Numerical Modelling of Microplastic Transport in the Confluence Area of the East Jiu River and the Maleia Stream Using a CFD–DPM Approach

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Abstract

Microplastic pollution in aquatic ecosystems represents a major environmental concern, and understanding the mechanisms governing transport, dispersion, and accumulation requires methodologies capable of describing particle–turbulence interactions. This study proposes an integrated methodology for investigating microplastic transport in the confluence area of the East Jiu River and the Maleia Stream, combining experimental data on polymer typology (reported in a previous study) with Computational Fluid Dynamics (CFD) numerical simulations. The numerical modelling was performed in ANSYS Fluent over a representative river reach, employing the Reynolds-Averaged Navier–Stokes (RANS) equations to describe the continuous phase and the Discrete Phase Model (DPM) within a Euler–Lagrange framework to track microplastic particles. Turbulence effects on particle trajectories were incorporated using stochastic tracking methods, enabling a realistic representation of particle dispersion within the flow field. The numerical model consistency was verified through hydrostatic pressure distribution analysis, velocity field evaluation, mass balance closure, and residual convergence assessment. Simulations were conducted for commonly encountered polymers in aquatic environments (PET, HDPE, LDPE, and PVC) with particle diameters ranging from 25 to 250 µm. The results reveal distinct transport behaviors governed by material density and particle size. Polymers with densities lower than water (HDPE, LDPE) are predominantly transported within the upper flow layers, polyethylene terephthalate (PET) exhibits turbulence-controlled dispersion, while polyvinyl chloride (PVC) demonstrates rapid and stable sedimentation. The proposed CFD–DPM approach proves effective in identifying potential accumulation zones and supporting monitoring and mitigation strategies for microplastic pollution in riverine systems, providing a transferable methodological framework for similar studies in other hydrological contexts.

Keywords: *CFD modelling; transport; dispersion; water; environment.*

1. Introduction

Microplastics (MPs) have been detected in a wide range of aquatic environments, from rural ponds and lakes to the deepest oceanic regions [1, 13]. Over recent decades, microplastic pollution has become one of the most pressing environmental issues affecting aquatic ecosystems, due to the high persistence of polymeric materials and their capacity for long-distance transport. In aquatic systems, microplastics represent a particularly complex emerging contaminant, as their behaviour is simultaneously governed by hydrodynamic conditions, riverbed morphology, and the physicochemical properties of the particles. Rivers act not only as transport vectors toward coastal environments but also as active zones of retention, redistribution, and temporary accumulation [12], especially in geomorphologically complex sectors such as tributary confluences.

Addressing river pollution and pollutant propagation requires predictive tools (namely pollutant transport models) to support pollution assessment, mitigation strategies, and informed management decisions. Microplastics enter river systems through precipitation, surface runoff, stormwater drainage networks, and wastewater treatment plant effluents originating from domestic sources. In this context, mathematical models capable of characterizing the fate and transport of MPs in riverine environments are essential for identifying transport pathways and understanding their interactions within surface water systems.

Field-based experimental studies [2] (reported in a previous work) provide essential information regarding polymer typology and particle size distributions; however, they are limited in their capacity to describe local transport mechanisms and interactions between particles and turbulent flow structures. In this regard, Computational Fluid Dynamics (CFD) modelling represents a valuable tool for investigating advection, dispersion, and sedimentation processes of solid particles in turbulent flows. Euler–Lagrange approaches enable individual particle tracking and detailed trajectory analysis relative to the fluid velocity field.

Although numerous CFD applications addressing particle transport in aquatic environments exist in the literature [6-11], most studies focus either on large-scale regional models or on idealized flow conditions, often without direct correlation to real experimental data and local geomorphological characteristics. Particularly in mountainous and sub-mountainous rivers, characterized by variable hydrodynamic regimes and heterogeneous riverbeds, relatively few studies have analysed microplastic transport at the local scale within confluence areas using an integrated approach.

