MICRO- AND MACROPLASTIC DEBRIS TRANSPORT AND DEPOSITION IN THE FLUVIAL SYSTEM OF THE TISZA RIVER: A GEOGRAPHICAL PERSPECTIVE
(NO. 134306)

Final report

At the time of preparing the project proposal, only limited studies existed on rivers' microplastic (MiP) and microplastic (MaP) transport. These previous researches empathized the need to better understand the MiP and Map transport and sedimentation processes and that detailed information on their spatiotemporal variability is needed. Besides, scientific data on MiP and MaP debris hardly existed in Central and Eastern Europe. After our three years of research, the Tisza became one of the most thoroughly studied rivers in the world.

The project proposal addressed several aims. All of them were fulfilled, and some were even further developed despite the premature closure of the research. At the time of the proposal writing, we did not plan to apply machine learning algorithms or develop a MiP transport model.. However, these modern methods were implemented due to the development of these technologies and the joining of new researchers in the group.

1. Floating macroplastic debris transport along the Tisza

1.1. Spatio-temporal changes in MaP pollution

Macroplastics highly endanger the mountainous sections of the Tisza River system due to improper communal waste management (Liro et al., 2023). Originally, we aimed to study riverine litter (including MaPs) based on a UAV survey. However, after performing some tests on the Lower Tisza, it became obvious that UAV surveys are not performable on longer sections with a frequent repetition time. Therefore, riverine litter transport was detected by applying Sentinel-2 and Very High Resolution (VHR) images and machine learning algorithms (Mohsen et al., 2023b). The VHR images served to identify riverine litter spots for training and validation. Altogether, five supervised machine-learning algorithms were applied, such as Artificial Neural Network (ANN), Support Vector Classifier (SVC), Random Forest (RF), Naïve Bays (NB) and Decision Tree (DT). To evaluate the generalization capability of the developed models, they were tested on larger unseen data under varying hydrological conditions and with different litter sizes. The best-performing model was used to investigate the spatiotemporal variations of riverine litter in the Middle Tisza. Almost all algorithms resulted in models with favourable metrics based on the validation dataset (e.g., F1-score for SVC: 0.94, ANN: 0.93, RF: 0.91, DT: 0.90, and NB: 0.83); however, during the testing process, they showed medium (e.g., F1-score for RF:0.69; SVC: 0.62, and ANN: 0.62) to poor performance (e.g., F1-score for NB: 0.48, and DT: 0.45). The pixel size of the Sentinel-2 images limited the capability of all models to detect litter.

The above results were compared with the citizen survey-based Clean Tisza Map (https://tisztatiszaterkep.hu/#/). The two surveys have large dissimilarities (Molnár et al., 2024). The volunteers (1) registered even very small accumulations ($\leq$0.01 m^3), (2) estimated the volume of waste accumulated at the polluted site, and (3) mapped the stranded waste on the floodplain and the banks. On the contrary, our Sentinel-based MaP survey is suitable for detecting (1) litter spot area larger than the pixel size ($\geq$100 m^2) and (2) floating waste on the surface of the river. Despite these dissimilarities, the volume of large accumulations registered by the citizens showed a good correlation (R^2 = 0.9) with the area of drifting litter revealed on Sentinel-2 images (2016–2022) using machine learning algorithms.

Based on the spatiotemporal investigation, hydraulic structures (e.g., Kisköre Dam, bridge pillars) create favourable conditions for developing large litter accumulation spots. The highest litter transport rate was detected during foods, but the largest litter spot area was observed at low stages in summer.

1.2. Relationship between the MaP and MiP pollution

The riverine litter accumulations registered by volunteers contained high amounts of plastic waste, and the drifting and stranded MaPs probably fragmented during their fluvial transport. However, no clear connection was found between the volume of litter accumulations and the mean microplastic fragment content of sediments collected between 2019 and 2022 (Molnár et al., 2024). It could be explained by (1) the slow fragmentation of MaPs, (2) earlier mobilisation and larger travel distances of MiP particles in suspension than the natural suspended sediments. However, in sections with declining flow velocities (e.g., impounded by dams), the trapping of the MaPs and the deposition of MiPs became similar, though they were not directly connected.

