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Mountains of plastic: Mismanaged plastic waste along the Carpathian watercourses

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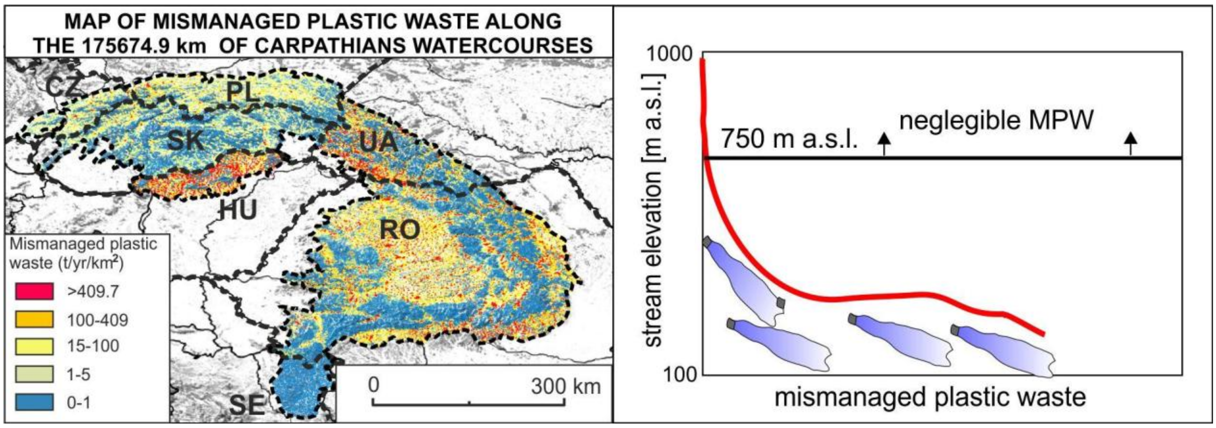
Graphical abstract



Abstract

Plastic waste poses numerous risks to mountain river ecosystems due to their high biodiversity and specific physical characteristics. Here, we provide a baseline assessment for future evaluation of such risks in the Carpathians, one of the most biodiverse mountain ranges in East-Central Europe. We used high-resolution river network and mismanaged plastic waste (MPW) databases to map MPW along the 175,675 kilometres of watercourses draining this region. We explored MPW levels as a function of altitude, stream order, river basin, country, and type of nature conservation in a given area. The Carpathian watercourses below 750 m a.s.l. (142,282 km, 81% of the stream lengths) are identified as significantly affected by MPW. Most MPW hotspots (>90th percentile) occur along rivers in Romania (6,568 km; 56.6% of all hotspot lengths), Hungary (2,679 km; 23.1%), and Ukraine (1,914 km; 16.5%). The majority of the river sections flowing through the areas with negligible MPW (< 1 t/yr/km^2) occur in Romania (31,855 km; 47.8%), Slovakia (14,577 km; 21.9%), and Ukraine (7,492; 11.2%). The Carpathian watercourses flowing through the areas protected at national level (4,0 km; 2.3% of all watercourses studied) have significantly higher MPW values (median = 7.7 t/yr/km^2) than those protected at regional (51,8 km; 29.5%) (median MPW = 1.25 t/yrkm^2) and international levels (0,07 km; 0.04%) (median MPW = 0 t/yr/km^2). Rivers within the Black Sea basin (88.3% of all studied watercourses) have significantly higher MPW (median = 5.1 t/yr/km^2, 90th percentile = 381.1 t/yr/km^2) than those within the Baltic Sea basin (median = 6.5 t/yr/km^2, 90th percentile = 84.8 t/yr/km^2) (11.1% of all studied watercourses). Our study indicates the locations and extent of riverine MPW hotspots in the Carpathians, which can support future collaborations between scientists, engineers, governments, and citizens to better manage plastic pollution in this region.

Key words: gravel-bed rivers; plastic disposal; plastic pollution; dumping; littering

Highlights

- Mismanaged plastic waste (MPW) was mapped along 175,675 km of the Carpathian Mountains' rivers;
- Most MPW hotspots (>409.7 t/yr/km^2) were in Romanian (6,567 km) and Hungarian rivers (2,679 km);
- Most MPW coldspots (<1 t/yr/km^2) were in Romanian (31,855 km) and Slovakian rivers (14,577 km);
- Rivers flowing through the areas protected at the national level should be managed in a way that avoids the input of detected MPW to their channels.

