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Short Communication

The unknown fate of macroplastic in mountain rivers

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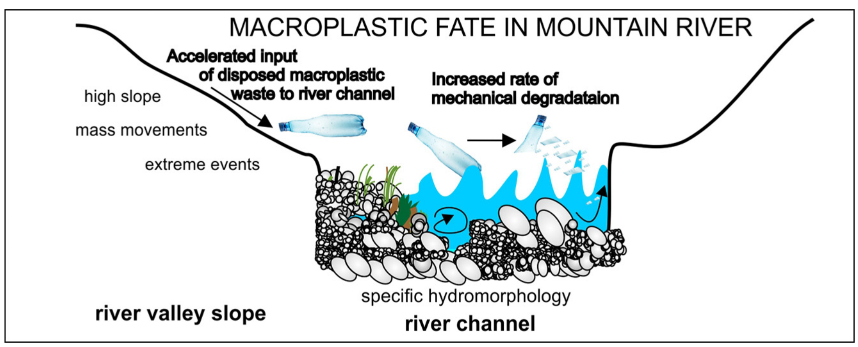
HIGHLIGHTS

- Mountain rivers (MR) in populated areas can act as microplastic factories.
- Natural processes can accelerate input of macroplastic waste to MR.
- Fragmentation rate of macroplastic can be increased by mountain river hydromorphology.

GRAPHICAL ABSTRACT



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ABSTRACT

Mountain rivers are typically seen as relatively pristine ecosystems, supporting numerous goods (e.g., water resources) for human populations living not only in the mountain regions but also downstream from them. However recent evidence suggests that mountain river valleys in populated areas can be substantially polluted by macroplastic (plastic item >25 mm). It is unknown how distinct characteristics of mountain rivers modulate macroplastic routes through them, which makes planning effective mitigation strategies difficult. To stimulate future works on this gap, we present a conceptual model of macroplastic transport pathways through mountain river. Based on this model, we formulate four hypotheses on macroplastic input, transport and mechanical degradation in mountain rivers. Then, we propose designs of field experiments that allow each hypothesis to be tested. We hypothesize that some natural characteristics of mountain river catchments can accelerate the input of improperly disposed macroplastic waste from the slope to the river. Further, we hypothesize that specific hydromorphological characteristics of mountain rivers (e.g., high flow velocity) accelerate the downstream transport rate of macroplastic and together with the presence of shallow water and coarse bed sediments it can accelerate mechanical degradation of macroplastic in river channels, accelerating secondary microplastic production. The above suggests that mountain rivers in populated areas can act as *microplastic factories*, which are able to produce more microplastic from the same amount of macroplastic waste inputted into them (in comparison to lowland rivers that have a different hydromorphology). The produced risks can not only affect mountain rivers but can also be transported downstream. The challenge for the future is how to manage the hypothesized risks, especially in mountain areas particularly exposed to plastic pollution due to waste management deficiencies, high tourism pressure, poor ecological awareness of the population and lack of uniform regional and global regulations for the problem.

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1. Unexplored problem of macroplastic in mountain rivers

Plastic pollution has recently been attracting the attention of scientists, engineers and the general public. This results from its global extent and numerous risks to human livelihood and ecosystem functioning, as well as non-optimistic perspectives of its further accumulation resulting from increasing production and long-term perseverance in the environment (Borelle et al., 2020). The fate of plastic in rivers is less understood than in the oceans (Blettler et al., 2018), and previous works have considered rivers mostly as transport pathways of land-derived plastic to the ocean (Liro et al., 2020). Recent works have suggested, however, that rivers are not only simple vectors of plastic transport from land to ocean but also a complex environment where plastic may be stored, remobilized and degraded (Liro et al., 2020; Weideman et al., 2020; Al-Zawaidach et al., 2021; Roebroek et al., 2021; van Emmerik et al., 2022). This implies that the presence of plastic-related environmental risks in river ecosystems may continue in the future, even when the input of new plastic debris to the fluvial systems will be decreased.