2. Temporal and spatial changes in microplastic transport and deposition along the Tisza

2.1. Short-term (5-day) temporal changes in MiP concentration in the water at one site

One of the study's uniqueness was the frequent sampling of MiP and suspended sediment (SS) transport of the Tisza. The measurements were performed with a return period of 5 days for two years, regardless of weather conditions or holidays. Altogether, 140 samplings were collected between May 2021 and May 2023 at Mindszent (Mohsen et al., 2023ac; Mohsen 2024; Balla et al., 2022, in print). During the studied period, the water stage fluctuated between –31 and 615 cm, and the low stages were interrupted by nine minor (H_{mean}: 118±84 cm) and ten medium flood waves (H_{mean}: 339±150 cm). Still, no large overbank flood occurred (Figure 1).

During the studied period, the surficial SS concentration (SSC_{mean}: 60±57 g/m^3) and MiP concentration ($MiPC_{mean}$: 35±27 item/m^3) followed a similar temporal pattern as the hydrograph. Thus, the lowest concentrations occurred during low stages (SSC: 34±14 g/m^3; MiPC: 21±16 item/m^3) and they increased by 32% (SSC: 45±27 g/m^3) and 95% (MiPC: 41±30 item/m^3) during minor floods, and further increased by 116% (SSC: 97±75 g/m^3) and 15% (MiPC: 47±27 item/m^3) during medium floods.

Water level (and thus discharge) changes strongly influence the temporal variation of SSC and MiPC. Besides, a strong positive (ρ=0.6) correlation between SSC and MiPC was revealed. The separation of various hydrological conditions (i.e., low stage, rising limb, peak, and falling limb of flood waves) revealed that a very strong positive correlation (ρ=0.7) existed during flood waves and negligible correlation (ρ=0.0) during low stages.

This is related to the low flow velocity (≤0.02 m/s) and stream power during low stages, stimulating SS and MiP deposition. Besides, during low stages, the water and MiP have different origins, as most of the water discharge originates from groundwater, but MiPs are from wastewater effluents. Meanwhile, during floods, the high flow velocity (>0.25 m/s) and highly turbulent flow mobilize the deposited SS and MiP from the riverbed into the water column. Additionally, slope sediments in the upland sub-catchments are mobilized, including MiP sources (Mohsen et al., 2023c).

Interestingly, even similar flood waves had different SSC and MiPC, as the first wave always had higher concentrations. The event sequence could explain it, as the first flood mobilizes natural sediments and MiP particles more effectively from the bottom of the channel. Hence, their concentration during the first wave is always higher than during the next similar or even higher flood waves.

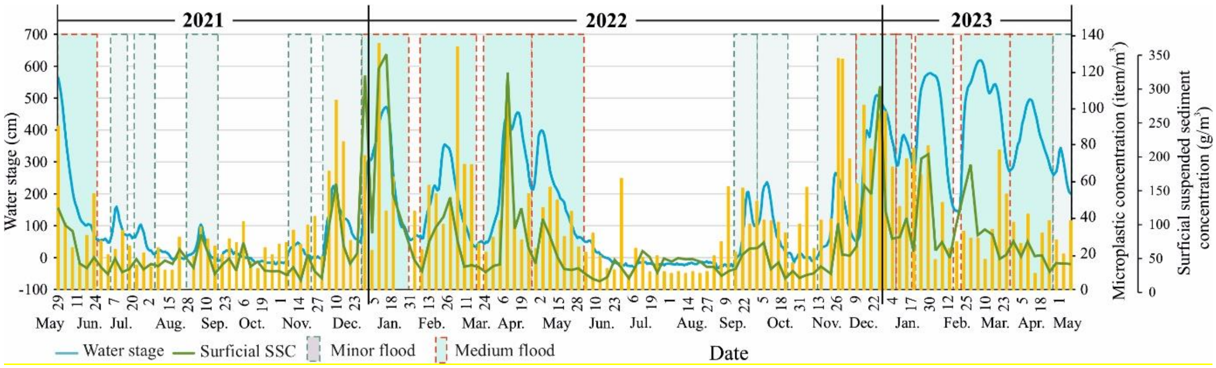

Figure 1. Temporal changes in daily water stages, suspended sediment, and microplastic concentrations during two years (May 2021–May 2023) at Mindszent (Hungary) based on sampling every five days.

