PREVENTING WOOD-RELATED HAZARDS IN MOUNTAIN BASINS: FROM WOOD LOAD ESTIMATION TO DESIGNING RETENTION STRUCTURES

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ABSTRACT

Large wood (LW) represents one of the main problems for risk prediction in Alpine streams, mostly because of its potential to clog bridges, culverts and narrow sections during flood events. In order to prevent wood from reaching critical sections, wood-trapping structures have long been built, but very often these works have been implemented without a rationale procedure and thus their efficiency has not been satisfactory. This paper presents a case study (the Rienz river just upstream of Bruneck, South Tyrol, Italy) where the design of a system (two structures) for wood trapping entailed – before structure and filter sizing – the determination of LW volumes from the hillslopes and from the river corridor, the definition of flood event scenarios, and hydraulic and morphodynamic modeling. The minimization of environmental impacts and the social acceptance of the structures were finally achieved before the actual implementation of the system.

Keywords: woody debris, flood scenarios, check-dams, debris racks

LARGE WOOD DYNAMICS IN MOUNTAIN RIVERS AND ITS MODELLING

In-channel large wood (LW) directly influences the physical, chemical and biological characters of aquatic ecosystems and as such is now recognized to represent a key component in river systems by ecologists and geomorphologists (Montgomery and Piégay, 2003). On the other hand, LW represents one of the main problems for risk prediction in Alpine streams mostly because of its potential to clog bridges, culverts and narrow sections during flood events (e.g. Comiti et al., 2008).

A reliable prediction of LW transport rates and volumes is still an open question, especially in relatively narrow mountain streams (Seo and Nakamura, 2009; Wohl and Goode, 2009). Focusing here on mountain river basins where LW transfer 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 their localization is of great value, along with transport distance (Comiti et al., 2006; Mao et al., 2008). 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 its characteristics (i.e. distribution of log length and diameter), which are required for siting and designing proper countermeasures. 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 relative short time scales (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 reach geometric and morphological characteristics (e.g. width and depth relative to log size, bedforms, abundance of boulders) for modeling LW transfer along the system, whereas the identification of unstable areas on basin hillsides should help model LW input from landslide and debris flows, which are often the dominant sources in mountain basins. Such conceptual models for LW transfer can be spatially distributed with their implementation in a raster GIS-based model (Rigon, 2009; Mazzorana et al., 2009a, 2010; Rigon et al., 2012) and thus help

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predict the location of recruitment sites as well as of LW transport and depositional reaches. However, model calibration and validation against field data is crucial for their application as in all modeling efforts.

Currently, most of the published research regarding LW input rates, storage and distribution in mountain rivers derives from investigations in unmanaged, quasi-pristine watersheds in North America, even though several publications on LW transfer during flood events in basins of the European Alps are long available in German (e.g. Bänzinger, 1989; Rickenmann, 1997). However, the present capability to predict LW transport rates and volumes during floods is absolutely lower compared to the estimation of sediment transport.

LARGE WOOD MANAGEMENT STRATEGIES

In mountain rivers, LW transport is null to negligible for low to moderate floods. Therefore, for most of the time LW lies relatively stable in the river system contributing to bed stabilization, to limit sediment transport and to create bedforms (such as steps and scour pools) that provide habitats for fish and macroinvertebrate communities (Coe et al., 2009). Considerable in-channel wood transport and wood recruitment from slopes and eroded banks takes place only during high-magnitude, infrequent floods (possibly >10-20 yr recurrence interval). Therefore, wood exerts his positive eco-hydro-morphological effects in rivers for most of the time, becoming a potential hazard only during much shorter flood times. However, given the relevant anthropic presence along rivers of the European Alps, the entire removal of LW and riparian trees from channels and floodplains has long been adopted in the attempt to prevent bridge/culvert clogging and their consequent flooding. Nevertheless, this traditional approach is not sustainable because its effectiveness can be quite low (i.e., it does not avoid sudden LW input from hillslopes, which is often dominant during flood events), it is very expensive, and most of all it causes negative effects on stream morphology, bed and bank stability (Lisle, 1995), fish population and on the overall ecological status of rivers (Harmon et al., 1986). Beside channel clearing, wood-trapping structures have long been built in Europe and in Japan (Lange and Bezzola, 2006; Figure 1) to prevent wood from reaching critical sections.

Fig. 1 Images of different types of wood retention structures in the European Alps (higher centered and lower left images are from Lange and Bezzola, 2006; the lower right from Geobrugg, 2007).