It is known that the natural characteristics of fluvial systems and their anthropogenic modifications are key controls of macroplastic (commonly defined as plastic item >25 mm (see e.g., Kershaw et al., 2019; Hurley et al., 2020)) transport pathways through rivers (van Emmerik and Schwarz, 2020; Liro et al., 2020; Gallitelli and Scalici, 2022; van Emmerik et al., 2022). However, how these controls operate in mountain rivers is mostly unexplored (cf. Honorato-Zimmer et al., 2021; Liro et al., 2022). Although most of the existing riverine macroplastic studies come from lowland rivers (van Emmerik and Schwarz, 2020), recent works also demonstrated their occurrence in mountain rivers (Mihai, 2018a; Honorato-Zimmer et al., 2021; Gallitelli and Scalici, 2022; Liro et al., 2022). Mountain rivers are characterized by, among others: steep gradient, high hydraulic roughness of channels and banks associated with bedrock and coarse bed material, highly turbulent flow, transport of coarse-bed sediments during floods, relatively narrow valley bottoms with limited development of floodplain, substantial spatial and temporal variation in discharge as well as high degree of landscape, hydrological and sediment connectivity (Wohl, 2010; Maier et al., 2021). It is unknown how these distinct characteristics of mountain rivers modulate macroplastic routes through them, and what risks could emerge. Answering this question in future research is important because plastic pollution may threaten high biodiversity, typically supported by mountain rivers (Hauer et al., 2016) as well as reducing goods that mountain rivers provide for human populations living not only in the mountain regions but also in the downstream areas (e.g., as water resources (Viviroli et al., 2007, 2020; Schickhoff et al., 2022)). Here, we present a conceptual and theoretical framework for narrowing this knowledge gap in future studies. Firstly, we outline the existing waste management challenges known from mountain rivers. Then, we conceptualize and hypothesize how distinct characteristics of mountain rivers can modulate macroplastic input, transport and mechanical degradation as well as proposing field experiments able to test our hypotheses. With our paper, we aim to stimulate future studies on macroplastics in mountain rivers and to accelerate the mitigation of macroplastic pollution in mountain rivers.

2. Waste management challenges in mountain river catchments

2.1. Distribution of plastic waste emission sources in the river proximity

The topography of mountain river catchments and the occurrence of mass movements favour the concentration of plastic emission sources on river floodplains, which are relatively flat and allow for easier construction of living and transport infrastructures compared to the remaining areas of mountain river catchments (slopes and headwater areas). Previous studies have indicated that human infrastructures (e.g., roads) in both urban and rural areas of mountain regions are predisposed to macroplastic pollution because they stimulate illegal dumping practices (Matos et al., 2012; Malinowski et al., 2015; Mihai and Grozavu, 2019; Mihai, 2018a) that frequently occur directly in the area of river floodplains (Mihai et al., 2012; Mihai, 2018b). We suggest this problem may be more important in the case of larger lower-lying mountain rivers flowing through more populated areas, having forested wide floodplains with numerous unpaved roads offering accessibility and relatively low visibility, favouring intentional dumping. The highest parts of mountain regions have more diffuse and less abundant sources of litter, which is disposed here due to waste management gaps related to underdeveloped transportation networks, limiting the access to proper waste management services (United Nations Environment Programme, 2016), and the littering behaviour of residents and tourists (Mihai and Grozavu, 2019; Mihai et al., 2022). In the lower part of mountain rivers, macroplastic input seems to be controlled mostly by dumping or improper disposal of plastic waste on or near the river floodplain (Mihai et al., 2012, 2022; Mihai, 2018a; Mihai, 2018b). The river floodplain zone here is wider than in the upstream part of the catchment, and in many populated areas of a mountain, it is used for multiple purposes, e.g., for agriculture, living and transport infrastructure and recreation. All these factors increase the potential for intentional or unintentional dumping, which seems preferentially concentrated along the roads (e.g., Matos et al., 2012). The number and area of local sources (e.g., roads or dumping sites) of macroplastic input to the river can be mapped in future works during field works or by using remote sensing materials (e.g., aerial photos). Such information collected for different spatial units of rivers (e.g., reaches, segments, forms, habitats) can then be related to the data on plastic abundances collected from them, allowing for testing of the relation between artificial inputs of macroplastics and their abundance in rivers (Liro et al., 2020). More locally, the abundances of plastic waste (e.g., items, gram/site, items/m^2, gram/m^2) in a given source can also be determined and the distance of macroplastic emission from it measured. For example, to quantify the importance of macroplastic input from roads, built-up areas, bridges and recreational sites, future works can compare macroplastic abundances (items/m^2, gram/m^2) within the plots located at different distances from such sources, taking into account river flow directions and local topography. The above suggests that the amount of macroplastic entering mountain rivers can be better explained by the characteristics of river valley bottoms (especially floodplains), which concentrate the majority of plastic emission sources, rather than by the characteristics of the whole river catchment.