2.2. Spatial changes in microplastic concentration in the water along the Tisza River (2021–2023)

The MiP pollution has a clear increasing temporal trend based on comparing the results of the three-year monitoring along the Tisza (Balla et al., 2022, in print). The mean MiPC of the entire Tisza was 19±13.6 item/m^3 in 2021, then it increased to 22.4±14.8 item/m^3 in 2022, and finally, it more than doubled to 52±41.6 item/m^3 in 2023 (Figure 2). The tributaries act as SS and MiP conveyors; therefore, they usually also transport considerably higher MiPCs (2021: no data, 2022: 27±19 item/m^3 and 2023: 70.3±53.2 item/m^3). Most of the particles (94-97.4%) were fibres, suggesting that they probably originated from the effluent water of wastewater treatment plants or uncleaned wastewater directly drained into the river system. The pollution was particularly high in the downstream section of the Upper Tisza (S2) and the Lower Tisza (S5), where wastewater treatment in the regions was relatively poor.

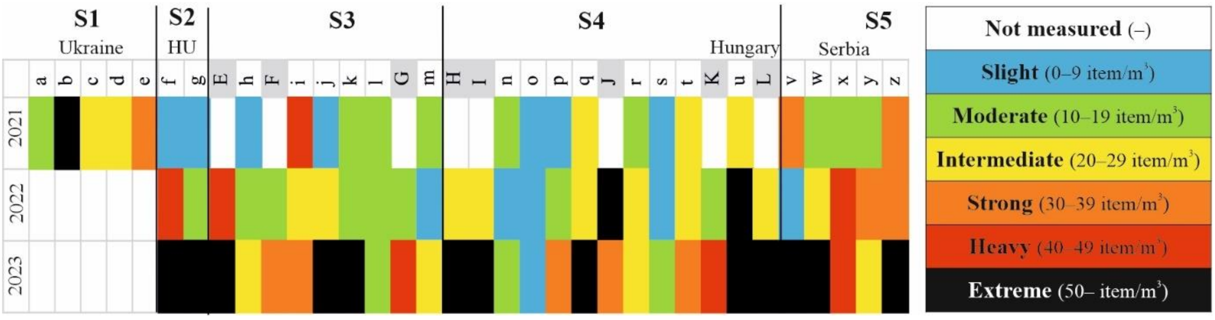

Figure 2: Changes in microplastic pollution on sampling sites between 2021 and 2023. Sampling was performed on the Tisza (a–z) and the main tributaries (E–L indicated also by grey background).

At a given moment, various number of flood waves could coexist in the fluvial system and gradually move downstream. The spatiotemporal pattern of the flood waves could be quite complex during heavy rainfall events in summer. Some sub-catchments could be more active this season, while others have very low stages. Thus, flood waves generated in a tributary could disrupt the low stages, especially on the main river. This mosaic spatial hydrological pattern caused the fluvial system's complex MiPC and SSC patterns.

Our measurements on SSC and MiPC suggest that the SS and MiP particles are transported in clouds, where the SSC and MiPC are higher than in between them. These clouds partially originate from tributaries, carrying different sediment loads, and the water mixing creates clouds (Mohsen et al., 2021). Clouds with larger SSC and MiPC are located further apart during low stages and move slowly, while during floods, shorter clouds follow each other quickly. However, less variability in MiPC was detected than in SSC, probably because the shear stress of the MiP particles is lower than SS grains. Some MiP particles are mobilized earlier than natural SS particles and may remain in suspension longer due to their light density and irregular shape.

2.3. Spatial changes in microplastic concentration in the sediments along the Tisza River (2019–2023)

Our measurements on the MiPC of the sediments suggest that the MiP content is highly dependent on the grain size of the sandy sediment. As the sand gradually gets finer along the Tisza from its source to its confluence, it influences the MiP content of the sediments. However, such a downstream trend was not found in the case of clayey sediments. Therefore, the downstream comparison of MiP content is based on fresh clayey sediments (*Figure 3)* collected at 74 points of the Tisza and the near-confluence zone of the tributaries (Kiss et al., 2021ab; 2022; Balla et al., 2024a). After the preliminary survey of 2019, the survey performed in 2020 could be considered as a baseline, as the MiP measurements were complemented with more sites, grain size analysis and suspended sediment measurements. The samples of the last survey (2023) are under preparation.

