Science of the Total Environment 838 (2022) 156354

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

First insight into the macroplastic storage in a mountain river: The role of in-river vegetation cover, wood jams and channel morphology

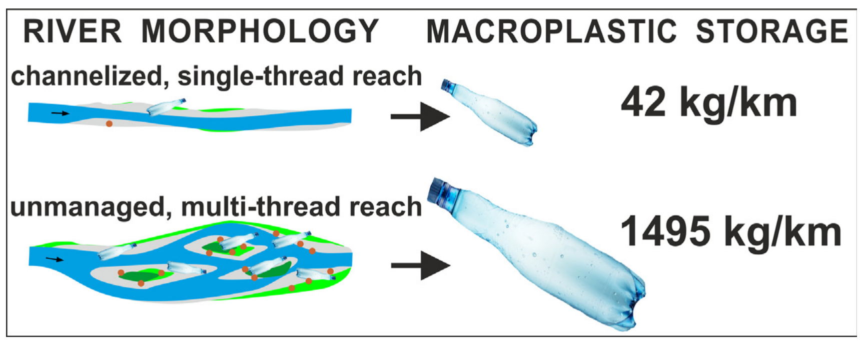
Maciej Liro *, Paweł Mikuś, Bartłomiej Wyżga

Institute of Nature Conservation, Polish Academy of Sciences, al. Mickiewicza 33, 31-120 Kraków, Poland

HIGHLIGHTS

- Storage of macroplastic debris in a mountain river was investigated.
- Effects of in-river vegetation cover, wood jams and channel morphology on macroplastic storage were determined.
- Wood jams and wooded islands were key features responsible for macroplastic entrapment in the mountain river.
- Multi-thread river reach stored 36 times more macroplastic per 1 km than channelized reach.
- Style of channel management and channel morphology control the pattern of macroplastic storage in mountain rivers.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damià Barceló

Keywords:
Macroplastic storage
Mountain river
Wood jam
Wooded island
Channel morphology

ABSTRACT

Macroplastic storage in mountain rivers remains unexplored and it is unknown how river morphology and different surface types of river areas modulate this process. Therefore, we sampled macroplastic debris stored on the surface of emergent river areas with different vegetation cover and on wood jams in a channelized, single-thread reach and an unmanaged, multi-thread reach of the Dunajec River in the Polish Carpathians. Total amounts of macroplastic debris retained in these reaches were then estimated on the basis of mean mass of macroplastic deposited on unit area of each surface type and the area of this surface type in a given reach. Exposed river sediments and areas covered with herbaceous vegetation stored significantly lower amounts of macroplastic debris (0.6 and 0.9 g per 1 m^2 on average) than wooded islands and wood jams (respectively 6 g and 113 g per 1 m^2). The amounts of macroplastic debris stored on wood jams exceeded 19, 129 and 180 times those found on wooded islands, areas covered with herbaceous vegetation and exposed river sediments. Wooded islands and wood jams covering 16.7% and 1.5% of the multi-thread reach stored 43.8% and 41.1%, respectively, of the total amount of macroplastic stored in that reach, whereas these surface types were practically absent in the channelized reach. Consequently, the unmanaged, multi-thread reach, 2.4 times wider than the neighbouring channelized reach, stored 36 times greater amount of macroplastic per 1 km of river length. Our study demonstrated that the storage of macroplastic debris in a mountain river is controlled by channel management style and resultant river morphology, which modulate river hydrodynamics and a longitudinal pattern of the zones of transport and retention of macroplastic conveyed by river flow.

1. Introduction

The storage of macroplastic in rivers has only recently started to be recognized (Gabbott et al., 2020; Hurley et al., 2020; Liro et al., 2020a; van Emmerik and Schwarz, 2020; van Emmerik et al., 2022) and remains unexplored in the case of mountain watercourses. However, understanding this

* Corresponding author.
E-mail address: liro@iop.krakow.pl (M. Liro).

http://dx.doi.org/10.1016/j.scitotenv.2022.156354
Received 16 March 2022; Received in revised form 9 May 2022; Accepted 26 May 2022
Available online 29 May 2022

process is crucial for planning future mitigation measures for riverine plastic pollution, because macroplastic debris constitutes most of riverine plastic in terms of mass (van Emmerik et al., 2019) and its fragmentation is a key source of secondary microplastic production in rivers (Horton and Dixon, 2017; Hurley et al., 2020). Moreover, presence of macroplastic debris in the riverine environment creates numerous risks: e.g., its ingestion or entanglement by aquatic and terrestrial animals (Jâms et al., 2020; Blettler and Mitchell, 2021), increased potential for clogging of flood-protection infrastructure (Honingh et al., 2020) and decreased aesthetic value of riverine landscapes (Al-Zawaidah et al., 2021; Lechthaler et al., 2020). The storage of macroplastic debris in rivers also creates a risk of its remobilization during future floods (Liro et al., 2020a; Roebroek et al., 2021). As a result of the long residence time of macroplastic debris in the riverine environment (Chamas et al., 2020) and the fact that substantial amounts of alluvial sediments are currently polluted by it (van Emmerik et al., 2022), a repeated storage–remobilization cycle may last for long periods of time, even after the disposal of new plastic waste to the river is reduced or eliminated (Liro et al., 2020a).

These problems are particularly important in mountain rivers that are typically characterized by the occurrence of high-energy floods and frequent sediment erosion (Wohl, 2010), favouring future remobilization of stored macroplastic debris. Moreover, mountain river ecosystems typically have high ecological potential and high aesthetic values (Hauer et al., 2016; Wohl, 2018), which may be significantly reduced by macroplastic pollution. Mountain rivers are shaped by reciprocal interactions among stream flow, sediment calibre and supply, riparian vegetation development (Church, 2002; Corenblit et al., 2007; Gurnell et al., 2009, 2016), and by human interventions such as channel regulation or dams (Gregory, 2006; Wohl, 2006). These factors control the occurrence of river reaches with different styles of channel management and morphology, such as unmanaged, multi-thread reaches and channelized, single-thread reaches (Gurnell et al., 2009), as well as the presence of different geomorphic units, e.g. low-flow channels, channel bars, wooded islands (Belletti et al., 2017), and the accumulations of driftwood within these reaches (Gurnell et al., 2002). These elements of mountain rivers were hypothesized to have different potential for the entrapment and storage of macroplastic (Liro et al., 2020a), but this has not been quantified previously. Gaining such information for these units of mountain rivers would create a baseline for the evaluation of ecological and other risks resulting from the storage of macroplastic debris and for assessment of the potential for its future remobilization by flood flows or sediment erosion. It would also provide data for upscaling the values and patterns of macroplastic storage to larger river units or entire river systems (Liro et al., 2020a; van Emmerik et al., 2022).

In this study, we used two neighbouring reaches of the gravel-bed Dunajec River (Polish Carpathians) with different styles of channel management and contrasting morphologies (channelized, single-thread and unmanaged, multi-thread) to examine the storage of macroplastic in the active river zone. We aimed: (i) to quantify differences in macroplastic storage between river geomorphic units that are emergent at low to medium flows, i.e. exposed river sediments, river areas overgrown with herbaceous vegetation and wooded islands, (ii) to recognize the potential of wood jams for the storage of macroplastic debris, and (iii) to identify and explain differences in the amounts of stored macroplastic between the two mountain river reaches.

2. Study area

The study was conducted in the gravel-bed Dunajec River draining the Western Carpathians in southern Poland. Fieldwork was performed in two river reaches located in the intramontane Orawa–Nowy Targ Basin, upstream from the Czorsztyn Reservoir (Fig. 1). Upstream from the study site, the river catchment has an area of 791 km^2 and elevations range from 533 to 2301 m a.s.l. This part of the Dunajec catchment is underlain by metamorphic rocks, granites, limestones, dolomites and flysch complexes (Zawiejska and Krzemień, 2004). The flow regime of the river is typified by low winter flows and flow maxima occurring in late spring or summer (Kundzewicz et al., 2014), although lower, less frequent floods may also occur during autumn (rain-caused floods) and winter (snow-melt floods) (Ruiz-Villanueva et al., 2016a). Such a hydrological regime is determined by the high-mountain part of the catchment where average annual precipitation totals amount to 1200–1700 mm (Niedźwiedź and Obrębska-Starklowa, 1991). At the Kowaniec gauging station situated 13.5 km upstream from the Czorsztyn Reservoir, the average for annual maximum discharges (1951–2018) is 248.4 m^3 s^{-1}. Prior to the onset of river channelization in the 1920s, the Dunajec in the Nowy Targ Basin flowed in a multi-thread channel (Zawiejska and Wyżga, 2010; Hajdukiewicz et al., 2019). Channelization conducted in the last century caused remarkable narrowing and incision of the river and the replacement of its multi-thread channel with a single-thread channel (Zawiejska and Wyżga, 2010; Hajdukiewicz et al., 2019).

Macroplastic sampling was carried out in two river reaches located 3.0–4.5 km (channelized reach 1) and 1.3–2.5 km (multi-thread reach 2) upstream from the Czorsztyn Reservoir (Fig. 1A). These reaches are not subject to backwater inundation from the reservoir (Liro et al., 2020b) and were delimited in the section where the Dunajec River receives no significant tributaries. In both reaches, the river was channelized in the 1920s–1930s and again in the 1960s–1970s (Zawiejska and Krzemień, 2004). Reach 1 has remained channelized and here the river channel is deeply incised (with bankfull channel depth of 3–3.5 m) and has relatively steep gradient of 0.0053 m m^{-1} and an average width of 69.8 m. The bed is formed of pebble to cobble material with the median grain size varying between 77 and 127 mm (Liro et al., 2020b). In this reach, the river supports a small proportion of gravel bars, whereas small wooded islands occur occasionally only on a gravel bar formed in a sharp channel bend (Fig. 1A). The floodplain is colonized by mature riparian forest composed mostly of willows and alder with a subordinate proportion of spruce and ash.