2.2. Limited areas suitable for waste landfilling

The natural characteristics of mountain river catchments limit the area suitable for proper landfill site construction. These landfill sites must comply with the environmental regulations regarding the proximity to water bodies, human settlements, and critical infrastructure (Mihai and Ichim, 2013). At the bottom of mountain river valleys (where most plastic waste emission sources are located) (Mihai, 2018a), such sites' location may be challenging to determine because of the steep slopes of the river valley bottom and the occurrence of mass movements. Locations of landfills on mountain river catchments may be more suitable within the flat areas of river floodplains. These sites must be selected with caution to avoid flood inundation zones. Improvement of waste management practices in line with circular economy principles will decrease the reliance on municipal landfill sites and new related construction demands in mountain environments (Mihai et al., 2022).

3. Conceptual model of macroplastic transport pathways through mountain river

3.1. Macroplastic input into river

Disposed macroplastic waste can enter the zone of active fluvial processes (river channels or floodplains) in two ways: (i) artificially (e.g., by dumping or improper disposal) or (ii) as a result of natural processes (e.g., wind, surface runoff, or landslide) (Liro et al., 2020; Mellink et al., 2022).

3.1.1. Macroplastic input is accelerated in mountain rivers (hypothesis 1)

We hypothesized that the natural characteristics of mountain rivers (e.g., steep valley slopes, mass movements, high precipitation and high surface runoff) (see Wohl, 2010) can not only constrain the landfill construction described in Section 2.2 but also favour macroplastic input into the river fed by mismanagement plastic waste through littering behaviour and illegal dumpsites (Mihai et al., 2022). The importance of these natural characteristics as a control of macroplastic input could be higher in the upper parts of mountain river catchments where valley slopes are steeper and the frequency and magnitude of extreme events are higher (see Wohl, 2010). In the lower part of mountain rivers, the river floodplains are also more frequently embanked in populated areas, which may provide a barrier for macroplastic input by natural processes.

3.1.2. Experimental design to test hypothesis 1

The above hypothesis can be tested in future works by comparison of results from tracer plastic items monitoring conducted in mountain and lowland river catchments (Fig. 2A). Such experiments can utilize both actually disposed plastic items or different types of fresh plastic items (polymer composition, shape, size) placed in the field. Together with the information on geomorphic and land cover characteristics of given locations as well as the magnitude and frequency of natural factors controlling macroplastic input to the river (e.g., wind, precipitation, surface runoff, landslides), it may be possible to quantify the effectiveness of macroplastic mobilization on slopes and thus its input into rivers. The gained information can also be applied to calibrate the existing numerical models used for tracking macroplastic movement within river catchments (see e,g., Mellink et al., 2022).

3.2. Macroplastic transport and remobilization in river

The initiation of macroplastic transport and remobilization depends on the characteristics of river floodplains and channel zones (e.g., vegetation cover, sediment characteristics), macroplastic properties (e.g., size, weight, surface area, shape), its position in/on the sediments or vegetation cover (e.g., depth in the subsurface sediments, height of the entrapment of riparian vegetation, see Gallitelli et al., 2022) and river flow hydrodynamics (e.g., flow velocity, water depth, bed shear stress) (Liro et al., 2020).

3.2.1. Downstream transport rates of macroplastic are higher in mountain rivers (than in the lowland one) (hypothesis 2)

Recent evidences suggest that mountain river hydrodynamics (e.g., high flow energy) will increase the transport rate of macroplastic (Honorato-Zimmer et al., 2021). We further hypothesized that such conditions occur especially along high-slope, bedrock-confined reaches (more common in the upper parts of catchments) and along channelized reaches (more common in the middle and lower parts of catchments).

3.2.2. Experimental design to test hypothesis 2

This hypothesis can be tested by monitoring the movements of tracked plastic litter items (so-called tracking experiments; for methods, see, e.g., Duncan et al., 2020; Newbould et al., 2021). Such experiments can allow for the collection of data on transport mechanisms (travel distance, travel time) (Fig. 2B) and their comparison between the lower and upper parts of the mountain river catchment or between mountain and lowland rivers in general. The gained data may be crucial to understand the mechanism of macroplastic transport along mountain rivers and, in conjunction with the data on morphological types of mountain river channels (see, e.g., Maier et al., 2021) and floodplains, allowing for regional and global assessment of macroplastic flux from mountain to lowland rivers.