Check-dams aimed at trapping both sediments and wood have first been developed adopting vertical and inclined buttresses as well as grids (Bezzola et al., 2004; Uchiogi et al., 1996; Figure 1). More recently, rope net barriers were designed for gravel and wood entrapment in small streams, and have been designed by physical modelling and field tests (Rimböck, 2004; Figure 2). In order to trap only floating wood in larger mountain rivers, cable-filter dams were also implemented. They are composed of harmonic steel cables fixed by tie-beams on the river banks and in some cases also within the channel by a buttress in order to reduce cables span length. A diagonal planimetric configuration forces the trapped wood to accumulate towards the river banks where it can be removed during floods

(Mazzalai et al., 2006). A different trapping system utilizes the so-called V-racks, where vertical metal piles fixed in the river bed can be arranged at different orientations but most commonly with a V-like planform pattern (Lange and Bezzola, 2006). However, the efficiency and the functional success of such protection measures depend on many factors which include LW volumes and rates, timing of LW transport during the flood, LW size distribution, interaction between bed, LW and sediment in the proximity of the structure, location and orientation with respect to the flow, and local flow characteristics (Rimböck, 2004).

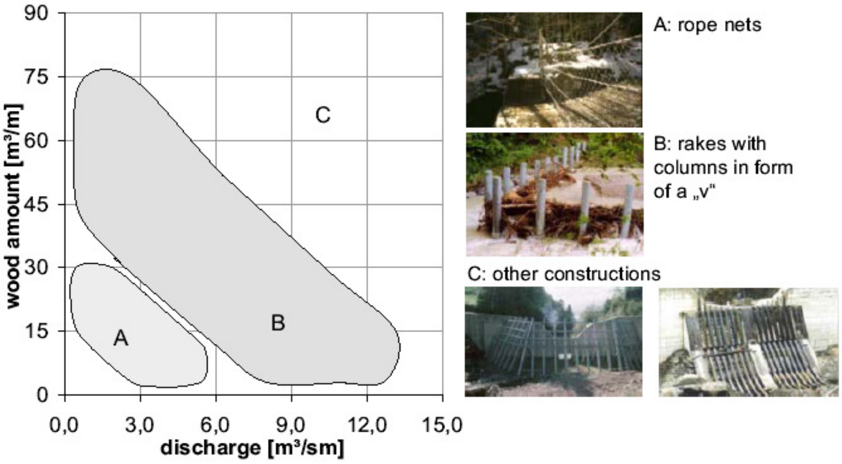

Fig. 2 The type of wood retention structure to be installed depends on expected wood load and unit flow discharge according to Rimböck (2004).

Indeed, given the huge uncertainties regarding LW transport rates and volumes during flood events, designing an efficient system for wood retention is not an easy task at all. The main goal of the paper is to describe a rational procedure to be applied in mountain basins for coping with wood hazard, a problem which has often been tackled by public agencies responsible for river management without a systematic framework to plan and design retention structures.

DESCRIPTION OF THE CASE STUDY

The case study presented is the Rienz river just upstream of Bruneck (South Tyrol, Italy, Figure 3) where two large retention structures are to be installed by 2012. The drainage area of the Rienz basin at Bruneck is about 640 km^2, the channel width is on average 10 m, the slope is about 1.5%, and the median grain size of the bed surface is 70 mm (D_{90} is 280 mm). The 300 yr discharge (Q_{300}, which is the design flow value used in South Tyrol for mountain rivers) is estimated to be around 300 m^{3}s^{-1} and flood duration about 30 hr (Scherer, 2008). Wood retention structures upstream of Bruneck are needed because many low bridges span the channel in the city, rendering the potential for wood clogging quite relevant (Mazzorana et al., 2011). In fact, large wood sources in the basin are widespread, including the main river corridor – which hosts mature spruce stands (Figure 4) on the floodplain and on the low terraces created by bed incision and channel narrowing occurred since the 1960s (from 17 m width in 1954 to 9 m in 2006) – and the hillslopes which present diffuse mass wasting processes. Harvested logs stored near river banks could represent an additional potential wood input in case of above-bankfull flows (Figure 4).

