trees and artificial structures such as bridges.

From an applicative perspective, maintenance of riparian vegetation present in the river corridors of study basins would have clearly reduced the recruited volumes. However, large LW quantities would have been still supplied by landslides, and these would have been probably enough to cause several bridge clogging and thus determine an increased flood hazard. Therefore, we believe that a renewed approach to bridge design and/or the installation of ad-hoc retention structures (Comiti et al., 2012) are the only solutions to reduce substantially the damages caused by wood transport during extreme floods. This points out the general suitability of these studies that document the patterns and amounts of LW erosion and deposition, which may be useful for the managers of mountain river basins who very often have to cope with wood transport processes during extreme events, a potential hazard still poorly considered in many hazard plans worldwide.

Acknowledgements. Funding for this study comes from the project TRUMPS (Towards a reliable inundation mapping in South Tyrol) granted by the Autonomous Province of Bozen-Bolzano. The Servizio di Protezione Civile della Provincia de La Spezia, the Autorità di Bacino Interregionale del Fiume Magra, and the Corpo Forestale dello Stato are warmly thanked for providing extremely valuable data and photos. The authors wish to thank the colleagues Stefano Crema and Alessia Viero for their collaboration in field surveys and landslide mapping.

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Table 1. Summary of the channel (2nd–5th column) and LW-related (6th–12th column) variables analysed statistically at the reach scale. For definition of the symbols, see Table A1.

	S	A km^2	Ω $W\,m^{-1}$	SPI	W_R	$LW_{r\,F}$ $m^3\,km^{-1}$	$LW_{r\,S}$ $m^3\,km^{-1}$	$LW_{r\,T}$ $m^3\,km^{-1}$	LW_d $m^3\,km^{-1}$	LW_{ex} m^3	$LW_{ex\,R}$
Gravegnola											
M_e	0.06	7.60	91 273	104	8	555	131	706	393	481	0.73
σ	0.07	8.71	40 367	1	5	265	223	298	725	661	0.19
c_v	0.54	0.60	0.45	0.39	0.88	0.30	0.84	0.82	0.44	0.80	0.57
Min	0.01	3.14	30 367	433	3	207	0	404	0	114	0.27
Max	0.28	30.12	220 621	382	24	1143	971	1273	2327	2388	1.00
25th perc.	0.03	3.71	69 393	130	5.9	390	37	555	200	358	0.67
75th perc.	0.13	11.70	195 497	273	10.5	691	266	982	636	966	0.84
Pogliaschina											
M_e	0.04	4.64	39 255	57.2	2.85	140	0	180	8.5	123	0.48
σ	0.03	5.04	53 664	47	2	129	129	171	259	287	0.37
c_v	0.55	0.93	0.77	0.72	0.40	0.40	0.74	1.08	1.37	1.89	0.71
Min.	0.00	0.11	600	9	1	20	0	20	0	0	0.00
Max.	0.15	20.56	254 800	262	8	520	486	626	1224	1162	1.00
25th perc.	0.02	1.30	7681	41.1	1.9	60	0	100	0	16	0.18
75th perc.	0.05	6.19	5800	76.9	4.0	220	88	370	88	364	0.97
P value	< 0.05	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	$>$ **0.1**

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Table 2. Spearman correlation coefficients. In bold are correlations statistically significant ($p < 0.05$). For symbols see Table A1.

	Gravegnola							Pogliaschina						
	$LW_{r\,F}$	$LW_{r\,S}$	$LW_{r\,T}$	LW_d	LW_{ex}	$LW_{ex\,R}$	W_R	$LW_{r\,F}$	$LW_{r\,S}$	$LW_{r\,T}$	LW_d	LW_{ex}	$LW_{ex\,R}$	W_R
S	−0.12	**0.52**	0.11	−0.11	**−0.46**	0.08	−0.41	**−0.41**	0.08	−0.22	0.05	**−0.51**	−0.04	**−0.39**
A	0.22	**−0.50**	0.01	0.22	**0.58**	−0.07	**0.50**	**0.50**	−0.29	0.19	−0.04	**0.56**	−0.12	**0.49**
Ω	0.35	0.38	0.41	0.25	−0.23	−0.09	0.07	−0.16	−0.07	−0.18	−0.24	0.01	−0.26	−0.10
SPI	−0.04	**0.48**	0.13	−0.05	−0.42	0.08	−0.33	−0.05	−0.26	−0.20	−0.14	−0.06	−0.28	−0.05

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Table 3. LW characteristics (dimensions and spatial density) in the Gravegnola catchment. For symbols see Table A1.

