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Field experiment confirms high macroplastic trapping efficiency of wood jams in a mountain river channel

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Identifying macroplastic deposition hotspots in rivers is essential for planning cleanup efforts and assessing the risks to aquatic life and the aesthetic value of river landscapes. Recent fieldwork in mountain rivers has shown that wood jams retain significantly more macroplastic than other emergent surfaces within river channels. Here, we experimentally verify these findings by tracking the deposition of 64 PET bottles after 52–65 days of transport in the mid-mountain Skawa River (Polish Carpathians) under low to medium flow conditions. Despite variations in river channel management and the resulting morphological patterns along the study reach, the majority (71.9%, $n = 46$) of tracked bottles were trapped by wood jams near the low-flow channel. The trapping efficiency was three times higher in the straight, regulated reach (14.8% per km) than in the highly sinuous, unregulated reach (4.5% per km). In the regulated reach, water inundations and wood jams are confined to a narrow zone near the low-flow channel, which may explain the high macroplastic trapping efficiency under low to medium flow conditions. In contrast, in the unmanaged, seminatural reach, where wood jams and water inundation occur over broader areas formed by extensive gravel bars, the trapping potential is lower under similar flow conditions. Previous observations showed that macroplastic deposition hotspots associated with wood jams predominantly form in wide, unmanaged river sections, where numerous jams are inundated during high flows. Our results detail this understanding, suggesting that under low to medium flows, macroplastic hotspots can also form on wood jams in regulated, narrow reaches. These findings suggest that the occurrence of wood jams, channel morphology and past flow conditions are key predictors of macroplastic hotspots formation in mountain rivers.

Keywords Field experiment, Macroplastic deposition, Macroplastic storage, Plastic-wood jams

Plastic pollution represents a growing global challenge with serious consequences for aquatic ecosystems, biodiversity, and human health[1,2]. Rivers function as both transport pathways[3] and accumulation zone[4–6] for macroplastics along its way from terrestrial sources to the ocean. Despite growing recognition of these issues[7–9] the information on macroplastic deposition hotspots in river remain very poorly understood[10].

Tracking macroplastic deposition hotspots in rivers is essential for understanding its pathways within fluvial systems, assessing risks to biota and human health, and guiding targeted cleanup efforts[10]. Mountain rivers, as unique components of fluvial systems, play a crucial role for humans, wildlife, and society by providing water resources, diverse habitats, and high aesthetic value[11,12]. However, these benefits can be significantly reduced by macroplastic pollution, though our understanding of its impacts remains limited[13]. Accurately identifying macroplastic deposition hotspots along mountain rivers is crucial for assessing risks and selecting sites where cleanup efforts will be most effective, ultimately enabling the removal of plastic debris from channels before it breaks down into microplastics[14] or is ingested by animals[14,15].

The presence of wood in rivers has recently been recognized as important in the context of macroplastic pollution[16]. Wood, along with mineral sediment, is one of the components of a river's load that can significantly interact with fluvial processes. It may exhibit even greater temporal and spatial dynamics than mineral sediment and the channel forms associated with it[17]. The distribution of wood in river channels depends on the structure of local forests, the intensity of channel processes, and the river's capacity to supply, transport, and retain wood in depositional forms[18]. The factors determining the deposition sites of large wood, as well as its influence on

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channel morphology, are largely dependent on stream size[19]. In contrast to the narrow channels of first- to third-order streams, where wood is generally not transported far and usually appears as entire trees spanning the channel[19,20], fifth- and higher-order rivers can transport wood supplied to them due to their greater channel width, depth, and high flood flows[19,21]. Resulted wood accumulations play a key role in shaping and evolving bars, altering water flow direction, and causing or preventing bank erosion[20]. Exposed surfaces within the active zone of mountain rivers provide ideal sites for the deposition of living driftwood and shrubs capable of vegetative regeneration, capturing fine-grained sediment from floodwaters and initiating island formation[22]. In low-energy sections of lowland rivers, large wood assume the role of "*chief engineer*" guiding channel processes[23].

Previous studies have shown that wood accumulations and macroplastics often coexist in various river systems due to their similar transport and deposition patterns[24–27]. Recent works have also shown that wood jams—heterogeneous mixtures of logs, branches, rootwads, fine organic matter, and mineral deposits[28]—function as highly effective macroplastic traps in mountain rivers[16]. For example, data obtained from mountain rivers in Polish Carpathians demonstrated that wood jams trap one to three orders of magnitudes more macroplastic debris (in terms of mass) than surrounding surfaces covered by woody vegetation, herbaceous vegetation, and unvegetated river sediments, respectively[16]. This high trapping efficiency of wood jams is attributed to their high surface roughness and specific structure, which create hydraulic conditions and specific obstacle for macroplastic transported in flotation (e.g., bottles) and suspension (e.g., foil bags)[16]. Moreover, the widespread occurrence of wood jams in wide, unregulated sections of mountain rivers results in a 36-fold increase in macroplastic trapping efficiency in their active channel zones compared to narrow, channelized reaches[16]. However, these findings are based on sampling macroplastics that were already trapped during previous flow events of varying magnitudes and have not yet been experimentally verified by tracking plastic items transported under specific hydrological conditions.