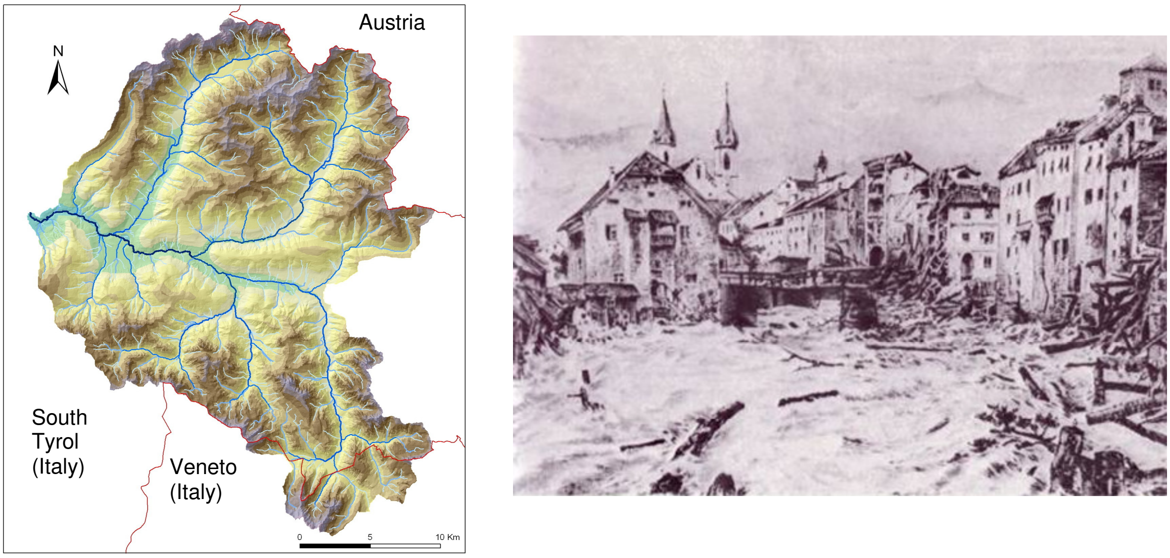

Fig. 3 Channel network of the Rienz basin (left) upstream of Bruneck, the city depicted in the painting (right) during the 1882 flood, when a great deal of floating large wood is displayed.

Fig. 4 Mature spruce stands on the floodplain (left) and cut logs lying on the channel banks (right).

PROCEDURE FOR DESIGNING WOOD RETENTION STRUCTURES

A rational procedure for a correct design of wood retention structures should entail all the steps necessary to achieve the most reliable trapping system, i.e. from the identification of LW input locations and volumes, passing through the definition of structure characteristics, filter type and size, to end up with a cost-benefit analysis and the achievement of social acceptance. In summary, the steps involved in the Rienz project are shown in Figure 5. In this paper, for sake of brevity we will focus on only some of the steps, specifically those dealing with LW volume estimation and filter design, which are the least established both in the scientific literature and in the practice.