1. Introduction

The disposal and fate of plastic waste in inland mountain rivers remains practically unexplored (Honorato-Zimmer et al., 2021; Liro et al., 2023), and most previous studies have focused on coastal rivers as the main sources of land-based plastic entering the oceans (Lebreton et al., 2017; Meijer et al., 2021). It was, however, suggested that mountain rivers can be particularly affected by plastic pollution because of their high biodiversity and physical characteristics (see Liro et al., 2023). Recent works have suggested that high energy flows occurring in mountain rivers may favour the remobilization and fast downstream transport of plastics inputted to these rivers. The occurrence of numerous obstacles in river flows (e.g., boulders, riffles, and large woody debris) in mountain rivers may accelerate the fragmentation of plastic debris in these channels, increasing secondary microplastic production and its subsequent transport (see Liro et al., 2023). Moreover, the presence of plastic waste may negatively impact human perceptions of mountain river landscapes and threaten the water (Viviroli et al., 2007, 2020; Schickhoff et al., 2022) provided by these highly biodiverse ecosystems (Wohl, 2010, 2018; Hauer et al., 2016; Maier et al., 2021). This can socially and economically negatively affect tourism, recreation, and human well-being, in general (Alfthan et al., 2016; Beaumont et al., 2019). Moreover, it has been found that mountain regions pose particular difficulties to effective local waste management due to specific settlement types and road network distributions (which tend to be concentrated in the river valleys bottoms), specific topography, and susceptibility to extreme events (e.g., floods and landslides), which create logistical difficulties and lead to high costs for waste management operations (Mihai, 2018a, b). These characteristics of mountain rivers make them prone to plastic leakage, fragmentation, mobilisation (Roebroek et al., 2021), producing numerous unexplored risks (Liro et al., 2023).

The Carpathian Mountains are an important biodiversity hotspot in Europe (e.g., Bálint et al., 2011; Kozak et al., 2013; Muntenau et al., 2018) that contains numerous protected areas. However, particularly in some rural regions (e.g., in Romania), they are exposed to substantial amounts of plastic pollution due to the local and regional waste management deficiencies (Mihai et al., 2012; Mihai 2018a). The regional pattern of mismanaged plastic waste occurrence along the rivers in this region has not yet been analysed. Such information, however, can be of crucial importance for targeting locations for future research on plastic pollution in this region.

To narrow this gap, here, we aimed to map the amount of MPW along the watercourses in the entire Carpathian region (total length of 175,674.9 km), utilising recently published databases of mismanaged plastic wastes (Lebreton and Andrady, 2019) and river networks (Lin et al., 2021). To make our results useful for future works exploring riverine plastic pollution in the Carpathian region from different spatial and topical perspectives, we determined the amounts of MPW among different river basins, countries, stream orders, and nature protection forms (national, regional, and international) in this region.

The main objective of this work is to indicate the locations and extent of hotspots of riverine MPW in the Carpathian region. Obtaining such information can help to target future field work and local remediation efforts, as well as to manage rivers in the Carpathian region to limit or prevent the input of MPW into their channels. It will also be important for the protection of biodiversity and landscape attractiveness in the Carpathian region, in line with the European Union's policy of reducing environmental pressures in areas of particular natural importance.

2. Methods

2.1. Study area

The Carpathian ecoregion (ca. 210,000 km^2) (CERI, 2001), situated in seven countries (Fig. 1) and inhabited by approximately 18 million people, is the largest and one of the most biodiverse mountain ecoregion in Central and Eastern Europe (CERI, 2001; Ruffini and Ptáček, 2008; Kozak et al., 2013; Munteanu et al., 2018; Papp et al., 2022). The mean elevation of the region is approximately 850 m a.s.l., and the highest peaks (reaching up to 2655 m a.s.l.) occur in the Tatra Mountains in Slovakia and Poland (Ruffini and Ptáček, 2008). The Carpathians have a temperate climate with a continental regime (increasing eastwards) (Cheval et al., 2014). The Carpathian rivers are characterised by a rain–snow regime, with floods occurring in the spring (March–April) and summer (June–July) (Ptáček et al., 2009). Most of the Carpathian area belongs to the Black Sea basin, and only the northern and north-western parts belong to the Baltic Sea basin. Most watercourses draining the area belong to the catchments of the Danube (the largest), Vistula, Odra, and Dniester rivers, respectively.

The Carpathian ecoregion supports high biodiversity and provides numerous habitats for flora and fauna (CERI, 2001; Mráz and Ronikier, 2016; Munteanu et al., 2018), which are protected on different levels (national, regional, and international) within approximately 18% of the surface area (36,000 km^2) (Butsic et al., 2017). This ecoregion is mainly characterised by agricultural and forestry activities (Munteanu et al., 2014), with moderately developed industry. The average population density in the region is 120 people/km^2, with high spatial variation. In the valleys and mountain forelands, the population density is relatively high (150 people/km^2), whereas the high mountain areas are substantially less inhabited (Illés and Gál, 2007). The Carpathians are a popular tourist destination, hosting approximately 45 million overnight stays per year (Meyer, 2018).