In reach 2, the construction of the Czorsztyn Reservoir in 1997 has induced in-channel deposition of gravelly material leading to the formation of mid-channel bars, bank erosion and re-establishment of a multi-thread channel pattern over the next two decades (Liro, 2016; Liro et al., 2020b). Currently bankfull channel depth amounts here to 2.5–3 m and channel gradient is 0.004 m m^{-1}. The active river zone has an average width of 166.5 m and is typified by a high proportion of bars and wooded islands (Fig. 1A). The river bed consists of pebble–cobble material with the median grain size ranging from 51 to 85 mm (Liro et al., 2020b). The floodplain is covered by a mixture of willow–alder riparian forest, spruce plantations and grassy surfaces (meadows and a soccer pitch). Young parts of wooded islands are overgrown with dense shrubs of willows, alder and German tamarisk (*Myricaria germanica* L.), whereas older parts are covered with less dense stands of alder and willows with the understorey of butterbur (*Petasites* Mill.). In the years without major floods, extensive parts of channel bars are covered by dense grassy and herbaceous vegetation.

The catchment of the upper Dunajec River has a relatively high population density of ~133 people per 1 km^2 (DYP, 2021). The town of Nowy Targ with 35,000 inhabitants is located 10 km upstream from the beginning of the study reach 1, but the catchment is mostly a rural area with a long history of dumping waste on river floodplains and along stream banks. With two national parks in its mountain parts, the area is visited by a few million tourists annually. Macroplastic debris dumped on the river floodplains and stream banks, scattered over the catchment or thrown into ravines and roadside ditches by local inhabitants and tourist visitors can be mobilized during floods and delivered to the study reaches of the Dunajec. However, no significant tributary that might be a point source of macroplastic input to the river joins it between the study reaches.

3. Study methods

3.1. Macroplastic sampling

Macroplastic sampling was conducted in August–September 2021 at base-flow conditions. The following geomorphic units were distinguished

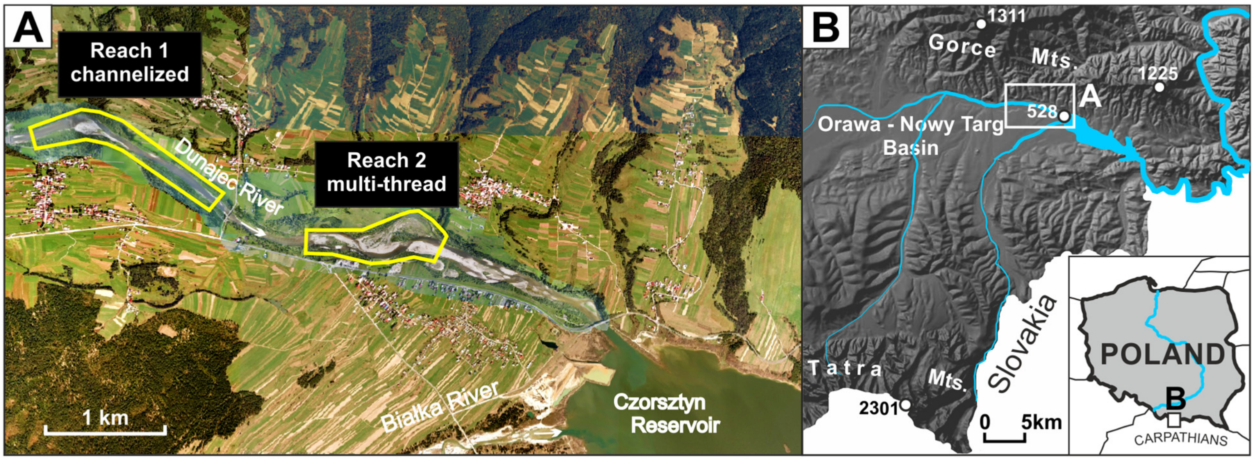


Fig. 1. Detailed location of the study reaches of the Dunajec River (A) and their location on the background of the topography of the upper part of the river catchment (B).

within the active channel/active river zone of the study reaches: (i) low-flow channels, (ii) exposed sediments (Fig. 2A), (iii) sediments overgrown with herbaceous vegetation (Fig. 2B), and (iv) wooded islands (Fig. 2C). Careful visual inspection of low-flow channels indicated that they lack macroplastic deposited on the bed surface and thus no sampling plots were located within this unit. In units ii–iv, sampling was conducted on plots with the size of 4×5 m (20 m^2). Plots were located to cover the entire range of elevation of given surface types above low-flow channels and of their distance from low-flow channels (Fig. S1 in the Supplementary materials), and their total number in the study reaches was approximately proportional to the river area in each reach.

Apart from plots located in different geomorphic units of emergent river areas, we also sampled macroplastic retained on wood jams (Fig. 2D). These are heterogenous mixtures of logs, branches, root boles, and twigs of various sizes as well as fine organic matter and inorganic sediment (Gurnell et al., 2000a; Wyżga and Zawiejska, 2010). Macroplastic items visible on jam surface were collected from 29 wood jams ranging in area from 0.42 m^2 to 18.7 m^2 (Table S1).

Horizontal position of surveyed plots and wood jams was measured with an RTK GPS receiver and their elevation above low-flow water level was determined with an optical level. Macroplastic items found on plots and surveyed wood jams were hand-collected by two people. Collected

Fig. 2. Types of surfaces within the emergent areas of the Dunajec River surveyed for the amount of stored macroplastic: (A) exposed river sediments, (B) sediments overgrown with herbaceous vegetation, (C) wooded islands, and (D) wood jam.

plastic samples were labelled and transported to a laboratory. Here, the samples were cleaned and macroplastic items from each sample were counted and weighed. The amount of macroplastic debris stored on each plot/surveyed wood jam was expressed as number of items per 1 m^2 (macroplastic abundance) and their total mass per 1 m^2. Moreover, average mass of macroplastic items retained on individual plots/wood jams was calculated.

For each macroplastic sample collected on the surveyed plots and wood jams, proportions of plastic items composed of different polymers and used for different purposes were determined according to the classification proposed by van Emmerik et al. (2020a, 2020b). It included 7 categories: polyethylene terephthalate (bottles), polystyrene (cutlery, cups, plates), expanded polystyrene (foams, food boxes), hard polyolefin (bottle caps, containers, rigid items), soft polyolefin (bags, sheeting), multilayer items (combined materials, food wrappings and packaging), and other plastics. For each sample, colour of macroplastic items was also determined and classified to one of the four categories: bright colours (red, orange, yellow), dark colours (black, grey, brown), white and transparent objects. This last classification was done in order to evaluate the potential of plastic items deposited on given surface types for being noticed during cleaning actions. Data about plastic type and item colour determined for individual samples were subsequently averaged for four surveyed surface types from the unmanaged reach and for exposed sediments and areas covered with herbaceous vegetation from the channelized reach.

3.2. Statistical analysis of data

In the multi-thread reach, we surveyed considerable numbers of plots located on exposed sediments, sediments overgrown with herbaceous vegetation and wooded islands. This allowed us to verify the statistical significance of differences in macroplastic abundance, average mass of macroplastic items and mass of macroplastic debris stored on 1 m^2 between the three geomorphic units of emergent river areas with a non-parametric Kruskal–Wallis test, while the significance of differences between pairs of geomorphic units was determined with a Fischer's least significance difference *post hoc* test. In the channelized reach, wooded islands occurred sporadically, and here only differences between exposed river sediments and sediments overgrown with herbaceous vegetation could be statistically verified with a non-parametric Mann–Whitney test.

The channelized reach supported only a few wood jams and potential differences in the parameters characterizing macroplastic storage between wood jams and different geomorphic units of emergent river areas could be statistically verified only for the multi-thread reach. Here, differences in macroplastic storage on the surface of wood jams and each of the three geomorphic units of emergent river areas were examined with the Mann–Whitney test. Differences analysed in the study were considered statistically significant if p-value <0.05.

3.3. Assessment of the amount of macroplastic stored in the study reaches

In September 2021, after the macroplastic sampling, 1849 photos of the study reaches were taken by a DJI Phantom 4 Advanced Drone. The photos were taken from the height of ~80 m at base-flow conditions in the river. Fifteen ground control points measured with an RTK GPS receiver in each reach were used for georeferencing of the photos. Orthophotos of the study reaches with a resolution of 2.5 cm were subsequently generated from the photos using the Agisoft Photoscan software (cf. Rusnák et al., 2018). The RMS error of the generated orthophotos equalled 0.13 m for the channelized reach and 0.28 m for the multi-thread reach; together with the very high resolution of the orthophotos, this allowed for detailed recognition and areal measurements of analysed river features in both reaches.

Boundaries of river geomorphic units and wood jams in the study reaches were digitized manually on the orthophotos and areas of all