Channel	N_{log}	M_eL_{log}	$L_{log\ 90}$	$N_{log\ L}$	$N_{log\ A}$	N_{jam}	M_eA_{jam}	$A_{jam\ 90}$	$A_{jam\ L}$	$A_{jam\ A}$
Casserola 1	376	4.34	9.9	11.2	0.44	77	7.4	19	29	1.1
Casserola 2	371	4.53	8.6	25.5	0.24	205	19.3	140	863	8.3
Suvero	444	5.26	10.9	24.8	0.47	62	19	72	139	2.7
Veppo	88	4.52	8.6	4.8	0.14	81	14.7	63	127	3.6
Gravegnola	468	3.61	7.9	15.5	0.21	229	24.5	114	433	6.0
Total	1747	4.37	9.6	15.2	0.28	654	17.3	104	275	5.1

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Table A1. Abbreviations.

M_e		Median
σ		SD
c_v		Coefficient of variation
Min.		Minimum
Max.		Maximum
25th perc		25th percentile
75th perc		75th percentile
$LW_{r\,F}$	$m^3\,km^{-1}$	LW recruitment rate in the fluvial corridor
$LW_{r\,S}$	$m^3\,km^{-1}$	LW recruitment rate in the slopes
LW_r	$m^3\,km^{-1}$	LW recruitment rate in both, fluvial corridor and slopes
LW_d	$m^3\,km^{-1}$	LW deposition rate
LW_{ex}	m^3	LW exported (LW input from upstream + LW recruited in the reach − LW deposited in the reach)
$LW_{ex\,R}$		LW export ratio (LW Export/LW input from upstream + LW recruited in the reach)
S		Longitudinal slope
A	km^2	Drainage area (using as outlet the higher limit of the reach)
Ω	$W\,m^{-1}$	Stream power
SPI	m	Stream Power Index ($S \cdot A^{0.5}$)
W_R		Widening ratio (pre event width/post event width)
N_{log}		Number of logs
M_eL_{log}	m	Median of the length of the logs
$L_{log\,90}$	m	Percentile 90 of the logs length
$N_{log\,L}$	logs*100 m	Number of logs per 100 m of streambed length
$N_{log\,A}$	log pieces*100 m^2	Number of logs per 100 m^2 of streambed area after flood
N_{jam}		Number of jams in the channel
M_eA_{jam}	m^2	Median of the area of the jams
$A_{jam\,90}$	m^2	percentile 90 of the jam area
$A_{jam\,L}$	logs*100 m	Number of logs per 100 m of streambed length
$A_{jam\,A}$	log pieces*100 m^2	Number of logs per 100 m^2 of streambed area after flood

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Figure 1. LW clogging in the Magra river catchment after the 2011 flash flood. **(a)** Upstream view of a bridge in the town of Brugnato. Note also the evident sediment deposition below the bridge; **(b)** downstream view of a huge wood jam trapped by a bridge in the village of Pignone; **(c)** street clogged by LW in town of Borghetto Vara. Source: Autorità di Bacino del Fiume Magra and Provincia di La Spezia.