Unmanaged or inadequately treated waste has become apparent in some parts of the Carpathian region. Waste management systems are poor or even non-existent in the mountainous areas of the catchments, especially in Ukraine, Serbia, and Romania (IFC, 2015; https://ec.europa.eu/eurostat). As mountainous areas are difficult to reach, a high level of waste-collection efficiency is difficult to achieve. Therefore, illegal dumpsites are common in the floodplains, and waste is often transported into the rivers (Mihai et al., 2012, 2018; Katona, 2019). The recycling rates of municipal waste range in Carpathian countries from 2.5% in Ukraine to 35% in Slovakia and Poland (IFC, 2015). A macro-level strategy to improve regional cohesion policies for the Carpathian region is discussed at the European Parliament level to be further developed in addition to the current four such EU macro-regions (e.g. Alpine region). This discussion identifies 'Management of environmental risk and natural threats' as a priority action part of the Green Carpathian objective (Jourde and van Liero, 2019). The first step should be to increase the efficiency of waste management to reduce local levels of MPW (e.g. capture rate of plastics through separate collection) in the Carpathian region through a multi-stakeholder perspective (Ekosphera, 2021).

2.2. Data and analysis

To estimate MPW along watercourses in the Carpathian ecoregion (CERI, 2001), we combined three datasets: river networks (Lin et al., 2021), digital elevation models (SRTM DEM), and MPW (Lebreton and Andrady, 2019), as seen in Fig. 2. The created map and dataset allowed us to conduct further regional and national analyses with respect to selected environmental variables (i.e., Strahler stream orders, basins, and type of protection form) (Fig. 2). Information about the spatial coverage of a given protection form was based on the data published by the European Environmental Agency (https://www.eea.europa.eu/data-and-maps).

2.2.1. Mismanaged plastic waste (MPW) dataset

We used a global dataset of modelled mismanaged plastic waste (Lebreton and Andrady, 2019) available as a 30 arc second map of annual MPW generation (pixel size: 1 x 1 km^2). This dataset (Leberton and Andrady, 2019) was developed using information on municipal solid waste generation (the fraction of plastic found within waste per capita) and the gross domestic product (GDP) at national level. The data are publicly available as a supplement to the paper by Lebreton and Andrady (2019). This database was previously successfully utilised for diverse purposes. Recently, Roebroek et al. (2021) and Meijer et al. (2021) used it for the assessment of flood-related remobilisation of MPW and the annual plastic emissions in rivers on a global scale. However, some recent studies (Schuyler et al., 2021) have indicated the possible inaccuracy of the MPW values in such a global dataset as population density may not be an accurate variable in estimating MPW.

2.2.2. River network dataset

To obtain information about the spatial distribution of the Carpathian watercourses, we used the global vector-based hydrography dataset created by Lin et al. (2021). This database represents all watercourses in a uniform way (as a vector layer), regardless of their size, and contains additional attributes (e.g., Strahler stream order and basin and catchment names). This simplified our calculations and decreased the time needed for assigning MPW values for all 175,674.9 kilometres (n = 127,940 polylines) of the watercourses analysed in the study (Table S1). However, the simplified nature of the database may have affected the accuracy of the estimates of MPW in relation to the amounts that actually enter the river channel between large and small watercourses. Specifically, larger rivers may have substantially higher channel and floodplain areas per unit of river length than smaller streams. Thus, in larger watercourses, the same MPW value along a given river length may result in a higher input of MPW to the fluvial system than in smaller watercourses (Roebroek et al., 2021).

2.2.3. Spatial distribution of MPW along the Carpathians watercourses

To determine the spatial distribution of MPW along the Carpathian watercourses, we intersected the pixel values of the MPW layer (Lebreton and Andrady, 2019) with polylines representing individual watercourses (Lin et al., 2021) in the Carpathian ecoregion (Fig. 2). This method takes into account the MPW values within the first 1 km surrounding the river, which interact with the river the most. A similar workflow was applied by Roebroek et al. (2021). The value of MPW for a given polyline (i.e., a river reach) was subsequently calculated as a median value of all the pixels of the MPW database (Lebreton and Andrady, 2019) intersecting that polyline (Fig. 2). The calculations were performed using R software (version 4.0.2. “Taking Off Again”; R Core Team, 2019).

The resolution of the MPW database (1 x 1 km^2 pixel size) (Leberton and Andrady, 2019) (see section 2.2.1.) may potentially oversimplify the MPW values along the smallest streams represented by polylines shorter than the pixel size. The median length of all analysed polylines was 1.09 km; however, 78% of the total lengths of all analysed watercourses were represented by longer polylines (Fig. S2). Taking into account that the proportion of short polylines (those shorter than 1.09 km) was evenly distributed along the whole elevation gradient of the study area (Fig. S2), we assumed that the potential for oversimplification of the MPW values along the short polylines had no substantial influence on the general spatial patterns of the MPW presented on our map (Fig. 3).