In this context, the present study aims to investigate microplastic transport in the confluence zone of the East Jiu River and the Maleia Stream (a tributary of the East Jiu River in western Romania) by combining experimental data with CFD numerical modelling. Turbulent flow is simulated in ANSYS Fluent over a representative reach, while particle dynamics are analysed using the Discrete Phase Model (DPM) within a Euler–Lagrange formulation. Microplastic particles with different physical properties

(PET, HDPE, LDPE, and PVC) are comparatively examined to highlight the influence of density and size on transport, dispersion, and sedimentation mechanisms. Through this approach, the study contributes to a more comprehensive understanding of microplastic behaviour in river confluence zones and provides a methodological framework applicable to similar analyses in other hydrological systems.

2. Methodology

2.1 Description of the computational domain and hydrodynamic conditions

Solving a problem using CFD involves the following stages: geometric modelling of the computational domain, domain discretization, model definition, property specification, establishment of initial and boundary conditions, numerical solution, and results analysis [3]. The numerical modelling was conducted on a representative reach of the East Jiu River, located upstream of its confluence with the Maleia Stream. The selected sector was chosen to reproduce stable hydrodynamic conditions and a relatively uniform riverbed geometry. The computational domain was defined in a two-dimensional (2D) formulation to simulate flow behaviour and microplastic transport within the experimental sector, considering longitudinal and vertical variations while assuming transverse uniformity, which was deemed appropriate for the scope of the analysis.

The modelled reach has a length of 1.0 m and a depth of 0.2 m, with a longitudinal slope of 0.6%, a bed roughness of $z_0 = 1 \times 10^{-3}$ m, and gravitational acceleration g = 9. 81m/s^2. These parameters were scaled to reproduce the flow regime characteristic of the analysed natural sector. At the inlet, a logarithmic vertical velocity profile was imposed, calibrated based on riverbed roughness and field-measured mean velocities. At the outlet, an outflow boundary condition was applied, while a symmetry condition was imposed at the free surface. The lower boundary was treated as a solid wall with equivalent roughness corresponding to the natural riverbed.

Fig. 1. Geometry and computational domain

Figure 1 illustrates the computational domain used for the numerical simulation of flow within the experimental reach of the East Jiu River, located upstream of the confluence with the Maleia Stream. The simplified geometry enables an accurate reproduction of local hydrodynamic conditions while maintaining reduced computational cost. The longitudinal slope and domain depth govern the velocity field distribution and the development of the shear layer, playing a fundamental role in the transport of solid particles.

2.2. Turbulent flow modelling

The most commonly employed numerical approaches for solving the Navier–Stokes equations include Direct Numerical Simulation (DNS), Reynolds-Averaged Navier–Stokes (RANS), Large Eddy Simulation (LES), and Detached Eddy Simulation (DES) [3,4].

Water flow was simulated by solving the Reynolds-Averaged Navier–Stokes (RANS) equations, using a turbulence model suitable for the fully turbulent regime characteristic of mountainous rivers. This framework allows for a robust description of the velocity field and turbulence parameters while ensuring moderate computational cost, which is appropriate for local-scale analyses.

The computational domain was discretized using a two-dimensional mesh comprising approximately 50,000 elements. The mesh elements were nearly isotropic, with very low geometric distortion values, ensuring minimal numerical diffusion and solution stability. Numerical convergence was assessed based on residual reduction below 10^{-5} and mass balance closure, with negligible relative deviation between inlet and outlet flow rates.

2.3. Microplastic transport modelling using a Euler–Lagrange approach

Microplastic transport was simulated using the Discrete Phase Model (DPM), implemented within a Euler–Lagrange framework in the ANSYS Fluent solver [5,6]. The continuous phase (water) was treated using a Eulerian formulation, while the discrete phase was represented by individual particles tracked in a Lagrangian manner. A one-way coupling assumption was adopted, justified by the low concentration of microplastics, whereby the fluid influences particle motion but particle feedback on the flow is neglected.

The trajectory of each particle was determined by integrating the particle motion equations, accounting for the dominant forces: drag force, gravity, buoyancy, virtual mass force, and lift force. Turbulence effects on particle motion were incorporated through stochastic tracking methods, enabling the capture of turbulent eddy influence on particle dispersion [10].

2.4. Particle properties and injection conditions

The simulations considered representative microplastic particles commonly found in natural aquatic environments: polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyvinyl chloride (PVC). Material densities were selected according to commonly reported literature values and confirmed through experimental analyses.