In this paper, we report the results of a short-term (52–65 days) field experiment using tracked 1-liter PET bottles, conducted during low- to medium-flow conditions in a 20-km-long mountainous section of the Skawa River in the Polish Carpathians. Based on the existing state-of-the-art[16], we test the hypothesis that wood accumulations will trap more tracked macroplastic objects than other surfaces present in the mountain river channel (H1) and that unregulated, wide channel section of the river will trap more macroplastic objects than a narrower, regulated one (H2).

Study area

The study was conducted in the Skawa River, located in the Polish Carpathians. The Skawa is a right-bank tributary of the Vistula, Poland's largest river, extending 103 km and originating at an elevation of 700 m a.s.l. The Skawa follows a mountainous hydrological regime, characterized by low hydrological inertia, which results in significant flow variability. The total catchment area covers 1,160 km^2, with an average annual flow of 11 m^3/s in its lower course. The riverbed is primarily composed of gravel and cobbles, with sections of bedrock present in the central part of the study area (Table 1). Regulation of the Skawa River began in 1904, and the majority of its course had been regulated by the mid-20th century (see Table A1 in[29]). The works included channel straightening and bank reinforcement. These interventions increased flow energy and reduced sediment supply, resulting in over 2 m of channel incision[30].

The field experiment was conducted along a 18-kilometer stretch of the river, from the village of Osielec to the Świnna Poręba Dam Reservoir (Fig. 1). Here the river's width varies from 5 to 40 m. Within this section, four reaches with distinct morphological patterns were identified based on the present-day characteristics of the river channel and its history of anthropogenic modification (Table 1). Reaches 1 and 2 illustrate regulated, straightened, and deepened Carpathian river channels flowing through densely populated valleys. In these sections, local gravel deficits have resulted in bedrock exposure. In contrast, Reach 3 represents spontaneous renaturalization, where previously regulated channels have returned to natural bar-braided and island-braided patterns with an alluvial bed. Due to their contrasting geomorphic characteristics (Fig. 2), similar lengths, and proximity, Reaches 2 and 3 were selected for a detailed comparison of macroplastic trapping efficiency to test hypothesis H2. Reach 4 remains regulated because of nearby road infrastructure, buildings, and the downstream dam reservoir. The emission of mismanaged plastic waste in the areas surrounding the study reach ranges from 1.6 tons/km^2/year in the uppermost reach to 261.2 tons/km^2/year in the lowermost reach[31].

Throughout the entire study section, the riverbanks are overgrown with shrubs and woody vegetation from the Salicaceae family, alongside mature riparian forests developing in the floodplain zones farther from the

Reach	Length [km]	Channel gradient (m/m)	Mean channel width (m)	Median grain size (mm)	Channel bottom	Channel pattern	Channel regulaion
1	8.62	0.00529	25	83	Alluvial-bedrock	Sinuous, single-thread	Rip-rap regulated banks
2	1.35	0.005619	43	71	Alluvial-bedrock	Straight, single-thread	Rip-rap regulated banks
3	3.34	0.00472	135	70	Alluvial	Sinuous, bar-braided, island-braided	No regulation
4	6.91	0.00403	58	66	Alluvial-bedrock	Sinuous, single-thread	Rip-rap regulated banks

Table 1. Basic geomorphological characteristics of the studied section of the Skawa River. Reaches selected for detailed analysis are underlined.

