

Methods to Assess Large Wood Dynamics and the Associated Flood Hazard in Polish Carpathian Watercourses of Different Size

Paweł Mikuś, Bartłomiej Wyźga, Virginia Ruiz-Villanueva,
Joanna Zawiejska, Ryszard J. Kaczka and Markus Stoffel

Abstract Applicability, advantages and limitations of a range of methods applied to determine large wood dynamics in Kamienica Stream and the Czarny Dunajec River, Polish Carpathians, are discussed. Results of a 6-year-long monitoring suggest an increased rate of wood recruitment to Kamienica Stream caused by recent bark beetle infestation of the spruce forests in the valley. However, both monitoring of wood transport and wood inventories indicate that the mobility of large wood in the stream is low and can increase only during major floods. Thus flood hazard to downstream valley reaches potentially resulting from the consid-

P. Mikuś (✉) · B. Wyźga
Institute of Nature Conservation, Polish Academy of Sciences,
al. Mickiewicza 33, 31-120 Kraków, Poland
e-mail: mikus@iop.krakow.pl

B. Wyźga
e-mail: wyzga@iop.krakow.pl

P. Mikuś · B. Wyźga · R.J. Kaczka
Faculty of Earth Sciences, University of Silesia, ul. Będzińska 60, 41-200 Sosnowiec, Poland
e-mail: kaczka@wnoz.us.edu.pl

V. Ruiz-Villanueva · M. Stoffel
Dendrolab.ch, Institute of Geological Sciences, University of Bern,
Baltzerstrasse 1+3, 3012 Bern, Switzerland
e-mail: virginia.ruiz@dendrolab.ch

M. Stoffel
e-mail: markus.stoffel@dendrolab.ch

V. Ruiz-Villanueva · M. Stoffel
Climatic Change and Climate Impacts, Institute for Environmental Sciences,
University of Geneva, Boulevard Carl Vogt 66, 1205 Geneva, Switzerland

M. Stoffel
Department of Earth Sciences, rue des Maraîchers 13, 1205 Geneva, Switzerland

J. Zawiejska
Institute of Geography, Pedagogical University of Cracow, ul. Podchorążych 2,
30-084 Kraków, Poland
e-mail: zawiejska.joanna@gmail.com

erable amounts of large wood stored in the upper stream reach is limited. In the Czarny Dunajec, wood inventories, a tracking experiment with logs tagged with radio transmitters, and numerical modelling indicated high potential for wood transport in the narrow river reaches formed by channelization or channel incision, and high potential for wood deposition in the wide, multi-thread channel. Vegetative regeneration of living willow wood considerably reduces its remobilization by subsequent floods. Efficient transport of large wood along narrow river reaches implicates that during floods substantial amounts of wood may be delivered from distant sources to the channel sections located downstream of the narrow reaches. Wide, multi-thread reaches operate as natural wood traps, considerably limiting further transfer of wood to vulnerable sites/reaches.

Keywords Large wood dynamics · Flood hazard · Wood inventory · Wood monitoring · Numerical modelling · Wood tracking

1 Introduction

Over the last decades, large wood (i.e. trees and shrubs fallen to river channels) has received increasing interest from scientists who recognize its significance as a functional component of fluvial ecosystems (Gurnell 2013; Wohl 2013; Le Lay et al. 2013). When large wood is being analysed, it is possible to conceptualize its recruitment/mobilization, transport and storage in rivers, which together constitute the river's wood budget (Benda and Sias 2003).

Individual pieces of wood and their aggregates (jams) create obstructions that can substantially increase the frictional resistance to flow (Shields and Gippel 1995; Curran and Wohl 2003). These obstructions modify flow velocity (Gippel 1995; Davidson and Eaton 2013) and increase local storage of sediment and organic matter around the wood (Faustini and Jones 2003). However, when large quantities of wood are mobilized (usually during floods), the resultant flow obstructions, particularly at critical sections such as bridges, can increase the magnitude, frequency, and duration of overbank flows (Ruiz-Villanueva et al. 2013, 2014c; Lucía et al. 2015). Therefore, our understanding of large wood dynamics and estimation of the related potential hazards requires in situ observations and measurements, which still remain very limited (MacVicar et al. 2009). Only a few field studies analysed wood dynamics using different approaches such as surveys from either field data or aerial imagery (Latterell and Naiman 2007; Wohl and Goode 2008), video cameras or time-lapse photography (Moulin and Piégay 2004; Bertoldi et al. 2014; Kramer and Wohl 2014) or tracer methods (Lassetre and Kondolf 2012; Schenk et al. 2014; Ravazzolo et al. 2015). Most of these studies were carried out in small streams, whereas much less is known about wood transport in large rivers where large wood dynamics and associated effects on fluvial processes might be very different (MacVicar and Piégay 2012). Modelling (physical and numerical) is a powerful tool to analyse large wood dynamics; however, few flume experiments

have been performed so far with the aim to characterise wood transport and deposition (Braudrick and Grant 2001; Welber et al. 2013; Bertoldi et al. 2014). As to numerical models, a few attempts have recently been made to analyse large wood phenomena in rivers (Ruiz-Villanueva et al. 2014a).

The type and accuracy of the information about large wood strongly depend on the approach and its spatial and temporal resolution (Gurnell 2013). In the case of large wood-related hazards, it is particularly important to gather accurate information as effective management of large wood requires an in-depth understanding of the stability of individual wood pieces and jams within channels and on floodplains, and physical and ecological effects created by wood (Wohl et al. 2016). Therefore, the recognition of potential impacts of large wood on flood hazard and its relevance for flood risk in mountain watercourses is still very challenging (Mazzorana and Fuchs 2010; Comiti et al. 2012; Kundzewicz et al. 2014; Ruiz-Villanueva et al. 2014b). Successful achievement of this goal may require a combination and adjustment of different techniques to river morphology and hydrological conditions as well as the duration of the study and the accuracy of the desired results.

The aim of this chapter is (i) to discuss different approaches to gathering data about large wood dynamics based on the study in two watercourses of different size in the Polish Carpathians, (ii) to indicate the advantages and limitations of particular techniques, (iii) to assess large wood dynamics in the two types of watercourses, and (iv) to infer about the large wood-related flood hazard in the watercourses under consideration and other watercourses of similar size in the region.

We summarize below investigations conducted in the second- to fourth-order reaches of Kamienica Stream within the Gorce Mountains National Park and in the middle course of the fifth-order Czarny Dunajec River. Recent bark beetle infestation and the resultant dieback of riparian forest along the headwater reach of Kamienica Stream could have considerably increased the delivery of fallen trees to the channel, and as the wood is not removed from the stream under the national park regulations, a question arises as to whether it can threaten downstream, developed parts of the valley. Pronounced development of riparian forest along the Czarny Dunajec occurred in the 20th century (Wyźga et al. 2012); as a result, substantial quantities of large wood are currently recruited to the river during floods (Wyźga and Zawiejska 2005, 2010). At the same time, considerable variability in channel morphology in the middle course of the Czarny Dunajec should be reflected in marked differences in large wood dynamics and the associated flood hazard between particular river reaches.