2.2.4. Data analysis

The MPW values among the watercourses of the given Strahler stream order (Strahler, 1952), countries, and catchments were compared using a Kruskall–Wallis test. A post hoc Bonferroni test was applied to investigate which pairs within the above comparisons were statistically different. The comparison of the MPW between the basins (Baltic Sea vs. Black Sea) and the protection form types (protected vs. unprotected) was completed using a Mann–Whitney U test (Fig. 2). All comparisons used statistically significant values of $p < 0.05$. The above non-parametric tests were used because a normal distribution did not occur in all the compared samples.

We defined MPW hotspot sections of the rivers using MPW values that were higher than the 90th percentile of the values mapped along the watercourses beyond the protected areas, and we defined MPW coldspots as those with MPW values of <1 t/yr/km^2.

3. Results

The median and the 90th percentile MPW values for the areas of all the flow-through Carpathian watercourses reached 5.2 and 320.2 t/yr/km^2, respectively (Tables S3). However, there were considerable spatial variations in relation to the elevation gradients (section 3.1), Strahler stream orders (section 3.2), catchments and basins (section 3.3), and protection forms (section 3.4).

3.1. Distribution of mismanaged plastic waste along the elevation gradients of watercourses

In general, the Carpathian watercourses above the elevation of 750 m a.s.l. (33312.1 km, 19% of the stream lengths) were typified by a negligible amount of MPW (Petitt test, $p<0.0001$, see Fig. 4). However, this threshold elevation varied among the Carpathian countries and catchments (Fig. 4C and 4D). The highest threshold elevation (determined using a Petitt test (see Fig. 2)) was detected along the watercourses in Poland (1100 m a.s.l.), and these thresholds became progressively lower in Slovakia (930 m a.s.l.), Romania (740 m a.s.l.), Ukraine (700 m a.s.l.), Czech Republic (590 m a.s.l.), and Hungary (330 m a.s.l.). These threshold values were detected to be relatively low in Hungary and Czech Republic because these two countries generally lack watercourses at higher elevations (see Table S2). Among the main investigated catchments, the highest threshold elevation was found along the watercourses in the Vistula catchment (1100 m a.s.l.), whereas the thresholds occurred at progressively lower elevations in the Dniester (760 m a.s.l.), Danube (730 m a.s.l.), and Odra (590 m a.s.l.) catchments (Fig. 4B).

3.2 Mismanaged plastic waste in watercourses of different Strahler stream order

For the all Carpathian watercourses, the median amounts of MPW in riparian zones increased from 1.1 t/yr/km^2 in the first-order watercourses to 2.1 t/yr/km^2 in the second-order watercourses to 6.1 t/yr/km^2 in the third-order watercourses to 23.0 t/yr/km^2 in in the fourth-order watercourses to 43.8 t/yr/km^2 in the fifth-order watercourses to 55.2 t/yr/km^2 in the sixth-order watercourses. For the seventh-order streams, the MPW values decreased to 18.3 t/yr/km^2, and they reached their highest values in the eighth- (88.2 t/yr/km^2) and ninth-order watercourses (85.4 t/yr/km^2) (Table S3). For all analysed watercourses, the median MPW values along watercourses of a given stream order increased as the elevation of such watercourses in a given country decreased, reaching their highest values in the lowest-lying areas of Hungary (Fig. 5).

The median MPW values were negligible (<1 t/yr/km^2) along the Carpathian watercourses flowing through Serbia and for the first- and second-order streams in Slovakia and Ukraine, and they were highest along the fifth-order watercourses in Hungary (907.1 t/yr/km^2), Czechia (52.9 t/yr/km^2), Romania (118.4 t/yr/km^2), and Poland (23.1 t/yr/km^2) and the sixth-order watercourses in Slovakia (1152.0 t/yr/km^2) (Table S3 and Fig. 5).

3.3. Mismanaged plastic waste within the Carpathian catchments

The Carpathian watercourses belonging to the Black Sea basin (88.3% of all the Carpathian watercourse lengths) flow through areas with significantly higher (p<0.001) MPW values (median = 5.1, mean = 279.7, and 90th percentile = 381.1 t/yr/km^2) than the watercourses flowing into the Baltic Sea (median = 6.5, mean = 36.1, and 90th percentile = 84.8 t/yr/km^2) (11.1% of the Carpathian watercourses) (Fig. 6A, B). The statistically significant (p<0.001) differences in watercourse MPW values were found between the main Carpathian catchments analysed (Fig. 6C). The median MPW value along watercourses within the Dniester catchment (2.6% of the Carpathian watercourses) was the highest (24.1 t/yr/km^2), and the lowest value was found along watercourses within the Danube catchment (4.8 t/yr/km^2) (85.6% of the Carpathian watercourses). The median MPW values for watercourses within the Vistula (6.4 t/yr/km^2) and Oder (9.1 t/yr/km^2) catchments were similar and were between the values mapped for the Dniester and Danube catchments (Figure 6C).