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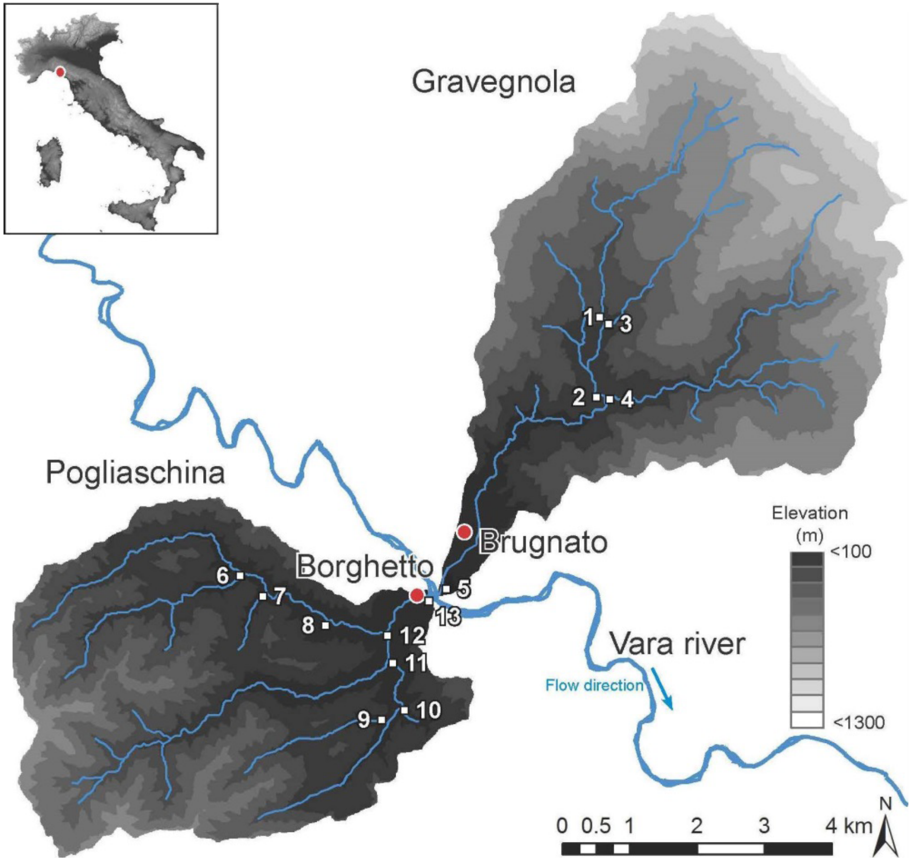

Figure 2. Geographical location and Digital Elevation Model (DEM) of the Pogliaschina and Gravegnola basin. The studied channels have been indicated with a number at their outlets: 1. Casserola 1, 2. Casserola 2, 3. Suvero, 4. Veppo, 5. Gravegnola, 6. Pogliasca, 7. Redovego, 8. Sottano, 9. Ginepro, 10. Benoia, 11. Redarena, 12. Cassana, 13. Pogliaschina.

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Figure 3. Images of the Pogliaschina **(a, b)** and the Gravegnola **(c, d)** creeks taken during the field surveys. **(a)** An incised reach; **(b)** a LW jam anchored on remaining vegetation, it retained sediment upstream; **(c)** LW jam deposits anchored in remaining vegetation; there are also landslides in the right-side slope and **(d)** a reach were a landslide was connected with the channel, that was aggraded downstream.

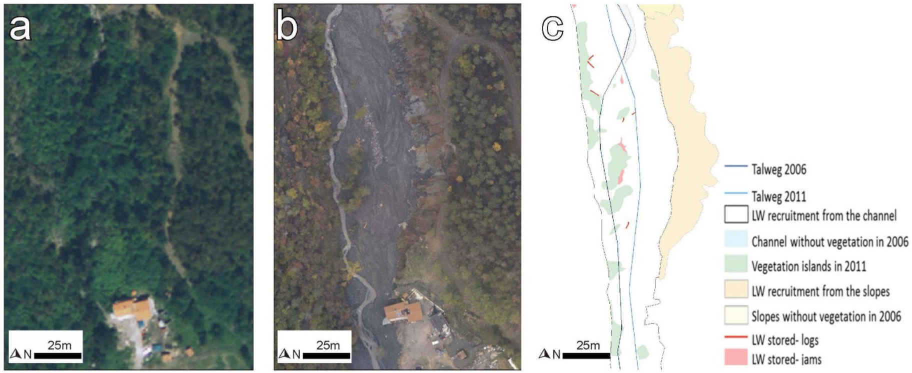

Figure 4. A reach in the Casserola 1 channel (Gravegnola) before **(a)** and after **(b)** the October 2011 event and the GIS mapping **(c)**.