2 Field Setting

Kamienica Stream drains mountains of medium height (with the highest peak in the catchment at 1311 m a.s.l.) in the Outer Western Carpathians (Fig. 1). In its upper course, the stream flows through a narrow, mostly V-shaped valley with 90 % of

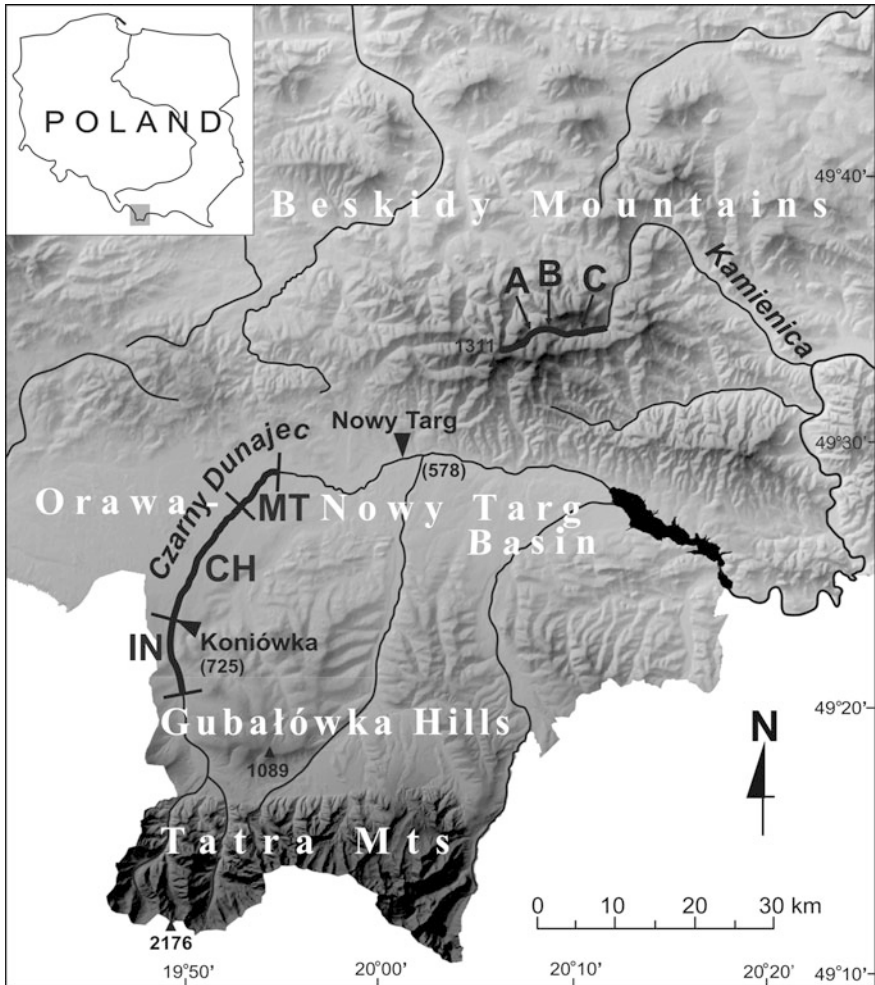


Fig. 1 Location of the studies of large wood dynamics in the watercourses of the northern foreland of the Tatra Mountains. Studied reaches of the Czarny Dunajec River and Kamienica Stream are indicated by *thick lines*. Reaches of the Czarny Dunajec: *IN* incised; *CH* channeled; *MT* multi-thread. *A*, *B* and *C* indicate reaches of Kamienica Stream with tagged riparian trees

the area covered by forest. Since the establishment of the Gorce Mountains National Park in 1980, this part of the stream has been almost free of human impact on the channel and the riparian zone. Over the last few years bark beetle infestation resulted in widespread dieback of spruce forest in the valley, that might have increased wood delivery to the channel and its transport to downstream, developed valley reaches. The study was conducted in second- to fourth-order stream reaches located between 0.3 and 9.1 km from the stream source. Along these reaches, the catchment area increases from 0.1 to 14.9 km² and channel slope decreases from

0.1 to 0.035 m m⁻¹. The second-order stream reach has an average channel width of 5.9 m and exhibits a step–pool channel pattern, with numerous steps developed on wood dams (Kaczka 2003). In the third- and fourth-order reaches, the channel is 10.3 m wide on average, with step–pool pattern in narrower parts of the stream and riffle–and–pool pattern in its wider parts. Along the most part of the study reaches, the banks of Kamienica Stream are overgrown with the upper subalpine forest composed of spruce (*Picea abies*), whereas the subalpine forest in the lowermost part of the study area is composed of spruce, beech (*Fagus sylvatica*) and fir (*Abies alba*).

The Czarny Dunajec River rises in the high-mountain Tatra massif, with the highest elevation in the catchment at 2176 m a.s.l. In the Tatra Mountains foreland, it flows through the Gubałówka Hills and the Orawa-Nowy Targ Basin to the confluence with the Biały Dunajec River at an altitude of 578 m (Fig. 1). Investigations of large wood dynamics were carried out in the middle river course, where the fifth-order Czarny Dunajec flows on a large glaciofluvial-alluvial fan and receives no significant tributaries. During the past few decades, some parts of the middle river course were considerably modified by channelization or gravel-mining-induced channel incision, whereas the other parts avoided significant human disturbances and remained unmanaged (Zawiejska and Wyżga 2010; Wyżga et al. 2012). As a result, currently the river's morphology varies considerably (Wyżga and Zawiejska 2005, 2010) with relatively narrow, single-thread, incised or channelized reaches and a wide, multi-thread reach (Fig. 1). Despite considerable variation in river widths, the middle course of the Czarny Dunajec—with its average width of 52 m and the maximum height of riparian trees amounting to 18 m—can be considered a large channel with respect to in-stream wood (Gurnell et al. 2002; Wyżga et al. 2015). The river flows through a forested corridor, with the riparian forest consisting of alder (*Alnus incana*) and a few willow species (*Salix eleagnos*, *S. purpurea*, *S. fragilis* and *S. alba*).