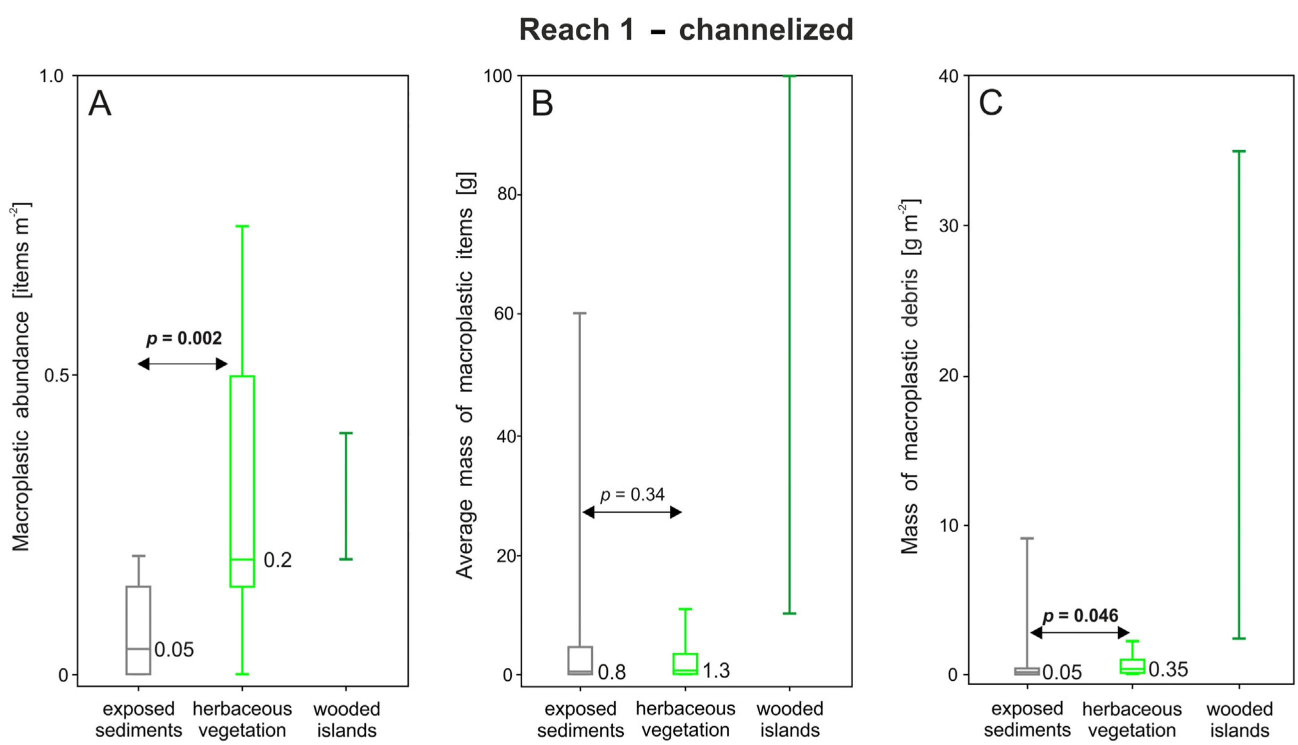


Fig. 3. Macroplastic abundance (A), average mass of macroplastic items (B) and mass of macroplastic debris stored on unit area of exposed sediments, sediments overgrown with herbaceous vegetation and wooded islands (C) in the channelized reach 1 of the Dunajec River. Diagrams for the first two surface types indicate extreme values (whiskers), the first and the third quartiles (the bottom and the top of the boxes, respectively) and median (the line inside the boxes and the number next to the line). As only 3 plots on wooded islands were surveyed in the channelized reach, the data for this surface type are presented with a range diagram. Statistical significance of the parameter difference between exposed sediments and sediments overgrown with herbaceous vegetation, determined with a Mann–Whitney test, is indicated. Statistically significant differences are indicated in bold.

polygons were measured with Quantum GIS software. Because wood jams occurred within various geomorphic units (i.e. exposed sediments, sediments overgrown with herbaceous vegetation, and wooded islands), the aggregated area of all jams present in a given geomorphic unit had to be subtracted from the aggregated area of all polygons of that unit in a given reach. In this way, absolute areas of the four river geomorphic units and wood jams in each reach were determined and their proportions in the total area of these reaches were then calculated. The amounts of macroplastic debris stored on given geomorphic units and wood jams of each reach were assessed as products of their total area and the mean mass of macroplastic debris found on unit area of these surfaces in that reach. Aggregation of macroplastic amounts estimated for all surface types yielded total amounts of surface-stored macroplastic in each reach. Finally, as the channelized and the multi-thread reaches have different lengths, the amounts were expressed as values per 1 km of river length to allow comparisons between the reaches.

4. Results

4.1. Effects of vegetation cover of emergent river areas on macroplastic storage

Only 3 plots in the channelized reach were located on wooded islands and this prevented statistical analysis of macroplastic storage on this surface type. Here, the amounts of macroplastic debris found on wooded islands ranged from 2.6 to 35 g m^{-2}, with the abundance of macroplastic items varying between 0.2 and 0.35 per 1 m^2 and their average mass between 10.4 and 100 g (Fig. 3, Table S1). Average mass of macroplastic items deposited in areas with herbaceous vegetation (median = 1.3 g) and on exposed river sediments (median = 0.8 g) did not differ statistically (Mann–Whitney test, $p = 0.34$) (Fig. 3B, Table S1). However, the number of macroplastic items retained in the areas covered with herbaceous vegetation (median = 0.2 item/m^2) was significantly higher ($p =$ 0.002) than on the exposed sediments (median = 0.05 item/m^2) (Fig. 3A, Table S1). As a result, the mass of stored macroplastic debris was also significantly higher ($p = 0.046$) on the former surface type (median = 0.35 g/m^2) than on the latter (median = 0.05 g/m^2) (Fig. 3C, Table S1).

A Kruskal–Wallis test indicated that the three geomorphic units with different surface types in the multi-thread reach differed significantly in number of macroplastic items ($p = 0.0003$), average mass of macroplastic items ($p = 0.0001$) and mass of stored macroplastic debris ($p = 0.004$) (Fig. 4). Number of macroplastic items did not differ significantly between areas with herbaceous vegetation (median = 0.25 item/m^2) and wooded islands (median = 0.28 item/m^2), but on both these surface types it was significantly higher (Fischer's LSD test, $p = 0.006$ and $p = 0.0005$, respectively) than on exposed river sediments (median = 0.1 item/m^2) (Fig. 4A, Table S1). Average mass of macroplastic items deposited on the exposed river sediments (median = 3.9 g) and in the areas covered with herbaceous vegetation (median = 2.8 g) was similar, but that of the items trapped on the wooded islands (median = 21.7 g) significantly exceeded those typifying the first ($p = 0.0002$) and the second surface type ($p = 0.0005$) (Fig. 4B, Table S1). Mass of deposited macroplastic debris also did not differ significantly between the exposed river sediments (median = 0.6 g m^{-2}) and the areas covered with herbaceous vegetation (median = 0.9 g m^{-2}), but on the wooded islands (median = 6 g m^{-2}) it was significantly higher than on the first ($p = 0.0002$) and the second surface type ($p =$ 0.003) (Fig. 4C, Table S1).

4.2. Effects of wood jams on macroplastic storage

A survey of 3 wood jams in the channelized reach indicated that the amount of macroplastic debris stored on the surface of these accumulations ranged from 281.2 to 666.7 g m^{-2}, macroplastic abundance varied

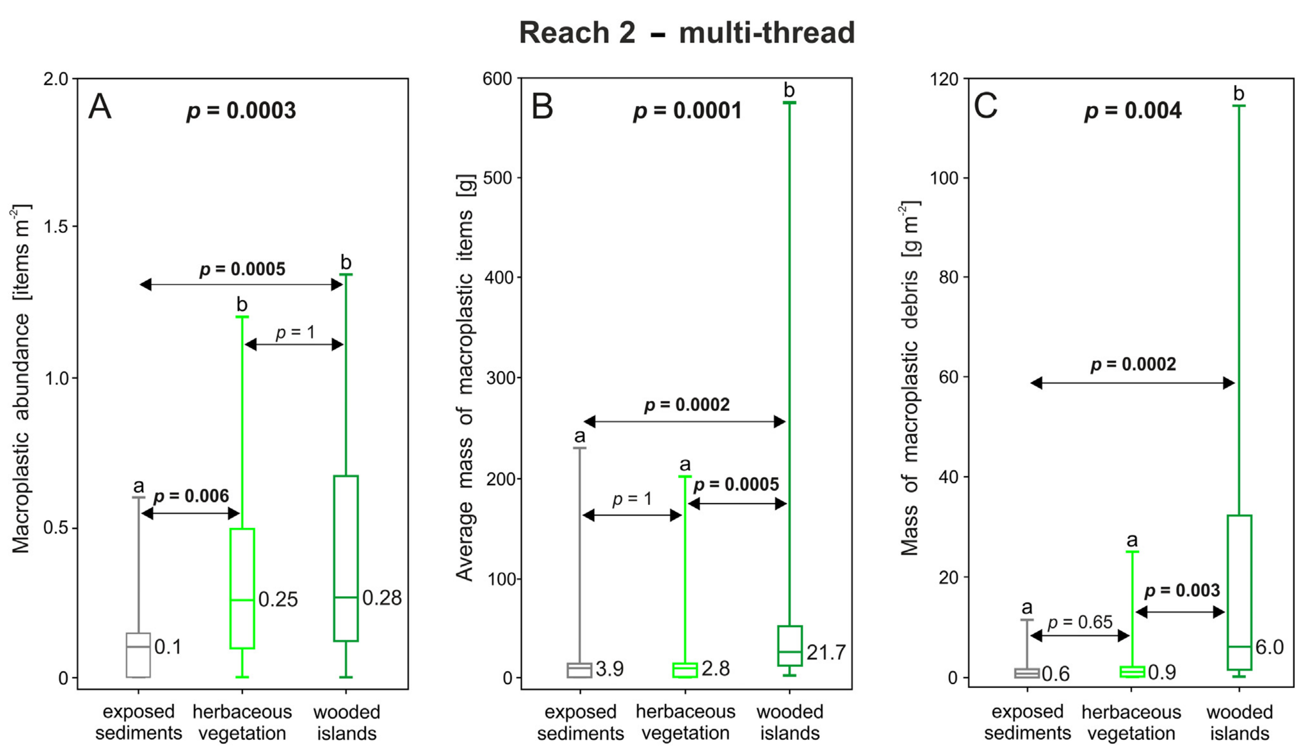


Fig. 4. Macroplastic abundance (A), average mass of macroplastic items (B) and mass of macroplastic debris stored on unit area of exposed sediments, sediments overgrown with herbaceous vegetation and wooded islands (C) in the multi-thread reach 2 of the Dunajec River. Diagrams indicate extreme values (whiskers), the first and the third quartiles (the bottom and the top of the boxes, respectively) and median (the line inside the boxes and the number next to the line). Statistical significance of the differences between the three river geomorphic units, determined with a Kruskal–Wallis test, is indicated at the top of the figure panels. Different letters denote statistically different samples indicated by a Fischer's LSD *post hoc* test and *p*-values above arrows indicate statistical significance of the differences between pairs of river geomorphic units determined with this test. Statistically significant differences are indicated in bold.

between 3 and 14.3 items per 1 m^2 of jam area and average mass of items ranged from 46.5 to 165.6 g (Table S1).