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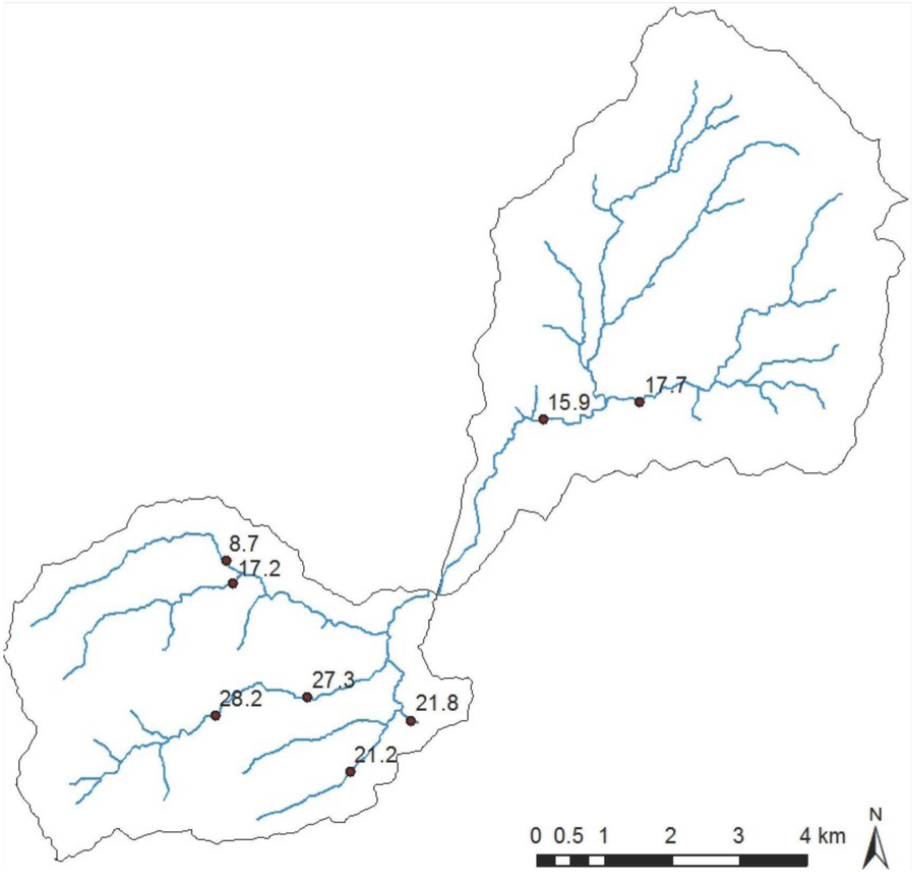

Figure 5. Location of the sections where peak discharges were measured with a red point and the value of peak discharge, in $m^3 s^{-1} km^{-2}$, are indicated in the labels. The surveyed sections are located in the following channels Veppo, Gravegnola, Pogliasca, Benoia, Redarena, Cassana, and Pogliaschina.

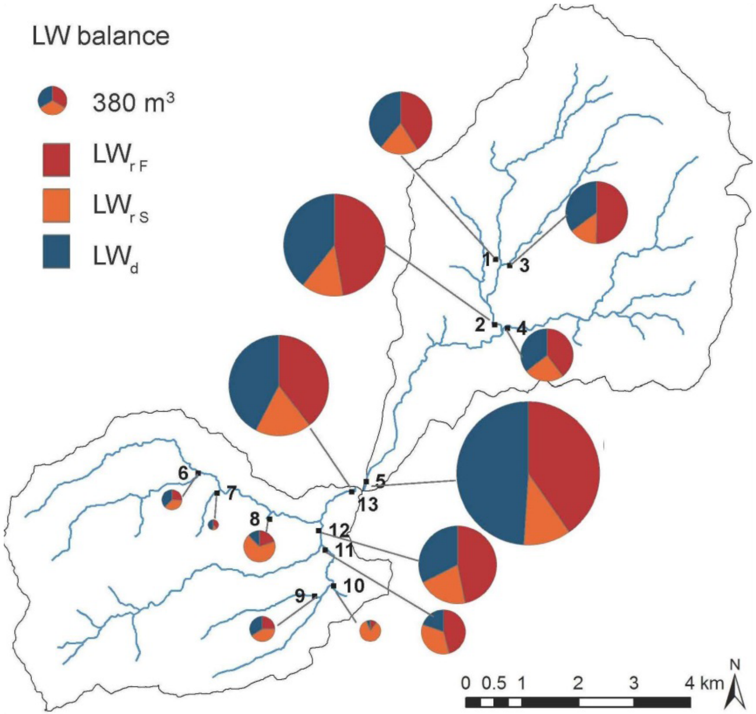

Figure 6. LW budget ($LW_{r F}$ = LW recruitment from floodplain, $LW_{r S}$ = recruitment from hillslopes, LW_d = LW deposited) in the different sub-catchments of the Gravegnola and Pogliaschina basins. The size of the circles depends on LW recruited in each sub-catchment (i.e. the input of the budget). 1 Casserola, 2 Casserola, 3 Suvero, 4 Veppo, 5 main Gravegnola, 6 Pogliasca, 7 Redovego, 8 Sottano, 9 Ginepro, 10 Benoia, 11 Redarena, 12 Cassana, 13 main Pogliaschina.