3 Investigations of Large Wood Dynamics in Kamienica Stream

3.1 Monitoring of the Recruitment and Transport of Large Wood in a Mountain Stream

The relatively small size of Kamienica Stream and the abundance of wood dams in its channel allowed us to expect relatively short distances of large wood transport; moreover, the relatively small channel size facilitated searching for displaced wood pieces. This is why we used metal plates as tags in the monitoring of wood dynamics in the stream. In October 2009, 429 trees growing along three reaches of the upper course of Kamienica Stream (Fig. 1) were tagged with numbered metal plates and their position was recorded with a Trimble GeoXT GPS receiver with

0.5 m precision. Different metals were used in particular study reaches: aluminium in reach A located at the distance of 2500–2950 m from the stream source, copper in reach B (4000–4450 m from the stream source), and steel in reach C (7850–8300 m from the stream source). The different metals were chosen so as to allow later use of a metal detector to distinguish between trees delivered to the stream in different reaches or to find a tagged tree in case the plate is impossible to reach (e.g. buried). In each reach, we tagged all trees with a diameter >10 cm and closest to the channel either on the floodplain or on the valley side; in fact, their distance from the channel margin ranged from 0.5 to 12 m. The positions of standing and fallen trees were monitored a few times per year, especially after flood or strong windstorm events in the region, to determine the causes and timing of the delivery of trees to the stream and their transport distance during particular flood events.

No significant floods occurred on Kamiénica Stream during the six years of monitoring. Over that time, 32 trees (7.5 % of the tagged sample) were recruited to the stream, with 17 (53 %) delivered as a result of windthrow of living specimens, 8 (25 %) first died as a result of bark beetle infestation and were next thrown by wind, 5 (16 %) were undercut by bank erosion, and 2 (6 %) fell because of snow overload (Fig. 2). Two high-intensity weather events occurred over the monitoring period. At the very beginning of that period, an intense snowfall occurred, (ca. 80 cm of snow over 2 days), resulting in the recruitment of 2 trees from snow overload. In summer 2010 a strong windstorm occurred and the associated rainfall resulted in a moderate flood; during this event 8 trees growing on steep, undercut stream banks were toppled in the lowermost reach A. Although bark beetle infestation has not been a direct cause of the recruitment of spruce trees, trees weakened or killed by the infestation were very susceptible to breakage by wind, and this type of wood recruitment was characteristic of spruce growing along the stream. If such trees fell perpendicular to the channel, they were often broken into several smaller fragments. Such relatively small logs could have been transported even by small floods over distances of a few tens of metres before they were braced against other, more stable wood pieces. By contrast, living trees were frequently anchored on both stream banks after they fell, resulting in the formation of complete dams (Fig. 3). Living coniferous or deciduous trees were recruited to the stream as a result of windthrow, bank erosion or snow overload.

Fig. 2 Percentage of tagged trees recruited to Kamiénica Stream between 2009 and 2015 as a result of particular factors: 1 windthrow of living trees; 2 tree dieback followed by windthrow; 3 bank erosion; 4 overloading with snow

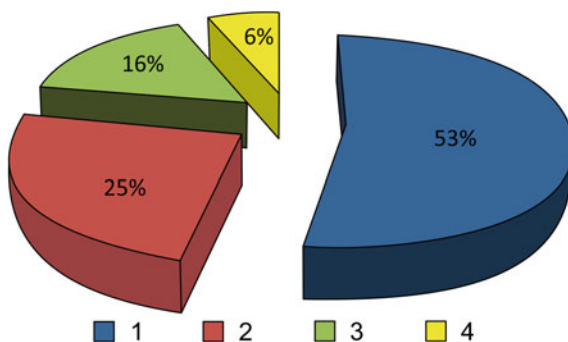




Fig. 3 Spruce tree fallen to the channel of Kamiénica Stream in a monitored reach. The tree was tagged with a numbered aluminium plate (shown by a *white arrow*) when growing close to the channel bank to allow its identification after displacement in the stream. The fallen tree forms a complete dam

Based on the number on the metal plate fixed to a tree, it is possible to determine the length of tree displacement from its initial position on a channel bank or its earlier position within the stream (Fig. 3). As the study period lacked major flood events, the majority of fallen trees were not transported and some were moved short distances, which did not exceed 100 m.

3.2 Wood Inventory in Kamiénica Stream

Further information about wood dynamics in Kamiénica Stream was obtained from the inventory of large wood performed in September–October 2012. It encompassed the whole lengths of second- and third-order stream reaches and the upper part of the fourth-order reach; in total, seventy 100-m channel segments were surveyed (Fig. 1). In each segment, channel slope was measured with a level and average channel width was determined from measurements at the beginning, middle, and end of the segment. Wood deposits were classified as logs or log jams, i.e. the aggregates of at least three logs. We measured the volume of logs, either isolated or aggregated into jams, which was next converted to wood mass by multiplying by the wood mass estimate of 500 kg m^{-3} to allow comparability of results with those from the Czarny Dunajec River. The orientation of individual

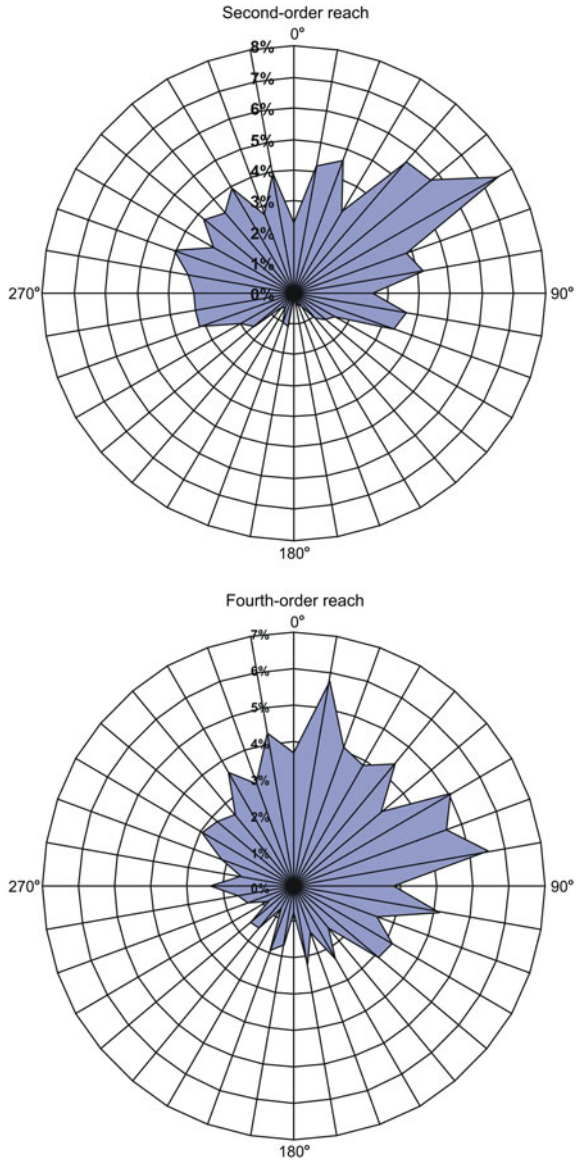
logs and log jams in relation to the channel axis was also measured. Finally, a degree of wood decay was classified into one of four categories (1—fresh, bark adheres tightly; 2—loose bark; 3—no bark, wood hard; 4—no bark, wood soft) according to the approach of Lienkaemper and Swanson (1987).