3.3. Macroplastic storage in mountain rivers

Macroplastic inputted (naturally or artificially) into river channels and floodplains, or deposited there during previous transport–remobilization events, can be stored as surface sediments (on bare mineral or organic sediments, on living vegetation, on hydrotechnical structures, etc.) or as subsurface sediments below the surface of the bed or river floodplain (Liro et al., 2020). Moreover, macroplastic can also be entrapped by riparian vegetation (Cesarini and Scalici, 2022; Gallitelli et al., 2022). The lowland rivers are typically much more vegetated than fast-flowing mountain rivers which can enhance macroplastic storage in vegetated riverbanks and river floodplains favouring lowland rivers as a major sink of riverine macroplastic (Gallitelli et al., 2022). Understanding the macroplastic storage dynamics is crucial for the detection of plastic accumulation hotspots and the planning of cleanup actions. Recent works from mountain rivers have suggested that high-surface-roughness elements of river channels frequently inundated by floods (e.g., wood jams, wooden islands) can store substantial amounts of macroplastic (Liro et al., 2022). The longevity of macroplastic storage will depend on the erosional potential of the given forms, which can be quantified using information on their half-life (for method see e.g., van der Nat et al., 2003). The storage of macroplastic on wood jams will last, for example, from a few months to a few years, whereas on a wooden island, it will last from a year to a few tens of years (see Liro et al., 2022 and literatures cited therein). We suggest that more long-term storage can be expected within delta–backwater zones of dam reservoirs, having a similar surface roughness and inundation frequency but significantly higher erosional resistance. The reconstruction of plastic debris abundances recorded in floodplain sediments (e.g., from undercut banks) could provide a relatively low-cost method for determining the amount of macroplastic stored in a given unit of river in the past. Such information, combined with data on river channel dynamics (e.g., collected from remote sensing materials), can be used not only for the detection of plastic accumulation hotspots but also for the assessment of the amount of plastic remobilized as a result of floodplain sediment erosion in the future (see Liro et al., 2020).

3.4. Mechanical degradation of macroplastic in mountain rivers

Along the whole route of macroplastic debris through a river, it can be degraded as a result of physical, chemical and biological processes (Hurley et al., 2020; Al-Zawaidach et al., 2021; Delorme et al., 2021; Andrady et al., 2022). The photo-oxidation is a primary process weakening and embrittling plastic exposed to UV radiation (Andrady et al., 2022) that can favour its further mechanical degradation during transport in river channel. The rate of photo-oxidation is limited for plastic buried into sediments, covered by biofilms or sank in deep water (Andrady et al., 2022). The result of macroplastic fragmentation is production of smaller, easily dispersed plastic particles (i.e., micro- and nanoplastics), which produce a serious risk for biota and human health (Gallitelli et al., 2021; Jeyavani et al., 2021; Sridharan et al., 2021). It was recently suggested that mountain rivers might accelerate fragmentation process of plastic litter because of continuous contact of transported macroplastic with their rocky substratum (Honorato-Zimmer et al., 2021). Here, we hypothesized that rate of mechanical degradation of plastic debris can be higher in mountain river not only during its transport (Hypothesis 3) but also during its storage in river channel (see Hypothesis 4) (in comparison to a lowland river) (Figs. 1 and 2).

3.4.1. Mechanical degradation of transported macroplastic items is higher on mountain river (than on the lowland one) (hypothesis 3)

Based on the suggestions from recent work by Honorato-Zimmer et al. (2021) we hypothesize that the presence of numerous obstacles to river flow (e.g., coarse bed sediments, wood jams, steeps), together with the relatively shallow water flow, will favour frequent mechanical contacts (and thus abrasion) of transported plastic items.