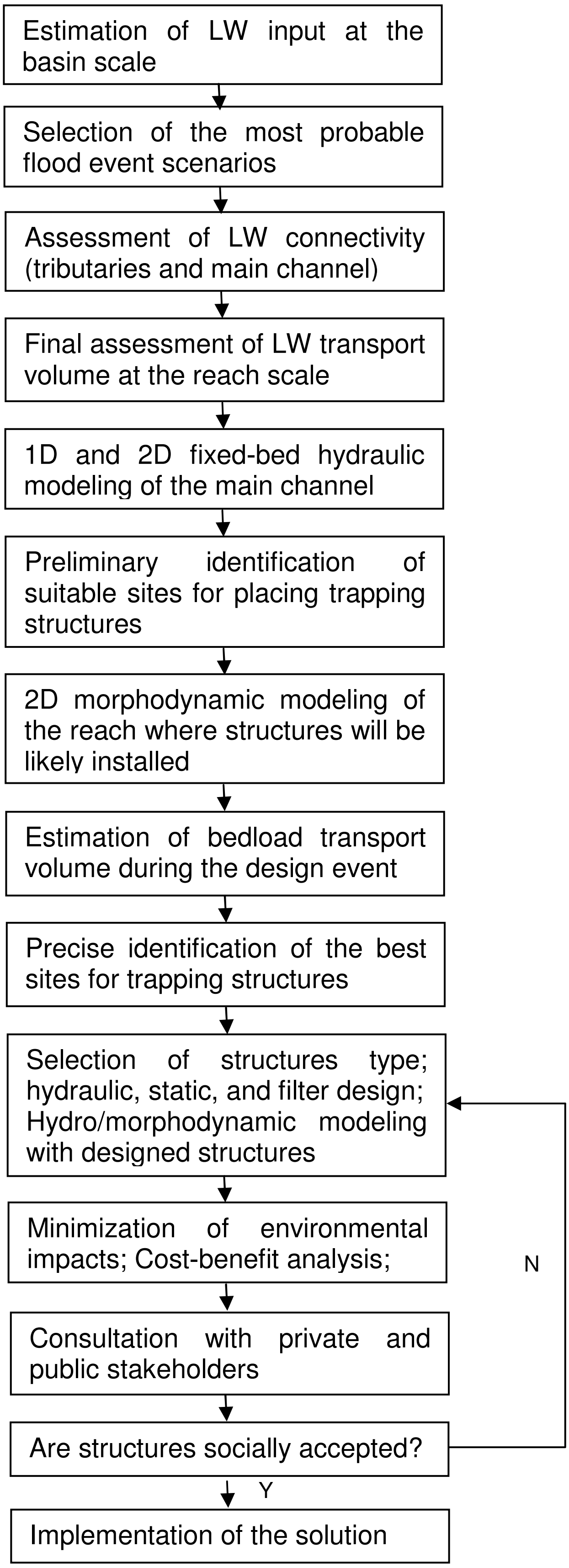

Fig. 5 Flow chart illustrating the procedure adopted in the Rienz project.

Estimation of LW input volumes at the basin scale

Calculation of LW input volumes was separated into hillslope and river corridor sources. For the former, a bivariate geostastistical model (Weight of Evidence, WofE) for mass wasting processes was applied to the entire Rienz basin following a detailed inventory of landslides. The instabilities maps – for 2 different probabilistic scenarios of occurrence, i.e. high and low instability – were then intersected with forest management maps. Downslope LW transfer was modelled using a decay function (Figure 6, see for details Rigon, 2009, and Rigon et al., 2012).

For the river corridor, a geomorphological approach was deployed (Figure 7). This was based on the visual identification of all erodible floodplain and low terrace surfaces using a detailed (2.5m cell) LiDAR-derived DTM. Woodland standing volume (in m^3ha^{-1}) was estimated from the combined use of the LiDAR DSM (providing the canopy height) and field plots were tree height and diameter were surveyed and then converted into tree volume by forestry growth tables. Here the assumption was that an extraordinary flood event (about 300 yr recurrence period) would cause tree uprooting from the entire river corridor, because this was almost entirely still active channel until 50 yr ago, before the narrowing due to dam construction and retention structures in the tributaries.

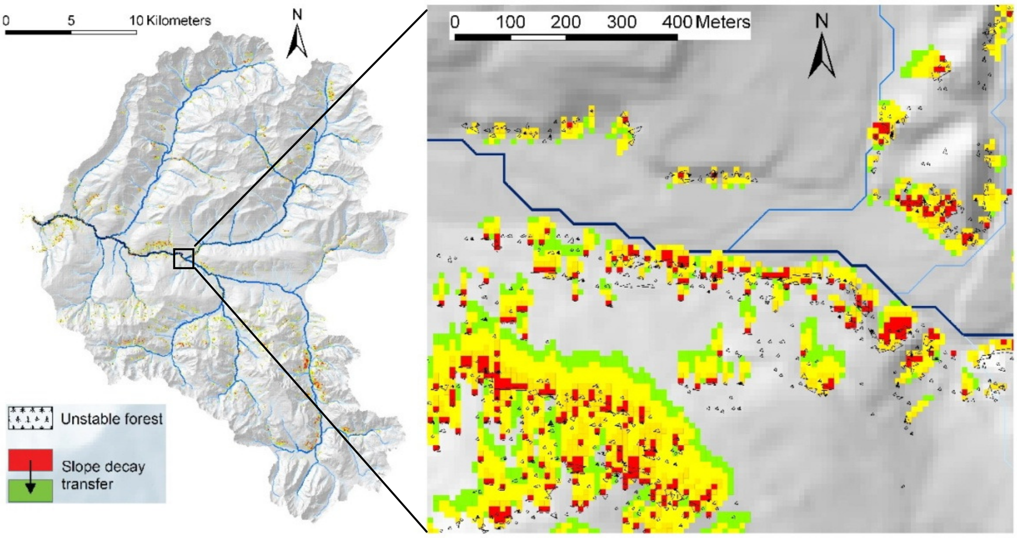

Fig. 6 LW input from the hillslope as modeled by the geostatistical stability model and downslope decay function. Left, the output for the entire basin, right a closer view.