In the surveyed part of the stream, channel width varied between 4 and 20.9 m. With the average height of mature trees on the channel banks amounting to 24 m, this part of the stream represents a watercourse of small- to medium-width (Wyźga et al. 2015). The total number of 2275 wood deposits was recorded, with particular stream segments retaining from 10 to 58 deposits, 32.5 on average. Of this total, 87 % was represented by individual logs and 12.3 % by log jams (28.5 logs and 4 log jams in a segment, on average). Mean mass of wood deposits was calculated as 167 kg and varied among the stream segments between 47 and 369 kg. Particular stream segments stored from 0.47 to 14.2 t of wood, with the average of 5.4 t (Wyźga et al. 2015). Notably, both the number and the mass of wood deposits in a segment were unrelated to channel width, and this was reflected in a lack of dependence of total wood storage (i.e. the total mass of wood in a channel segment) on channel width. Only the number of jams in a segment increased by 1 with each 3-m increase in channel width; however, with the small proportion of jams in the total number of wood deposits, this relationship was not reflected in an increase in the number of wood deposits with increasing channel width. The average value of specific wood storage (i.e. the amount of wood per unit channel area) for the surveyed segments of Kamienica amounted to 69.7 t ha^{-1} . However, the generally invariable total amounts of wood in stream segments were reflected in a nonlinear decrease of specific wood storage with increasing channel width. According to the estimated reciprocal regression model, the values of specific wood storage decreased from ca. 140 t ha^{-1} in the narrowest channel segments to ca. 25 t ha^{-1} in the widest segments (Wyźga et al. 2015).

Comparison of the patterns of large wood orientation recorded in the second- and fourth-order reaches of Kamienica indicates a change in the predominant wood orientation with increasing stream size (Fig. 4). In the second-order reach, a near-perpendicular orientation predominated, with a mode at 60° . A single mode indicating a predominant alignment of fallen trees towards the right stream bank and some deviation from the fully perpendicular orientation of wood pieces may be attributed to the predominant wind direction from NW rather than to the reorientation of wood pieces by stream current in the headwater reach. The fourth-order reach was typified by a bimodal orientation of wood pieces, with the longitudinal alignment slightly predominating over the orientation towards the right bank. Here, a proportion of wood pieces were apparently reoriented by stream current, whereas perpendicular alignment typified some other pieces, especially those longer than the channel width that formed complete and active dams. The patterns of large wood orientation in the stream were typified by a greater proportion of perpendicular to near-perpendicular alignment of wood pieces than those recorded shortly after the large flood of 1997 (Kaczka 1999).

In the second-order reach of Kamienica, 16 % of wood pieces were relatively fresh, representing class 1 and class 2 of wood decay, whereas as much as 84 % of

Fig. 4 Orientation of wood pieces in relation to the channel axis in the second-order reach (*upper diagram*) and the fourth-order reach (*lower diagram*) of Kamienica Stream



pieces exhibited an advanced state of decay linked with classes 3 and 4. In the fourth-order reach, classes 1 and 2 constituted 31 % of all wood pieces, while 69 % were classified as representing class 3 and class 4. These results differed considerably from those recorded after the large flood in 1997 (Kaczka 1999). In the second-order reach, 56 % of wood pieces were then associated with classes 1 and 2, whereas 44 % were in an advanced state of decay (classes 3 and 4). In the

fourth-order reach, 65 % of pieces were classified as representing class 1 and class 2, while only 35 % exhibited an advanced state of decay (classes 3 and 4).

4 Investigations of Large Wood Dynamics in the Czarny Dunajec River

4.1 Wood Inventories in a Wide Mountain River

Wood inventories in the Czarny Dunajec were carried out in 2001 and 2011, and were completed by less systematic observations performed after the 20-year flood of May 2014. During the inventories wood deposits were classified into three categories: logs, wood jams, or whole shrubs and trees. Wood jams occurring in the river consisted not only of logs but they were heterogeneous mixtures of logs, branches, root boles, and twigs, sometimes with a considerable addition of fine organic matter and inorganic sediment (see Fig. 6a below). As the volume of wood contained in wood jams and shrubs and trees cannot be easily measured, we used the method developed by Thévenet et al. (1998) that involves measuring the volume of wood deposits and multiplying it by wood mass estimates for particular types of wood deposits (50, 100 and 500 kg m⁻³ for shrubs and trees, jams, and logs, respectively). Wood deposits were recorded in 100-m river segments, for which river width was determined based on the measurements performed at each end of every segment.

Below we indicate results of the inventory performed after the 7-year flood of July 2001 (Wyźga and Zawiejska 2005, 2010; Wyźga et al. 2015). Wood deposits were recorded in 89 river segments distributed along 17.2-km long section of the Czarny Dunajec with three geomorphological styles: incised, channelized and multi-thread (Fig. 1). In the section, river width varied between 18.5 and 148.5 m. The variation in river width and geomorphological river style was reflected in substantial variation in the number and the mean mass of wood deposits. Particular river segments stored between 0 and 154 wood deposits, with an average of 19.7 deposits in a segment. Logs constituted 21.3 %, shrubs and trees 37.6 %, and jams 41.1 % of the deposits. Mean mass of wood deposits stored in particular segments equalled 233 kg; it ranged from 0 (in a few segments that lacked large wood) to 733 kg. However, the mean mass differed considerably among particular types of deposits and amounted to 23 kg for logs, 182 kg for shrubs and trees, and 389 kg for wood jams. Both the number and the mean mass of wood deposits in a river segment increased linearly with increasing river width and the relationships were highly significant statistically.

Total wood storage in a 100-m segment of the Czarny Dunajec varied between 0 and 40.7 t, with an average of 4.6 t. The values of total wood storage were directly related to river width; on average, they increased by 1 t with each 5-m increase in river width. Despite similar values of total wood storage in the Czarny Dunajec

River and Kamienica Stream, the substantially greater width of the river was reflected in markedly lower values of specific wood storage— 7.9 t ha^{-1} on average. Specific wood storage varied between 0 (in the segments lacking wood deposits) to 33 t ha^{-1} and was directly related to river width; on average, it increased by 1 t ha^{-1} with each 6-m increase in river width. The values of total and specific wood storage differed markedly between relatively narrow, single-thread river segments with a heavily regulated or incised channel and wider segments with a partly constrained or unmanaged, multi-thread channel. Average values of total wood storage amounted to 0.53 t in the former and 10 t in the latter, whereas the respective values of specific wood storage equalled 1.6 and 10.6 t ha^{-1} . Moreover, the two types of river segments differed considerably in the pattern of large wood distribution (Wyźga and Zawiejska 2010). Narrow, single-thread river segments were typified by random wood distribution, reflected in a lack of dependence of total and specific wood storage on channel width. By contrast, in wider river segments the values of total and specific wood storage were directly related to river width. These different patterns of wood distribution in the two types of river segments are illustrated with the results of the wood inventory carried out in 2011 (Fig. 5). Even though the absolute amounts of wood recorded in 2011 were smaller than in 2001, perhaps reflecting the lower magnitude of the preceding flood, the spatial patterns of wood distribution in the river were the same as those found 10 years before.