3.4.2. Experimental design to test hypothesis 3

The rate of mechanical degradation of macroplastic debris occurring during its transport in mountain river channel can be quantified by future field experiments that we have designed, as shown in Fig. 2C. Specifically, to collect data on the mechanical degradation of macroplastics during their transport in river channels, a combination of the tracked plastic method (Duncan et al., 2020; Newbould et al., 2021) and approaches utilized

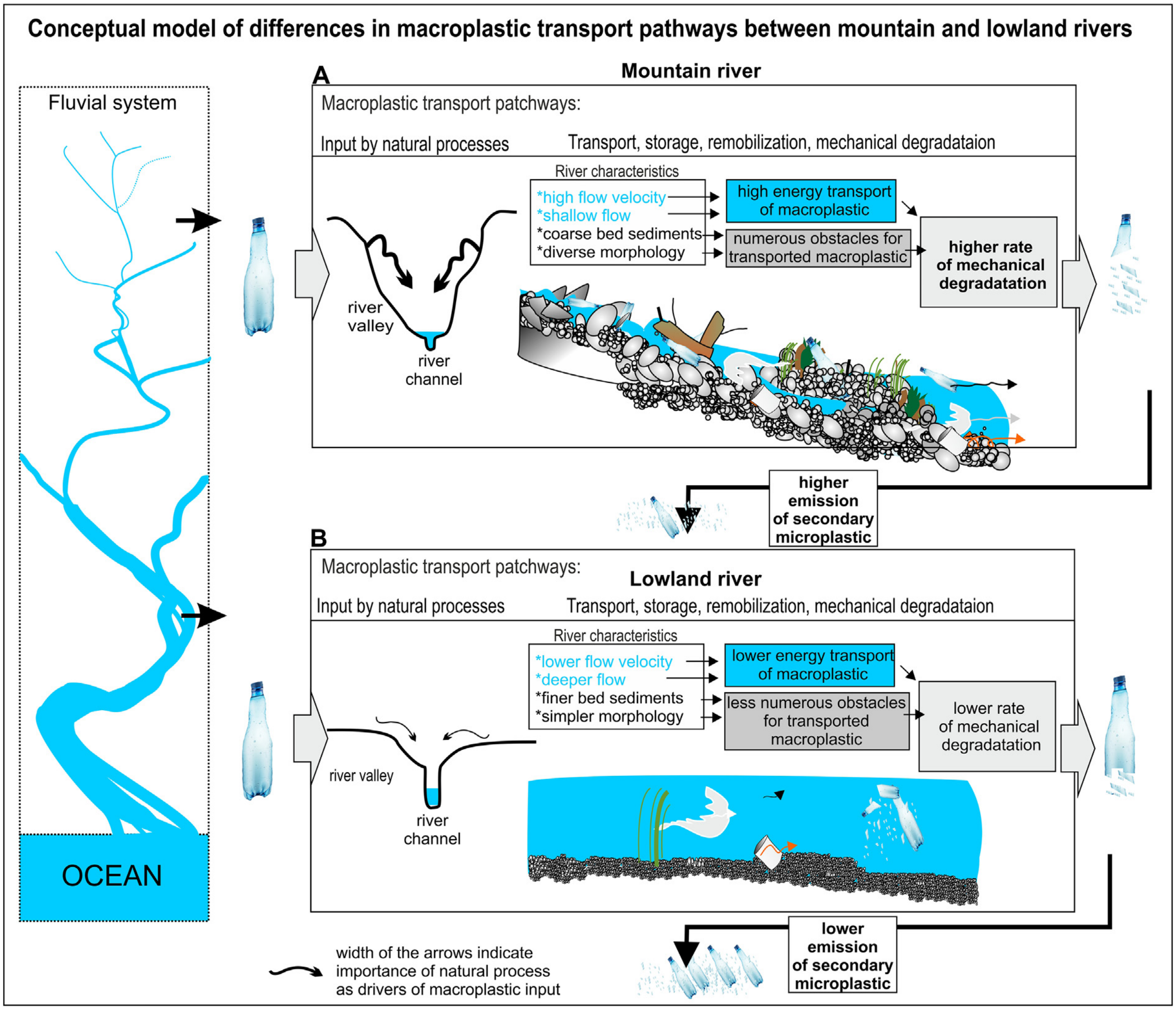

Fig. 1. Conceptual model of differences in macroplastic transport pathways between mountain (A) and lowland rivers (B).