The multi-thread reach supported the occurrence of numerous wood jams and data from the survey of 26 jams allowed for a statistical comparison of macroplastic storage between the wood accumulations and different geomorphic units of emergent river areas. Here, macroplastic abundance on the surface of wood jams (median = 9.5 items/m^2) was 95 times higher than that recorded on exposed river sediments (Mann–Whitney test, $p < 0.000001$), 38 times higher than in areas covered with herbaceous vegetation ($p < 0.000001$), and 34 times higher than on wooded islands ($p < 0.000001$) (Fig. 5A, Table S1). The average mass of macroplastic items stored on wood jams (median = 11.1 g) exceeded nearly 3 times that on the exposed river sediments ($p = 0.001$) and 4 times that in the areas overgrown with herbaceous vegetation ($p = 0.001$) but did not differ significantly from that on wooded islands ($p = 0.12$) (Fig. 5B, Table S1). The amount of macroplastic debris stored on 1 m^2 of wood jams (median = 113.2 g m^{-2}) was 180 times higher than on the exposed river sediments ($p < 0.000001$), 129 times higher than in the areas covered with herbaceous vegetation ($p < 0.000001$), and 19 times higher than on the wooded islands ($p = 0.00001$) (Fig. 5C, Table S1). All these data indicate that wood jams are disproportionately important for the entrapment of macroplastic debris in the multi-thread river reach (Fig. 6).

4.3. Types and colours of plastic items retained on given surface types

In both study reaches, bags and sheeting made of soft polyolefin constituted more than half of the total number of macroplastic items deposited on exposed river sediments and in the areas covered with herbaceous vegetation, with somewhat greater proportion of such items retained on these surface types in the unmanaged reach (62%–63%) than in the channelized reach (52%–57%). Together with pieces of foam and food boxes made of expanded polystyrene, these two types of relatively light plastic items represented from 67% to 83% of all macroplastic pieces deposited on exposed sediments and in areas with herbaceous vegetation (Fig. 7). On wooded islands, bottles made of polyethylene terephthalate (PET) constituted one-third of all deposited items, whereas 54% of all items was represented by this type together with containers and other rigid pieces made of hard polyolefin. In turn, 36% of all items consisted here of relatively light pieces—bags and shredded plastic sheeting together with pieces of polystyrene foam and food boxes (Fig. 7). Wood jams also supported a variety of plastic

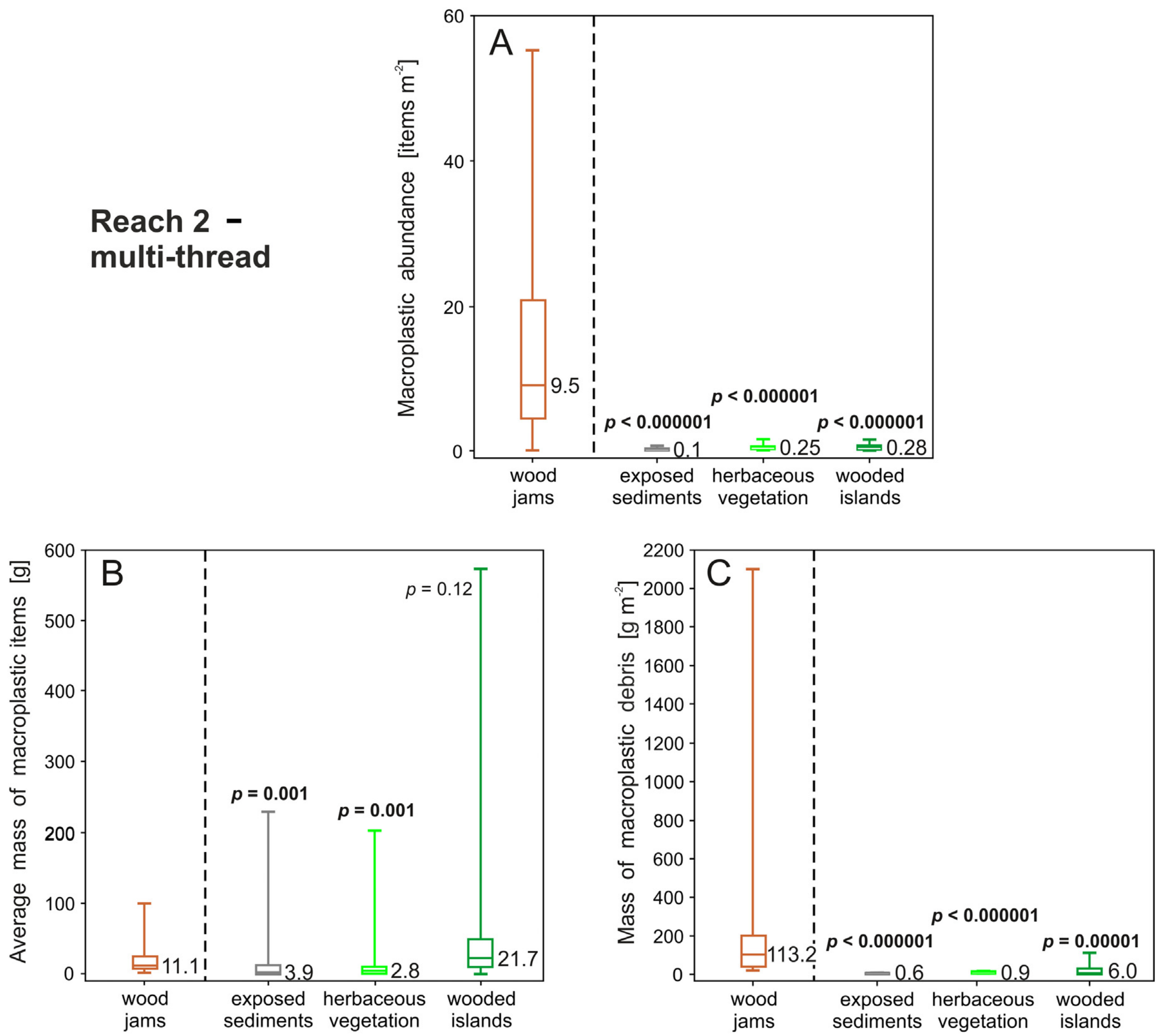


Fig. 5. Differences in macroplastic abundance (A), average mass of macroplastic items (B) and mass of macroplastic debris stored on unit area (C) between wood jams and exposed river sediments, sediments overgrown with herbaceous vegetation and wooded islands in the multi-thread reach of the Dunajec River. Diagrams indicate extreme values (whiskers), the first and the third quartiles (the bottom and the top of the boxes, respectively) and median (the line inside the boxes and the number next to the line). *p*-values indicate statistical significance of the differences between wood jams and a given surface type of emergent river areas determined with a Mann–Whitney test. Statistically significant differences are indicated in bold.

types, but bags and sheeting together with pieces of foam and food boxes constituted 59% of all retained items, whereas 30% were represented by bottles, containers and other rigid pieces (Fig. 7).

Transparent and white plastic items prevailed on all surveyed surface types, together representing from 68% to 76% of all pieces. In turn, items with dark colour represented 15% of all pieces on wood jams, 18% on wooded islands, 18%–20% in the areas with herbaceous vegetation and 24%–28% on exposed sediments (Fig. S2).

4.4. Effects of river morphology on macroplastic storage

The channelized and the multi-thread study reaches of the Dunajec River differed markedly in absolute and relative area of analysed geomorphic units and wood jams (Figs. 8–9, Table S2). In the channelized reach with an area of 69,772 m^2 per 1 km of river length (Fig. 9B), low-flow channel covered 59.2% of the river area (Fig. 9A). Areas emergent at low to medium flows represented ca. two-fifths of the river area, with sediments overgrown with herbaceous vegetation constituting 25% of the river area, exposed river sediments 13.95%, wooded islands 1.76% and wood jams only 0.01% (Fig. 9A, Table S2). The multi-thread reach had an area of 166,489 m^2 per 1 km of river length, ~2.4 times larger than in the channelized reach (Fig. 9B). Here, low-flow channels covered a similar absolute area as in the channelized reach (45,058 m^2 versus 41,333 m^2; Fig. 9B) but represented only 27% of the river area (Fig. 9A). Of nearly three-fourths of the river area represented by emergent areas, sediments overgrown with herbaceous vegetation constituted 37.3% of the river area, exposed river sediments 17.4%, wooded islands 16.7% and wood jams 1.5% (Fig. 9A, Table S2).

Storage of macroplastic debris in both reaches took place only on emergent surfaces (Fig. 9C, D), but differences in the amount of stored macroplastic between the reaches did not simply reflect either their different total area or the different total area of their emergent surfaces. The total mass of macroplastic debris stored in the multi-thread reach (1495.4 kg per 1 km of river length) was ~36 times larger than that stored in the channelized reach (41.8 kg per 1 km of river length) (Fig. 9D, Table S2). In the channelized reach, wooded islands covering a small proportion of the river area stored 46.6% of the total amount of macroplastic, 27.3% was stored in the areas overgrown with herbaceous vegetation, 17.9% on exposed river sediments and 8.2% on wood jams (Fig. 9C, Table S2). In the multi-thread reach, 43.8% of the total amount of macroplastic was stored on wooded islands, but wood jams covering a small proportion of the river area stored a similar amount—41.1%—whereas 12.85% was retained in the areas overgrown with herbaceous vegetation and 2.25% on exposed river sediments (Fig. 9C, Table S2).

5. Discussion

5.1. Macroplastic storage in different river geomorphic units

An inspection of low-flow channels of the Dunajec River did not indicate the occurrence of macroplastic debris. Most of macroplastic items can be transported in flotation or suspension because they are made of materials lighter than water, are buoyant due to contained air and their large surface area/mass ratio results in substantial drag exerted by flowing water (Shumilova et al., 2019; van Emmerik and Schwarz, 2020). In mountain rivers with fast-flowing water, such items either become deposited in emergent river areas or are transported downstream. In turn, items made of plastic materials heavier than water may under live bed conditions be stored in channel sediments below the bed surface or be rapidly abraded to microplastic as a result of collisions with bed material particles.