3.4. Mismanaged plastic waste in protected areas

For all of the Carpathian watercourses, the median MPW values were significantly higher in unprotected areas (7.2 t/yr/km^2; 68.2% of all analysed watercourses) than those of the protected ones (1.7 t/yr/km^2; 31.8% of all analysed watercourses) (Fig. 7A). The median MPW values varied significantly among the protection form types (Fig. 7B). The MPW values along the watercourses flowing through areas protected at the national level (72.1 t/yr/km^2) (2.3% of all analysed watercourses) were higher than those of the areas protected at the regional (1.25 t/yr/km^2) (29.5% of all analysed watercourses) and international (0 t/yr/km^2) (0.04% of all analysed watercourses) levels (Fig. 7B). There were no statistical differences in the MPW values along the watercourses flowing through areas protected at the regional and international levels (Fig. 7B).

3.5. Hot spots of MPW along the Carpathian watercourses

To spatially summarise the above results, we mapped the MPW hotspots and coldspots (see section 2.2.4) (Figure 8B). For all of the Carpathian watercourses, we indicated 11616.9 km of MPW hotspots and 66599.2 km of MPW coldspots. Most of the hotspots were mapped in Romania (56%, 6567.5 km), Hungary (23.1%, 2679.2 km), and Ukraine (16.5%, 1914.3 km), or at a larger spatial scale, within the Danube catchment (94.6 %, 10987.3 km) and the Black Sea basin (98.3%, 11415.7 km). Most of the MPW coldspots were mapped in Romanian (47.8%, 31855.4 km), Slovakian (21.9%, 14577.2 km), and Ukrainian watercourses (11.2%, 7491.6 km). Similarly, for hotspots, their proportions were the greatest in Carpathian watercourses belonging to the Danube catchment (87.6%, 58370.1km) and the Black Sea basin (90.9%, 60528.0 km) (Table 1).

We took into account that the different spatial units considered (country, catchment, and basin) covered different proportions of the Carpathian Mountains area, and thus, they covered different lengths of the watercourses belonging to them (see Table S1). To reduce the bias resulting from this, we presented the proportions of MPW hotspots and coldspots in these spatial units as values (%) normalised to the watercourse lengths belonging to them. This showed that the proportions of MPW hotspots were the highest for Hungary (33.4%), Ukraine (12.9%), and Romania (6.9%), and at the larger spatial scale, they were highest for watercourses belonging to the Danube catchment (7.3%) and the Black Sea basin (7.4%). The proportions of MPW coldspots, calculated in the same way, were the highest for Romania (47.8%) and Slovakia (21.9%), and at the larger spatial scale, they were the highest for watercourses belonging to the Danube catchment (87.9%) and the Black Sea basin (90.9%).

4. Discussion

4.1. MPW mapping uncertainty

The MPW values presented in our map should be interpreted with caution due to the limitations resulting from the methods and datasets used. First, the databases used here as sources of information on MPW (Leberton and Andrady, 2019) consider the amount of MPW as annual input/leakage per year for a given pixel area (1 x 1 km). This means that the higher MPW values recorded on our map along a given watercourse section may not be simply equated to a greater amount of plastic debris entering the river channel or floodplain zone in that section. The possibility of disposed plastic in a given part of the fluvial system entering a river channel depends on numerous characteristics of that particular river catchment and riparian zone (e.g., wind, surface runoff, land cover, and relief) (see, e.g., Mellink et al., 2022). To explore the relationship between the mapped MPW values and plastic pollution in a given section of the Carpathian rivers, future studies can, for example, map the densities of dumping sites on river floodplains (for methods, see, e.g., Matos et al., 2012), quantify the amount of MPW transported by river water (for methods, see, e.g., van Emmerik et al., 2020) or stored in river sediments (for methods, see, e.g., Liro et al., 2020, 2022) in the locations characterised by different MPW values. Despite the above, future studies can also shed light on how much MPW can enter rivers by utilising the recently developed numerical model of plastic pathways within a river catchment (Mellink et al., 2022) or by conducting field experiments (Liro et al., 2023) which are able to gain data on the amount and the rate of plastic input from river valley slopes to river channels. Future findings should be integrated into local and regional waste management strategies across the Carpathian region (Mihai et al. 2022b).