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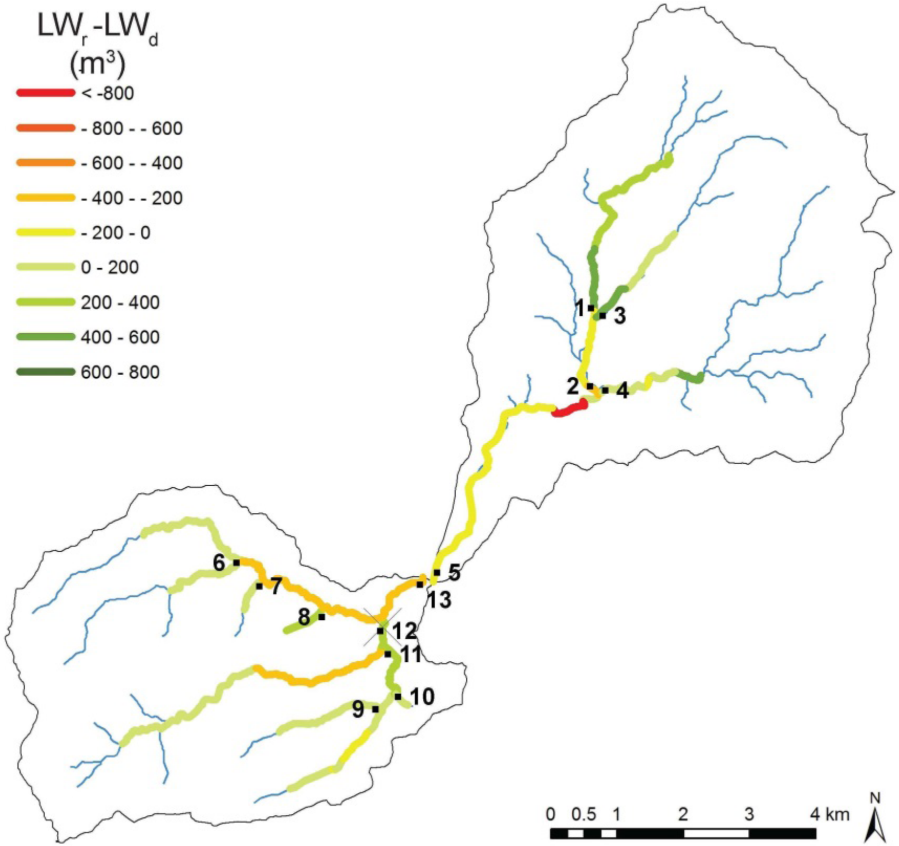

Figure 7. Difference between LW recruitment and deposition occurred within each reach. Numbers identify the catchments: 1 Casserola, 2 Casserola, 3 Suvero, 4 Veppo, 5 main Gravegnola, 6 Pogliasca, 7 Redovego, 8 Sottano, 9 Ginepro, 10 Benoia, 11 Redarena, 12 Cassana, 13 main Pogliaschina.

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Dynamics of large wood during a flash flood in two mountain catchments

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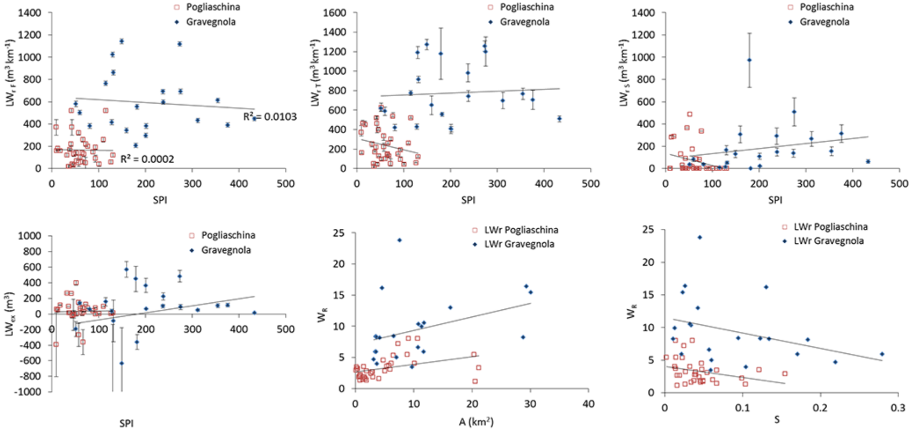

Figure 8. Relationships between selected control factors and LW variables. The relationship between widening ratio and drainage area and channel slope is shown too. The error bars express the uncertainty deriving from the range of assumptions for the estimate of LW volumes (see methods).