Particle size ranges between 25 and 250 µm were investigated to capture the distinct behaviour of fine and medium-sized particles. Particles were injected at the inlet boundary, positioned within the upper region of the water column, with negligible initial velocity compared to the flow velocity, ensuring that particle dynamics were primarily governed by the local hydrodynamic field.

It should be noted that the quantification of particle numbers across size intervals (10–25 µm, 25–50 µm, 50–100 µm, and

250–500 µm) in water samples collected from the Maleia Stream was performed in a previous study [2]. That investigation employed a combination of visual, instrumental, and analytical methods to ensure accurate identification and detailed characterization of polymer types, including Fourier Transform Infrared (FTIR) spectroscopy and analysis using a Shimadzu AIRSIGHT infrared microscope operating in reflection mode.

2.5. Simulation strategy and results analysis

The simulations were conducted under transient conditions, using a time step selected to satisfy the Courant criterion and ensure numerical stability. Particle trajectories were comparatively analysed for each polymer type and size class, focusing on spatial distribution, dispersion tendencies, and sedimentation behaviour along the modelled reach. This methodological framework enables the identification of local mechanisms governing microplastic transport in river confluence zones and provides a basis for interpreting behavioural differences among polymers with distinct physical properties.

3. Results and discussions

3.1. Flow field and turbulent structure

The numerical simulation of flow within the representative reach of the East Jiu River revealed a velocity field characteristic of a fully turbulent regime, controlled primarily by riverbed roughness and longitudinal slope. Vertical velocity profiles exhibit reduced values in the immediate vicinity of the bed, followed by a progressive increase toward the free surface, consistent with the typical structure of open-channel flows.

The distribution of turbulent kinetic energy indicates maximum values within the near-bed shear layer, where velocity gradients are pronounced, followed by a gradual decrease toward the upper region of the water column. This behaviour suggests the presence of intense turbulent structures capable of significantly influencing the dispersion of fine particles, particularly within the lower and median regions of the flow. The stability of the obtained hydrodynamic field, confirmed through residual convergence and mass balance closure, provides a robust framework for the subsequent analysis of microplastic particle trajectories.

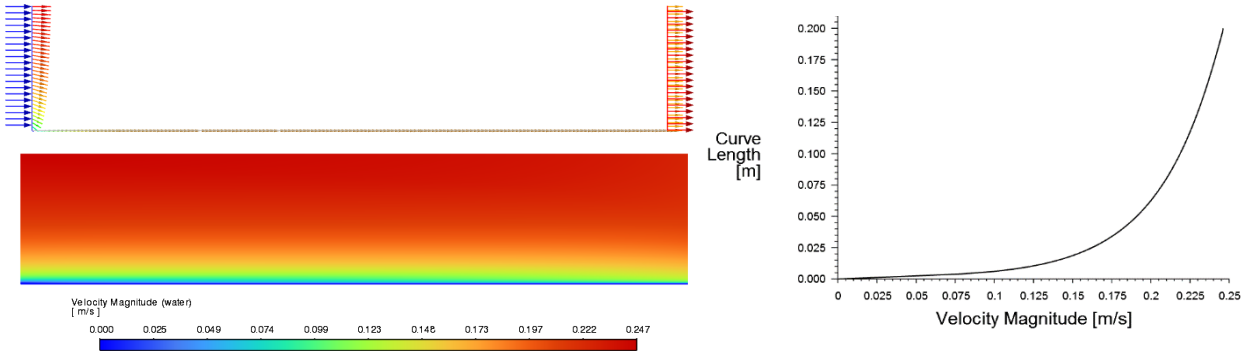


Fig. 2. Longitudinal velocity profile within the computational domain

Figure 2 illustrates the velocity field distribution within the computational domain, highlighting a pronounced vertical gradient characteristic of open-channel flows. Reduced velocity values near the riverbed are associated with frictional and roughness effects, whereas the upper flow layers exhibit higher velocities. This hydrodynamic structure generates an active shear layer responsible for the development of turbulent structures that significantly influence the dispersion of fine microplastic particles.

