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LARGE WOOD STORAGE IN CHANNELIZED AND UNMANAGED SECTIONS OF THE CZARNY DUNAJEC RIVER, POLISH CARPATHIANS: IMPLICATIONS FOR THE RESTORATION OF MOUNTAIN RIVERS

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The amounts and distribution pattern of large wood stored in a 17 km long reach of the wide, mountain Czarny Dunajec River, southern Poland, were investigated following a 7-year flood to determine the potential of naturally recruited woody debris for restoration of mountain rivers affected by channelization and channel incision. The quantity of stored wood as well as the number and mean mass of wood accumulations were found to be directly related to the length of eroded, forested banks and river width, and inversely related to unit stream power at the flood peak. A regression line for the relationship with river width testifies to the existence of minimum channel width, below which no wood was typically retained in the river. Numerous wood accumulations of relatively high mass were retained in wide, multi-thread river sections. In these sections, wood was deposited in a variety of depositional sites, considerably contributing to the diversity of physical and biotic processes in the river. In contrast, very small number of wood accumulations of relatively low mass were retained in narrow, single-thread sections of regulated or bedrock channel. Here, wood was mainly deposited along the channel margins and has exerted little influence on the river functioning. The recognised pattern of wood storage indicates that in a mountain river wider than the height of trees growing on its banks, environmentally-significant quantities of large wood are deposited in wide, multi-thread sections already remaining in a relatively healthy environmental state but cannot be retained in narrow, channelized or incised river sections. This questions the utility of naturally recruited large wood for restoration of mountain rivers affected by channelization and channel incision. Successful restoration of such rivers would require the previous reduction of their transporting power or should be undertaken with the use of artificially placed wood structures.

Key words: mountain river; large woody debris; wood storage; wood mobility; river restoration; Polish Carpathians

1. INTRODUCTION

OUTLINE OF THE PROBLEM

After a long period of human actions aiming to remove fallen trees from channels and to isolate forest streams and rivers from their riparian areas (e.g. Sedell & Froggatt 1984), an extensive research carried on over recent decades has brought an increasing understanding of the role that large woody debris plays in functioning of fluvial systems. Large wood enhances availability and diversity of aquatic habitats in forest channels (Harmon *et al.* 1986, Gurnell *et al.* 1995, Gregory *et al.* 2003) and promotes vegetation establishment on floodplains and channel bars and thus, riparian forest development in river networks (Fetherston *et al.* 1995, Gurnell *et al.* 2001). Moreover, woody debris advantageously influences a number of physical characteristics of fluvial systems. Wood accumulations in channels increase their morphological complexity (Gurnell *et al.* 1995), hence leading to an increased variability of flow velocity (Gippel 1995) and depth, observed both in the cross-section and in the longitudinal profile of the watercourses. Large wood increases flow resistance, facilitating dissipation of stream energy (Gippel 1995, Manga & Kirchner 2000), and enhances the potential for in-channel sediment storage (Mosley 1981, Keller *et al.* 1995).

Woody debris influences fluvial processes and the resultant forms and sediments at a range of spatial and temporal scales. Spatially, its impact is manifest from bed-surface grain size (Buffington & Montgomery 1999) through the formation and spacing of channel forms, such as pools (Montgomery *et al.* 1995) and steps (Keller & Swanson 1979), to channel dimensions and capacity (Brooks *et al.* 2003) and channel pattern (Gurnell & Petts 2002). Among temporal effects, it is important that in the short term, wood accumulations tend to accommodate large, localised inputs of sediment and regulate bedload transport along channels (Keller *et al.* 1995); in the long term, they enable the existence of alluvial channel beds in mountain streams and rivers (Montgomery *et al.* 1996) and sustain equilibrium channel conditions under low sediment supply rates (Brooks & Brierley 2002).

Rivers draining the Polish Carpathians were extensively channelized and deeply incised during the 20th century, and the increase in transport capacity of the artificially straightened and narrowed channels coupled with their isolation by bank-protection structures from bed-material calibre sediments stored on the valley floors have been identified as major reasons for bed degradation of the rivers (Wyżga 2008, Zawiejska & Wyżga 2010). Both the channelization and channel incision have resulted in a number of detrimental effects, with a marked increase in flood hazard to downstream reaches (Wyżga 2008) and a loss of the ecological integrity of the rivers (Wyżga *et al.* 2008) being the most important harms manifested at the regional scale. Therefore, there is an urgent need for formulating management strategies that would promote re-establishment of the dynamic equilibrium conditions in the rivers and an amelioration of their degraded ecosystems. With the mentioned benefits to watercourses resulting from the presence of large wood, its delivery to channels, whether through natural recruitment processes or artificial placement, can be reasonably viewed as a way to enhance ecological and physical functioning of streams and rivers (Gregory & Davies 1992, Bragg & Kershner 1999, Reich *et al.* 2003; Erskine & Webb 2003, Kail *et al*. 2007, Wyżga 2007, Lester & Wright 2009). Placement of stable logs in channels has increasingly been used as a technique in restoration of streams in recent years (e.g. Wallace *et al.* 1995, Reich 2000, Kail & Hering 2005). Higher mobility of woody debris in the wider channels of rivers may limit the use of large wood to restore the watercourses because of the associated risks of increasing flood levels by jammed debris and damaging bridges or other infrastructures by floated wood (Shields & Nunnally 1984).

Successful management of large wood in rivers requires knowledge about the amounts of wood stored in such watercourses and the factors governing its mobility and distribution along the channels. However, most of the previous research of in-channel wood has been focused on small streams, with few studies performed in rivers wider than 20 m (cf. Gurnell *et al.* 2000a). Formulation of a methodology for the assessment of wood mass associated with particular types of debris accumulations (Thévenet *et al.* 1998) has enabled estimation of the amount and distribution of wood stored in large gravel-bed rivers and such studies were performed in two Alpine rivers: the Drôme River in France (Piégay *et al.* 1999) and the Fiume Tagliamento, Italy (Gurnell *et al.* 2000a, b).

AIM AND SCOPE OF THE STUDY

This paper reports on the amounts and distribution pattern of wood deposited by two floods of June and July 2001 in the Czarny Dunajec, southern Poland. Particular sections of this relatively wide, fifth-order, mountain river differ markedly with respect to channel management and morphology, and the paper aims to answer how the variability in these characteristics was reflected in the pattern of wood storage. The observational data are next utilized: (i) to indicate features of mountain river channels favourable for retention of large wood, and (ii) to discuss the possibilities of using naturally recruited large wood to restore mountain rivers affected by channelization and channel incision.

Some results from the study on wood retention in the Czarny Dunajec, focused on the variability in specific wood storage, that is wood quantity per unit river area, have already been published elsewhere (Wyżga & Zawiejska 2005). In this paper, considerations concerning the utility of naturally recruited large wood for mountain river restoration are based on an analysis of the variability in total wood storage, that is the quantity of wood stored on a given length of a river. Recent observations of the authors indicate that the relationship between spatial patterns of specific and total wood storage in wide mountain rivers differs markedly from that known from streams narrower than the height of trees growing on their banks. Total wood storage deserves attention as it jointly reflects variations in the number of wood accumulations and in their average mass along a river. Moreover, it is useful for characterising some environmental features, such as the absolute abundance of wood-related habitat structures or the potential of a given river section to trap floated debris dangerous for the downstream-located bridges or infrastructures. Total wood storage is rarely considered because it depends on river size and thus cannot be used for comparisons between rivers or along a longer reach of a given river. However, its consideration in the present study is justified by a specific location of the investigated reach of the Czarny Dunajec.

2. FIELD SETTING

The gravel-bed Czarny Dunajec (Fig. 1) constitutes the upper part of the Dunajec, one of the largest rivers of the Polish Carpathians. The Czarny Dunajec rises at about 1500 m a.s.l. in the high-mountain Tatra massif and joins with the Biały Dunajec River in the town of Nowy Targ at an altitude of 578 m (Fig. 1B). In the 20th century, the river reach within the Tatra Mountains foreland was subject to spatially variable human impacts, including channelization and intense gravel mining (Krzemień 2003, Zawiejska & Krzemień 2004, Zawiejska & Wyżga 2010). The gravel mining induced up to 3.5 m of channel incision and transformation from an alluvial to bedrock bed in many river sections within the Gubałówka Hills (Zawiejska & Wyżga 2010). As a result of the human impacts and subsequent channel adjustments, the contemporary river represents, especially in its middle course, a variety of geomorphological styles comprising both unmanaged and channelized sections as well as alluvial and bedrock channel sections.

Two floods that occurred in June and July 2001 delivered much woody debris to the river and redistributed it along its course. At the Koniówka station in the middle river course (Fig. 1B), where the catchment area is 134 km^2 and mean annual discharge amounts to 4.4 $m^3 \cdot s^{-1}$, the floods had the same peak discharge of 94 $m^3 \cdot s^{-1}$ with a 7-year recurrence interval. Following the second flood, an inventory of the stored wood was made in a 17.2 km long river reach between the villages of Chochołów and Długopole, in which the Czarny Dunajec flows on a large, fluvioglacial-alluvial fan and where water divides between the main river and its tributaries run very close to the river channel. Along the reach, the catchment area increases relatively little and the river receives no significant inflow from tributaries (Fig. 1B). As a result of this hydrographic setting, bank undercutting and transport from upstream were the only processes responsible for wood delivery to the reach during the flood events. Moreover, the authors' observations indicated that in the reach, peak flows of both floods were conveyed entirely within the channel/active zone of the river so that no wood was transferred onto the floodplain (Wyżga & Zawiejska 2005).