Second, the utilised MPW database (Leberton and Andrady, 2019) uses the gross domestic product, which may overlook some portion of MPW input resulting from tourism, recreation, and sport activities, which are popular in the Carpathian region. It may be interesting for future works to conduct the direct quantification of disposed plastic as the result of different types of tourism, recreation, and sport activities. The combination of field-based data on plastic disposal (e.g., number of items/m^2, mass of items/m^2, and types of plastic items) and numerical models able to predict the plastic waste movement through a catchment (Mellink et al., 2022) can provide some estimates for the amount of MPW produced and input to rivers by different types of tourism or sport activities.

Despite the fact that our map was not suitable for a direct quantification of the amount of plastic entering a river in a given section, it still offers a spatially uniform source of information on the potential riverine MPW hotspots in the Carpathian region (Fig. 3, Table 1). Together with the statistical data on regional and country levels (Table S3), this can be used to inform local communities and stakeholders about plastic problems in a given region.

4.2. The hotspots of mismanaged plastic waste along the Carpathian watercourses

Our results suggest that fourth-, fifth-, and sixth-order (Fig. 3, Table S3) watercourses should be further investigated as potential storage and remobilization zones of plastics (Liro et al., 2020 and van Emmerik et al., 2022). Such watercourses in mountainous areas typically have wide floodplains and valley bottoms and low valley slopes. These relief parameters make these valleys easier for human use, and therefore, they are typically densely populated and industrialised (Wohl, 2010). The challenges for future works will be to evaluate how such plastic storage zones are operating between and during large floods (van Emmerik et al., 2022) and to identify the effects of human modifications to rivers (dams, river regulation, and floodplain embankment) on the spatial and temporal patterns of plastic storage, remobilisation, and downstream transport (Mihai 2018a; van Emmerik et al., 2022; and Liro et al., 2020, 2022, and 2023). Thus, future efforts to manage plastic pollution in the larger (fourth, fifth, and sixth order) watercourses in the Carpathian region should be focused not only on the river channel and near-channel zones but also on the entire floodplain area (Liro et al., 2023). It seems that the roads, in particular, in these areas should be further verified as local input zones (see, e.g., Matos et al., 2012 and Mihai 2018a). Recent observations have also suggested that attention should be paid to dams and reservoirs (Mihai, 2018a) and wide, multi-thread sections of a river (Liro et al., 2022) as potential locations for clean-up actions. Some clean-up efforts completed on reservoirs in Romania during 2005–2012 (Mihai, 2018a) and those on the Tisza River in Hungary since 2007 (Katona, 2019) have suggested, however, that the temporally and spatially limited scale of such actions has not reduced the problem in the years that followed (Mihai et al., 2022a, b). An additional solution for the future may be the installation of macroplastic trapping infrastructures on dam crests, along reservoir shorelines, or across a river (see, e.g., Mihai, 2018a and Katona, 2019) and especially on dams located immediately downstream of MPW hotspots (Fig. 3).

4.3. Mismanaged plastic waste in protected areas of the Carpathian region

Our results highlight the need to further investigate the plastic pollution within the areas protected at the national level, where the amount of MPW mapped along the watercourses in the protected areas was the highest (Fig. 7). It is generally known that the amount of plastic in a protected area depends on the area's vicinity to anthropogenic resources, the lifestyles and consumption levels of local citizens, local waste management systems, tourism infrastructure, and leisure activities (Mihai, 2018b and Napper et al., 2020). There is a need to further verify the relation of the mapped MPW values with the macroplastic input (e.g., dumping sites) and its amounts in the river water and sediments of the protected areas in this region. In mountainous tourist areas (towns, ski resorts, trails, and viewpoints), plastic waste disposal is likely closely related to the movements of tourists, and so particular attention should be paid to the streams flowing through or near such areas. The Carpathian