One of the key findings of the inventory from 2001 was a marked difference in the state of wood preservation and the predominant types of wood deposits between different parts of the wide, unmanaged river reach (Wyźga and Zawiejska 2005). Close to the end of the narrow, channelized reach, most wood was highly disintegrated and abraded and structured into jams. At a larger distance from the end of the channelized reach, many shrubs and trees were well preserved, with unbroken crowns and intact leaves and bark, and shrubs and trees constituted a considerable proportion of the total mass of wood. The same differences in the appearance of large wood were also observed after the 20-year flood of May 2014 (Fig. 6).

4.2 Observations of the Vegetative Regeneration of Living Wood

Capability of some tree species to re-sprout after deposition in a river considerably reduces their potential for remobilization during subsequent flood events. Below an altitude of ca. 800–900 m, riparian forests of Polish Carpathian rivers, including the Czarny Dunajec, are composed of alder and Salicaceae (willows, in lower altitudes also poplars). Alder exhibits relatively little capability to re-sprout, but willows can vigorously regenerate vegetatively after being deposited on relatively moist surfaces (Fig. 7) (Moggridge and Gurnell 2009). A study carried out in a multi-thread reach in the middle course of the Czarny Dunajec indicated that a considerable proportion of willow shrubs and trees deposited on gravel bars sprout and root to

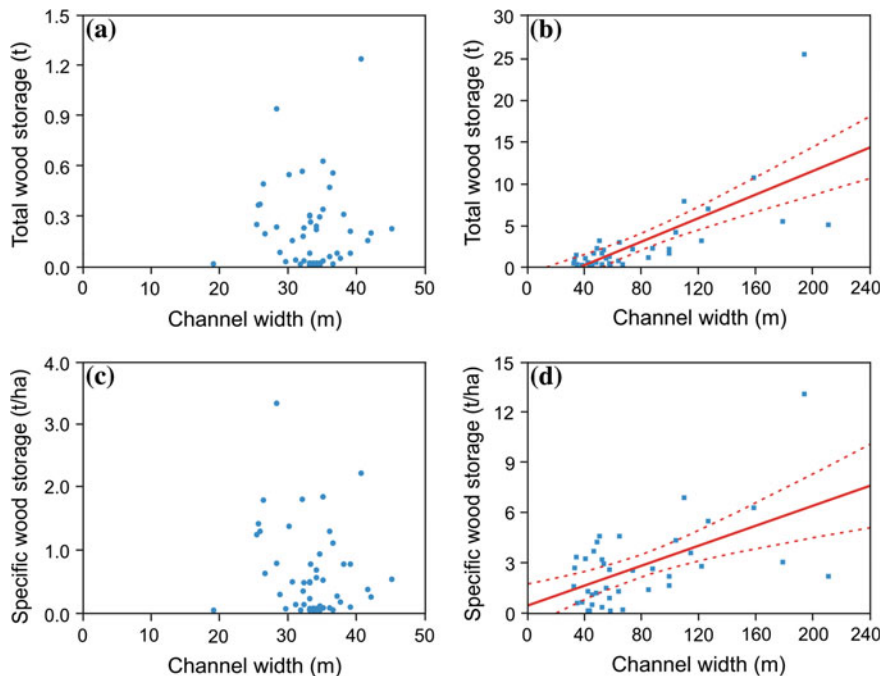


Fig. 5 Scatter plots and estimated regression relationships between total or specific wood storage and river width in heavily channelized and incised segments of the Czarny Dunajec (**a**, **c**) as well as partly reinforced and unmanaged river segments (**b**, **d**). The diagrams present results of the wood inventory performed in the Czarny Dunajec in 2011. *No regression lines* are indicated for the relationships which are not significant

the bar surface, developing into pioneer islands (Mikuś et al. 2013). The elevation of these pioneer islands ranged from 0.2 to 1 m above the water surface in the nearest low-flow channel, indicating that pioneer islands in the multi-thread reach can develop in a wide range of relative elevation. This can be partly attributed to the high ability of deposited willow shrubs and dense shoots sprouting from them to effectively trap fine sediment (Mikuś et al. 2013; cf. Gurnell and Petts 2006) that subsequently provides moisture for the developing willow shrubs. Moreover, some proportion of wood pieces contained in jams deposited at the head of older, building and established islands sprout leading to the upstream growth of the islands (Wyźga and Zawiejska 2010; Mikuś et al. 2013; cf. also Kaczka et al. 2008). The development of shrubs from the living willow driftwood effectively binds all wood pieces contained in the jams formed at island heads, preventing their remobilization during subsequent floods.

Notably, pioneer islands do not form in narrow, single-thread reaches of the Czarny Dunajec with a regulated or incised channel. Wider parts of the incised reach and narrower parts of the multi-thread reach with bar-braided morphology

(a)**(b)**

Fig. 6 Large wood deposited in the upstream **(a)** and middle **(b)** parts of the wide, multi-thread reach of the Czarny Dunajec, ca. 700 and 1600 m below the narrow, channelized river reach, during a 20-year flood in May 2014. Wood deposited close to the channelized reach is highly disintegrated and aggregated into jams **(a)**, whereas farther downstream many shrubs and trees are well preserved, with unbroken crowns **(b)**



Fig. 7 4-year pioneer island formed by dense shoots sprouted from a living willow shrub deposited on a gravel bar of the Czarny Dunajec by the flood of 2001. The shrub from which the pioneer island developed is still visible during the cold part of a year but disappears from the riverscape during vegetation season

support only scarce, pioneer and building islands (Mikuś et al. 2013) which are thus only transient traps for the large wood delivered from upstream.