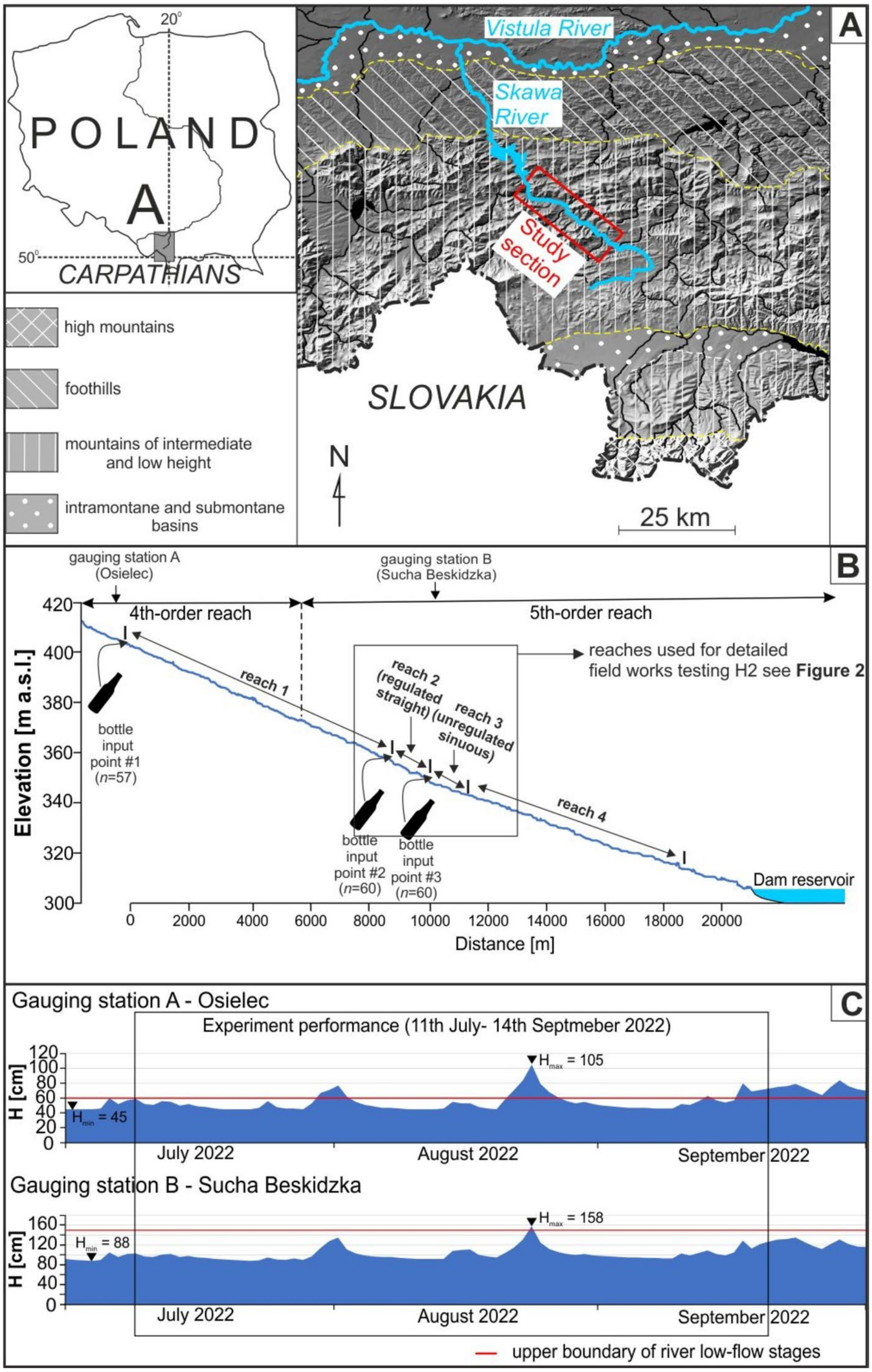

Fig. 1. Location of the study site in the Carpathians (**A**), the detailed location of bottle input points for the experiment within the river (**B**), and water hydrograph during the experiment (**C**). The maps were created using a free software QGIS version 3.34 (https://www.qgis.org/download).

channel. This vegetation provides a source of woody debris, varying in size, which is transported into the river channel during flood events.

Field inventory of wood jams and geomorphic characteristics

To collect additional data explaining potential differences in trapping efficiency between river reaches with contrasting morphological patterns (reaches 2 and 3), a detailed inventory of wood jams—suggested by previous studies as effective macroplastic traps—was conducted after the experiment in these two reaches. The inventory focused on the zones inundated by the highest river flows observed during the experiment (Fig. 1C). The maximum water inundation during the experiment reached 1.30 m above the average low-flow level (Fig. 2).