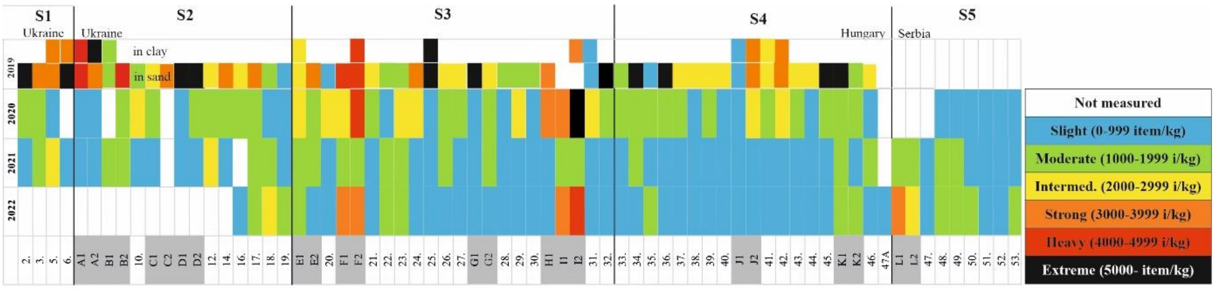

Figure 3. Changes in microplastic pollution of the clayey sediments on the sampling sites between 2019 and 2022. Sampling was performed on the Tisza (1–53) and the main tributaries (A–L).

The mean MiPC of the sediments was the highest in 2019 (3177±1970 item/kg), but it could also be related to insufficient contamination control. So, the first reliable data is from 2020, when the MiP content was 1291±618 item/kg, and gradually decreased (2021: 730±568 item/kg; 2022: 766±437 item/kg). The upstream and downstream sections were the most polluted due to local improper sewage treatment. In 2020, 63% of the sites were considered hot spots (≥2000 item/kg), but their number decreased to one-third in 2021 and 2022. The dominance of fibres (≥95%) refers to the waste water origin of the MiP pollution.

The comparison of the results of the years reflects that MiP pollution levels and the spatial trend of their changes were different each year. In 2019, the highest pollution was measured in the S1 and S3 sections. In 2020, the MiP pollution still peaked in the S3 section, and the downstream section was the least polluted (S5). In contrast, in 2021, the MiP gradually declined from the most polluted S1 section, reaching the least polluted S4 section, before increasing again in the S5 section. Finally, in 2022, the S2 section became the most polluted, and the least polluted was again the S4 section. These continuously changing spatial MiP pollution patterns reflect that the MiP pollution is continuously re-mobilized; thus, some sections and sites were emptied and acted as sources, while others had intensive aggradation and acted as sinks.

The number of locations of pollution hot spots (≥2000 item/kg) varied yearly, as some were emptied, while others became more polluted. The temporally stable hot spots refer to nearby MiP sources (e.g., sewage outlet, contaminated tributary). The gradual redistribution of MiPs is driven by flood waves, which can effectively mobilize MiP sinks. The largest mobilization and emptying were detected between 2020 and 2021 when higher stages and longer flood waves successfully mobilized and transported away the already deposited sediments and their MiP content from the fluvial system of the Tisza River.

Highly various environmental factors influence the MiP pollution of the sediments:

1) The geomorphological setting of a site is important, as most of the hot spots were on sidebars. The sediment sheets showed the greatest MiP variability. The different MiP sink–source dynamism of the forms could be explained by the different hydro-morphological conditions of their formation.
2) Tributaries, which are found to be more polluted (by 1.5–2.6 times) than the Tisza River; play a significant role in influencing the MiP pollution status of the main river. The sediments they mobilize can have a substantial impact on the overall pollution levels of the main river.
3) Between surveys, the MiP pollution of sediments can be effectively rearranged by bankfull or higher flood waves. This underscores the dynamic nature of sediment pollution and its susceptibility to environmental changes.
4) The downstream pattern of MiP pollution in the reservoirs is dissimilar. The sediments of the in-channel reservoirs (at Tiszalök and Novi Becej Dams) can be effectively mobilized when the floodgates are opened; therefore, the MiP content of the reservoir's sediments gradually decreases downstream. In the floodplain reservoir (at Kisköre Dam), the sedimentation rate increases downstream; therefore, the MiP pollution also gradually increases. Downstream (ca. 35 km-long section) of a dam, the clear-water erosion increases the proportion of the pristine sediments; thus, the MiP concentration decreases.