4.3 Tracking Experiment with Radio Transmitter-Tagged Logs

Relatively large distances of wood displacement in wide rivers (Van der Nat et al. 2003; Schenk et al. 2014; Ravazzolo et al. 2015) and large channel area of such rivers underlay a decision to use radio telemetry in a tracking experiment intended to study large wood dynamics in the Czarny Dunajec. The single-frequency, microprocessor-controlled pulsed radio transmitters LPI 2800, produced by Wildlife Materials (USA), were purchased for the experiment. They are water resistant and emit signal in the band of 150–151 MHz (with the frequency of particular devices differing by 0.01 MHz) via 25 cm-long external antenna. We also prepared 30 alder logs of 3 m length and a diameter between 16 and 24 cm. When a weather forecast in mid-May 2014 indicated a possible flood on mountain rivers in the region, the transmitters were activated, mounted and sealed (with spray polyurethane foam) in the previously prepared holes in the logs (Fig. 8a). During the rising limb of the flood, the tagged logs (10 at each place) were put into the river at



Fig. 8 **a** Installation of a radio transmitter in an alder log prepared for the tracking experiment. **b** Searching for the tagged logs after the flood of May 2014 using a TRX 1000WR signal receiver and a Yagi antenna

three locations: (i) at the beginning of the incised river reach, (ii) close to the beginning of the channelized reach, and (iii) 1 km upstream from the beginning of the wide, multi-thread reach. After the flood we systematically searched for the logs on about 50 km of the river length (to the Czorsztyn Reservoir on the Dunajec River—Fig. 1) using a TRX-1000WR signal receiver and a handheld Yagi antenna (Fig. 8b). In total, twenty-four logs were found, eight from each set, such that recovery rate was 80 %. The log found farthest downstream was deposited 7.7 km from the place of its delivery and 19.6 km from the uppermost delivery site. With unknown fate of the lacking logs, only the recovered logs were taken into account in the analysis.

Considerable differences in the length of displacement were found between the logs put into the river at the three locations (Wyźga et al. in press). Logs delivered at the beginning of the incised reach were displaced between 3.7 and 14.6 km, 11.4 km on average. Logs delivered close to the beginning of the channelized reach were displaced by 0.03–9.0 km, with the mean displacement by 6.4 km. Finally, logs delivered 1 km upstream from the beginning of the multi-thread reach travelled from 1.2 to 7.6 km, with an average of 2.6 km. Only one out of the 8 recovered logs delivered to the river at the beginning of the 4.6-km long incised reach was retained in this reach. Out of the 15 logs that entered the 4.6-km long channelized reach, 5 were deposited in it. Finally, 18 logs entered the 4-km long multi-thread reach and 17 were deposited there, mostly in the uppermost part of the reach.

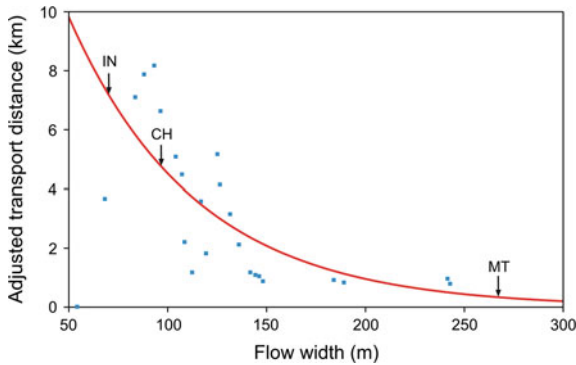


Fig. 9 Relationship between adjusted transport distance of the logs tagged with radio transmitters and average flow width over that distance at peak discharge of the 20-year flood of May 2014. Adjusted transport distance is a product of the distance to a given river cross-section with deposited log and a proportion of logs that were transported on that distance. *Arrows* indicate average flow widths at peak discharge of the flood in the incised (*IN*), channelized (*CH*), and multi-thread (*MT*) reaches of the Czarny Dunajec

The three river reaches differed markedly in the flow width at the flood peak; on average, it amounted to 70 m in the incised reach, 97 m in the channelized reach and 267 m in the multi-thread reach (Fig. 9). Average flow width between a site of log delivery to the river and particular cross-sections where consecutive tagged logs were deposited was found to be a highly significant predictor of the length of transport distance. Figure 9 presents a nonlinear regression model estimated for the so-called adjusted transport distance; this parameter is calculated as a product of the transport distance and a proportion of logs that are transported on that distance. Average flow widths along the whole distance of log travel to particular depositional cross-sections, described by the regression model, can be compared with average flow widths in particular reaches of the Czarny Dunajec (shown by arrows). The comparison indicates that at the flow width of the 20-year flood, typical of the incised reach, logs can be transported long distances along the river, whereas the length of log displacement dramatically diminishes as the flood flow expands to the width typical of the multi-thread reach.

4.4 Numerical Modelling of Large Wood Dynamics in Contrasting River Morphologies

Numerical modelling provides another approach to understanding processes, testing hypotheses and running scenarios, and thus it is a potentially powerful tool for analyzing large wood dynamics. We applied the 2D hydrodynamic model developed by Ruiz-Villanueva et al. (2014a) to two reaches of the Czarny Dunajec with

different morphology to analyze various aspects of large wood dynamics in the wide mountain river. The model is based on the finite volume method with a second-order Roe Scheme coupled to a Lagrangian model for the simulation of individual pieces of wood. The incipient motion of logs, considered as cylinders, is determined by the balance of forces acting on the centre of mass of each log. Once the log is put in motion, two possible transport mechanisms are implemented: sliding on the river bed or floating. In all cases, translation and rotation are considered depending on the velocity field. When the piece of wood is sliding on the river bed, friction is the main control factor of movement, and thus its velocity may be very different from the flow velocity. If the log is floating, its velocity is assumed to be the same as the flow velocity, unless turbulence is considered. Turbulent fluctuations of velocity affect wood motion, introducing a random component into the movement of logs. This model fully couples the hydrodynamics with the large wood transport. The presence of wood adds a new shear stress (produced by the drag force of the logs) term in the Saint Venant equations. In addition, the velocity and movement of logs can also be modified when they interact with the river boundaries or between logs themselves (Ruiz-Villanueva et al. 2014a, b, c).

The numerical model needs initial and boundary conditions for wood. The initial position of each log (x , y coordinates of the mass centre and angle with respect to the flow), its length, diameter and wood density for the initial time step should be provided. Moreover, inlet boundary conditions (i.e. logs entering the river reach) can also be assigned to the simulation domain boundaries, specifying a number of wood pieces per minute and their characteristics. Based on detailed knowledge of the fluvial corridor, riparian vegetation, and wood availability, ranges of the main characteristics of logs need to be established: maximum and minimum lengths, diameters and density of wood. Stochastic variations of these parameters together with position and angle are used to characterize the wood entering the domain.

This model was applied to the Czarny Dunajec with the aim to analyze factors controlling wood transport and retention such as wood size, flow conditions and river morphology (Ruiz-Villanueva et al. 2016a, b). Analysis was based on a multi-run scenario simulation in order to include the complexity and stochastic variability of large wood dynamics in the deterministic model. Large wood dynamics was simulated in two river reaches of similar length: single-thread, channelized reach with a relatively narrow and deep channel and multi-thread, unmanaged reach with a wide and shallow channel. Data from the Koniówka stream gauging station was used to characterize the inlet flow and design several flood scenarios, and the available rating curve was used for roughness (Manning's n) calibration. In total, more than 200 scenarios have been designed under steady and unsteady flow conditions, and using different sizes of logs and different wood inputs.