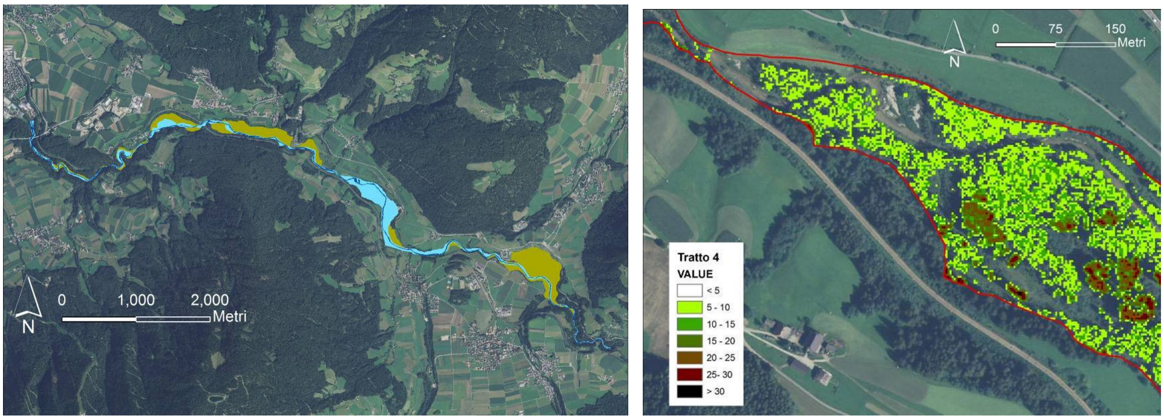

Fig. 7 LW input from the river corridor. Left, the identification of active channel (blue), floodplain (light blue) and low terraces (green). Right, classes of canopy height (in m) as calculated from the LiDAR-derived DSM.

Selection of the most likely flood event scenarios

The necessity of building formative scenarios for ex-ante flood event analysis is becoming widely accepted (Mazzorana et al, 2009b, 2012). In particular, the interaction of flow with sediment and LW, as well as the response of control structures during the event, are the factors which are difficult to treat and predict analytically, and thus a probabilistic approach is more suitable for their inclusion into flood management. The 300 yr event – for which the structures are to be designed following the requirements of the Autonomous Province of Bolzano – in the Rienz river at Bruneck is most likely generated by relatively large and long-lasting (>24 hr) cyclonic storms due to the large size of the basin. Indeed, the largest event historically recorded in the Rienz occurred during the second half of September 1882 and lasted for several days. This implies that high-magnitude debris flows and floods along the steeper, smaller tributaries are quite unlikely to take place simultaneously to a large flood in the main channel, as the former are usually triggered by short-duration summer thunderstorms. Therefore, LW input from these tributaries *during the design event for the Rienz* should be considered rather low (i.e. much smaller than their potential). Only the larger tributaries (Antholzer, Wielen, Furkel, Brunst, see Figure 8) could possibly exhibit very large discharges with the associated sediment and LW fluxes, estimated from high instability scenarios, during such long cyclonic event. Within the scenario selection, it was finally explicitly assumed that all key structures in the basin, including dams and retention check-dams, would be stable and functioning.

Evaluation of LW connectivity between tributaries and the main channel

LW volumes potentially recruited in the tributaries is not always going to be delivered to the main channel. Indeed, dams, wood-trapping structures and low bridges may effectively disconnect tributaries and thus reduce the total LW volume reaching the main channel. This is the case of the Rienz, where one large dam at Welsberg disconnects the upper basin (432 km^2) both in terms of sediments and LW (Figure 8), thus simplifying substantially the system. Furthermore, most of the nine tributaries entering the Rienz river downstream of the dam (Figure 8) present grid check-dams for wood retention and/or several bridges (Figure 9) which most likely would cause jamming during high-magnitude events, as it turned out based on simple 1D, uniform flow hydraulic calculations.

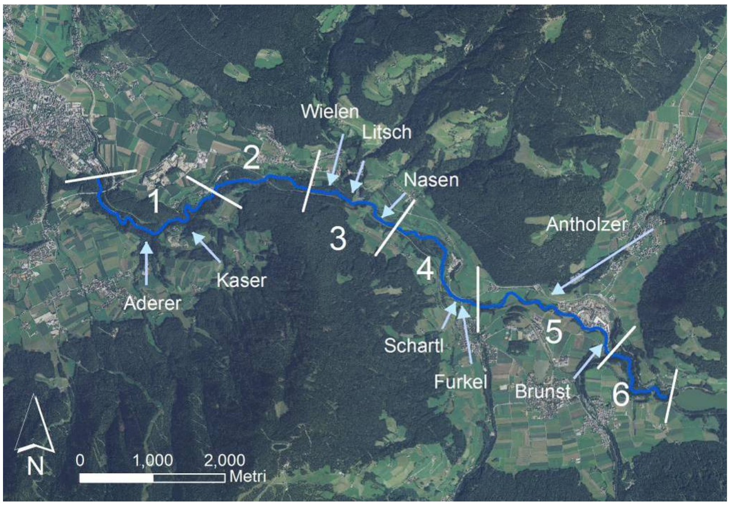

Fig. 8 Subdivision of the Rienz river between Bruneck (on the left) and the Welsberg dam (right) into six reaches for LW input evaluation. Tributaries are marked by arrows.