3. Developing a model to map microplastic pollution in a fluvial system based on suspended sediment as a proxy

Our results on SSC and MiP (Mohsen et al., 2021, 2023c; Balla et al., 2022), machine learning-based modelling of discharge (Mohsen et al., 2022) enabled us to develop a model to detect SSC and MiPC on longer sections based on Sentinel images (Mohsen et al., 2023a). Altogether, 122 Sentinel-2A-B images (3–5-day temporal resolution) and high-resolution PlanetScope images were employed and acquired to develop the model. The models were built by the multi-layer perceptron (MLP) neural network regressor. The k-fold cross-validation in the scikit-learn library was applied to split the data into five training and validating folds. The temporal testing data covered all hydrological situations (i.e., low stages and rising, peak, and falling phases of floods). In contrast, the spatial data covered eight sites between Aranyosapáti and Tiszaroff sampled in July 2022.

The indirect estimation method of MiP using SSC as a proxy demonstrated higher accuracy (R^2=0.17-0.88) than the direct method (R^2=0-0.2) due to the limitations of satellite sensors to directly estimate the very low MiPC in rivers. The estimation accuracy of the indirect method varied with lower accuracy (R^2=0.17, RMSE=12.9 item/m^3 and MAE=9.4 item/m^3) during low stages and very high (R^2=0.88, RMSE=7.8 item/m^3 and MAE=10.8 item/m^3) during floods. The best-performing model for estimating SSC was based on Sentinel-2, and the best-performing model for MiPC was achieved by PlanetScope, though its estimation accuracy is still low.

The SS and MiP models demonstrated favourable generalization capability during the temporal testing, while it declined notably during the spatial testing, because the temporal testing encompassed various hydrological conditions, while the spatial testing was limited to low stages. Therefore, additional longitudinal measurements during floods are necessary.

Besides, we report some limitations:

1) The SSC has low sensitivity to the MiPC changes during low stages, though it can still provide reasonable estimates (but not highly accurate).
2) The established relationship is highly sensitive to sudden changes in the sources of sediment and/or MiP either in space or time; hence it needs to be calibrated recurrently.
3) The derived SS–MiP relationship needs to be calibrated at confluences, dams, and effluents of waste-water treatment plants.

Based on the developed model, changes in the spatiality of the MiPC could be analysed *(Figure 4)*. In this way, we were able to detect MiP clouds in the Tisza and analyse the influence of a polluted tributary was analysed (Balla et al., in print). However, the model has further applicability in analysing the deposition and mobilisation patterns, and the MiP transport on the floodplain during floods.