Results showed that a larger proportion of all logs introduced upstream of the study reach is transported downstream the single-thread, channelized reach than downstream the multi-thread reach, and, accordingly, a larger proportion of all

introduced logs is deposited in the latter. In the single-thread channel, log length was found to predominantly control large wood transport, whereas in the wider, multi-thread channel, log diameter was more important (Ruiz-Villanueva et al. 2016b). This agrees with the findings of other researchers who observed the same pattern in the field and in flume experiments (Welber et al. 2013; Bertoldi et al. 2014). In each reach, the elevation of deposition of simulated logs above the low-flow water surface was found to significantly differ between various flood magnitudes, generally increasing with increasing flood discharges. At each flood magnitude considered, it was also significantly higher in the single-thread channel than in the multi-thread channel (Fig. 10). The preferential sites for large wood to be deposited at different flood magnitudes were identified by means of depositional probability. Results showed that the preferential sites of wood deposition vary with flood magnitude and that the probability of deposition is significantly controlled by the relative elevation of the different geomorphic units in relation to the water level (Ruiz-Villanueva et al. 2016a).

Simulating unsteady flow conditions, Ruiz-Villanueva et al. (2016c) analyzed the influence of a flood hydrograph (in terms of peak discharge, time to peak, and total flood duration) on the transport of wood. Results revealed a lag between the beginning of a flood and large wood remobilization, which is related to the flood responsible for the initial wood deposition. Furthermore, the peak in large wood transport is generally reached before the flood peak, and wood transport decreases close to or slightly after the hydrograph peak. During the falling flood limb, large wood transport is likely negligible, unless an additional supply of wood is provided to the river as wood has already been subject to the same or larger discharges during the rising limb. This results in a hysteresis between discharge and large wood transport, which was also recorded using video monitoring in the Ain River (MacVicar and Piégay 2012).

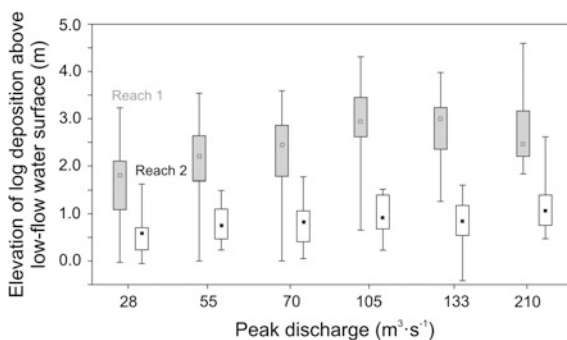


Fig. 10 Elevation of the deposition of simulated logs above the low-flow water surface in single-thread Reach 1 and multi-thread Reach 2 of the Czarny Dunajec River at different peak discharges. Box and whisker plots show median (squares), 25th and 75th percentiles (boxes) and extreme values (whiskers) of the elevation distribution

5 Discussion and Conclusions

5.1 *Suitability of the Used Methods for Examination of Large Wood Dynamics in the Watercourses*

Tagging riparian trees along Kamiénica Stream and their subsequent monitoring appeared to be highly informative about large wood dynamics in the stream. This approach allowed us to approximately date their delivery to the channel, to infer about its cause, and to determine the lengths of displacement of fallen trees during particular flood events. Tagging trees with metal plates was highly cost-effective; the cost of metal plates was, on average, two orders of magnitude lower than that of radio transmitters. This enabled us to tag a relatively large number of riparian trees, with the total length of the monitored stream reaches of 1.35 km. Moreover, the tags are typified by long functionality; during six years of the monitoring, no tag was lost or destroyed. The lack of major floods precluded verification of the tag effectiveness in case of long-distance displacement of fallen trees. In turn, tagging logs with radio transmitters provided useful information about large wood dynamics in the Czarny Dunajec during a major flood event. With relatively long distances of log displacement in the river during a single flood event and the large river area, gaining the information would not be possible without the use of radio telemetry. However, after the tracking experiment we did not find 6 out of 30 devices and 3 others could not be retrieved as the logs were retained underwater. This means 30 % total loss of the devices and indicates relatively high costs of tracking large wood dynamics in wide rivers.

Large wood inventories in the stream and in the river were associated with similar surveying effort; the number of wood deposits recorded in Kamiénica Stream exceeded that in the Czarny Dunajec by 30 %, but with the substantially larger area of the river, both morphometric and wood surveys were more effort- and time-consuming. The inventories in both watercourses revealed different spatial patterns of large wood distribution, with an increase in channel width reflected in decreasing specific wood storage in the stream and increasing in the river. These different patterns of wood distribution were attributed to different mechanisms of large wood retention in watercourses narrower and wider than the height of riparian trees (Wyźga et al. 2015).

Wood inventories provided detailed information about the amounts, location and character of large wood in the river and some relations of these parameters to morphometric river characteristics at discrete time periods. Wood and morphometric surveys were easy to do and inexpensive. However, they recorded a static image of large wood, without information on the time of its recruitment and deposition in the river (for instance, the inventory in 2001 was performed after two flood waves from June and July 2001 with the same peak discharges), whereas the length of wood transport could be only indirectly inferred from the state of wood preservation. As the inventories were time-consuming, their spatial scale was limited, and the obtained results may not be easily extrapolated to other river

reaches with a specific combination of morphometric, hydraulic, channel boundary and riparian vegetation conditions.

Observations of the vegetative regeneration of wood were a valuable source of information about the fate of living wood deposited in wider river reaches, indicating that a considerable proportion of such wood becomes rooted to the bar surface and subsequently buried, acting as propagules from which new willow/alder shrubs and trees develop (Mikuś et al. 2013). However, obtaining quantitative information about the amount of deposited wood that becomes permanently immobile as a result of vegetative regeneration would require systematic classification of all wood deposits into dead and living wood (Gurnell et al. 2000) during an inventory performed after a flood and verification of the fate of the living wood (that can die as a result of unfavourable moisture conditions, be remobilized before it is buried, or be eroded together with the underlying bar) in the subsequent years. As vegetative regeneration of living wood typically occurs in the widest reaches of the Czarny Dunajec with the largest amounts of deposited wood, this would be nearly equivalent with repetition of the wood inventory in each of a few subsequent years.