A survey of emergent river areas with different vegetation cover indicated that wooded islands stored an order of magnitude greater amounts of macroplastic on unit river area than exposed sediments and areas covered with herbaceous vegetation, which mostly reflected substantially greater average mass of macroplastic items deposited on islands than on the two other surface types. Woody vegetation increases the intensity of water turbulence, exerts drag forces on the flow and causes flow non-uniformity, and thus decreases flow velocity and shear stress exerted on the island surface and obstacles to the flow, such as stems, branches and leaves of trees and shrubs as well as understorey plants (Burkham, 1976; Aberle and Järvelä, 2015). This promotes deposition of sediments transported by river flows (Gurnell, 2014), including macroplastic debris (Williams and Simmons, 1997; Delorme et al., 2021; Newbould et al., 2021; Cesarini and Scalici, 2022). Moreover, wooded islands occur in the highest parts of channel bars (Fig. S1) and this additionally decreases water depth, flow velocity and bed shear stress on the islands during floods in comparison with lower-located areas with exposed sediments and herbaceous vegetation (cf. Liro et al., 2020b). A combination of the decreased hydrodynamics and the presence of physical barriers (Williams and Simmons, 1997; Newbould et al., 2021)—represented on our island plots by individual tree stems and the entire patches of vegetation—must have been a key factor resulting in greater amounts of retained macroplastic debris. Relatively rigid stems of trees and shrubs overgrowing wooded islands were able to trap large plastic objects, such as bottles and rigid plastic pieces, which could not be trapped by thinner and flexible herbaceous vegetation, and thus these types of macroplastic items were very common in the samples collected on the islands. In turn, the high elevation of wooded islands above low-flow channels facilitated the entrapment of light plastic items, such as pieces of foam and plastic bags, which typically float on the surface of floodwaters.

Fig. 6. Examples of the entrapment of macroplastic debris on wood jams in the multi-thread reach of the Dunajec River.

River areas covered with exposed sediments or herbaceous vegetation are typified by considerably lower surface roughness than those overgrown with woody vegetation (Chow, 1959). This, together with lower elevations of these areas above low-flow channels (Fig. S1), conditions higher velocities of flood flows (Liro et al., 2020b) resulting in greater momentum of floating objects, whereas higher water depth prevents their anchoring to the surface. Therefore, these two surface types retained relatively small plastic objects made of light materials (plastic bags, sheeting, pieces of foam), which were typified by relatively small momentum and were most likely deposited during flood wave recession. Plastic pieces deposited on exposed sediments can be particularly readily remobilized by the subsequent flow pulse, and thus this surface type was typified by the lowest abundance of macroplastic items.

In the rivers of the temperate climatic zone, the potential of wooded islands for macroplastic entrapment should change during a year, being greater during the growing season—when understorey vegetation and leaves of woody vegetation contribute to the resistance to flow—and lower in the remaining part of a year. It can also change during the passage of flood waves, if understorey or (more rarely) woody vegetation is bent down to the ground or uprooted.

5.2. Macroplastic storage on wood jams

The mass of macroplastic debris stored on unit area of wood jams exceeded that on exposed river sediments and in areas covered with herbaceous vegetation by more than 2 orders of magnitude and that on wooded islands by more than 1 order of magnitude. This high efficiency of wood jams in macroplastic entrapment most likely reflects a few ways in which wood jams affect and interact with flood flows. A three-dimensional structure of wood jams causes that they can trap floating macroplastic debris at various water levels during floods—not only on the upper surface but also on jam sides. Jams surveyed in the Dunajec River were up to 1.6 m high, which indicates that individual wood accumulations were able to trap macroplastic at considerably different flood levels. Wood jams increase resistance to flow (Dudley et al., 1998) as they block a portion of flow field, causing backwater effect, and induce flow non-uniformity: flow decelerates on the upstream side of a jam, separates around it and forms eddies immediately behind the obstacle (Abbe and Montgomery, 1996; Manners et al., 2007). This not only causes dissipation of flow energy (Radecki-Pawlik et al., 2016) but also allows plastic objects to be braced against the upstream jam side and to accumulate in the lee of a jam. As wood jams are formed of wood pieces of different size and orientation (Manners et al., 2007), they are porous structures (Spreitzer et al., 2020) with the porosity ranging from 13% to 90% (Thevenet et al., 1998). The flow of floodwater through a jam induces negative pressure acting on plastic objects braced against its upstream side, which causes that they adhere the jam and cannot be readily detached by water flowing around the wood accumulation. This effect can be described as filtering out plastic objects from the flow through the surface of a wood jam. Finally, wood jams usually have highly irregular surface conditioned by different size and orientation of constituent wood pieces (Fig. 6) and this hampers remobilization of plastic objects, once they were trapped by a jam. These diverse interactions of wood jams with flood flows and the occurrence of wood jams at varied elevations above low-flow channels (Fig. S1) are reflected in the retention of various plastic types on wood accumulations.

5.3. Macroplastic storage in river reaches of different morphology

The amount of macroplastic debris that can be retained in a given river reach is a function of macroplastic delivery from upstream and local sources, flood magnitude defining the extent of the zone of possible macroplastic deposition in the river cross-section, and river morphology reflecting channel management style and determining the occurrence of surface types with differing efficiency of macroplastic entrapment (Liro et al., 2020a; van Emmerik and Schwarz, 2020; van Emmerik et al.,

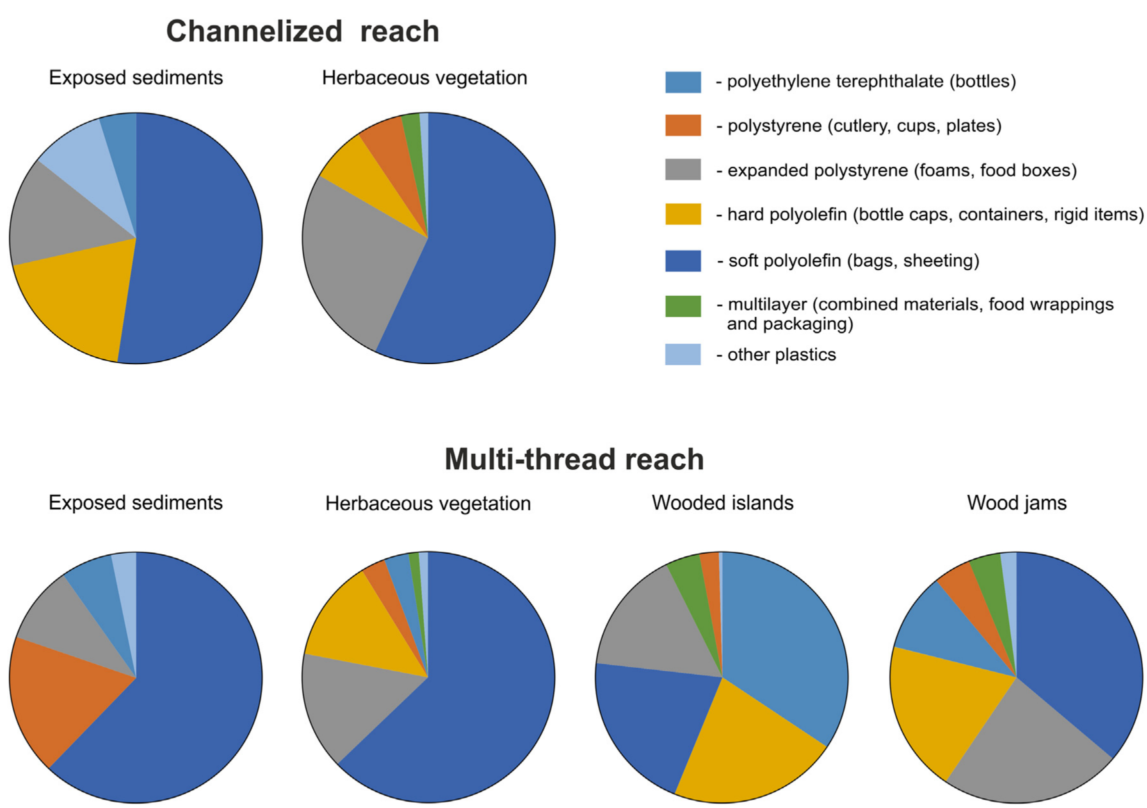


Fig. 7. Proportions of plastic items composed of different polymers and used for different purposes, that were found on sampled surfaces in the channelized and multi-thread reaches of the Dunajec River. The categories of wood jams and wooded islands from the channelized reach are not presented because of small number ($n = 3$) of surveyed plots on these surface types.

2022). As a result of the lack of significant tributaries along and between the closely-spaced study reaches, they do not differ in hydrological conditions (convey similar flows) and receive similar fluxes of macroplastic from the upstream catchment. Moreover, our observations did not indicate differences in the local delivery of macroplastic (e.g. resulting from illegal dumping of waste, recreational or touristic activities) to the river channel between the reaches. All this made an opportunity to identify and explain differences in macroplastic retention resulting from differing morphology of the study reaches.

The unmanaged, multi-thread reach of the Dunajec had 2.4 times larger total river area and 4.3 times larger emergent river area but stored 36 times greater amount of macroplastic debris than the channelized, single-thread reach. Notably, the channelized reach is located upstream from the multi-thread reach and the relatively small amounts of macroplastic debris retained in the former cannot be attributed to the high efficiency of macroplastic entrapment in the latter (which might be argued with the opposite configuration of the reaches). Instead, the remarkable difference in the storage of macroplastic debris between the reaches must reflect differences in the hydrodynamics of flood flows and the abundance of surface types with high entrapment potential—i.e., wooded islands and wood jams—resulting from differing morphology of the reaches.

In high-energy, mountain rivers, islands are formed through vegetation encroachment and development on mid-channel bars separating low-flow channels (Rinaldi et al., 2013) and their occurrence and longevity depend on the intensity of flood disturbance dictating the rate of periodic turnover of active river zone (Gurnell and Petts, 2006; Mikuś et al., 2013). Thus, islands do not develop in channelized river reaches which lack mid-channel bars and where the concentration of flood flows in the narrow channel results in high flow velocity and bed shear stress preventing persistence of woody vegetation. Research on island formation in the Raba, another Polish Carpathian river, indicated that islands begin to develop where river width attains 120% of the width in channelized reaches, and that the proportion of river area covered by islands increases with increasing river width (Mikuś et al., 2019). In the studied multi-thread reach of the Dunajec, islands covered 16.7% of the river area and retained 43.8% of the total amount of macroplastic debris stored in that reach (Table S2).