Along the reach selected for the study, the riparian forest is composed of alder and willow species with predominating young, shrubby forms of *Alnus incana*,

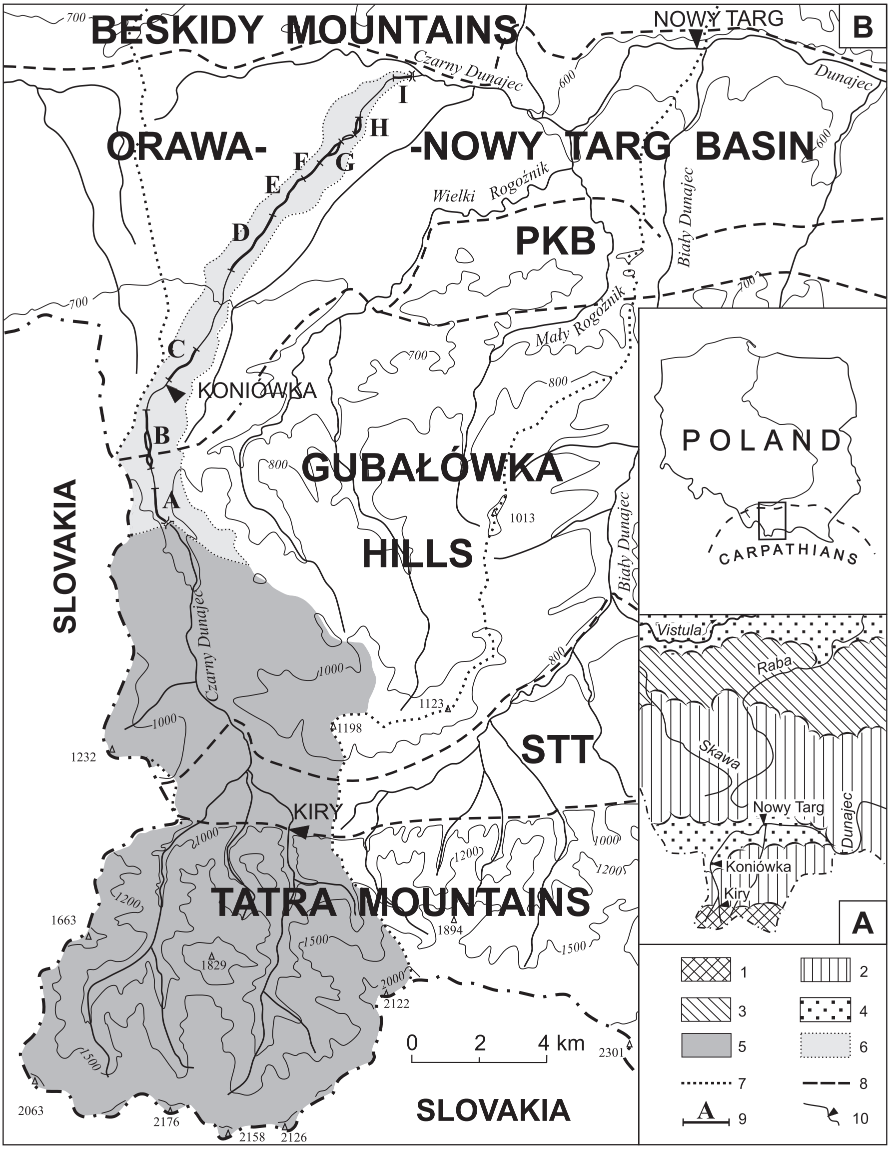

Fig. 1. (A) Location of the Czarny Dunajec River on the background of physiogeographic regions of southern Poland. (B) Drainage network and physiography of the Czarny Dunajec catchment and detailed setting of the investigated sections of the river

1 – high mountains; 2 – mountains of intermediate and low height; 3 – foothills; 4 – intramontane and submontane depressions; 5 – the Czarny Dunajec catchment to the beginning of the study reach; 6 – catchment area increment along the study reach; 7 – boundary of the Czarny Dunajec catchment; 8 – boundaries of physiogeographic units; 9 – river sections investigated; 10 –water-gauge stations; PKB – Pieniny Klippen Belt; STT – Sub-Tatran Trough (after Wyżga and Zawiejska 2005, with permission of Wiley and Sons)

Salix eleagnos, *S. purpurea* and *S. fragilis*, less frequent stands of older *A. incana* trees and occasional *S. alba* trees (Koczur 1999). Older parts of the riparian forest are periodically subject to limited tree harvest, especially focused on the larger trees growing close to the channel and threatened by erosion. As measured after the flood of July 2001, mean width of the channel/active zone of the river amounted here to 52 m and was 3-4 times greater than the height of trees growing on the banks. With the channel width far greater than the length of all wood pieces delivered from the riparian zone, the Czarny Dunajec represents a typical wide river (cf. Gurnell *et al.* 2002; Piégay 2003). Two characteristics of the reach appeared especially suitable for investigating the dynamics and storage of wood in such a watercourse. The river width varied here between 18 and 166 m and the high variation in this parameter must have been reflected in considerable variability of the transporting power of the flood flows along the channel. At the same time, substantial variation in the type of channel management and river morphology within the reach must have resulted in spectacular differences in the availability of wood retention sites as well as in the delivery of debris from eroded banks between particular river segments.

3. STUDY METHODS

DEFINITION OF THE INVESTIGATED SEGMENTS AND SECTIONS OF THE RIVER

Eighty-nine river segments of about 100 m in length (double the average river width) were delimited along the study reach. Some of the segments had to be shorter or longer than the standard length, depending on the limitations of visibility along river axis at channel bends and island-supporting river sections. Moreover, in the river sections channelized with the use of drop structures, the length of delimited river segments was adjusted to span successive structures (typically ranging from 120 to 180 m). Successive segments of a given type of channel management and similar morphology were grouped into nine river sections, designated A to I (Fig. 1B, Photo 1). Particular sections consist of 5 to 16 river segments (Table 1) and have a length between 496 and 1703 m (Fig. 2). Their detailed characteristics are indicated further in the paper.

The investigated river segments had a total length of 9.9 km, representing 58% of the length of the study reach. Parts of the study reach excluded from the analysis comprised: (i) river sections from which a proportion of deposited debris had been removed for firewood before we were able to made the inventory; (ii) a part of the river course channelized with the use of drop structures that was omitted in order to avoid sample bias towards this type of channel management; and (iii) a river section, a few hundred metres long, located downstream of a bridge which intercepted a considerable amount of transported wood on the upstream side of its piers.

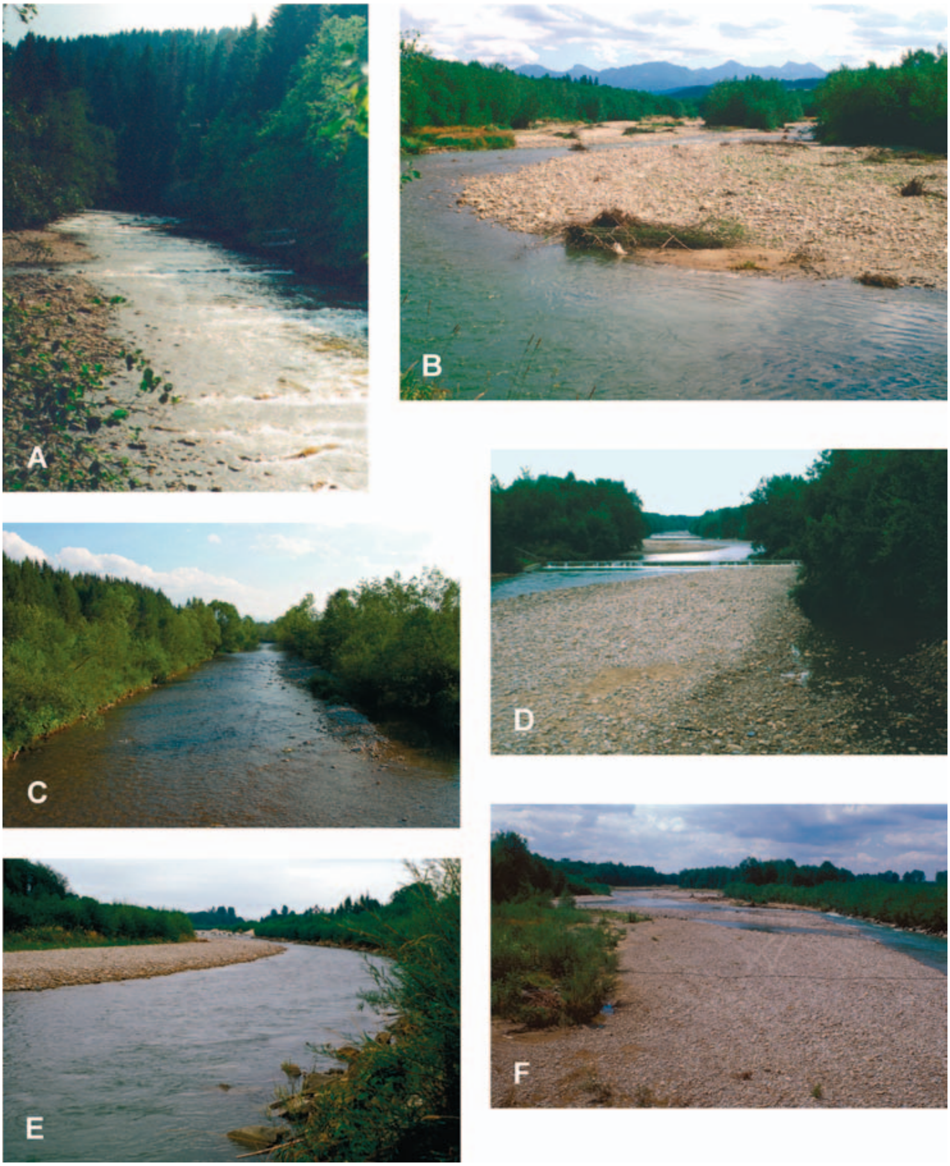

Photo 1. View of the Czarny Dunajec in the investigated river sections of a given type of channel management and similar morphology