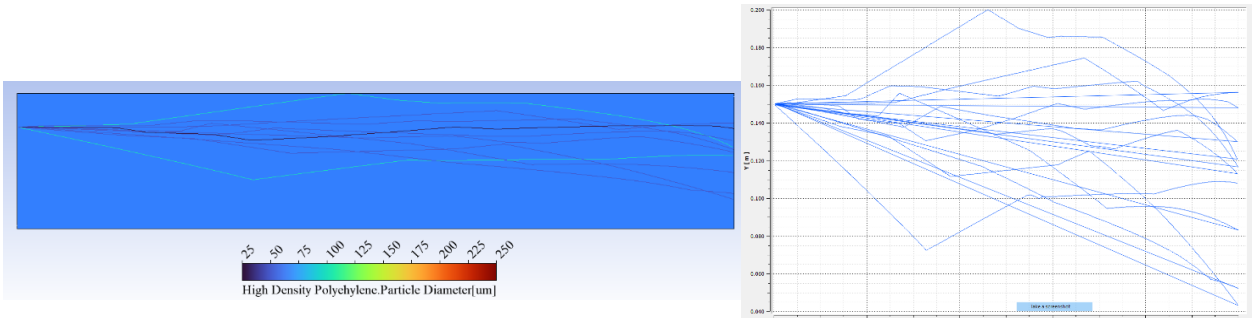
3.2. Transport and dispersion of light microplastic particles (HDPE and LDPE)

High-density polyethylene (HDPE) and low-density polyethylene (LDPE) particles, characterized by densities lower than that of water, exhibit buoyancy-dominated behaviour. The simulated trajectories indicate that they are maintained predominantly in the upper layers of the flow, with pronounced lateral dispersion for small-sized particles (25–75 µm).

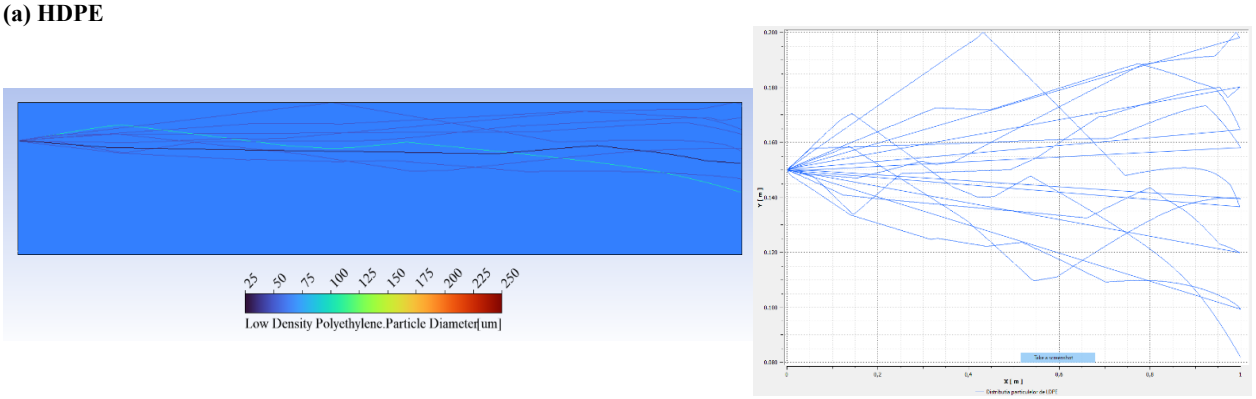
For these size ranges, the high ratio between drag force and particle mass leads to increased sensitivity to turbulent fluctuations, which results in irregular trajectories and extended spatial dispersion. In contrast, larger particles (100–250 µm) exhibit more coherent trajectories, with reduced vertical oscillations and motion controlled mainly by the longitudinal current.

The results indicate that, within the analysed reach, HDPE and LDPE particles do not show tendencies toward sedimentation, being efficiently transported downstream. This behaviour is relevant for understanding the role of rivers as transport vectors for light microplastics toward downstream sections and, subsequently, toward lacustrine or coastal environments.

Figure 3 presents the trajectories of HDPE and LDPE particles for size ranges between 25 and 250 µm. For both types of polymers, characterized by densities lower than that of water, a predominant maintenance in the upper layers of the flow is observed. Fine particles exhibit irregular trajectories, strongly influenced by turbulent structures, while larger particles follow more coherent trajectories, controlled by the main current. The absence of sedimentation tendencies confirms the role of these microplastics as long-distance transport vectors in fluvial systems.