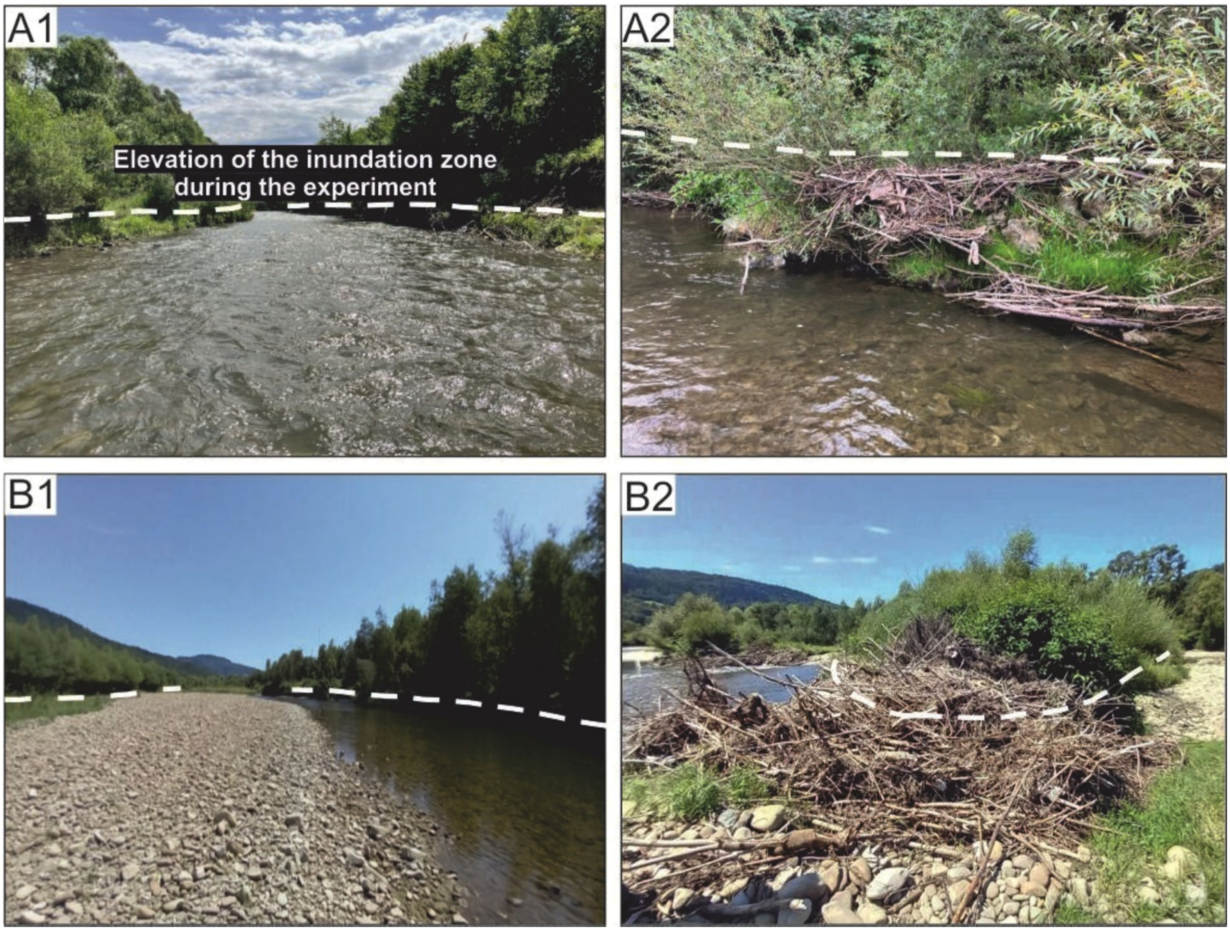

Fig. 2. The views of the morphological patterns and wood jams present in reaches 2 and 3 used for detailed field work testing H2. (**A1**) a view of the narrow section; (**A2**) typical wood jam stored on vegetated riprap within the narrow section; (**B1**) view of the multi-thread section; (**B2**) typical wood jam accumulated on a gravel bar within the multi-thread section.

For each wood jam (as defined by[28]), dimensions, surface area, mass, volume, height above the water surface, and the type of surface were recorded. The inventoried wood jams were generally small (Table 2) and were of a similar structure and build. In the narrow section (reach 2), wood jams were strongly associated with high-roughness areas, such as cobbles and shrubby vegetation, primarily located on the concave banks of the channel, particularly downstream of riffles (Fig. 2A1, 2A2). In contrast, in the wide, unregulated section (reach 3), wood jams were typically found in the frontal and lateral zones of bars and islands separating the low-water channels (Fig. 2B1, 2B2). Almost all wood jams in the narrow section consisted of fine woody debris deposited around living willows. In the wide, multi-thread section, wood jams were often deposited on bare gravel, grass, or shrubs, with initial accumulation around a 'key member', such as a single log, root wad, or shrub (for details, see Fig. 2B2).

Results and discussion
Plastic bottle deposition
During the 52 to 65 days of low-flow conditions in the studied reach, we recorded transport distances ($n = 64$) ranging from 0.37 km to 16.27 km, with a median of 1.68 km (Fig. S1). Most bottles were deposited on wood jams (71.9%, $n = 46$) (Fig. 3A), and the proportion of deposition on wood jams compared to other surface types varied across reaches: 61.8% in Reach 3, 68.4% in Reach 1, 68.8% in Reach 2, and 100% in Reach 4. The elevation above the low-flow water level at which bottles were deposited was normally distributed, ranging from 0 to 1.2 m, with a mean of 0.44 m (SD = 0.29). No statistically significant differences in deposition elevation were observed among the four reaches (Fig. 3B).

The trapping efficiency of plastic bottles (the proportion of bottles introduced into the reach that were deposited along its 1 km length) was three times higher in the straight, regulated reach (14.8% per km) compared to the sinuous, unregulated reach (4.5% per km).