Sections A–F and I are viewed upstream and sections G and H in the downstream direction. Note that practically no large wood is visible in narrow sections of bedrock (A) and regulated channel (C–E, I), whereas the widest river sections (G, H) store numerous wood accumulations

Photo 1. Continued

Table 1. General characteristics of the nine investigated sections of the Czarny Dunajec

River section	Segment number	Number of segments in section	Geomorphological style of section
A	1–10	10	narrow and deep, steep-sloped, single-thread bedrock channel
B	11–26	16	moderately wide with alternating multi-channel, multi-thalweg and sinuous single-thread morphologies
C	27–37	11	narrow, straight channel regulated with high, widely spaced drop structures, and with banks stabilized by groins
D	38–51	14	narrow, straight channel regulated with low, closely spaced drop structures, and with banks stabilized by groins
E	52–63	12	narrow, sinuous channel regulated with widely spaced concrete ramps, and with banks lined with rip-rap
F	64–70	7	moderately wide, sinuous single-thread to braided channel with concave banks lined with rip-rap
G	71–79	9	multi-thread channel rapidly widening and changing from braided to heavily island-braided along the section length
H	80–84	5	wide, multi-thread channel, island-braided to heavily island-braided
I	85–89	5	narrow and deep, regulated channel with banks lined with rip-rap

ASSESSMENT OF THE MASS OF LARGE WOOD STORED IN THE REACH

The mass of wood stored in the Czarny Dunajec was estimated by means of the method developed by Thévenet *et al.* (1998) and applied in the previous studies on the Drôme (Piégay *et al.* 1999) and the Tagliamento (Gurnell *et al.* 2000a, b). First, each discrete wood accumulation was classified into one of the following categories: (i) 'logs' being isolated, unbranched wood pieces greater than 1 m in length and 10 cm in diameter; (ii) 'jams', i.e. heterogeneous mixtures of logs, branches, root boles and twigs as well as fine organic matter and inorganic sediment; and (iii) 'shrubs and whole trees' representing isolated and uprooted shrubs or trees with a large branch-to-trunk volume and the resultant three-dimensional structure. Accumulations were then measured with a metal tape, with an accuracy of 1 cm for log diameter and 5 cm for log length and the length, width and height of jams, shrubs and whole trees. The volume of logs was directly calculated from their measured length and diameter, whereas for jams and shrubs/trees, the wood/air volume of each accumulation was determined by measuring its width, length and height. Subsequently, the total mass of wood in each accumulation was estimated by multiplying the wood/air volume of shrubs /trees and jams and the volume of logs by wood mass estimates of 50, 100 and 500 kg·m^{-3}, respectively.

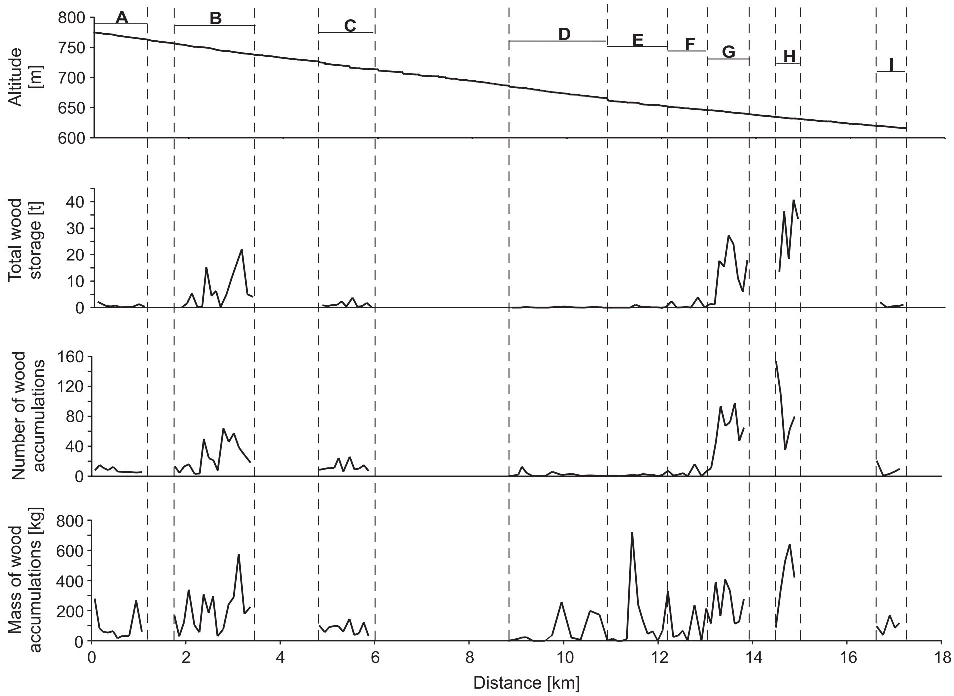

Fig. 2. Location of the nine investigated sections (A to I) of the Czarny Dunajec in relation to changes in altitude along the study reach, and the distribution of total wood storage as well as the number and mean mass of wood accumulations for the 89 investigated segments of the river

Note that the high mean mass of wood accumulations recorded in a single segment of section E refers to only two accumulations retained in this segment.

The wood mass estimates used in the present study are the same as those applied in the previous studies in the Alpine rivers of France (Thévenet *et al.* 1998) and Italy (Gurnell *et al.* 2000a, b), which is justified by the similar composition of riparian forests bordering these rivers and the Czarny Dunajec. Although the use of such estimates, not calibrated in the local conditions, may cast some doubt on the absolute amounts of large wood in the Czarny Dunajec, it nevertheless provided an effective method of estimating the variation of wood storage along sections of the studied reach.

Two modifications of the above-outlined methodology were introduced in the present study, their detailed justification being presented elsewhere (Wyżga & Zawiejska 2005). The first one concerned estimation of the mass of large willow trees with thick, rigid branches and thus with a large wood/air volume of the fallen specimens. The trunk and branches of such trees were treated separately from distal parts of their crowns and the mass of the elements was estimated according to the 'log' and 'shrub' formulas, respectively. Second, we included into the large wood inventory atypical logs with one dimension, length or diameter, far greater than the threshold value and the other one falling below the threshold if their mass exceeded 4 kg (i.e. the mass of a log 1 m in length and 10 cm in diameter, with the density of undecayed wood amounting to 500 $kg \cdot m^{-3}$ (cf. Harmon *et al.* 1986)).

The final step of the procedure was integration of the mass estimates for particular wood accumulations yielding the total mass of large wood stored in each river segment. The number and the average mass of wood accumulations in particular segments were also determined (Fig. 2).

DETERMINING THE PARAMETERS EXPLAINING DISTRIBUTION OF WOOD QUANTITIES

Concurrently with the wood inventory, a set of variables potentially explaining the distribution of wood quantities along the study reach was identified, including river width, flood-water slope, unit stream power at the peak of the 2001 floods, and the length of eroded wooded banks (cf. Wyżga & Zawiejska 2005).

The river width was estimated from measurements taken at each end of every segment. In the river sections without islands, the channel width was measured, whereas in island-supporting sections the measurements across the active channel (comprising low-flow channel(s) and gravel bars) and islands were summed to yield the active zone width (cf. Gurnell *et al.* 2000a, 2001).

Following the floods, a long profile of the study reach was surveyed at mean flows and the data were used to estimate the hydraulic gradient at flood conditions for successive river segments. Along the river sections without drop structures, the slope of the flood-water surface at a given segment was approximated by averaging the mean-water slope over the upstream, downstream and current segments. For the river segments located between closely spaced drop structures, the best available approximation of the slope of flood-water surface was obtained from the water-surface slope measured at mean flows between the points positioned immediately below the end sill of a drop structure and on the crest of the downstream weir.

The difference in catchment area between a given river segment and the gauge cross-section at Koniówka was measured on a 1:10 000 scale map. The peak flow of the 2001 floods at each successive segment was then calculated from known gradients (averaged for both floods) of the peak-discharge increase with increasing catchment area between the gauging stations at Kiry, Koniówka and Nowy Targ (Fig. 1B). This indicated that along the study reach, the peak discharge of the floods must have changed from 94% to 106% of that recorded at the Koniówka station. With river width, flood-water slope and the peak discharge of the floods measured or estimated, unit stream power at the flood peak was calculated for successive river segments and considered to be an index of the river's ability to transport wood during the flood events (cf. Gurnell *et al.* 2000b).

The length of eroded, wooded banks of the channel and islands was measured at each river segment to provide an index of large wood recruitment during the 2001 floods. For each segment, the combined length of the eroded, wooded banks in this and the upstream segment was also calculated.

ANALYSIS

Values of the length-dependent parameters, i.e. total wood storage, the number of wood accumulations and the length of eroded banks, were adjusted to a standard segment length of 100 m to make comparisons between river segments of different length possible and the analysis of relationships between various river characteristics meaningful. For instance, in the case of a 107 m long segment, the values of the parameters were divided by 1.07. Next, average values of all investigated parameters were determined for the nine identified river sections of a given type of channel management and similar morphology (Table 2). Again, to enable comparability of

Table 2. Values of wood quantities, morphometric and hydraulic parametres and the length of eroded banks averaged for the nine investigated sections of the Czarny Dunajec

River section	Channel/ active zone width [m]	Flood water slope [$m \cdot m^{-1}$]	Unit stream power [$W \cdot m^{-2}$]	Length of eroded banks [m]	Total wood storage [t]	Amount of wood accumulations	Mean mass of wood accumulations [kg]
A	34.8	0.01070	275.1	13.9	0.726	7.7	94.2
B	60.7	0.01089	166.3	118.6	6.091	26.2	232.6
C	33.4	0.00643	179.4	20.3	1.160	12.4	93.8
D	35.6	0.00578	155.5	25.1	0.113	2.1	55.0
E	35.9	0.00634	167.0	4.4	0.200	1.1	175.9
F	49.5	0.00629	131.9	24.5	1.281	5.7	223.9
G	107.0	0.00770	75.3	83.1	13.513	55.3	244.3
H	129.1	0.00667	49.6	180.2	28.547	88.3	323.3
I	33.8	0.00601	196.9	19.4	0.807	7.6	106.3

Length of eroded banks, total wood storage and the amount of wood accumulations are averages per 100 m channel length the results among river sections, the total values of the length-dependent parameters had to be divided by the total aggregated length of a given section.