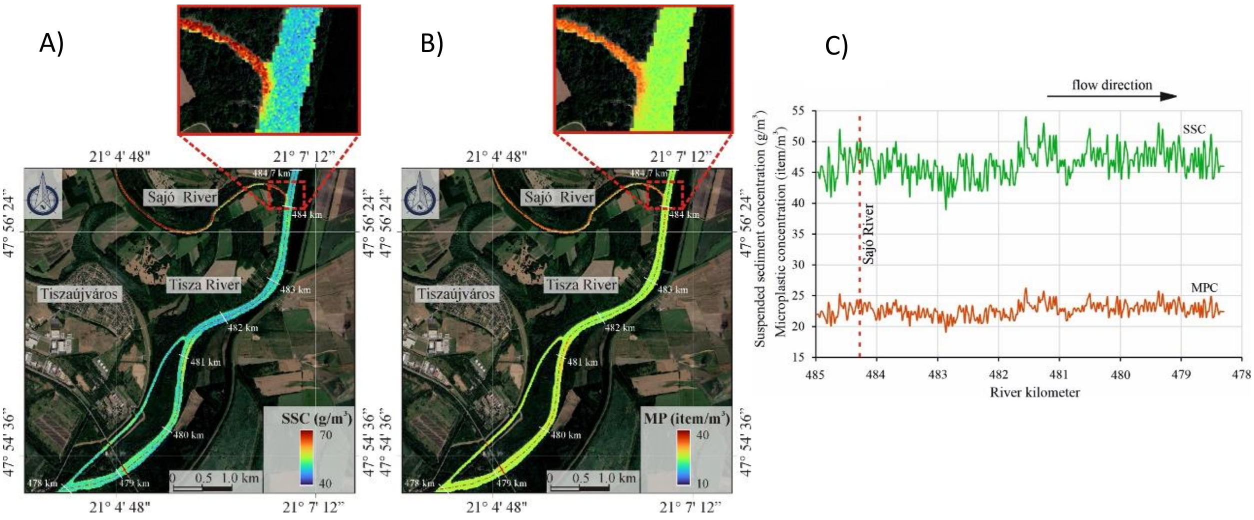

Figure 4: Modelled suspended sediment (A) and microplastic concentration (B) at the confluence area of the Sajó–Hernád Rivers after a bankfull flood in August 2023. Changes in suspended sediment and microplastic concentrations along the centerline of the channel (C).

4. Microplastic pollution of the floodplain: floodplain forms and vertical profiles

The spatial pattern of MiPs was studied on the floodplain section south of Mindszent and the point-bar of Csongrád (Kiss et al., 2021a; Fórián and Kiss, 2022). On the floodplain, the sediments of swales (458–1300 item/kg) and point-bars (220–1600 item/kg) were the most polluted (*Figure 5A)*, but the samples from the low-lying clay pits were also highly contaminated (818–880 item/kg). The active point bar and the natural levee have lower levels of MiP contamination (100–620 item/kg). As complex flow patterns could develop over the natural levees during overbank floods, no clear downstream trend MiP pollution of the surface sediments was found.

In the natural levee along the channel, microplastics are present to a depth of 50 cm (1753–4800 item/kg), while in the distal parts of the floodplain, only the upper 0–10 cm sediment layer is polluted. The deeper layers contain a higher amount of MiP, referring to the higher pollution level of the Tisza in the late 20th century. As the floodplain forms have different elevations, probably the uppermost sediments were not deposited by the same floods, as along the Lower

Tisza, the last flood covering the entire floodplain was recorded in 2013, and ever since, the floodplain was flooded just partially.

Many samples were collected from the large point-bar at Csongrád, to test the homogeneity of the MiP content of samples collected on the same form (*Figure 5B).* The measurement revealed a large difference between the MiP content of the samples, and no spatial trend (downstream or towards the thalweg) was identified. Therefore, the samples should always be collected from the same point with the similar characteristics (e.g., the axis of a form, by the distance from the thalweg).