The obtained results highlight significant differences in macroplastic deposition between sites with and without wood jams, confirming previously observed patterns of macroplastic and woody debris coexistence in fluvial systems[24,26,27]. Our data not only corroborates earlier findings that macroplastic and woody debris

	Wide reach (R3)	Narrow reach (R2)	
A. Geomorphic and wood jams features (not tested statistically)			
Section length (km)	3.34	1.35	
Total area of low-flow water table (ha)	16.63	3.5	
Total area of inundated zone (ha)	23.75	5.77	
Total volume of wood jams within the inundated zone (m^3)	140.6	87.9	
Total mass of wood jams within the inundated zone (t)	10,547	6592	
Number of wood jams within the inundated zone (items per 1 km of river length)	10.5	50.4	
Number of wood jams within the inundated zone (items per 1 ha)	2.1	11.8	
Specific mass of wood jams within the inundated zone (kg per ha)	1480	2892	
Volume of wood jams within the inundated zone (m^3 per 1 ha)	5.92	15.2	
Specific wood area in the inundated zone (m^2 per 1 km of river length)	48.7	97	
Volume of wood jams within the inundated zone (m^3 per 1 km of river length)	20.3	67.1	
	$n=35$	**$n=68$**	***p* value**
B. Geomorphic and wood jam features (tested statistically)			
Mean width of low-flow channel (m)	26.1	23.1	$p=0.14$
Mean width of inundated zone (m)	75.2	42.4	**$p<0.0001$**
Mean mass of wood jams within the inundated zone (t)	301.3	96.9	**$p<0.0001$**
Mean elevation of wood jams above low-flow water table (m)	0.53	0.83	**$p=0.0002$**
Total wood area in the inundated zone (m^2)	163	131	**$p<0.0001$**
Mean volume of wood jam within the inundated zone (m^3)	4	1.29	**$p<0.0001$**

Table 2. Comparison of (A) geomorphic and (B) wood jam characteristics in reaches 2 and 3. Statistical comparisons were performed based on measurements done and calculated based on Statistically significant differences between the reaches for the given parameters are highlighted in bold.