The style of channel management and morphology of mountain rivers also control the formation and abundance of wood jams. For instance, research on large wood in the Czarny Dunajec, a headwater part of the Dunajec River, indicated that wide, multi-thread river reaches stored ~1.5 order of magnitude greater number of wood jams per unit river length than narrow, channelized reaches (Wyżga and Zawiejska, 2010). We recorded only 3 wood jams in the 1.5-km-long channelized reach of the Dunajec, whereas the 1.2-km-long unmanaged, multi-thread reach supported the occurrence of 89 jams (Fig. 8). Large water depth and high unit stream power of flood flows and a general lack of wood retention features prevent wood deposition and facilitate its downstream transport in narrow, channelized reaches of mountain rivers. In contrast, shallower depths and lower unit stream power of flood flows and the abundance of wood retention features—such as crests of channel bars, heads and margins of wooded islands—create the conditions promoting wood deposition and the formation of wood jams in wide, unmanaged reaches (Gurnell et al., 2000b; Wyżga and Zawiejska, 2005; Ruiz-Villanueva et al., 2016a, 2016b). Wood jams were efficient traps for macroplastic debris in

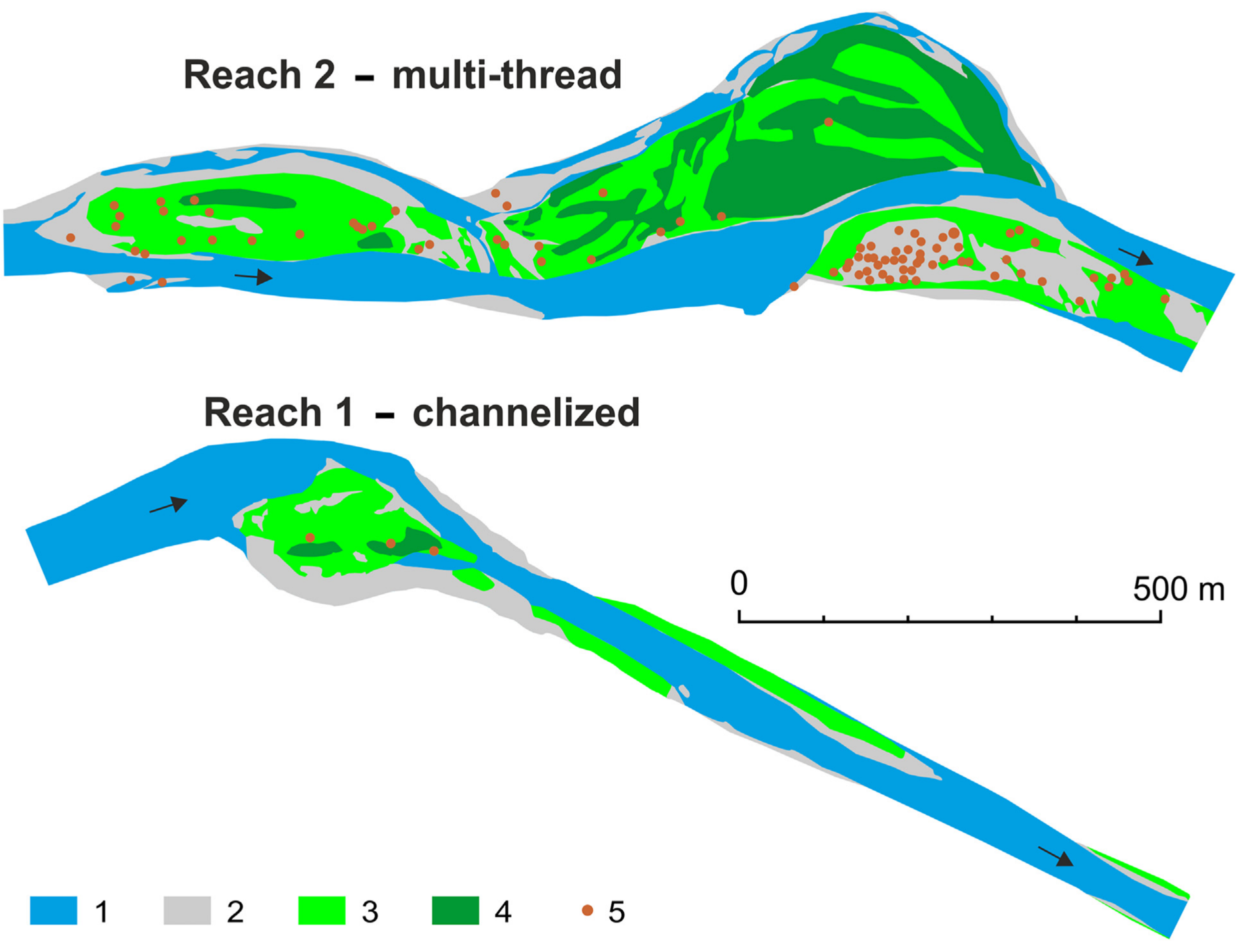


Fig. 8. Distribution of the geomorphic units of active channel/active river zone and wood jams in the study reaches of the Dunajec River. River areas emergent at low to medium flows are divided depending on the occurrence/type of the vegetation cover of their surfaces. 1 – low-flow channel; 2 – exposed river sediments; 3 – sediments overgrown with herbaceous vegetation; 4 – wooded island; 5 – wood jam.

both study reaches of the Dunajec, but their abundance in the multi-thread reach caused that they were responsible for the retention of as much as 41.1% of the total amount of macroplastic stored in that reach (Table S2).

Our results indicate that the vast majority of macroplastic debris disposed to single-thread, regulated or incised channels of mountain rivers or delivered to them by tributaries will be transported downstream and will have a possibility to be retained in the first wide, multi-thread reach. Most sections of Polish Carpathian rivers were channelized and their channel morphology was simplified from multi- to single-thread in the 20th century (Hajdukiewicz et al., 2019) and similar changes also affected most river sections in other mountain areas of Europe (Gurnell et al., 2009; Hohensinner et al., 2021). This means that these river sections currently function as transport zones of the fluvial systems, through which macroplastic debris can be transferred long distances until it arrives at places favouring macroplastic retention, such as preserved or restored multi-thread reaches or dam reservoirs. In the future, insight into the above described patterns may be obtained by the application of tracking experiments (cf. Duncan et al., 2020; Tramoy et al., 2020; Newbould, 2021; Newbould et al., 2021) that should allow for more detailed quantification of temporal and spatial scales of macroplastic transport and storage in river reaches with different management styles and morphologies.

Particular elements of gravel-bed rivers differ in the frequency of the disturbance of their surfaces by scouring floods (Van der Nat et al., 2003) and thus in the duration of storage of the macroplastic trapped on these surfaces. The bare surface of exposed river sediments indicates a recent disturbance and such sediments may be turned over many times in a year. Surfaces with a dense cover of herbaceous vegetation have not been scoured for at least a few months, but usually not more than 1–1.5 years, the time sufficient for the emergence of saplings. Wood jams persist from part of a year to a few years (Van der Nat et al., 2003), but in the rivers supplied with the large wood of tree species capable of re-sprouting, as it is in the study river, some wood jams may be transformed into pioneer islands (Mikuś et al., 2013, 2016). Finally, the longevity of wooded islands ranges from a year to a few tens of years (van der Nat et al., 2003; Mikuś et al., 2013). Notably, initial stages of the development of islands are typified by a rapid sediment accretion on island surface (Gurnell and Petts, 2006; Mikuś et al., 2013), which may change the surface storage of macroplastic deposited on islands into a subsurface one, additionally preventing macroplastic remobilization. It is thus apparent from the above specification that narrow, channelized reaches of mountain rivers consist almost exclusively of the elements allowing for only short-term retention of macroplastic, with subsequent flow pulses resulting in remobilization and downstream transfer of macroplastic debris. In contrast, multi-thread reaches represent a mosaic of surfaces with highly varied duration of macroplastic storage.

Regardless of the varied duration of macroplastic storage on different surface types, large amounts of macroplastic debris retained in multi-thread reaches make these reaches a suitable location of undertaking river cleaning actions. A detailed survey of colours of macroplastic items deposited on different surface types of the Dunajec indicated that most of the items are made of transparent, white or bright plastic and thus should be readily noticed by persons undertaking such actions. Only the plastic pieces of dark colour may be difficult to notice if deposited on vegetated parts of the river or wood jams, but the proportion of such pieces is relatively small (Fig. S2).

6. Concluding remarks

The study gave a first insight into spatial patterns of macroplastic storage in the active zone of a mountain river, identifying wooded islands