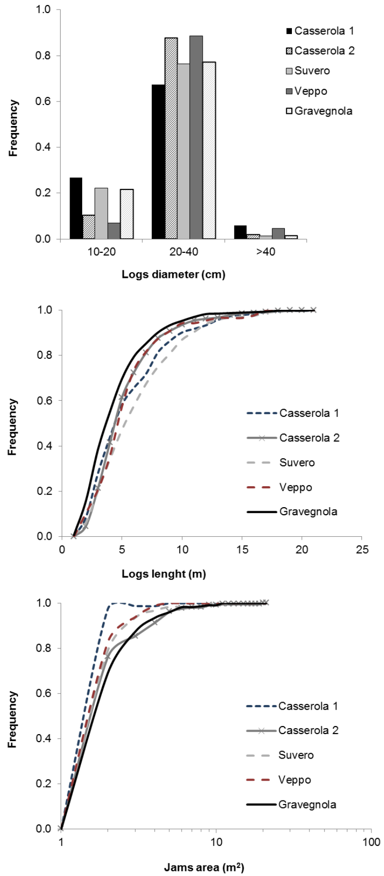

Figure 9. Frequency of log dimensions: the three categories of Log diameter (above) the length (middle) and the jam area (below) in the different channels.

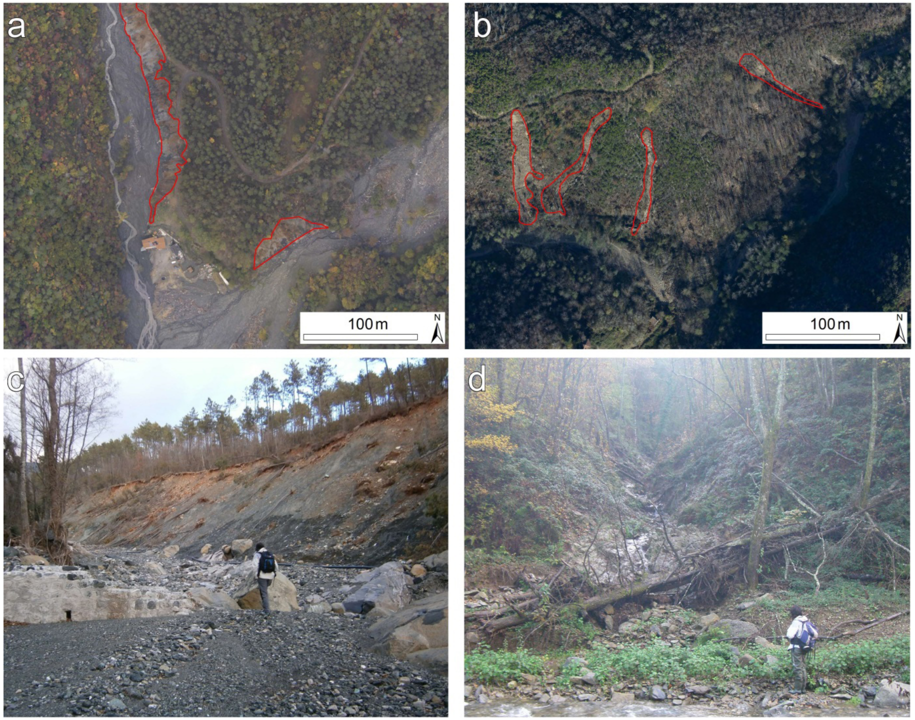

Figure 10. Example of lateral inputs (marked in red in the orthophotos, **a**, **b**) of sediment to the channel. In the Gravegnola **(a, c)** the lateral input consists in large landslides connected to the channel, while in the Pogliaschina **(b, d)** the connectivity of sediments from the slopes is lower because it mostly occurs through earth flows, which are partly buffered by valley floors, and channelized erosion in ephemeral streams that are sometimes blocked by LW pieces.

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