LW input volume from the larger tributaries (Antholzer, Wielen, Furkel and Brunst) was then reduced to take into account the effect exerted by these wood-trapping structures. The estimation was based exclusively on expert judgement. For the remaining smaller and steeper channels, the relatively small LW input (assessed based on the flood scenarios considerations mentioned above) was further reduced either because of the presence of control works or for the narrow channel section strongly limiting LW transfer in non-debris flow channels.

Fig. 9 Wood retention check-dams and several bridges are present in most of the Rienz tributaries.

Final assessment of LW transport volume at the reach scale

A simplified wood budget approach was applied – at the temporal scale of the design flood event – for the estimation of LW volumes, wherein it was assumed that LW potentially floating down to Bruneck equals the input to the main channel, i.e. LW storage in the channel during the 300 yr event is negligible due to the high-energy characteristics of the Rienz river.

LW input to any given reach of the Rienz may originate from i) by fluvial erosion processes in the main river corridor; ii) by mass wasting processes on the hillslopes adjacent to the main channel; iii) by fluvial transport in the tributaries (debris flow-transported LW was excluded in the scenario analysis, see above). The relative magnitude of these three components is depicted in Figure 10. Total LW input at the reach scale ranges from about 270 m^3 km^{-1} (reach 5) to 1,000 m^3 km^{-1} (reach 2). The total LW volume cumulated at Bruneck (sum of the input from all the reaches) results to be about 6,000 m^3. It can be observed that the dominant source is the river corridor. Accounting for a certain forest growth (15%) over the next decades, the design LW volume at Bruneck attains a value of about 7,000 m^3 (620 m^3 km^{-1}), which represents the design LW volume for designing the trapping system.

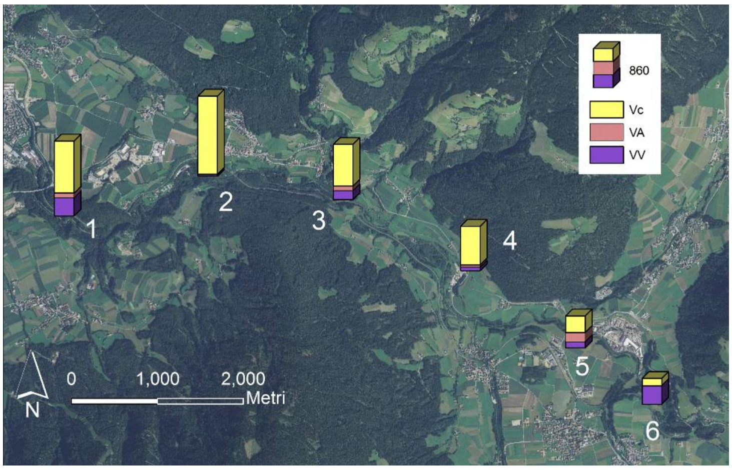

Fig. 10 LW input volumes (in m^3) at the reach scale, divided into river corridor (Vc), tributaries (Va), and hillslopes (Vv).

Hydraulic modelling

After a preliminary 1D hydraulic modeling (by means of HEC-RAS) of the entire river segment from the Welsberg dam to Bruneck, a 2D hydraulic modeling of reaches 1, 2 and 3 (Figure 10) was carried out using the numerical model FLO-2D (O' Brien, 2007). In FLO-2D, the floodplain DTM was aggregated into 5m cells starting from the original 2.5m. Manning's n roughness coefficient of the channel bed was assigned based on grid-by-number grain size distributions by using the equation proposd by Limerinos (1970), whereas for vegetated areas different values of the roughness coefficient were attributed based on vegetation characteristics (height and diameter) following the indication of Cowan (1956) and DVWK (1991). The simulations allowed to derive flow paths, flooded areas, flow depth and velocity, as well as Froude number distributions, all these being essential information for a proper identification of the most suitable sites for the installation of retention structures.