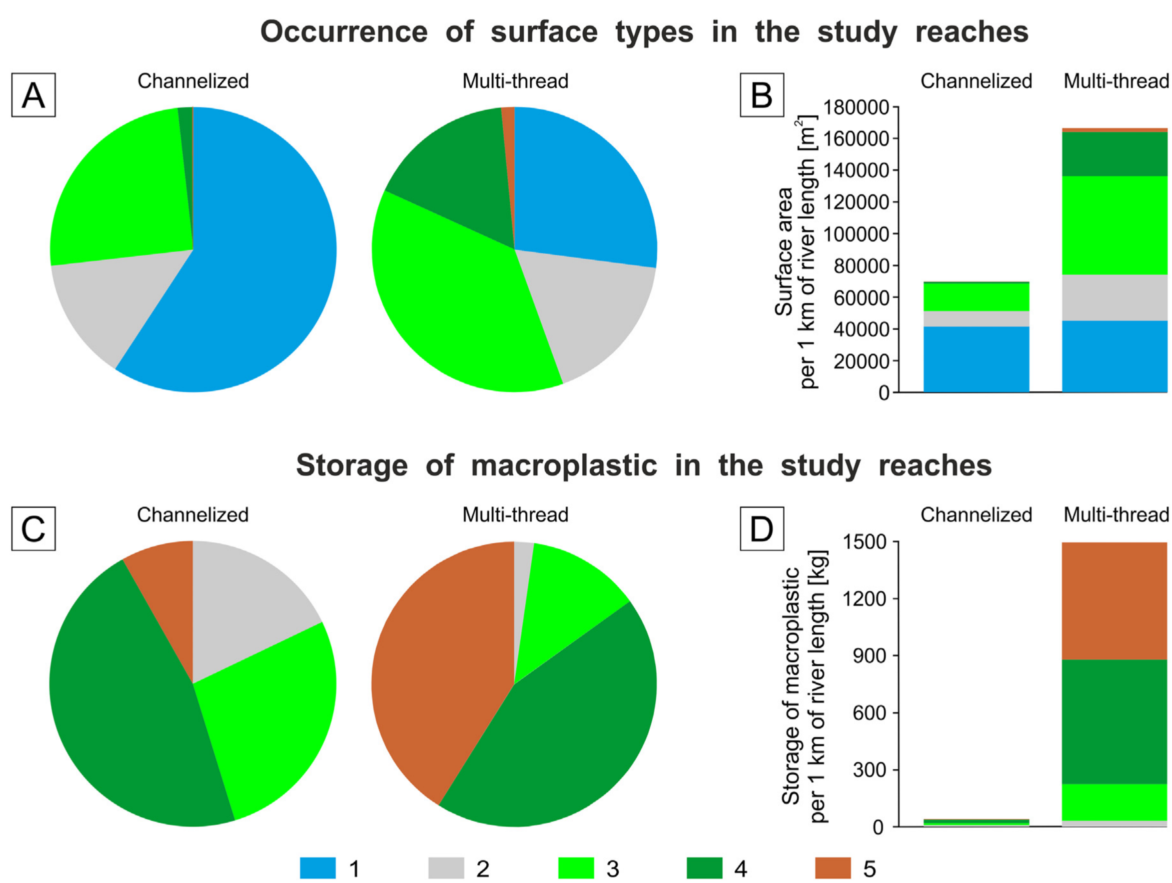


Fig. 9. Relative (A) and absolute (B) areas with different surface types representing river geomorphic units and wood jams in the channelized and the multi-thread study reaches of the Dunajec River, and relative (C) and absolute (D) amounts of macroplastic debris stored on these surface types in the reaches. 1 – low-flow channel; 2 – exposed river sediments; 3 – sediments overgrown with herbaceous vegetation; 4 – wooded island; 5 – wood jam.

and wood jams as efficient traps for macroplastic debris and demonstrating that a wide, multi-thread reach stores substantially larger amounts of macroplastic debris than a narrow, channelized reach. The amounts of macroplastic retained in the multi-thread reach are disproportionately large in relation to the area of this reach, which is explained by the abundance of wooded islands and wood jams with high macroplastic trapping efficiency. The observed spatial pattern of stored amounts of macroplastic debris indicates that multi-thread reaches of mountain rivers function as storage zones for macroplastic in the fluvial systems, while channelized reaches act as transport zones.

In the future, efforts should be made to quantify temporal patterns of macroplastic storage in different types of natural and human-made sinks occurring along Anthropocene mountain rivers. This may be done with use of tracking experiments or numerical modelling. To fully quantify the amounts of macroplastic stored in given parts of fluvial systems, future studies should also analyse macroplastic storage within the alluvium (i.e. subsurface storage) and on river floodplains (cf. Liro et al., 2020a), which was not explored in this study.

CRediT authorship contribution statement

All co-authors contributed to the realization of the study and writing of the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The study was partly supported by the statutory funds of the Institute of Nature Conservation, Polish Academy of Sciences, and completed within the scope of the Research Project 2020/39/D/ST10/01935 financed by the National Science Centre of Poland. We thank Malia Volke for improving the English style of the manuscript and two anonymous reviewers for their critical comments on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156354.

References

Abbe, T.B., Montgomery, D.R., 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regul. Rivers Res. Manage. 12, 201–221.

Aberle, J., Järvelä, J., 2015. Hydrodynamics of vegetated channels. In: Rowiński, P., Radecki-Pawlik, A. (Eds.), Rivers – Physical, Fluvial and Environmental Processes. Springer, Cham, pp. 519–541 https://doi.org/10.1007/978-3-319-17719-9.

Al-Zawaidah, H., Ravazzolo, D., Friedrich, H., 2021. Macroplastic in rivers: present knowledge, issues and challenges. Environ. Sci. Process. Impacts 23, 535–552. https://doi.org/10.1039/D0EM00517G.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A.M., Mao, L., Nardi, L., Vezza, P., 2017. Characterising physical habitats and fluvial hydrogeomorphology: a new system for the survey and classification of river geomorphic units. Geomorphology 283, 143–157. https://doi.org/10.1016/j.geomorph.2017.01.032.

Blettler, C.M., Mitchell, C., 2021. Dangerous traps: macroplastic encounters affecting freshwater and terrestrial wildlife. Sci. Total Environ. 798, 149317. https://doi.org/10.1016/j.scitotenv.2021.149317.

Burkham, D.E., 1976. Hydraulic effects of changes in bottom-land vegetation on three major floods, Gila River in southern Arizona. U.S. Geol. Surv. Prof. Paper 655-J, pp. 1–14.

Cesarini, G., Scalici, M., 2022. Riparian vegetation as a trap for plastic litter. Environ. Pollut. 292, 118410. https://doi.org/10.1016/j.envpol.2021.118410.

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M., Scott, S.L., Suh, S., 2020. Degradation rates of plastics in the environment. ACS Sustain. Chem. Eng. 8, 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635.

Chow, V.T., 1959. Open-channel Hydraulics. Blackburn Press, Caldwell (700 pp).

Church, M., 2002. Geomorphic thresholds in riverine landscapes. Freshw. Biol. 47, 541–557. https://doi.org/10.1046/j.1365-2427.2002.00919.x.

Corenblit, D., Tabacchi, E., Steiger, J., Gurnell, A.M., 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth Sci. Rev. 84, 56–86. https://doi.org/10.1016/j.earscirev.2007.05.004.

Delorme, A.E., Koumba, G.B., Roussel, E., Delor-Jestin, F., Peiry, J.L., Voldoire, O., Garreau, A., Askanian, H., Verney, V., 2021. The life of a plastic butter tub in riverine environments. Environ. Pollut. 287, 117656. https://doi.org/10.1016/j.envpol.2021.117656.

Dudley, S.J., Fischenich, J.C., Abt, S.R., 1998. Effect of woody debris entrapment on flow resistance. J. Am. Water Resour. Assoc. 34, 1189–1197. https://doi.org/10.1111/j.1752-1688.1998.tb04164.x.

Duncan, E.M., Davies, A., Brooks, A., Chowdhury, G.W., Godley, B.J., Jambeck, J., Maddalene, T., Napper, I., Nelms, S.E., Rackstraw, C., Koldewey, H., 2020. Message in a bottle: open source technology to track the movement of plastic pollution. Plos ONE 15, e0242459. https://doi.org/10.1371/journal.pone.0242459.

DYP, 2021. Demographic Yearbook of Poland 2021. Statistics Poland, Warsaw 530 pp.

Gabbott, S., Russell, C., Yohan, Y., Zalasiewicz, J., 2020. The geography and geology of plastics: their environmental distribution and fate. In: Letcher, T.M. (Ed.), Plastic Waste and Recycling. Academic Press, London, pp. 33–63 https://doi.org/10.1016/B978-0-12-817880-5.00003-7.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79, 172–191. https://doi.org/10.1016/j.geomorph.2006.06.018.

Gurnell, A., 2014. Plants as river system engineers. Earth Surf. Process. Landf. 39, 4–25. https://doi.org/10.1002/esp.v39.110.1002/esp.3397.

Gurnell, A., Petts, G., 2006. Trees as riparian engineers: the Tagliamento River, Italy. Earth Surf. Process. Landf. 31, 1558–1574. https://doi.org/10.1002/esp.1342.

Gurnell, A., Surian, M., Zanoni, L., 2009. Multi-thread river channels: a perspective on changing European alpine river systems. Aquat. Sci. 71, 253–265. https://doi.org/10.1007/s00027-009-9186-2.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., 2000a. Wood storage within the active zone of a large European gravel-bed river. Geomorphology 34, 55–72. https://doi.org/10.1016/S0169-555X(99)00131-2.

Gurnell, A.M., Petts, G.E., Harris, N., Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., 2000b. Large wood retention in river channels: the case of the Fiume Tagliamento, Italy. Earth Surf. Process. Landf. 25, 255–275.

Gurnell, A.M., Piégay, H., Swanson, F.J., Gregory, S.V., 2002. Large wood and fluvial processes. Freshw. Biol. 47, 601–619. https://doi.org/10.1046/j.1365-2427.2002.00916.x.

Gurnell, A.M., Corenblit, D., De Jalón, D.G., Del Tánago, M.G., Grabowski, R.C., O'Hare, M.T., Szewczyk, M., 2016. A conceptual model of vegetation–hydromorphology interactions within river corridors. River Res. Appl. 32, 142–163. https://doi.org/10.1002/rra.2928.

Hajdukiewicz, H., Wyżga, B., Zawiejska, J., 2019. Twentieth-century hydromorphological degradation of Polish Carpathian rivers. Quat. Int. 504, 181–194. https://doi.org/10.1016/j.quaint.2017.12.011.

Hauer, F.R., Locke, H., Dreitz, V.J., Hebblewhite, M., Lowe, W.H., Muhlfeld, C.C., Nelson, C.R., Proctor, M.F., Rood, S.B., 2016. Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. Sci. Adv. 2, 1–13. https://doi.org/10.1126/sciadv.1600026.

Hohensinner, S., Egger, G., Muhar, S., Vaudor, L., 2021. What remains today of pre-industrial alpine rivers? Census of historical and current channel patterns in the Alps. River Res. Appl. 37, 128–149. https://doi.org/10.1002/rra.3751.

Honingh, D., van Emmerik, T., Uijttewaal, W., Kardhana, H., Hoes, O., van de Giesen, N., 2020. Urban river water level increase through plastic waste accumulation at a rack structure. Front. Earth Sci. 8, 28. https://doi.org/10.3389/feart.2020.00028.

Horton, A.A., Dixon, S.J., 2017. Microplastic: an introduction to environmental transport processes. WIREs Water 5, e1268. https://doi.org/10.1002/wat2.1268.