The general pattern of wood storage in the study reach was analysed with regard to the differences in river geomorphological style existing between particular sections of the Czarny Dunajec. The statistical significance of hypothesized relations between the parameters characterizing wood storage (total wood storage, the number and mean mass of wood accumulations) and the morphometric and hydraulic characteristics of the river as well as the length of eroded banks was tested by means of simple and multiple regression models. Data about the types of wood jams and the mean mass of particular types of accumulations were used to infer the degree of debris mobility in the river. More detailed inferences about the length of wood transport in narrow and wide river sections were drawn from the analysis of proportions of particular types of accumulations in the total mass of stored wood along the study reach and from observations of the state of wood preservation downstream of the channelized, middle part of the reach. Finally, observations of the preferential sites of debris deposition and of the influence exerted by large wood on physical and biotic processes in the river were compared between narrow and wide sections of the Czarny Dunajec.

4. RESULTS

GENERAL CHARACTERITICS OF RIVER GEOMORPHOLOGICAL STYLE AND WOOD STORAGE IN THE STUDY REACH

In the study reach, the geomorphological style of the Czarny Dunajec is highly variable due to differences in river morphology and the type of channel management (Photo 1, Table 1). After the recession of the flood of July 2001, spectacular differences in the amount of retained wood were apparent between particular river sections (Photo 1, Table 2), thus raising the question about reasons for the observed variability in wood storage.

In the uppermost section A, the river flows in a single-thread, narrow, bedrock channel (Photo 1A), incised into resistant sandstones. This section was typified by a small length of eroded banks and the highest value of unit stream power at the flood peak among the investigated sections (Table 2). A small number of wood pieces of relatively low mass were deposited in the section, this being reflected in the relatively low value of total wood storage (Fig. 2, Table 2).

In the moderately wide section B (Photo 1B), three types of river morphology alternate at short, 100-250 m intervals: (i) multi-channel morphology, with particular channels incised into bedrock and separated by elevated, wooded islands, which were not inundated during the 2001 floods; (ii) multi-thalweg morphology, with braids separated by either gravel bars or low islands, and (iii) sinuous single-thread morphology. This section was typified by moderately high unit stream power and the length of eroded banks about ten times greater than in section A (Table 2).

The average number and mean mass of wood accumulations in a river segment were about three times greater than in section A, and the values of total wood storage amounted to 6 t on average and up to 21 t in a single segment (Fig. 2, Table 2).

Sections C-E (Photo 1C-E) represent the middle part of the study reach channelized with the use of drop structures. In sections C and D with mostly straight channel, the structures are concrete weirs. They are about 1.5 m high and situated every few hundred metres in section C, while in section D they are 0.7-1.0 m in height, but more closely spaced (120-180 m apart). In the recently channelized section E, the channel is sinuous and its banks are lined with rip-rap, whereas the drop structures are concrete ramps 0.5-1.1 m in height. Sections C-E were characterised by a small channel width, relatively high unit stream power and a small length of eroded banks (which were almost absent along section E) (Table 2). The channelized sections retained a very small number of wood accumulations of relatively small mass and, consequently, they were typified by the lowest wood quantities among all the investigated sections; in the segments of section D, the total mass of stored wood was as low as 0.1 t on average (Fig. 2, Table 2).

Along sections F to H the river becomes increasingly wide (Photo 1F-H). The growing complexity of the flow pattern in the downstream direction is here accompanied by a progressive increase in the proportion of island surfaces within the active zone at the expense of open gravel areas. In section F, which starts below the last drop structure, concave banks are protected from erosion by rip-rap, whereas no artificial bank reinforcement occurs in sections G and H. A remarkable increase in the length of eroded wooded banks was recorded along sections F to H; in an average segment of section H, the length was about seven times greater than in section F (Table 2). With little difference in the hydraulic gradient, the widening of the river was reflected in the progressively lower unit stream power in the successive sections (Table 2). A marked increase in the average number of wood accumulations was recognised along this part of the study reach, from one accumulation per river segment in section E to 88 within section H, and the trend was associated with a less spectacular but consistent growth in the mean mass of accumulations (Fig. 2). As a result, the quantities of stored wood progressively increased in the downstream direction, with about 1 t of wood retained in an average segment of section F, 13.5 t in section G and 28.5 t in section H (up to 42 t in a single segment of this section) (Fig. 2, Table 2).

In section I the river flows in a deep, single-thread, regulated channel (Photo 1I), which narrows rapidly towards a bridge at Długopole and attains the smallest width within the study reach just upstream of the bridge. With flow concentrated in the narrow channel, this section was characterised by high unit stream power at the flood peak, but lining of the banks with rip-rap resulted in a small length of eroded banks (Table 2). Few wood accumulations of relatively small mass were retained in the section and the average value of total wood storage was here about 35 times lower than in section H (Fig. 2, Table 2).

Data averaged for the nine investigated sections of the Czarny Dunajec (Table 2) show that the total mass of wood stored in a 100 m long river segment varied among the sections by 2.3 orders of magnitude, from 0.1 to 28.5 t. The average number of wood accumulations in a river segment varied between 1 and 88, i.e. by almost two orders of magnitude, whereas the mean estimated mass of accumulations was less variable, ranging from 55 to 323 kg. The largest amounts of wood (up to 42 t in a river segment) were retained in wide, unmanaged, multi-thread sections of the Czarny Dunajec (Photo 1B, G, H), which were typified by low transporting power of the flood flows and where a considerable length of eroded channel and island banks was identified following the floods. In contrast, very low quantities of wood were stored in narrow, single-thread sections of regulated (Photo 1C-E, I) or bedrock channel (Photo 1A) in which unit stream power during flood flows was high and which were characterised by a small length of eroded channel banks.

RELATIONSHIPS BETWEEN WOOD STORAGE PARAMETERS AND EXPLANATORY VARIABLES

The considerable variation in wood quantities observed in the studied reach of the Czarny Dunajec together with the collected data on morphometric characteristics of the river, unit stream power at the flood peak and the length of eroded banks make it possible to verify usefulness of the parameters to explain/predict the variability in wood storage along a wide mountain river. To investigate relations between total wood storage as well as the number and mean mass of wood accumulations (further called "wood storage parameters"), and the potential explanatory variables, linear and non-linear regression models were estimated for the 89 segments and the nine sections of the Czarny Dunajec (Fig. 3, Table 3).

None of the three wood storage parameters appeared to be significantly related to flood water slope, whereas they were found to increase linearly with an increase in river width (Fig. 3, Table 3). This distinction occurred despite a similar range of variation in both parameters (by a factor of 7 for flood water slope and 8 for river width) in the sample of short river segments, indicating an important physical mechanism underlying the relation of the wood storage parameters with river width. All wood storage parameters were directly related to the length of eroded wooded banks. Relationships with the length of eroded banks in the same river segment, in the upstream segment as well as with the accumulated length across both segments were analysed, indicating the length of eroded banks in two segments to be the best predictor of the wood quantities (Table 3), and the relationships for this last parameter are shown herein (Fig. 3). Total wood storage as well as the number and mean mass of wood accumulations were also found to increase nonlinearly with decreasing unit stream power at the flood peak (Fig. 3, Table 3).

Relations between the wood storage parameters and flood water slope, river width and the length of eroded banks were further investigated by means of multiple

Table 3. Explanation and significance of regression models estimated between total wood storage, number and mean mass of wood accumulations, and potential explanatory variables along the Czarny Dunajec for 89 river segments and nine river sections of a given type of channel management and similar morphology

	89 segments			Nine sections			
Dependent variable / Independent variable	Total wood storage	Number of wood accumulations	Mean mass of wood accumulations	Total wood storage	Number of wood accumulations	Mean mass of wood accumulation	Type of regression
Flood water slope	$R = 0.09$ $p = 0.39$	$R = 0.16$ $p = 0.14$	$R = 0.03$ $p = 0.76$	$R = 0.01$ $p = 0.98$	$R = 0.06$ $p = 0.86$	$R = 0.11$ $p = 0.77$	linear
Channel/active zone width	$R = 0.80$ $p < 0.00001$	$R = 0.85$ $p < 0.00001$	$R = 0.49$ $p < 0.00001$	$R = 0.96$ $p < 0.0001$	$R = 0.97$ $p < 0.00001$	$R = 0.85$ $p < 0.01$	linear
Unit stream power at the flood peak	$R = -0.71$ $p < 0.00001$	$R = -0.66$ $p < 0.00001$	$R = -0.53$ $p < 0.00001$	$R = -0.98$ $p < 0.00001$	$R = -0.95$ $p < 0.0001$	$R = -0.80$ $p < 0.0001$	non-linear
Length of eroded banks*	$R = 0.69$ $p < 0.00001$	$R = 0.66$ $p < 0.00001$	$R = 0.51$ $p < 0.00001$	$R = 0.91$ $p < 0.001$	$R = 0.91$ $p < 0.001$	$R = 0.79$ $p < 0.01$	linear

* 'Length of eroded banks' represents the length or eroded banks in analysed segment and the upstream segment