The tracking experiment with logs tagged with radio transmitters indicated that log displacement distance differed between reaches into which they had been delivered and that it depended on the flow width at the flood peak. The use of logs with the same dimensions that were consistently placed in the river at very similar parts of the flood hydrograph (Wyźga et al. in press) was an unquestionable advantage of the experiment; it allowed us to consider differences in the length of log displacement as reflecting different morphological and hydraulic conditions in particular river reaches. Disadvantages comprised (i) relatively high cost of the radio transmitters that limited the number of devices used in the experiment, (ii) limited representativeness of the logs for the range of large wood types recruited to and deposited in the river, and (iii) limited number of places where the logs could be safely delivered to the river at flood conditions (this is why the lowermost delivery site was located 1 km upstream from the beginning of the multi-thread reach).

Numerical modelling of large wood phenomena in channelized and multi-thread reaches of the Czarny Dunajec confirmed different potential of these river morphologies for the transport and deposition of wood previously demonstrated by wood inventories, indicated log length as a major control on wood dynamics in the channelized reach and log diameter in the multi-thread reach, revealed the dependence of the vertical and horizontal location of wood deposition on flood magnitude and a complex temporal pattern of wood remobilization during the passage of flood waves. The definite advantage of this source of information was that it provided the opportunity to examine (i) wood dynamics during floods of various magnitudes, (ii) temporal and spatial complexity of wood mobilization, transport and deposition, and (iii) the influence of changes in wood parameters on wood dynamics. The most important weakness seems related to the limited representation by the simulated logs of the natural complexity of large wood delivered to the Czarny Dunajec, with whole shrubs and trees representing more than one-third of the total number of wood deposits recorded in the river.

5.2 *Large Wood Dynamics in the Mountain Stream and the Mountain River*

Based on the rate of delivery of riparian trees to Kamienica Stream during six years of monitoring, the turnover period of riparian trees is estimated at 80 years, provided that the same rate is maintained in the long term. However, the monitoring period lacked major floods such as the one that occurred in 1997 when plenty of large wood was recruited to the stream from cutbanks and valley-side landslides (Kaczka 1999). The occurrence of such a flood in the monitoring period would result in even faster turnover of riparian trees. At the same time, the riparian area supports trees with ages up to ~ 160 years. This indicates that bark beetle infestation considerably increased tree delivery to the stream and accelerated the turnover of the riparian forest.

The obtained evidence indicates that mobility of large wood is very low in the second-order reach of the stream and greater but still limited in the fourth-order reach. In the former, the very low mobility is indicated by the predominance of near-perpendicular orientation of wood pieces, the occurrence of numerous wood dams (Kaczka 2003, 2009), and the prevalence of highly decayed wood. In the latter, considerable mobility of large wood must have typified the flood of 1997 as evidenced by the failure of numerous wood dams and the occurrence of longitudinal wood orientation (Kaczka 1999). Kamienica Stream is ungauged but anecdotal evidence from local farmers indicated the flood as occurring once in a few tens of years. Since that event the mobility of wood in the fourth-order reach of the stream must have been substantially lower as indicated by the formation of the second mode of wood orientation with near-perpendicular alignment of pieces, considerably increased proportion of the wood in advanced state of decay, and the maximum displacement by 100 m of tagged fallen trees during the six years of monitoring.

By contrast, the fifth-order Czarny Dunajec is typified by relatively large, although spatially highly diverse wood mobility. The tracking experiment and the numerical modelling indicated high potential for long-distance transport of large wood in single-thread river reaches, and this was also implicated by the high degree of mechanical disintegration of the wood deposited by floods immediately below the narrow, channelized reach. The high potential for wood transport is typical of rivers with channel width equal to or somewhat larger than the riparian tree height, in which flows are fast and deep and a general lack of major roughness elements such as bars or islands prevents wood retention (Wyżga et al. 2015). It also agrees with the observation by Seo and Nakamura (2009) that fluvial export of wood is maximised in the rivers with channel width somewhat larger than wood piece length and with relatively high stream power.

In turn, the wide, multi-thread river reach exhibits much less potential for the transport of wood and much higher potential for its retention. This reflects lower flow depths and unit stream power facilitating wood deposition on gravel bars and on the floodplain, and the abundance of retention features such as islands, against

which wood can be braced. Rapid flow expansion immediately downstream of the end of the narrow, channelized reach causes a large proportion of wood pieces transported from the upstream reaches to be deposited on short distances in the wide, multi-thread reach. Much of the remaining wood delivered from the upstream reaches is trapped in wood jams that form at the head of islands (Wyźga and Zawiejska 2010) and along concave banks of channel bends (Mikuś et al. 2016). Vigorous bank erosion occurring in the multi-thread reach during floods results in the delivery of substantial amounts of large wood to the river; however, it mostly consists of whole shrubs and trees with complex, three-dimensional structure, many of which are stranded on the nearest channel bars (Wyźga and Zawiejska 2005; cf. Welber et al. 2013). Willows constitute a large proportion of shrubs and trees deposited in the reach and often root to the bar surface, which limits the potential for their subsequent entrainment even if hydraulic conditions in the reach facilitate wood remobilization (Ruiz-Villanueva et al. 2016c).

5.3 Implication of Large Wood Dynamics in the Mountain Watercourses of Different Size to Flood Hazard

Bark beetle infestation that resulted in the widespread dieback of spruce forest in the Kamienica valley must have increased the rate of tree delivery to the stream. Despite this greater recruitment of large wood to the channel, little potential for wood export to the downstream, developed valley reaches exists, except during large, rare floods. However, a large proportion of wood pieces stored in the stream are in the advanced state of decay and will be subjected to rapid mechanical disintegration if entrained by a large flood. This allows us to conclude that large wood retained in the studied reach of the Kamienica valley within the national park does not represent a significant flood hazard to downstream valley reaches. However, the location of Kamienica within the national park precludes a simple generalization of the above conclusion for other mountain streams in the region. On the one hand, removal of wood from streams that is a common practice in the Polish Carpathians greatly reduces the amounts of wood that might be exported to downstream valley reaches during floods. On the other hand, wood dams—abundant in Kamienica channel—facilitate dissipation of stream energy and trap a proportion of wood pieces mobilized by floods; a general lack of such dams in the mountain streams outside nature-protected areas will thus facilitate flushing out of wood recruited to these streams during floods.

The reaches of the Czarny Dunajec and other mountain rivers narrowed as a result of channelization or channel incision provide conditions for efficient transfer of large wood over relatively long distances. As a result, during floods channel sections located downstream of such reaches may be supplied with substantial amounts of wood from distant locations irrespective of protection measures (e.g. bank reinforcement, riparian forest clearing) undertaken in the vicinity of

vulnerable sites such as bridges or urban reaches. In turn, wide, multi-thread reaches with their high potential to efficiently retain wood delivered from the upstream operate as natural wood traps that can considerably and efficiently limit further transfer of wood to vulnerable sites/reaches (Wyżga and Zawiejska 2010). Preservation or restoration of such reaches is thus crucial not only because of their high environmental value but also for the enhanced management of flood hazard related to presence of large wood in mountain rivers (Mikuś et al. 2016).

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