Mountains are visited by an increasing number of visitors (approximately 45 million overnight stays per year; Meyer, 2018). The amount of generated waste is often determined by the activities and practices of tourism companies and local governments and, especially, by the behaviours of the tourists themselves (Manfredi et al., 2010 and Byers, 2014). Our map showing potential MPW hotspots and coldspots along Carpathian watercourses (Fig. 8) can be seen as background material for testing the relationship between the amount of plastic debris in river sediments and water and such activities in the region on a more local scale. Seasonal tourism put additional pressure on waste operators in coping with increasing waste generation rates in addition to domestic waste (residential sources), which could add to the plastic pollution of freshwater bodies in Central and Eastern Europe (Mihai et al., 2022a). Waste reduction is recognized as a key environmental policy for reducing environmental pollution across the Carpathian region (Bösze et al., 2014). In practice, implementation is difficult without effective waste management infrastructure and raising public awareness. Plastic waste has a significant share of dumped waste (15%) in Slovakia in addition to the household and construction fractions (Sedova, 2015), while the Eastern Carpathians of Romania are facing massive plastic pollution along the Bistrita catchment area (Mihai, 2018a). Source-separated plastic collection schemes for residents and tourist accommodation units are basic steps in mitigating MPW in the Carpathian region in Romania and Ukraine (Murava and Korobeinykova, 2016 and Brătucu et al., 2017), including protected areas. For example, Ceahlau National Park (eastern Carpathians, Romania) has checkpoints that monitor tourist flows on trekking routes and mountain huts, and the Park provides separate collection bins for plastic packaging materials (Mihai et al., 2012). Earlier studies have also pointed out that the mountain rivers and creeks flowing from the eastern Carpathians were exposed to the household waste dumping practices on riverbanks, which included plastic waste fractions (Mihai et al., 2012 and Mihai et al., 2018) (see Fig. 9). Increasing the public's awareness about this issue should be the first step in overcoming the problem. Such efforts should be undertaken in the future, for example, by presenting information on plastic's fate and the related risk in mountain river environments (see, e.g., Liro et al., 2023) within the mapped MPW hotspots (Fig. 8). Future works can also quantify the MPW emissions at the different levels of administrative units based on modelling that utilises waste management data (see, e.g., Mihai, 2018a).

The depletion of plastic to the environment depends on its global usage (e.g., Mihai et al., 2022b). The first step towards depleting the MPW along the Carpathian watercourses should be improved sourced-plastic collection schemes and, in the long-term perspective, a reduction in plastic packaging. Such changes should be combined with law enforcement and campaigns increasing environmental awareness to Carpathian citizens (Mihai, 2018b and Mihai and Grozavu, 2019). However, such behavioural alterations need to be supported by scientific data, effective educational actions on consumption practices, policies, and product design, which must be clearly passed to the public by trustworthy knowledge and legislation (Grodzińska-Jurczak et al., 2020 and Stanton et al., 2021). To be effective, these actions must be implemented at the local scale. The MPW hotspots along the Carpathian watercourses mapped in this work (Table 1 and Fig. 3) can be seen as a potential base for targeting such actions in the future.

5. Conclusion

We mapped mismanaged plastic waste (MPW) along 175,674.9 km of the Carpathian watercourses, documenting the following:

- The Carpathian watercourses below an elevation of 750 m a.s.l. (142282 km, 81% of the stream lengths) are affected by MPW (Fig. 4).

- The amount of MPW increases linearly as the watercourse elevations decrease, with the maximums values detected along the fifth- and sixth-order stream (Fig. 5 and Table S3).
- The 11616.9 km of rivers flowing through areas have very high levels of MPW. A majority of these hotspots occur in Romania (56%, 6567.5 km), Hungary (23.1%, 2679.2 km), and Ukraine (16.5%, 1914.3 km) (Fig. 8).
- We also found that rivers flowing through the areas protected at the national level have significantly higher MPW levels than other protected areas (Fig. 7).

We hope that the map and statistics we provided here can help to target future field works and local clean-up action as well as manage rivers in the Carpathian region in a way that limits or avoids the input of MPW to their channels, and decrease related risk caused by its downstream transport and fragmentation. Obtained data give also a unique source of information for comparison with other mountain regions, which can implement methodological approaches applied in this study.

Data availability statement

All data used in this study are openly available. The data on mismanaged plastic waste can be found as a supplement to the study by Lebreton and Andrady (2019) (https://figshare.com/articles/Supplementary_Data_for_Future_scenarios_of_global_plastic_waste_generation_and_disposal_/5900335), and a vector-based global river network dataset can also be used as a supplement to the study by Lin et al. (2021) (https://doi.org/10.1038/s41597-021-00819-9). Map and statistics created in this study are freely available as Supplementary Material and .kml file (https://figshare.com/ndownloader/files/40203682).

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.

Author Contributions

M.L., conception, data curation, formal analysis, writing—original draft, and creating the first versions of the figures; A.Z., data calculation, data curation, formal analysis, and contributions to the writing of the original draft and the figures preparation and their revisions; J.L.,T.V.M., M.G.J., T.K., and F.C.M., contributions to writing and revising the manuscript.

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Figures captions

Figure 1. Location of the Carpathian Mountains (bounded by the yellow line) in Central Eastern Europe. Countries with a proportion of their territory in the Carpathian Mountains: CZ–Czech Republic; HU–Hungary; PL–Poland; RO–Romania; SK–Slovakia; SR–Serbia, and UA–Ukraine. The background map source was https://webgate.ec.europa.eu/

Figure 2. The workflow applied in this study.

Figure 3. Spatial distribution of mismanaged plastic waste along the Carpathian watercourses. Abbreviations of the names of the countries are as stated in Fig. 1.