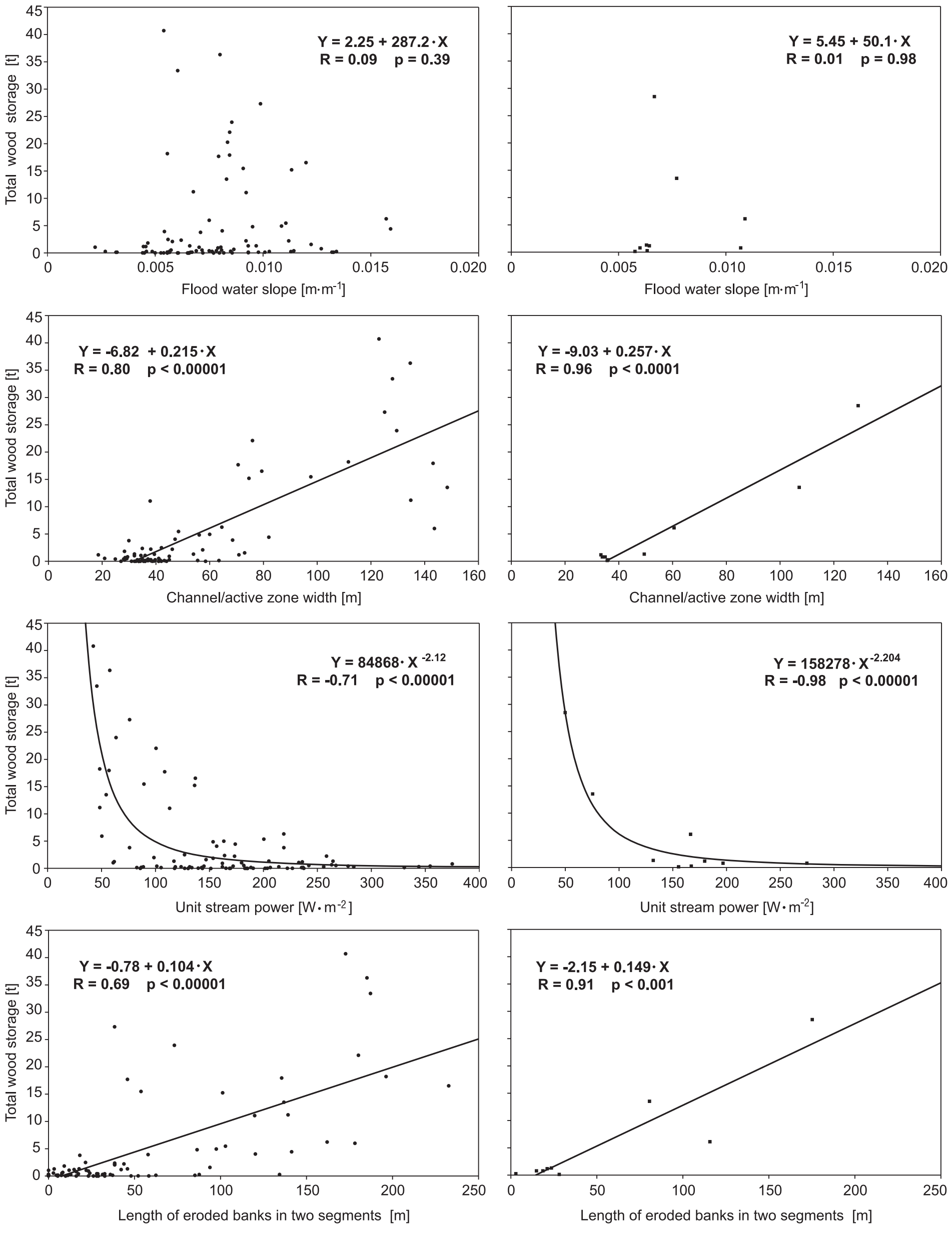

Fig. 3. Scatter plots and estimated regression relationships between total wood storage, and flood water slope, river width, unit stream power at the flood peak and the length of eroded banks in the Czarny Dunajec for 89 river segments of about 100 m length (left diagrams) and for nine river sections of a given type of channel management and similar morphology (right diagrams)

No regression line is indicated for the regression model between total wood storage and flood water slope which is not significant regression models estimated for 89 short river segments (unit stream power, calculated from flood water slope and river width and thus being a redundant variable, was excluded from these analyses). Stepwise regression procedure was used and particular variables were allowed to enter the models if they were significant at $p < 0.10$ in the final equations. The following equations were obtained:

$$\text{TWS} = -6.202 + 0.171\ \text{WIDTH} + 0.034\ \text{LEB}$$
$$(R = 0.82;\ p < 0.000001)$$

and

$$\text{MMA} = 32.557 + 0.848\ \text{LEB} + 1.226\ \text{WIDTH}$$
$$(R = 0.54;\ p < 0.000001)$$

where TWS is total wood storage in a 100 m long river segment (t/100 m); MMA is mean mass of wood accumulations (kg); WIDTH is the channel/active zone width (m) and LEB is the length of eroded banks averaged for the current and the upstream segment (m). No significant multiple regression model was obtained for the number of wood accumulations in a 100 m long river segment (NWA), and the variation in this parameter was best explained by the following equation of the linear relationship with river width:

$$\text{NWA} = -20.68 + 0.754\ \text{WIDTH}$$
$$(R = 0.85;\ p < 0.000001)$$

Multiple regression analysis was not applied for the sample of longer river sections as the relatively small number of degrees of freedom (nine elements in the sample minus three regressors) might cast doubt on its results. However, it is apparent from the estimated simple regression models that the variation in river width alone explains almost all the variation in total wood storage and in the number of wood accumulations and a very large percentage of the variation in mean mass of wood accumulations observed among the longer river sections (Table 3).

A few observations can be made from examination of the recognizsed relationships between the wood storage parameters and the explanatory variables. First, the relationships established for longer river sections of a given type of channel management and similar morphology explain a considerably greater portion of the total variation in the wood storage parameters than in the case of short river segments (Fig. 3, Table 3). The high variation in the wood storage parameters within the sample of short river segments, that is not explained by the developed regression models, must have reflected the operation of other factors determining the amount of debris recruitment, such as the amount of bank retreat and the volume of trees/shrubs per unit river area of eroded forest (cf. Piégay *et al.* 1999), or influencing the river's potential for wood storage, such as local-scale changes in channel morphology and in the configuration of riparian vegetation. However, the above-mentioned additional factors apparently exerted little influence on wood storage at the section scale, probably because their effects were mutually counterbalanced over the length of 10–30 average channel widths (Wyżga & Zawiejska 2005).

Second, although river width and the length of eroded banks separately explain a considerable portion of the total variation in the wood storage parameters (Table 3), combining the two variables into multiple regression models only slightly increased explanation of the variation in total wood storage and in the mean mass of wood accumulations, while adding nothing to explanation of the variation in the number of accumulations. This reflects some correlation between the variables, with 54% of the variation in the length of eroded banks explained by the variability in river width. Narrow river segments are typified by the scarcity of bank undercuts due to either channel constriction by bedrock in the incised section A or to lining the banks with artificial structures in channelized sections. On the other hand, the widest segments represent island-braided to heavily island-braided style of river morphology and are characterised by considerable length of eroded channel and island banks.

Moreover, a regression line for the relationship between total wood storage and river width intersects the abscissa at the width of 32 or 35 m, depending on the diagram for either short segments or longer river sections, respectively (Fig. 3). This threshold width corresponded to about double the maximum height of trees growing on the banks of the Czarny Dunajec. Such a location of the intersection point testifies to the existence of minimum channel width, below which no large wood was generally retained in the river during the flood wave passage, most likely because of excessive transporting power of the flood flows.

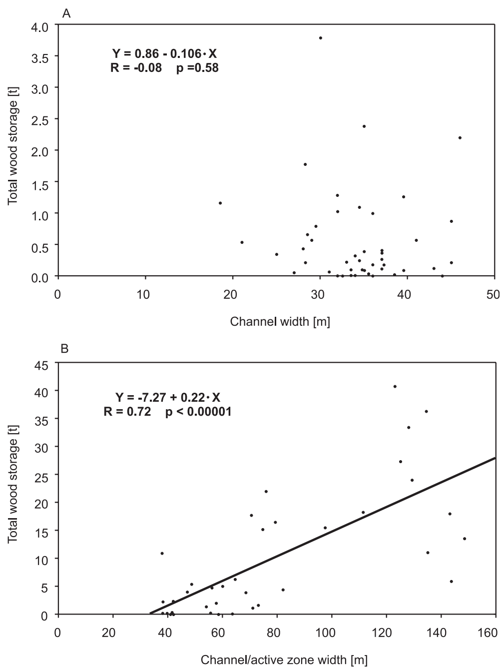

Fig. 4. Scatter plots and estimated regression relationships between total wood storage and river width in heavily channelized and incised segments of the Czarny Dunajec (A) as well as partly reinforced and unmanaged river segments (B).

No regression line is indicated for the first regression model which is not significant

Simple regression models for the relations between total wood storage and river width, unit stream power at the flood peak and the length of eroded banks were also estimated separately for 51 heavily channelized and incised river segments and 38 partly reinforced and unmanaged river segments (Fig. 4 – see the relations with river width). The relationships established for the latter group were highly significant (Fig. 4B), indicating a clear dependence of the amounts of wood stored in such segments on the identified explanatory variables. In contrast, relatively low amounts of wood stored in the heavily channelized and incised river segments were unrelated to the investigated parameters (Fig. 4A). Apparently, the retention of wood in these segments was not governed by flow hydraulics during the flood wave passage and the intensity of wood recruitment. Instead, it rather occurred accidentally due to the anchoring of floated wood pieces on the trees growing along channel margins.

MASS OF WOOD ACCUMULATIONS

Average mass of 1754 wood accumulations retained in the investigated sections of the Czarny Dunajec amounted to only 233 kg, equivalent to about 0.5 m^3 of wood. This can be attributed to the small size of woody debris recruited from a young, managed riparian forest growing in the river corridor, high specific energy of the river (considerably increased in some sections owing to channel regulation) facilitating physical breakdown of wood during transport, and to the removal of larger trees from the channel for firewood (see below).