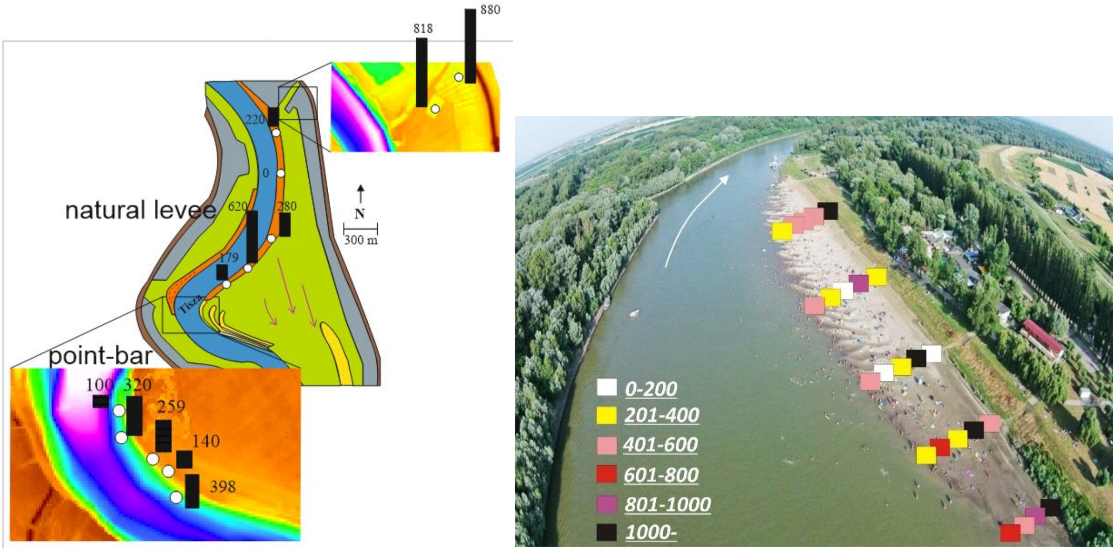

Figure 5: Microplastic content of various floodplain forms at Mindszent (A) and on the point-bar at Csongrád (B).

5. Microplastic monitoring considerations

5.1. Water sampling

The results suggest that MiPCs fundamentally differ during low stages or various phases of a flood wave, and the SS and MiP particles are transported in clouds. The complex spatiotemporal hydrological activity of the sub-catchments results in a mosaic pollution pattern. Thus, when planning MiP monitoring, we recommend considering a river's hydrological characteristics, such as the duration and level of floods and their event sequence, based on historical regime data. In the case of repeated measurements, sampling is offered at the same hydrological situation (e.g., low stage, rising limb, peak or falling limb of a flood) to make the data comparable. Recording and publishing the hydrological conditions during the measurement for comparability is also important.

Tributaries act as conveyor belts for SS and MiP, and their role can be particularly important during their flood while the main river has a low stage. Therefore, the sampling site should be carefully chosen downstream of tributaries, as the sampled water body could represent the waters of the joining rivers with different pollution degrees. Therefore, we suggest to sample upstream of confluences, and the effect of impoundment should also be avoided.

5.2. Sediment sampling

The MiP content of the clayey sediment samples can vary significantly in subsequent years at section and site scales, reflecting continuous spatial and temporal rearrangement of MiPs. Therefore, a single, snapshot-like study could not give a precise picture of the MiP contamination of a river. Thus, studying MiP dynamism over longer periods under various hydrological conditions is recommended to identify continuous or temporal MiP sources and sinks.

Our measurements on various in-channel and floodplain forms along the Tisza revealed that the superficial sediments have high intra- and inter-form variability. Therefore, in longitudinal studies, it is recommended to collect samples from the same form and from the same location (e.g., upstream or downstream end or axis) of a form. In sampling floodplain and channel forms, the flooding frequency and the time of the last flood covering the form should also be considered.

Tributaries, reservoirs, clear-water erosion downstream of dams, and the sampling point's morphology strongly influence the number of MiPs in sediments and the dynamics of the sediment deposition. Thus, if a study aims to investigate longitudinal changes in MiP over a long river section, it is recommended to collect samples from the same geomorphological form, which appears all along the river. In addition, the influence of tributaries and reservoirs on the spatial distribution of MiPs should be investigated by dense spatial and temporal measurements since the MiPs are mobilized and transported in pulses. In addition, due to the different hydrological conditions (e.g., stage, slope, flow rate) of the two joining rivers, the mixing of their waters and the impoundment should also be considered.

Based on our results, it is highly advised to

1) Collect clayey samples rather than coarser-grained ones, as this could eliminate the MiP dependency on grain size.
2) Repeat the measurements in space and time to identify continuous hot spots and evaluate remobilization.
3) Reveal the sources of the pollution.
4) Collect samples from the main tributaries to understand their MiP conveyor function.
5) Select sites with similar in-channel morphology.
6) Carefully analyse the MiP deposition of those areas where the slope of the river changes (e.g., mountains vs. lowlands, upstream and downstream of dams).

6. Communication and dissemination of the results

The project results were presented numerous times in TV and radio reports. Each year, several open classes were organised for primary and secondary school students, and we also appeared on the European Researcher's Night each year.

The researchers involved in the project actively disseminate their results. Altogether 14 articles were published in high ranked journals (summarized impact factor: 54.55). The results were presented on several conferences. Altogether 11 BSc/MSc thesis were written with the support of the project. Besides, our young researcher, A. Mohsen successfully defended his PhD in 2024 and A. Balla, in her third year of PhD studies, is on track for a successful defence in 2025.