previously for the estimation of macroplastic weight loss used in laboratory experiments (see, e.g., Gerritse et al., 2020) can be implemented (Fig. 2C). In more detail, we propose measuring the difference in the mass of macroplastic items before and after their transport in river channels, applying methods successfully used previously in mesocosm experiments (see, e.g., Gerritse et al., 2020). Together with the data on river hydromorphology, time and travel distance, as well as the type of plastic items used for the experiment, this gives us a unique opportunity to evaluate numerous controls of mechanical degradation of macroplastic in mountain rivers. This experimental setup can utilize different types of plastic objects (e.g., bottles, boxes and cups), plastic polymer types (PET, PVC, biodegradable plastics, etc.) and trackers (e.g., GPS, RFID, radio transmitters and printed items). Recorded data on macroplastic degradation should be corrected using information on the degradation of control plastic items, located in the riverside zone where the experiment will be performed, but not affected by fluvial transport. Such comparison will give some estimation about the rate of photo-oxidation and biochemical degradation occurring in a given region. The time span of such an experiment is from weeks to months depending on the specific study goal, river characteristics and tracking technology used (Duncan et al., 2020; Newbould et al., 2021).

3.4.3. Mechanical degradation of stored macroplastic items is higher on mountain river (than on the lowland one) (hypothesis 4)

We hypothesized that plastic bags and foil items tend to be preferentially trapped on the obstacles occurring in mountain river channels (bedrock, boulders, large woody debris, tree roots) and then become mechanically degraded by the water, which overflows them. These types of plastic items are very common as single-use packaging materials and are thus frequently found in rivers in populated areas (Plastic Europe, 2021). Such items typically have a film shape (large area and low thickness), allowing for their transport in suspensions, which increases the probability of their entanglement on obstacles occurring in relatively shallow channel. The mechanical stress connected with their motion in overflowing water is hypothesized to increase the rate of their mechanical degradation. Our observations suggest that suitable conditions for trapping and further *in-situ mechanical degradation* of trapped plastic items occur especially in the shallow, fast-flowing water sections of channels (e.g., riffles).

3.4.4. Experimental design to test hypothesis 4

To quantify the rate of mechanical degradation during macroplastic storage in mountain river channels, we propose a simple short-term experiment utilizing plastic foil sheets of known sizes (see Fig. 2D). The information on mechanical degradation can be gained by comparison of the surface area (and thus mass) before and after such items are trapped in river channel zones in a given time period (Fig. 2D). We propose measuring the mass loss of different types of plastic foil items (thickness, polymer types) based on changes in their surface area during the experiment. Such a measurement can be effectively performed using a photo comparison of plastic foil items (see, e.g., O'Brine and Thompson, 2010; Kalogerakis et al., 2017) and allow for avoiding the problems with destroying soft plastic items during