However, narrow and wide river sections differed markedly with respect to the size (mass) of wood accumulations, both its mean value and variation (Fig. 5). Despite distinct average mass of particular accumulation types in the river (amounting to 23 kg for logs, 182 kg for shrubs and whole trees and 388 kg for jams), the pattern of the differences among the investigated river sections was similar for the three types of wood accumulations. Accumulations stored in the narrow, bedrock (A) and channelized (C-E, I) river sections were relatively small and showed little variation in size. In contrast, accumulations retained in the wide, multi-thread river sections (B, G-H) had a few times larger average mass and varied highly in size. The increased size variability of the accumulations stored in these sections predominantly reflected a greater size range of wood accumulations larger than average (Fig. 5). Although in all the investigated cross-sections the distribution of mass of wood accumulations was positively skewed, the distribution skewness ranged from 0.73 to 3.70 in the narrow sections and between 2.75 and 7.35 in the wide sections. The estimated mass of the largest accumulations stored in the wide sections exceeded the respective value for the narrow sections by a factor of 4.5 in the case of logs, 5.7 for shrubs and whole trees, and 7.4 for jams.

TYPES OF WOOD JAMS

Recognition of the types of wood jams occurring in a river provides important information about the mobility of large wood in its channel (Abbe & Montgomery 2003). Examination of wood accumulations in the Czarny Dunajec enabled identification of the vast majority of them (whether individual pieces or their aggregates) as unstable debris, with most of the jams representing bar top and bank edge types. Such a situation

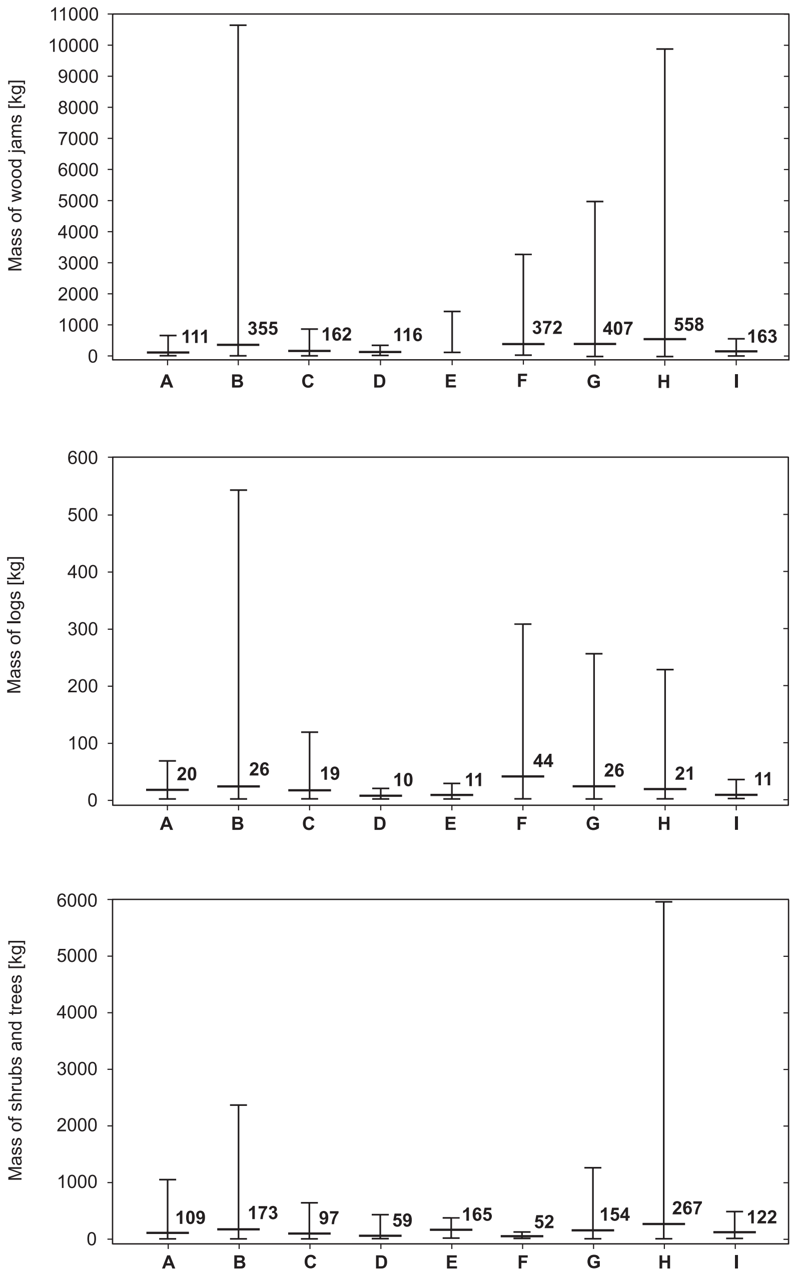

Fig. 5. Mean and variation of the mass of wood stored in different accumulation types in the investigated river sections of a given type of channel management and similar morphology. Figures on the right of each range plot indicate mean mass of particular wood accumulation types. Only two jams were retained in section E and thus no mean value of the jam mass is indicated for this section

reflects an almost complete lack of delivery to the river of trees being sufficiently large to remain stationary in its main channel and become key wood pieces; in fact, such trees were absent in the Czarny Dunajec shortly before the 2001 floods, and during the floods only a few large specimens of *Salix alba* fell to its channel within section H. Flood jams were scarce but they represented the largest wood accumulations in the study reach; such jams originated from the debris braced against the heads of vegetated islands in the wide, multi-thread river sections. Finally, a few debris dams were recorded in the narrow, side channels within the multi-thread sections G and H. These structures, representing combination jams in the classification of Abbe and Montgomery (2003), owed their stability to the anchoring of fallen trees on the trees overgrowing the opposite channel bank.

AMOUNT OF WOOD ACCUMULATIONS OF PARTICULAR TYPES AND THEIR CONTRIBUTION TO THE WOOD STORAGE ALONG THE STUDY REACH

Remarkable differences in the number of wood accumulations were apparent between the narrow and wide sections of the Czarny Dunajec (Fig. 6), and these differences were the principal reason for the discrepancy in the total quantities of stored wood observed between the two types of river sections. Variation in the number of wood accumulations explained 97% of the variation in total wood storage recorded among the investigated river sections, whereas only 64% of the latter variation was explained by variation in the mean mass of wood accumulations.

Among 1754 wood accumu-lations retained in the investigated sections of the Czarny Dunajec, 21.5% was represented by logs, 37.6% by shrubs and whole trees, and 40.9% by jams. However, with the considerable differences in average mass of particular wood accumulation types, their share in the total mass of stored wood was markedly different. Of 407.4 t of large wood retained in the investigated sections of the study reach, 2.1% was stored as single logs, 29.4% as shrubs and whole trees, and 68.5% as jams. Much larger proportion of the total mass of wood contained in shrubs and whole trees than in logs reflects species composition of the riparian forest, with the deciduous shrubs and trees recruited to the river being characterised by complex three-dimensional structure, and with logs originating only as a result of the breakdown of shrubs and trees during their fall and transport. A striking feature of the Czarny Dunajec is, however, the high degree of structuring of woody debris into jams, shown by the high proportion of this type of accumulation in the total mass of stored wood. Some reasons for this are the predominantly small size of the shrubs and trees delivered to the river as well as the high river energy, which together conditioned high mobility of the debris and facilitated its physical breakdown during transport. Moreover, the considerable complexity of the flow pattern typifying the wide river sections as well as the high density of trees within the relatively young forest covering the established islands in the Czarny Dunajec (Wyżga & Zawiejska 2005) facilitated trapping of the floated debris from flood water and its aggregation into jams in distinct areas within the active zone of the river.