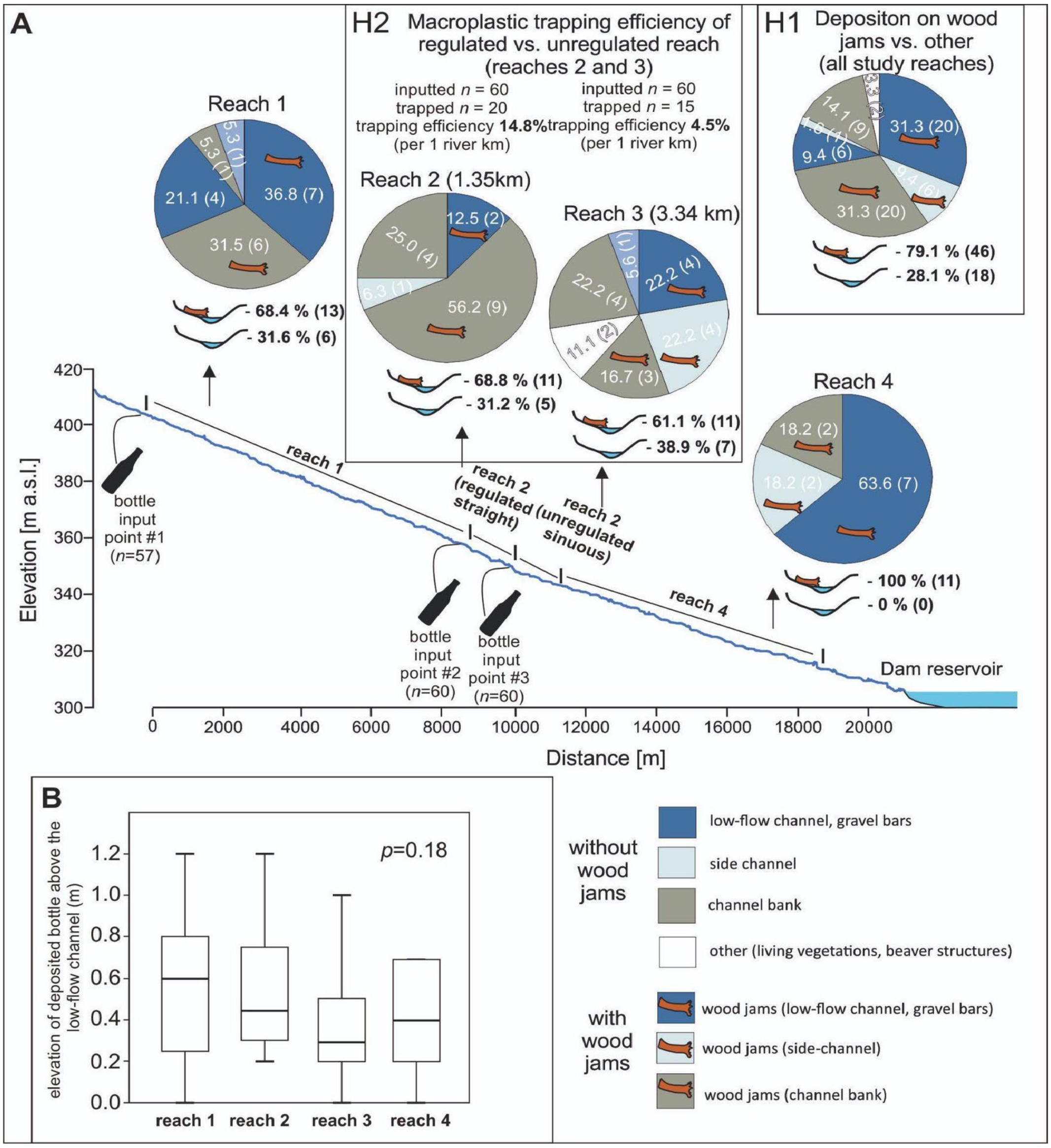

Fig. 3. The proportions of experimental bottles deposited on different types of emergent surfaces of river channel with and without wood jams.

deposition coincide spatially due to their similar properties and transport dynamics[24]. It also demonstrates that, beyond these similarities, wood jams themselves act as highly effective macroplastic traps[16]. Previous field studies in mid-sized mountain rivers in temperate climates and small mountain streams in Mediterranean climates indicates that the amount of macroplastic deposited on wood jams exceeded that found on other surfaces, such as woody vegetation, herbaceous vegetation, and exposed river sediments, by factors of 19, 129, and 180[16] and by factors of 10, 150, and 600[32]). Despite differences in river flow conditions, sizes, and riparian vegetation types across the above-mentioned studies, consistently wood jams were documented as the most effective macroplastic traps within active river channels.

Our short-term experiment confirms these findings using macroplastic tracking technique (Fig. 4A). While confirming previously indicated patterns of high macroplastic trapping efficiency (H1), our results also provide novel insight, offering a new perspective to the previous observations on different macroplastic trapping efficiencies of river reaches having different morphologies (H2). Previous work suggested that wider, unmanaged river sections (Fig. 4B) trap more macroplastic than narrower, regulated ones[19]. However, our results show that during low to medium flow conditions, where inundation is confined to areas near the low-flow channel, substantially more macroplastic is trapped in the narrower, regulated reach (Fig. 4C). These findings suggest that river morphology is an important predictor of macroplastic deposition hotspots, with the influence of flow conditions playing a critical role. Specifically, it can be hypothesized that hotspots of macroplastic deposition are more likely to form in regulated river reaches during low to medium flows (as shown in our experiment),