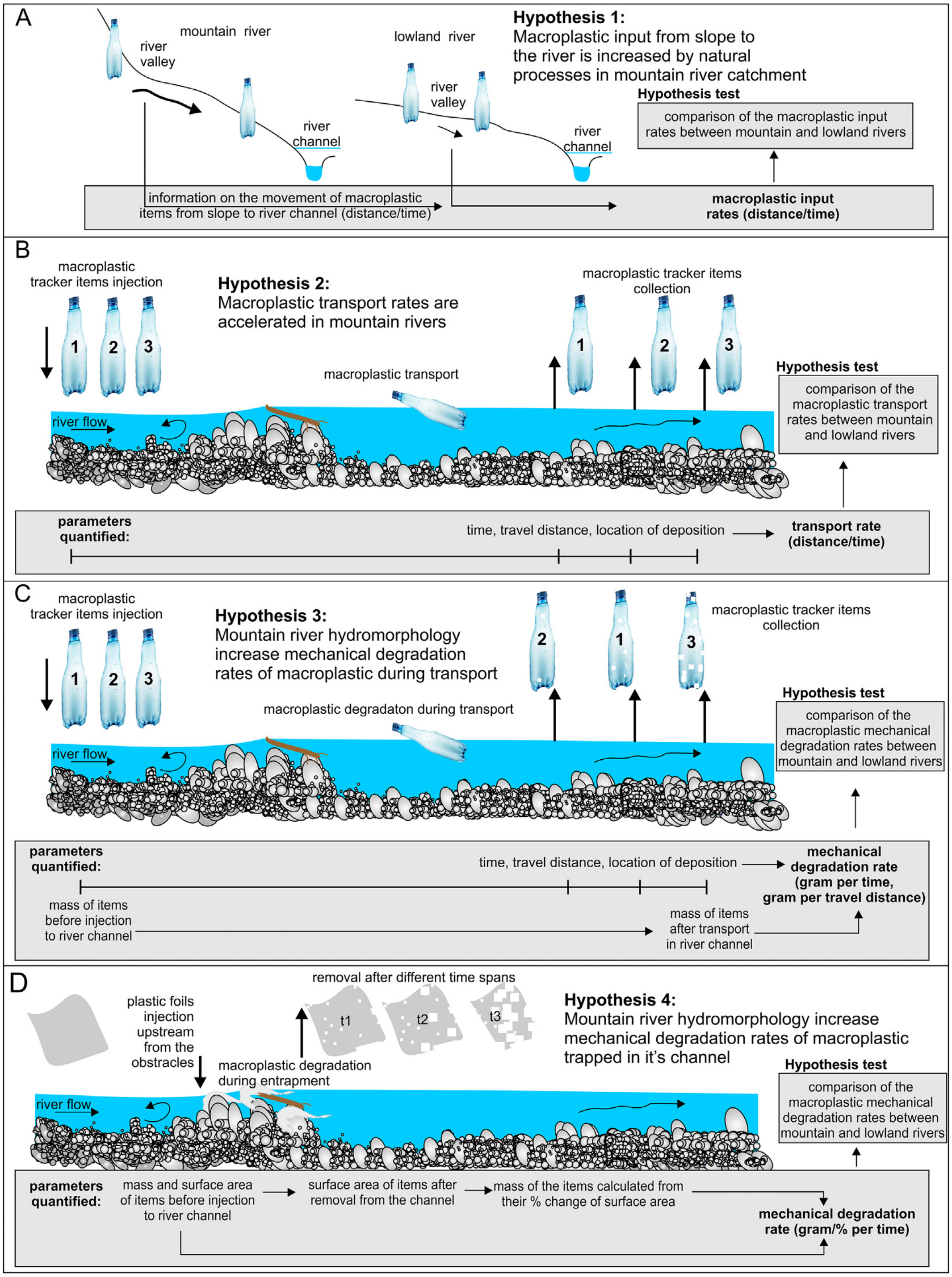

Fig. 2. The designs of field experiments proposed to test hypotheses on macroplastic input (A) transport (B) and mechanical degradation (C-D) in mountain rivers (see Section 3).

cleaning and drying before traditional weighing. The time span of the field part of such an experiment can last from hours to weeks, depending on the river hydrograph and observed rate of mechanical degradation.

All experiments are designed to be carried in mountain and lowland rivers of similar size and climatic conditions. During planned experiments some amount of plastic waste could be emitted to the environment. We see the opportunity to maximize plastic items recovery by using proposed trackers (e.g., GPS, RFID, radio transmitters, printed items), which allow for effective collections of plastic items after the experiments 1–3. Utilization of these trackers is a conventional method for research on riverine plastic (e.g., Duncan et al., 2020; Tramoy et al., 2020; Newbould et al., 2021; Ledieu et al., 2022) and e.g., on woody debris transport (e.g., Ravazzolo et al., 2015; Wyżga et al., 2017). To compensate negative effects of microplastic emission during experiments 3 and 4, we propose to perform river cleaning actions along the river studied. This allow for the removal from the fluvial system the amount of macroplastic items which are few orders of magnitude higher than those produced during planned experiments. Moreover, such actions can involve local stakeholders and school children, and these campaigns could improve environmental awareness of local communities about the riverine plastic pollution problem and initiate future citizen-science based projects.

4. Future outlook

Based on our conceptualization, we hypothesize that mountain rivers in populated areas can act as *microplastic factories*, which are able to produce more microplastic from the same amount of macroplastic waste inputted into them (in comparison to less energetic lowland rivers). This results from the natural characteristics of mountain river catchments and hydromorphological conditions occurring in their channels, which can not only accelerate the input of macroplastics from the slope to the river but also favour their mechanical degradation in river channels. The above suggests that, despite the fact that mountain rivers are typically seen as relatively pristine ecosystems, the input of macroplastic waste to them can produce a serious risk that can probably be quickly transferred downstream to the lowland rivers. The challenge for the future is how to manage these risks, especially in mountain areas particularly exposed to plastic pollution due to waste management deficiencies, high tourism pressure, poor ecological awareness of the population and lack of uniform regional and global regulations for the problem.

Author contributions

ML: conceptualized paper idea, wrote the original draft and created original figures. TvE, AZ, LG, FCM: contributed to the writing and editing of the paper and corrected figures. All authors contributed to the article and approved the submitted version.

Data availability

No data was used for the research described in the article.

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.

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