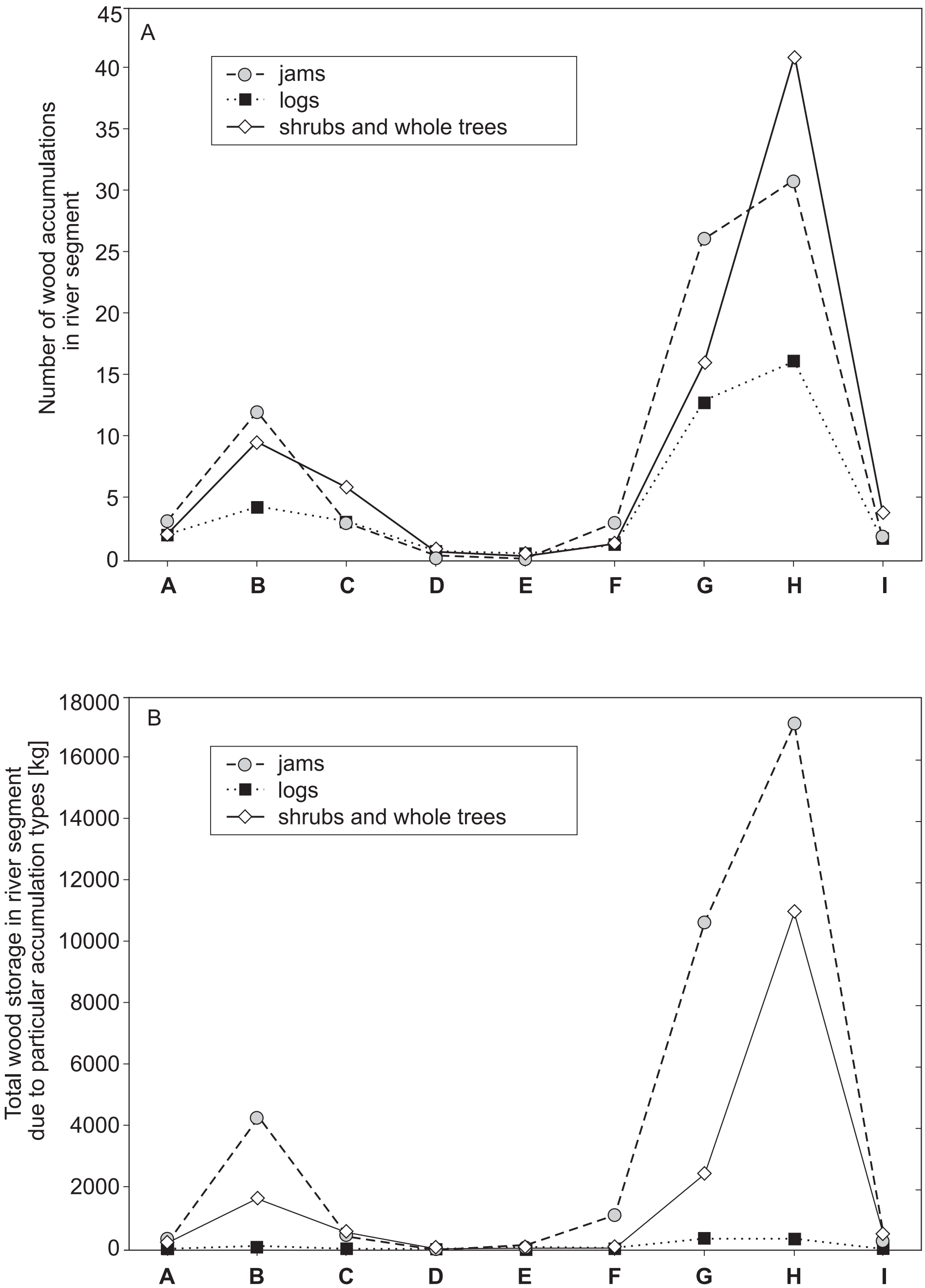

Fig. 6. Number of wood accumulations (A) and the total mass of wood stored in different accumulation types (B) in an average segment of the investigated river sections of a given type of channel management and similar morphology

The rapid increase in wood storage downstream of the 7.4 km long, channelized reach of the Czarny Dunajec (comprising sections C to E) was associated with significant changes in the composition of wood accumulations as well as in the contribution of their different types to the total mass of stored wood (Fig. 6). In section F, located immediately below the narrow, channelized part of the study reach, and in section G, located at a distance of 0.8–1.7 km from it, jams represented the largest part of the total number of wood accumulations, whereas in section H, 2.3–2.8 km downstream of the channelized reach, shrubs and whole trees were the most numerous accumulations. At the same time, the proportion of jams in the total mass of stored wood progressively decreased in the downstream direction, from 90.3% in section F to 60.3% in section H, in favour of that of shrubs and whole trees, which increased from 5.5% in section F to 38.5% in section H.

The changes in the significance of particular wood accumulation types with increasing distance from the channelized reach were accompanied by marked alterations in the state of preservation of the debris (Wyżga & Zawiejska 2005). The vast majority of the debris deposited within sections F and G, close to the channelized reach, was highly disintegrated and abraded (Photo 1G), indicating considerable destruction of the wood during transport (cf. Moulin & Piégay 2004). This implies transport of such wood from a distant location and the scarcity of undercut banks within the channelized reach (Table 2) suggests that the majority of the highly degraded debris was most likely recruited to the river upstream of this reach. The debris was readily transported along the narrow, channelized reach, in which the high stream power (Table 2) and the lack of retention features (Photo 1C–E) resulted in conditions unfavourable for wood storage. Below the channelized reach, the widening of the channel and the reduction in transporting power of the river enabled deposition of the debris, whereas the abundance of retention features facilitated its structuring into jams. In section H, further downstream of the channelized reach, many shrubs and trees deposited in the river were well preserved, with unbroken crowns (Photo 1H) and intact leaves and bark. Here, much large wood was evidently recruited from the local riparian forest and, due to a high trapping efficiency of the section, was transported only for short distances.

DEPOSITIONAL SITES AND ENVIRONMENTAL ROLE OF LARGE WOOD IN NARROW AND WIDE RIVER SECTIONS

The environmental role of large wood depends not only on the amount and size characteristics of the retained debris but also on the location of its deposition within the active zone of a river. Observations of the preferential sites of debris deposition made immediately after the 2001 floods as well as of the influence that large wood has exerted on the functioning of the Czarny Dunajec in the post-flood time enhance the distinction between the narrow, channelized and incised river sections, and wide, unmanaged sections. Most of the scarce wood accumulations retained in the narrow river sections became anchored at high flow on trees growing along

Photo 2. Examples of the environmental role played by large wood in the wide, multi-thalweg sections of the Czarny Dunajec

(A) Deflecting flow in wide, active channels that increases their sinuosity; (B) Forcing pool formation and providing habitat structures in narrow, side channels

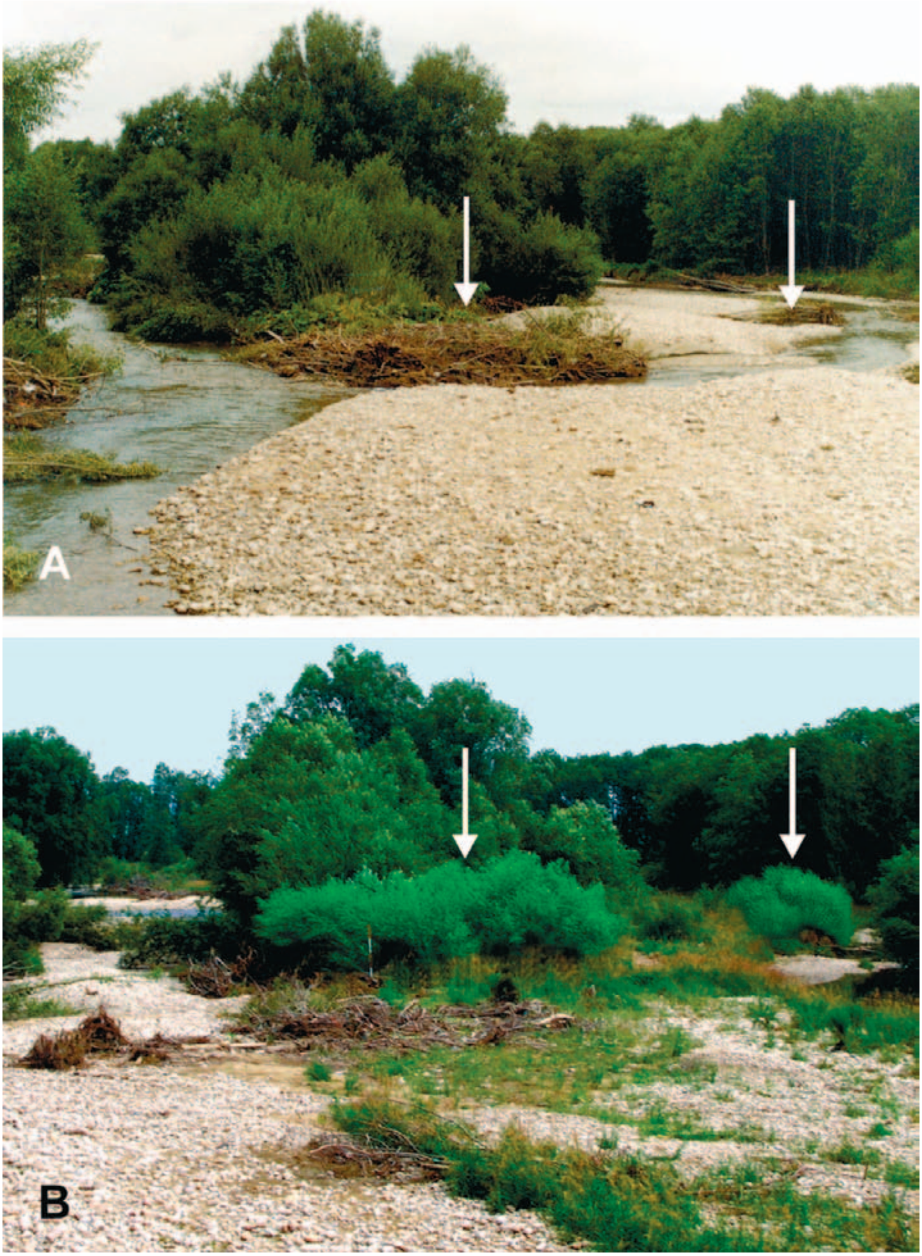

Photo 3. Development of pioneer islands from sprouting pieces of living driftwood deposited in the wide, multi-thalweg section H of the Czarny Dunajec

The photo taken in July 2005 (B) shows willow vegetation about 3 m high developed from jam (centre) and shrub (right) deposited by the July 2001 flood (A). Note the upstream-decreasing height of trees overgrowing the established island the channel margins and some logs were deposited on side bars during flood recession. Deposited outside the low-flow channel, these accumulations have had little influence on physical and biotic processes in the river. In the wide, multi-thread river sections, large wood was retained in a variety of depositional sites. Most individual shrubs and trees were deposited along retreating river and island banks, on bar surfaces and, in the case of large specimens of *Salix alba*, also in the middle of low-flow channels. The debris structured into jams accumulated on bar surfaces, at the heads and margins of established islands, in the areas located upstream of shrub patches, and in narrow low-flow channels. The heads and margins of established islands, point bar crests as well as narrow, steep-gradient side channels actively eroding laterally were found to preferentially retain woody debris in the wide sections (Wyżga & Zawiejska 2005).

Our observations have indicated considerable morphological, hydraulic and ecological impacts of large wood retained in the wide, multi-thread sections of the Czarny Dunajec. The wood braced against the heads of vegetated islands or deposited as lateral ribbons along their margins protects the islands from erosion and funnels flood flows in the intervening low-flow channels, thus promoting the maintenance of the island-braided channel pattern. Trees and shrubs fallen into wide, active channels but still attached by their roots to a bank direct flow into the opposite bank (Photo 2A) and, by stimulating its fast retreat and deposition of a gravel bar on the downstream side of the trees, promote the increase in sinuosity of the channels. Although such fallen trees function hydraulically in a similar way to flow-deflection jams described by Abbe and Montgomery (2003) from the Queets River in the Pacific Northwest, their relatively small size means that their impact finishes when the trees become detached from the bank. Trees fallen to narrow, side channels dam them, inducing scouring of pools and forming relatively stable habitat structures for aquatic biota (Photo 2B).