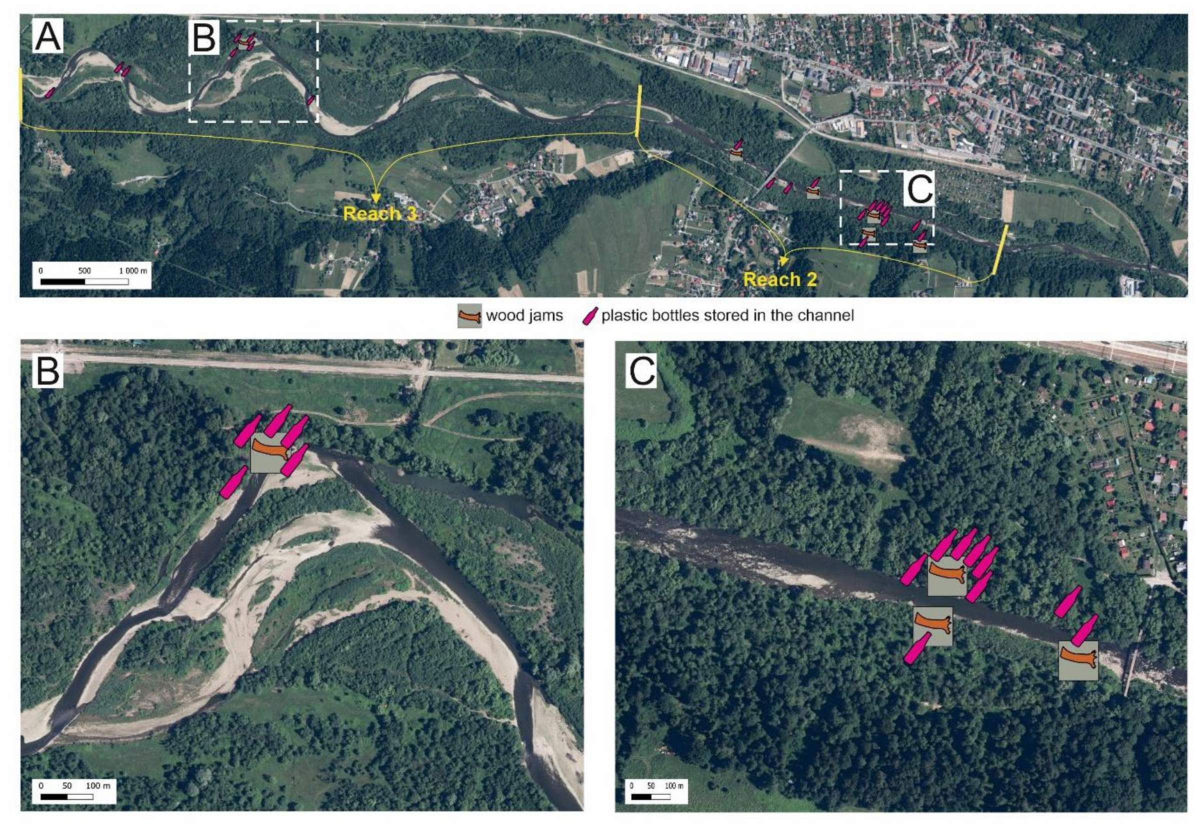

Fig. 4. An overview (**A**) and hydromorphological features of the narrow, regulated Reach 2 (**B**) and the unmanaged, sinuous Reach 3 (**C**), with the locations of wood jams and accumulated tagged plastic bottles. The maps were created using a free software QGIS version 3.34 (https://www.qgis.org/download).

whereas unregulated reaches may have a higher potential for hotspot formation during flood events, when wood jams more distant from the low flow channel in wider reaches also start to operate as plastic trap.

Field mapping indicates that the higher abundance of wood jams in the narrower, inundated zone during low to medium flows in the regulated reach, compared to the wider, unregulated one (Table 2), plays a significant role in macroplastic trapping. Additionally, increased surface roughness from dense woody vegetation and riprap reinforcement along the banks in the regulated sections likely contributes to this effect. While our experimental method—using printed trackers inserted into plastic bottles—offers a low-cost approach, it also has few limitations. Specifically, this method allowed us to track only a small proportion of the bottles introduced into the study reach, limiting the completeness of the data. For instance, it does not provide detailed information on the number of remobilization events or the residency time of bottles within different surface covers or morphologies. We were also unable to evaluate transport distances of bottle which were not found during field surveys in the study which limit potential for assessing the exact travel distance of bottle in the studied river. Definitely, future studies employing more advanced and precise tracking technologies, such as GPS or RFID tags (see e.g.[33]), will offer more comprehensive insights into the transport, remobilization, and storage patterns of macroplastic within river reaches of varying morphologies (e.g., regulated vs. unmanaged) and surface characteristics. Such improvements will enhance our understanding of macroplastic dynamics, particularly in relation to different surface cover types and bank reinforcement strategies, thereby advancing the accuracy and applicability of our findings.

The lifespan of macroplastic deposition hotspots formed by wood jams, as well as their remobilization, is closely related to the fluvial processes that govern the formation and persistence of wood jams—specifically, occurrence of flood events[16]. It is well-documented that wood accumulation in rivers typically occurs during the falling limb of the flood wave, that is, at high water levels (e.g.[34–36]). Our previous research has demonstrated that wood jams, regardless of their elevation above the low-flow channel, trap similar amounts of macroplastic. This suggests that macroplastic deposition on these structures can occur both during high-flow stages, when wood jams are formed, and during lower flows, which are still capable of inundating the wood jams developed but still not too high to remobilise them[16]. This indicates a dual mechanism for macroplastic deposition: high flows facilitate the formation of wood jams and the trapping of macroplastic, while subsequent lower flows can continue to deposit macroplastic on the already-formed jams, enhancing their long-term effectiveness as traps. Throughout our experiment, water level fluctuations remained within the range of a 1-year flood (Fig. 1). Detailed field mapping within this zone revealed notably higher concentrations of wood jams in the narrower, single-thread sections inundated during the experiment, compared to the wider, unmanaged section. In these narrower sections, wood jams were mostly found in the distal parts of riffles and immediately downstream, particularly along channel banks regulated by ripraps and overgrown with young Salicaceae shrubs. In wider, multi-thread sections, wood jams typically occurred in the proximal parts of islands or at eroded bends, where flow direction changes abruptly. Overall, the experiment confirms that wood debris accumulations are primary sites for intense macroplastic deposition in mountain river channels[16]. Furthermore, the results from our experiment provide a more detailed view of this process, showing that during low to moderate flows, only wood accumulations located in the immediate vicinity of the active channel contribute to trapping macroplastics transported by the river. Thus, presence of wood jams in the close proximity of the low-flow channel is crucial for controlling macroplastic deposition during these flow stages. This finding supplements our earlier observations, which indicated that, when analyzing the entire active channel zone inundated during low, medium, and high flows, wide, multi-thread sections capture significantly more macroplastic—often dozens of times more—than narrow, regulated reach[16]. Our fieldwork indicated that significantly more wood jams are concentrated within the low- to moderate-flood zone in the regulated reach (Table 1), which may explain why the trapping efficiency of this reach—calculated as the percentage of bottles introduced to each reach ($n = 60$ per reach) and found within one kilometer of their lengths—was higher than in the wider, unmanaged reach (Figs. 3 and 4). Future field experiments conducted in river reaches with varying morphological patterns and spanning both low and high flow stages could further verify our findings (for methods see e.g[33]).