Figure 4. Distribution of the amounts of mismanaged plastic waste (MPW) along the elevation gradients of the Carpathian watercourses from different countries (A), from the main river catchments (B) and the average threshold elevations of MPW values in the watercourses from different countries (C), and from the main river catchments (D).

Figure 5. Distribution of the amounts of mismanaged plastic waste (MPW) within the given stream orders of the Carpathian watercourses. Statistical significance levels are described as follows: n.s.–not statistically significant, *–*p* <0.05, **–*p*<0.01, and **–*p*<0.001.

Figure 6. Comparison of the amounts of mismanaged plastic waste between the basins and catchments of the Carpathian watercourses. The dots mark the median values and the whiskers mark the 90th percentiles. The comparison of the basins was completed using a Mann–Whitney U test. The comparison of the catchments was completed using a Kruskall–Wallis test. The statistical descriptions are the same as those used in Figure 5.

Figure 7. Comparison of the amounts of mismanaged plastic waste (MPW) between the Carpathian watercourses flowing into the areas of different protection form types. The dots mark the median values and the whiskers mark the 90th percentiles. Comparisons between the national, regional, and international protection form types for the whole Carpathian region was completed using a Kruskall–Wallis test. Comparisons between the national and regional protection form types for a given country were completed using a Mann–Whitney test. The statistical descriptions are the same as those used in Figure 5.

Figure 8. The sections of Carpathian watercourses defined as hotspots (MPW>409.7 t/yr/km^2) (A) and clean spots (MPW<1 t/yr/km^2) (B) of mismanaged plastic waste. The dotted line is representing boundary of the Carpthian ecoregion.

Figure 9. Plastic pollution line (close up) at Izvoru Muntelui Lake in the eastern Carpathians of Romania. The mismanaged plastic waste was transported from upstream localities by previous high flows of the Bistrita River and its tributaries, and during the summer drought of 2022, the water line retreat supported the trapping of the pollution (photo taken by F.C.M., August 2022)

Table 1. Proportion of Carpathian watercourses lengths in the areas defined as hotspots (MPW>409.7 t/yr/km^2) and clean spots (MPW<1 t/yr/km^2) of mismanaged plastic waste. *normalised value refers to the percentage of river lengths within hotspots and coldspots divided by the river lengths in the given spatial unit considered (country, catchment, and basin).

Figure S1. Recycling rate (%) of municipal waste in the countries of the Carpathian ecoregion (based on data from https://ec.europa.eu/eurostat).

Figure S2. The distribution of the lengths of the polylines representing the Carpathian watercourses across the elevation gradients.

Table S1. Proportion of Carpathian watercourse lengths according to Strahler stream order.

Table S2. Elevation of Carpathian watercourses according to Strahler stream order.

Table S3. Mismanaged plastic waste (median and 90th percentile) along the watercourses of a given Strahler stream order of Carpathian countries.

Table 1. Proportion of Carpathian watercourses lengths in the areas defined as hotspots (MPW>409.7 t/yr/km^2) and clean spots (MPW<1 t/yr/km^2) of mismanaged plastic waste. * normalised value refers to the percentage of river lengths within hotspots and coldspots divided by the river lengths in the given spatial unit considered (country, catchment, and basin).

The length (km) and proportion (%) of watercourses	Hotspots of MPW			Coldspots of MPW		
	km	%	% (normalized)*	km	%	% (normalized)*
Country						
Czechia	64.1	0.6	1.3	1084.9	1.6	21.5
Hungary	2679.2	23.1	33.4	1461.5	2.2	18.2
Poland	157.9	1.4	0.9	4002.5	6.0	23.4
Romania	6567.5	56.5	6.9	31855.4	47.8	30.4
Serbia	0	0	0	6126.1	9.2	99.4
Slovakia	233.9	2.0	0.8	14577.2	21.9	51.2
Ukraine	1914.3	16.5	12.4	7491.6	11.2	48.5
Total	**11616.9**	**100.0**		**66599.2**	**100**	
Catchment						
Danube	10987.3	94.6	7.3	58370.1	87.6	38.8
Dniester	428.4	3.7	2.3	2157.9	3.2	46.9
Oder	37.5	0.3	3.0	323.5	0.5	25.8
Vistula	163.6	1.4	3.6	4594.4	6.9	25.2
Other	0	0	0	1153.3	1.7	100
Total	**11616.9**	**100.0**		**66599.2**	**100.0**	
Basin						
Baltic Sea	201.2	1.7	1.0	4917.9	7.4	25.2
Black Sea	11415.7	98.3	7.4	60528.0	90.9	39.0
Other	0	0	0	1153.3	1.7	100
Total	**11616.9**	**100.0**		**66599.2**	**100**	