During the 2001 floods newly recruited large specimens of *Salix alba* played a role of key wood pieces, dividing thalweg and inducing the formation of mid-channel bars around them. However, their functioning as large, stable roughness elements in the river (cf. Abbe & Montgomery 1996) was terminated during the subsequent year as the trunks and branches of the trees were removed for firewood. The removal of larger fallen trees from the river must have been practised also in the past decades as indicated by an apparent lack in the Czarny Dunajec of established islands with the age of growing trees decreasing in the downstream direction, typical of the islands developed along large, stationary fallen trees (cf. Fetherston *et al.* 1995; Abbe & Montgomery 1996, 2003). On the other hand, numerous observations have indicated regeneration by sprouting of living willow driftwood deposited both on open gravel areas (Photo 3 – right) and at the heads of established islands (Photo 3 – centre). The growth of vegetation from living driftwood has been much faster from that germinating from seeds (cf. Gurnell *et al.* 2001) and during four years following the 2001 floods led to the development of 3 m high pioneer islands (Photo 3B) in comparison with 1 m height attained by the trees growing from seedlings.An upstream-decreasing age of trees typical of some established islands in the Czarny Dunajec (Photo 3) shows that in this river with relatively small, highly mobile driftwood, the deposition during successive floods of living wood on the upstream margin of vegetated islands and its subsequent regeneration may be important mechanisms of the island growth.

5. DISCUSSION

Wood inventory performed in the Czarny Dunajec after a 7-year flood indicated that the average estimated mass of wood accumulations in the studied river reach amounted to only 233 kg, equivalent to about 0.5 m^3 of wood. A partial explanation to this may be the young age of the riparian forest in the multi-thread sections (Wyżga & Zawiejska 2005), reflecting a relatively rapid turnover of the riparian zone in the sections (cf. Piégay & Gurnell 1997, Gurnell *et al.* 2002), which conditions the relatively small size of recruited woody debris. But largely, the small size of debris accumulations in this European river reflects various forms of management (cf. Gurnell 2003), including: (i) riparian woodland management, with the harvest of larger trees reducing the quantity and size of wood pieces recruited to the river, (ii) channel management that in some sections considerably reduced the delivery of large wood to the river owing to the artificial bank reinforcement and increased the energy of flood flows, hence facilitating the mobility and physical breakage of woody debris, and (iii) the removal of larger fallen trees from the river for firewood. The small size of the debris accumulations implies high mobility of the wood and the latter is actually evidenced by considerable destruction of most of the debris deposited immediately downstream of the narrow, channelized reach (Wyżga & Zawiejska 2005), the high degree of wood structuring into jams and recognition of most of accumulations as unstable debris.

Investigations in the Czarny Dunajec revealed considerable differences in the amounts of stored wood as well as in the style of deposition and the environmental role of wood debris between narrow, channelized and incised river sections and wide, unmanaged sections. In the narrow, single-thread sections of regulated or bedrock channel, very small number of wood accumulations of relatively low mass were retained, with the total mass of wood stored in an average river segment being as low as 0.11 t. The amounts of wood retained in particular, narrow river segments were unrelated to the investigated morphometric and hydraulic parameters. Wood accumulations in the narrow sections were typified by small size variation and were mainly deposited along the channel margins, exerting little influence on the river functioning. In wider, partly reinforced and unmanaged river sections, the amounts of stored wood were directly related to river width and the length of eroded banks and inversely related to unit stream power at the flood peak. A threshold width of about 32–35 m, corresponding to about double the maximum height of trees in the riparian forest, separated depositional conditions for wood debris from those under which no large wood was generally retained in the river during the flood wave passage. Numerous wood accumulations of relatively high mass were retained in wide, unmanaged, multi-thread sections, with the total wood storage reaching up to 28.5 t in an average segment of the widest river section. In these sections, large wood accumulated in a variety of depositional sites, considerably contributing to the diversity of physical and biotic processes in the river, and showed relatively great size variation.

Recently Gurnell *et al.* (2002) have indicated usefulness of the analogies between processes governing the sediment transfer of mineral and organic components of a river's load for understanding the wood-related processes in watercourses. Indeed, the smaller size variation of wood accumulations stored in the narrow river sections of uniform morphology and the greater one of those retained in the wide sections of variable morphology seems analogous to the degree of sorting of mineral sediment deposited in the environments of uniform and variable energy of the transporting current, respectively. However, it is difficult to find a mineral sediment analogy that would help to explain the smaller average size of wood accumulations, not only jams but also individual pieces, stored in the narrow river sections of high unit stream power, and the greater average size of accumulations retained in the wide reaches of low unit stream power. The described situation is undoubtedly related to the predominant mode of wood transport in flotation (Braudrick *et al.* 1997) and, moreover, seems to be specific of the rivers wider than the height of trees growing on their banks. In such rivers fallen trees cannot be supported by the opposite bank and are readily entrained, provided that they can float in sufficiently deep water. In the narrow sections of the Czarny Dunajec, lacking wood retention features, deep and highly energetic flood-peak flow was competent to move all the wood pieces delivered to the channel. Retained in the sections could have been relatively small wood pieces which little protruded into the flow when deposited on the channel margins, or which entered the sections from upstream at the final stage of the flood. In the wide, multi-thread sections, flow was generally shallower and less energetic (its energy was distributed over the larger river width), and the abundance of retention features, such as bar tops and vegetated islands, enabled anchoring of floated wood. Such conditions facilitated the retention of larger wood pieces and their aggregation into jams. Moreover, in the widest section H, large trees recruited to the river during the 2001 floods remained stationary, thus avoiding disintegration during transport (Wyżga & Zawiejska 2005).

This study has illustrated an increasing tendency of the values of total wood storage with increasing width of the wide mountain river. This tendency mimics a similar tendency of specific wood storage in the river, documented in the previous paper. Notably, both these tendencies differ from the relationships between total and specific wood storage and channel width known from watercourses narrower than the height of trees growing on their banks. In such streams transported wood is preferentially deposited in narrower channel sections (Gurnell *et al.* 2002), and hence these watercourses exhibit a lack of the dependence of total wood storage on channel width (that reflects increasing size of wood accumulations and average spacing between them as width increases – see e.g. Bilby & Ward 1989) and decreasing values of specific wood storage as the channels widen. In the wide Czarny Dunajec River wood was preferentially retained in wider river sections. As a result, both the average size and the number of wood accumulations remarkably increased with increasing river width, and thus total wood storage also increased as the river widened. As the rate of the increase in total wood storage accompanying widening of the river was higher than that of channel area, the values of specific wood storage also increased with increasing river width. These findings point to different mechanisms governing wood retention in mountain watercourses narrower and wider than the height of trees in the riparian forest.

6. PRACTICAL IMPLICATIONS OF THE STUDY

Observations from the Czarny Dunajec indicate that in a mountain river wider than the height of trees growing on its banks, environmentally significant quantities of large wood are deposited in wide, multi-thread sections but cannot be retained in narrow, channelized or incised river sections. The high potential of the wide, multi-thread sections for wood storage reflects efficient debris recruitment accompanying free migration of the active channels across the riparian woodland as well as low unit stream power and the abundance of retention features facilitating deposition of transported wood. While the sections remain in a relatively healthy environmental state (Wyżga *et al.* 2008), large wood significantly contributes there to the maintenance of their morphological and hydraulic complexity, the presence of habitat structures in channels and regeneration of riparian forest. Thus, avoiding the removal of large wood from such sections is important for the preservation of their good environmental status.

Moreover, the results from this study question the utility of naturally recruited large wood for restoration of mountain rivers affected by channelization and channel incision. Both processes resulted in the formation of a single-thread channel in which high stream power, the high depth of flood flows and the lack of retention features prevent deposition of wood debris and facilitate its removal to downstream sections. Successful restoration of such rivers with the use of naturally recruited woody debris would require the previous reduction of their transporting power. The latter could be attained by considerable widening of trained channels diminishing unit stream power of flood flows, or by constructing artificially elevated boulder riffles within incised channels reducing their in-channel flow capacity (Bojarski *et al.* 2005, Wyżga *et al.* 2005). Alternatively, restoration of channelized and incised mountain rivers might be undertaken with the use of artificially placed wood structures (engineered log jams) (cf. Abbe *et al.* 2003, Brooks *et al.* 2004). Such measures would not only increase the diversity of habitat conditions in the rivers but would also promote re-establishment of dynamic equilibrium conditions in the channels by reducing their flow capacity, forcing bed material deposition and initiation of bank erosion leading to the increase in channel sinuosity. Recent experimental construction of engineered log jams in an incised Australian river indicated effectiveness of the measures in preventing bed degradation and enhancing in-channel sediment storage (Brooks *et al.* 2006).

Finally, results from the presented study are instructive about management tools enabling retention of large wood upstream of intensively managed valley reaches. While allowing woody debris recruitment to watercourses and its subsequent downstream transfer within weakly managed valley reaches are increasingly recognised as important components of a new, environment-friendly policy of river management (e.g. Gregory & Davis 1992, Piégay & Landon 1997), jamming of the debris and damaging bridges or other infrastructures by floated wood remain threats to be avoided in urbanised areas. In relatively narrow, sinuous watercourses, artificial trapping structures constructed on the floodplain may filter much wood from flood water, but this tool will be inefficient in the case of wide, relatively straight rivers. In such rivers, far better solution seems to be stimulating/allowing the formation of a wide, multi-thread reach with the river and vegetated island banks artificially protected from erosion. Low river energy in such a reach and high island roughness would result in the great potential of the reach for wood retention, whereas preventing bank erosion would here eliminate recruitment of new woody debris to the river.

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