Identification of the best sites for wood retention structures

As pointed out by Rimböck (2004) and Lange and Bezzola (2006), the efficiency of wood-trapping structures is strongly augmented when sediment and wood phases are kept separated in space. This goal can be achieved by the implementation of more structures rather than just a single one, where each of them is designed to fulfill a different task. In the Rienz, in order to trap the large LW volumes potentially recruited in the lower reaches near Bruneck, the wood-trapping system should be placed not much upstream of the city. An ideal site was preliminarily identified at the narrowest section of the river where bedrock emerges on both sides, and where a natural widening of the river corridor is present upstream (Figure 11, right of the image). Here, sediment transport calculations based on 1D and 2D hydraulic models as well as on 2D morphodynamic simulations (using FLO-2D under mobile-bed conditions) indicated that most of the bedload during the Q_{300} tends naturally to deposit in the first half of the widening for the sudden reduction in energy slope and flow depth. A wood retention structure located in the narrow section thus would be ideal to take advantage of and to increase further the bedload deposition upstream, so that LW reaching the structure would be poorly affected by sedimentation in its surrounding. At this section, LW was estimated to be around 5,200 m^3. However, given the large LW input (1,700 m^3) assessed for reach 1 (downstrem of this section), an additional structure was deemed necessary and the most suitable site – featuring lower flow velocities and natural backwater areas prone to retain LW during the event – was identified (Figure 11).

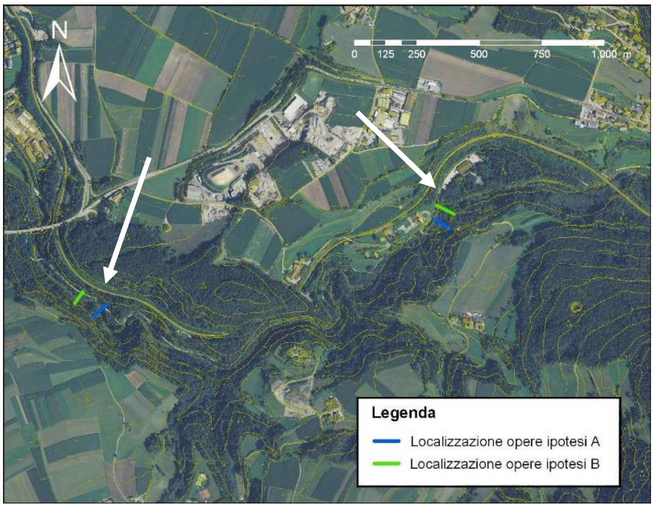

Fig.11 Arrows indicate the sites identified for the placement of the two structures comprising the trapping system, with two options (A and B) differing slightly in terms of structure size and exact location. Flow is from right to left.

Within these general sites for the two structures (arrows in Figure 11), two options regarding their exact location and height were tested by means of numerical simulations whereby the structures were simulated as if their filters (still not designed) were completely clogged and thus functioning as normal check-dams (i.e. the worst-case hydraulic scenario). The final decision on location and height was achieved by comparing the storage capacity upstream of the structures for these two options.

Selection of structure type and design

The designed system comprises two structures (Figure 12) located about 1 km apart: an inclined-grid check-dam (6.5 m high, 30 m wide) upstream, and V-shaped inclined metal racks (4m high) downstream. The latter is to retain the LW recruited in the intervening reach (reach 1) and as a back-up solution in case of LW spilling over the upstream structure. Both structures were designed to minimize the impact on the longitudinal river continuity both in term of sediment and fish mobility. This was achieved by providing a large "opening" sized to convey the entire bankfull discharge (estimated about 70 m^3s^{-1}) in the lower part of the inclined-grid check-dam (Figure 12). Instead, the widely-spaced metal racks (see below) should not interfere with the longitudinal continuity during low to normal flood events.

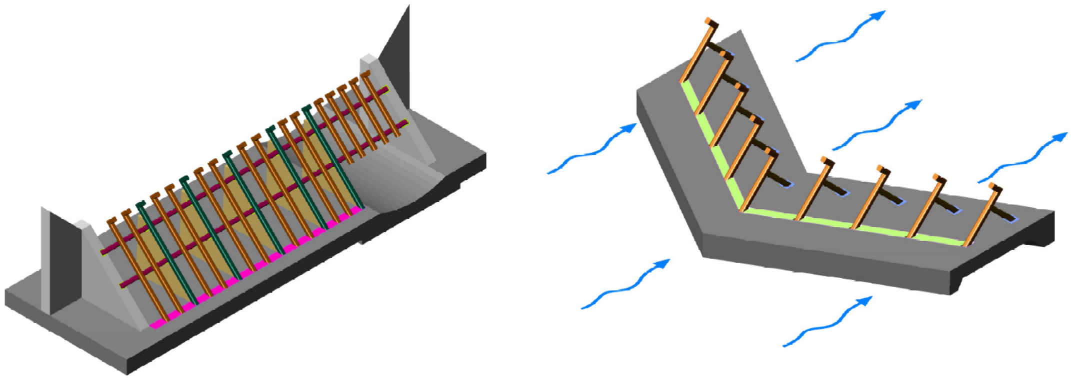

Fig. 12 Three dimensional view of the two wood retention structures: left, the inclined-grid (45°) check-dam to be installed upstream; right, the V-shaped inclined (45°) racks to be constructed downstream.