Hurley, R., Horton, A., Lusher, A., Nizzetto, L., 2020. Plastic waste in the terrestrial environment. In: Letcher, T.M. (Ed.), Plastic Waste and Recycling. Academic Press, London, pp. 163–193 https://doi.org/10.1016/B978-0-12-817880-5.00007-4.

Jâms, I.B., Windsor, F.M., Poudevigne-Durance, T., Ormerod, S.J., Durance, I., 2020. Estimating the size distribution of plastics ingested by animals. Nat. Commun. 11, 1594. https://doi.org/10.1038/s41467-020-15406-6.

Kundzewicz, Z.W., Stoffel, M., Kaczka, R.J., Wyżga, B., Niedźwiedź, T., Pińskwar, I., Ruiz-Villanueva, V., Łupikasza, E., Czajka, B., Ballesteros-Canovas, J.A., Małarzewski, Ł., Choryński, A., Janecka, K., Mikuś, P., 2014. Floods at the northern foothills of the Tatra Mountains — a Polish-Swiss research project. Acta Geophys. 62, 620–641. https://doi.org/10.2478/s11600-013-0192-3.

Lechthaler, S., Waldschläger, K., Stauch, G., Schüttrumpf, H., 2020. The way of macroplastic through the environment. Environments 7, 73. https://doi.org/10.3390/environments7100073.

Liro, M., 2016. Development of sediment slug upstream from the Czorsztyn Reservoir (southern Poland) and its interaction with river morphology. Geomorphology 253, 225–238. https://doi.org/10.1016/j.geomorph.2015.09.018.

Liro, M., van Emmerik, T., Wyżga, B., Liro, J., Mikuś, P., 2020a. Macroplastic storage and remobilization in rivers. Water 12, 2055. https://doi.org/10.3390/w12072055.

Liro, M., Ruiz-Villanueva, V., Mikuś, P., Wyżga, B., Bladé-Castellet, E., 2020b. Changes in the hydrodynamics of a mountain river induced by dam reservoir backwater. Sci. Total Environ. 744, 140555. https://doi.org/10.1016/j.scitotenv.2020.140555.

Manners, R.B., Doyle, M., Small, M., 2007. Structure and hydraulics of natural woody debris jams. Water Resour. Res. 43, 1–17. https://doi.org/10.1029/2006WR004910.

Mikuś, P., Wyżga, B., Kaczka, R.J., Walusiak, E., Zawiejska, J., 2013. Islands in a European mountain river: linkages with large wood deposition, flood flows and plant diversity. Geomorphology 202, 115–127. https://doi.org/10.1016/j.geomorph.2012.09.016.

Mikuś, P., Wyżga, B., Ruiz-Villanueva, V., Zawiejska, J., Kaczka, R.J., Stoffel, M., 2016. Methods to assess large wood dynamics and the associated flood hazard in Polish Carpathian watercourses of different size. In: Kundzewicz, Z.W., Niedźwiedź, T., Stoffel, M., Wyżga, B. (Eds.), Flood Risk in the Upper Vistula Basin. Springer, Cham, pp. 77–101 https://doi.org/10.1007/978-3-319-41923-7_5.

Mikuś, P., Wyżga, B., Walusiak, E., Radecki-Pawlik, A., Liro, M., Hajdukiewicz, H., Zawiejska, J., 2019. Island development in a mountain river subjected to passive restoration: the Raba River, Polish Carpathians. Sci. Total Environ. 660, 406–420. https://doi.org/10.1016/j.scitotenv.2018.12.475.

Newbould, R.A., 2021. Understanding river plastic transport with tracers and GPS. Nat. Rev. Earth Environ. 2, 591. https://doi.org/10.1038/s43017-021-00212-5.

Newbould, R.A., Powell, D.M., Whelan, M.J., 2021. Macroplastic debris transfer in rivers: a travel distance approach. Front. Water 3, 724596. https://doi.org/10.3389/frwa.2021.724596.

Niedźwiedź, T., Obrębska-Starklowa, B., 1991. Klimat (Climate). In: Dynowska, I., Maciejewski, M. (Eds.), Dorzecze górnej Wisły. PWN, Warszawa-Kraków, pp. 68–84.

Radecki-Pawlik, A., Wyżga, B., Czech, W., Mikuś, P., Zawiejska, J., Ruiz-Villanueva, V., 2016. Modelling hydraulic parameters of flood flows for a Polish Carpathian river subjected to variable human impacts. In: Kundzewicz, Z.W., Stoffel, M., Niedźwiedź, T., Wyżga, B. (Eds.), Flood Risk in the Upper Vistula Basin. Springer, Cham, pp. 127–151 https://doi.org/10.1007/978-3-319-41923-7_7.

Rinaldi, M., Wyżga, B., Dufour, S., Bertoldi, W., Gurnell, A., 2013. River processes and implications for fluvial ecogeomorphology: a European perspective. In: Shroder, J., Butler, D., Hupp, C.R. (Eds.), Treatise on Geomorphology. Ecogeomorphologyvol. 12. Academic Press, San Diego, pp. 37–52. https://doi.org/10.1016/B978-0-12-374739-6.00321-3.

Roebroek, C.T., Harrigan, S., van Emmerik, T., Baugh, C., Eilander, D., Prudhomme, C., Pappenberger, F., 2021. Plastic in global rivers: are floods making it worse? Environ. Res. Lett. 16, 1–11. https://doi.org/10.1088/1748-9326/abd5df.

Ruiz-Villanueva, V., Stoffel, M., Wyżga, B., Kundzewicz, Z.W., Czajka, B., Niedźwiedź, T., 2016a. Decadal variability of floods in the northern foreland of the Tatra Mountains. Reg. Environ. Chang. 16, 603–615. https://doi.org/10.1007/s10113-014-0694-9.

Ruiz-Villanueva, V., Wyżga, B., Hajdukiewicz, H., Stoffel, M., 2016b. Exploring large wood retention and deposition in contrasting river morphologies linking numerical modeling and field observations. Earth Surf. Process. Landf. 41, 446–459. https://doi.org/10.1002/esp.3832.

Rusnák, M., Sládek, J., Kidová, A., Lehotský, M., 2018. Template for high-resolution river landscape mapping using UAV technology. Measurement 115, 139–151. https://doi.org/10.1016/j.measurement.2017.10.023.

Shumilova, O., Tockner, K., Gurnell, A.M., Langhans, S.D., Righetti, M., Lucía, A., Zarfl, C., 2019. Floating matter: a neglected component of the ecological integrity of rivers. Aquat. Sci. 81, 25. https://doi.org/10.1007/s00027-019-0619-2.

Spreitzer, G., Tunnicliffe, J., Friedrich, H., 2020. Porosity and volume assessments of large wood (LW) accumulations. Geomorphology 358, 107122. https://doi.org/10.1016/j.geomorph.2020.107122.

Thevenet, A., Citterio, A., Piegay, H., 1998. A new methodology for the assessment of large woody debris accumulations on highly modified rivers. Regul. Rivers Res. Manage. 14, 467–483.

Tramoy, R., Gasperi, J., Colasse, L., Silvestre, M., Dubois, P., Noűs, C., Tassin, B., 2020. Transfer dynamics of macroplastics in estuaries – new insights from the Seine estuary: part 2. Short-term dynamics based on GPS-trackers. Mar. Pollut. Bull. 160, 111566. https://doi.org/10.1016/j.marpolbul.2020.111566.

van der Nat, D., Tockner, K., Edwards, P.J., Ward, J.V., Gurnell, A.M., 2003. Habitat change in braided flood plains (Tagliamento, NE-Italy). Freshw. Biol. 48, 1799–1812. https://doi.org/10.1046/j.1365-2427.2003.01126.x.

van Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREs Water 7, e1398. https://doi.org/10.1002/wat2.1398.

van Emmerik, T., Strady, E., Kieu-Le, T., Nguyen, L., Gratiot, N., 2019. Seasonality of riverine macroplastic transport. Sci. Rep. 9, 13549. https://doi.org/10.1038/s41598-019-50096-1.

van Emmerik, T., Seibert, J., Strobl, B., Etter, S., den Oudendammer, T., Rutten, M., bin Ab Razak, M.S., van Meerveld, I., 2020. Crowd-based observations of riverine macroplastic pollution. Front. Earth Sci. 8, 298. https://doi.org/10.3389/feart.2020.00298.

van Emmerik, T., Roebroek, C., de Winter, W., Vriend, P., Boonstra, M., Hougee, M., 2020b. Riverbank macrolitter in the Dutch Rhine-Meuse delta. Environ. Res. Lett. 15, 104087. https://doi.org/10.1088/1748-9326/abb2c6.

van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., 2022. Rivers as plastic reservoirs. Front. Water 3, 786936. https://doi.org/10.3389/frwa.2021.786936.

Williams, A.T., Simmons, S.L., 1997. Movement patterns of riverine litter. Water Air Soil Pollut. 98, 119–139.

Wohl, E., 2006. Human impacts to mountain streams. Geomorphology 79, 217–248. https://doi.org/10.1016/j.geomorph.2006.06.020.

Wohl, E., 2010. Mountain Rivers Revisited. Water Resour. Monogr. 19. American Geophysical Union, Washington (576 pp.).

Wohl, E., 2018. Sustaining River Ecosystems and Water Resources. Springer, Cham https://doi.org/10.1007/978-3-319-65124-8 159 pp.

Wyżga, B., Zawiejska, J., 2005. Wood storage in a wide mountain river: case study of the Czarny Dunajec, Polish Carpathians. Earth Surf. Process. Landf. 30, 1475–1494. https://doi.org/10.1002/esp.1204.

Wyżga, B., Zawiejska, J., 2010. Large wood storage in channelized and unmanaged sections of the Czarny Dunajec River, Polish Carpathians: implications for the restoration of mountain rivers. Folia Geogr. Ser. Geogr.-Phys. 41, 5–34.

Zawiejska, J., Krzemień, K., 2004. Human impact on the dynamics of the upper Dunajec River channel: a case study. Geogr. Čas. 56, 111–124.

Zawiejska, J., Wyżga, B., 2010. Twentieth-century channel change on the Dunajec River, southern Poland: patterns, causes and controls. Geomorphology 117, 234–246. https://doi.org/10.1016/j.geomorph.2009.01.014.