Given the growing body of evidence suggesting a direct link between woody debris presence and macroplastic storage[16,26,27], future studies could examine this relationship more closely along the entire river continuum, including streams of various orders with differing interactions between stream size and the effects of woody debris on fluvial processes (see, e.g[17,20]). This could be achieved, for example, by evaluating macroplastic trapping at individual wood jams throughout the river course, from headwaters to the river mouth. Future research should also examine the amount of macroplastic remobilized by floodwaters in conjunction with mobilized wood jams. Numerical modelling approaches previously used to track wood transport and deposition in rivers appear well-suited for such studies (for methods see, e.g[37,38]).

Our findings, along with previous studies, suggest that effective cleanup operations targeting macroplastic hotspots in mountain rivers should account for the occurrence of wood jams, channel morphology, and historical flow conditions. In the context of the studied Skawa River and similar mountain river systems in the Carpathians, integrating wood jam monitoring into regional water management plans could greatly enhance the identification of macroplastic hotspots, enabling more targeted and efficient cleanup efforts see[10]. These strategies could be scaled to address macroplastic pollution in other Carpathian rivers with wood jams, contributing to broader initiatives in systematic cleanup efforts, including those that leverage citizen science approaches[39]. Utilizing publicly available aerial photo time series to analyze the distribution, extent, and age of wood jams (indicating trapping duration) can aid in selecting optimal cleanup areas along rivers. Moreover, this approach allows for the identification of sites with adequate accessibility while ensuring the safety of operations, such as by avoiding steep riverbank sections.

Outlook

This study demonstrates that wood jams can significantly enhance macroplastic deposition in rivers—an effect that should be integrated into future analyses of macroplastic pathways in fluvial systems. We found that this enhancement depends on both river morphology and flow conditions. Our results show that narrow, regulated river reaches with wood jams along the riverbank trap more macroplastic during low to medium flows, while previous studies indicate that wider, unregulated reaches serve as deposition hotspots during flood flows. These findings highlight the need for further research connecting large woody debris dynamics with the fate of macroplastic debris throughout entire fluvial systems to improve our understanding of its transport, remobilization, and storage patterns in rivers with diverse morphologies and surface characteristics.

Our findings suggest that effective cleanup of macroplastic hotspots in mountain rivers should consider wood jams occurrence, channel morphology, and flow history.

Methods

Field experiment

All bottles were numbered using foil markers placed inside, securely sealed with caps, and released into the studied section of the Skawa River at three locations (Fig. 1A, B) on July 11th, 2022. A total of 57, 60, and 60 one-liter PET bottles were introduced directly into the low-flow channel at the uppermost points of reaches 1, 2, and 3, respectively. The bottles were not introduced into reach 4 at the beginning of experiment, and all bottles found there were transported from the upstream reaches. Field surveys to recover the marked bottles were conducted 52 days (September 1st), 57 days (September 6th), and 65 days (September 14th) after release. Four individuals (two on each riverbank) retrieved 64 of the 196 tagged bottles during these surveys.

The travel distance for each bottle was measured as the thalweg distance between the release point and the retrieval location using a Trimble R4 RTK GPS receiver. In all four reaches, data on deposition sites were collected and categorized as follows: low-flow channels, gravel bars, side channels, and channel banks. To test H1, deposition in each of these geomorphic features was further classified based on whether it occurred with or without wood jams throughout the entire study section. Macroplastic trapping efficiency, defined as a percentage of bottles introduced and trapped within 1 km of a specific river reach, was calculated for reach 2 (narrow, regulated) and reach 3 (wide, unmanaged) to test H2.

Data analysis

The data sampled for each group of surface covers were non-normally distributed (Shapiro-Wilk test). Characteristics of inventoried wood jams and the geomorphology of the studied reaches 2 and 3 were compared using the Mann-Whitney U test. Parameters showing significant differences ($p < 0.05$) were highlighted in bold (Table 2) and visualized graphically using violin plots (Fig. S2).

To determine if wood jams trap more macroplastic than other surface types, the proportion (%) of tracked bottles found on surfaces with and without wood jams was evaluated for each of the four study reaches (H1). To assess whether greater amounts of macroplastic is trapped in the wide, unmanaged reach compared to the narrow, channelized reach (H2), the macroplastic trapping efficiency of these two reaches was calculated as the percentage of bottles introduced to each reach ($n = 60$ per reach) and found within one kilometer of their lengths. All statistical analyses and visualizations were performed in the R programming environment.

Data availability

Data would be made available by the corresponding author upon request.

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Declarations

Competing interests
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