6.1. Publications supported by the project:

2021: Summarised IF: 14.15

Kiss T.; Fórián Sz.; Sipos Gy. 2021a. A Tisza és mellékfolyói üledékében a mikroműanyag szennyezettség mértéke Rahó és Mindszent között. *Hidrológiai Közlöny* 101/2, 54-61.

Kiss T.; Fórián Sz.; Szatmári G.; Sipos Gy. 2021b Spatial distribution of microplastics in the fluvial sediments of a transboundary river – A case study of the Tisza River in Central Europe. *Science of the Total Environment* 785, 147306. (IF: 10.753)

Mohsen A.; Kovács F.; Mezősi G.; Kiss T. 2021 Sediment Transport Dynamism in the Confluence Area of Two Rivers Transporting Mainly Suspended Sediment Based on Sentinel-2 Satellite Images. *Water*, 13, 3132. (IF: 3.4)

2022 Summarised IF: 8.6 (in total: 22.75)

Balla A.; Mohsen A., Gönczy S., Kiss T., 2022 Spatial Variations in Microfiber Transport in a Transnational River Basin. *Applied Sciences* 12, 10852. (IF: 2.7)

Fórián Sz.; Kiss T. 2022 Ártéri üledékek mikroműanyag tartalma az Alsó-Tisza egy kanyarulata mentén. *Földrajzi Közlemények* 146/1. 1–15.

Kiss T.; Gönczy S.; Nagy T.; Mesaroš M.; Balla A. 2002 Deposition and Mobilization of Microplastics in a Low-Energy Fluvial Environment from a Geomorphological Perspective. *Applied Sciences* 9, 4367. (IF: 2.7)

Mohsen A.; Kovács F.; Kiss T. 2022 Remote Sensing of Sediment Discharge in Rivers Using Sentinel-2 Images and Machine-Learning Algorithms. *Hydrology* 9/5, 88. (IF: 3.2)

2023 Summarised IF: 18.8 (in total: 41.55)

Mohsen A., Kovács F., Kiss T. 2023a Riverine Microplastic Quantification: A Novel Approach Integrating Satellite Images, Neural Network, and Suspended Sediment Data as a Proxy. *Sensors* 23. 9505. (IF: 3.85)

Mohsen A., Kiss T., Kovács F. 2023b Machine learning-based detection and mapping of riverine litter utilizing Sentinel-2 imagery. *Envi. Science and Pollution Res.* 30, 67742-67757. (IF: 5.19)

Liro M.; Zielonka A.; van Emmerik T.H.M.; Grodzińska-Jurczak M.; Liro J.; Kiss T.; Mihai F.C.; 2023 Mountains of plastic: Mismanaged plastic waste along the Carpathian watercourses. *Science of the Total Environment* 888, 164058 (IF: 9.8)

Mohsen A.; Balla A.; Kiss T. 2023c High spatiotemporal resolution analysis on suspended sediment and microplastic transport of a lowland river. *Science of the Total Environment* 902, 166188p. (IF: 9.8)

2024 Summarised IF: 13.0 (in total: 54.55)

Balla A.; Teofilovic V.; Kiss T. 2024a Microplastic Contamination of Fine-Grained Sediments and Its Environmental Driving Factors along a Lowland River: Three-Year Monitoring of the Tisza River and Central Europe. *Hydrology* 11, 11 (IF: 3.2)

Molnár, A.D.; Málnás, K.; Bőhm, S.; Gyalai-Korpos, M.; Cserép, M.; Kiss, T. 2024 Comparative Analysis of Riverine Plastic Pollution Combining Citizen Science, Remote Sensing and Water Quality Monitoring Techniques. *Sustainability* 16, 5040. (IF: 3.9)

Balla A.; Moshen A.; Kiss T. Microplastic clouds in rivers: Spatiotemporal dynamics of microplastic pollution in a river system. *Evironmental Sciences Europe* (in print) (IF: 5.9)

Mohsen A. 2024: A multi-scale investigation of sediment and plastic pollution transport in the Tisza River applying remote sensing and machine learning: A hydrological perspective. PhD Thesis, SZTE–TTIK, p. 120.