The hydraulic design of filters is similar for the two structures, and its goal is to leave unaltered most of the bedload transport through the lower part of the filter while trapping LW in the upper part of the retention racks/grid. Only the inclined-grid check-dam (Figure 12, left) is described here; this structure has already been built, while the social acceptance (Figure 5) of the V-shaped check-dam is still under discussion. According to D'Agostino et al. (2000), an inclination of 45° may be appropriate to obtain the sliding up of floating LW during a flood event. The net opening (s) between two adjacent steel beams was preliminary set to $s>3\ D_{90}$ (in this case s>0.84 m) in order to prevent filter clogging by bedload transport (D'Agostino, 2006). The efficiency (T) of trapping LW (i.e. the ratio between the number of retained LW elements and the number of those arrived to the filter) was then selected to be around 65% considering an expected modal log length (L_{log}) of about 2.5 m. With this assumptions the following formula (D'Agostino et al., 2000) was applied:

$$T = 0.0015\ K^2 - 0.092\ K + 1.23 \tag{1}$$

where K is a dimensionless variable defined as $K=s/(L_{log}\ Fr^2)$, with Fr being the Froude number of the subcritical flow behind the filter. K expresses the ratio between the opening width – directly proportional to filter "permeability" – and the variables directly proportional to its "impermeability", i.e. log length and flow kinetics. Equation 1 is valid under conditions of uncongested LW transport (1 element per second) and for cylindrical LW without branches (D'Agostino et al., 2000). For this reason the value T=0.65 can be considered a minimum assumption of the actual trapping efficiency. The application of Equation 1 (with Fr=0.24 at Q=300 m^3s^{-1} from the 2D modeling) led to an opening width s of about 1 m. A smaller value (s=0.9 m) was suggested for the part of the grid facing the main flow where larger rates of LW are expected, whereas opening width up to 1.2 m could be placed near the banks, where retention is enhanced by reduced flow velocity and secondary currents. Furthermore, the variation of the trapping efficiency T for LW elements of different length (L_{log}) was assessed using Equation 1 (Figure 13).

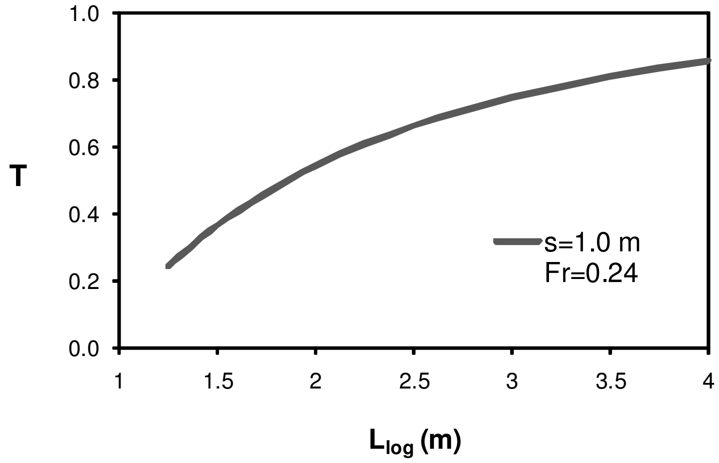

Fig. 13 Variation of trapping efficiency T (dimensionless) as a function of log length for a filter opening of 1 m under the kinetic conditions (Fr=0.24) estimated upstream of the inclined-grid check-dam.

CONCLUSIONS

A sustainable management of in-channel wood transport is of the greatest relevance for mountain basins of the European Alps and elsewhere. The installation of efficient wood retention structures is crucial to assure protection against excessive wood transport during flood events in vulnerable sites. At the same time, they permit to leave sufficient wood storage in the channels and mature vegetation in the riparian areas, which are fundamental factors to be maintained for the hydromorphological quality of river systems, as provided for also by the EU Water Framework Directive. Nonetheless, a correct planning and design of trapping structures is not straightforward and subject to large uncertainties, so that marked improvements may be achieved in the near future through the adoption of rationale design procedures such as the one described in this paper and by monitoring trapping efficiency of existing structures.

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