(a) HDPE



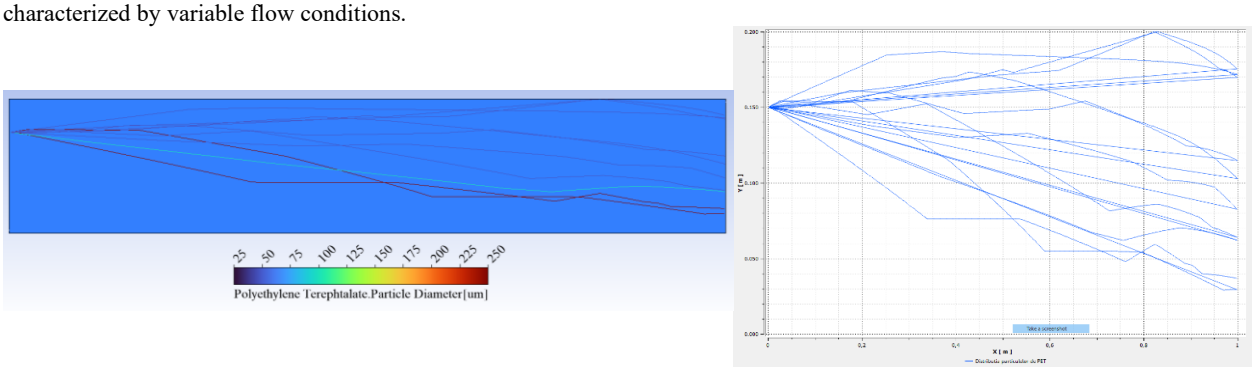
(b) LDPE

Fig. 3. Distribution of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) within the experimental reach

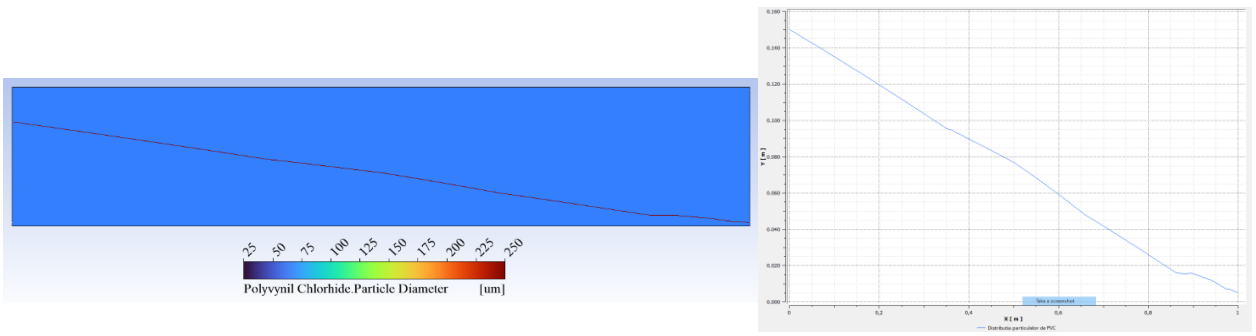
3.3. Turbulence-controlled dispersion of PET Particles

Polyethylene terephthalate (PET), with a density close to that of water, exhibits behaviour intermediate between buoyancy and sedimentation. The simulations indicate pronounced dispersion of fine particles, primarily controlled by the turbulent structures of the flow. For small particle sizes (25–50 µm), PET trajectories are strongly influenced by turbulent eddies, resulting in extended distribution in both longitudinal and vertical directions. This sensitivity to turbulence promotes the maintenance of particles in suspension over significant distances. As particle diameter increases, inertial effects become more pronounced, and trajectories tend to stabilize, accompanied by reduced lateral dispersion.

The observed PET behaviour highlights the role of turbulence in governing the transport of microplastics with densities close to that of water and accounts for the frequent presence of this polymer type throughout the water column, particularly in sectors characterized by variable flow conditions.



(a) PET – dispersion



(b) PVC – sedimentation

Fig. 4. Distribution of polyethylene terephthalate (PET) compared to polyvinyl chloride (PVC) within the experimental reach (density contrast)

Figure 4 compares the behaviour of PET and PVC particles within the simulated flow field. PET particles, having a density close

to that of water, exhibit pronounced turbulence-controlled dispersion, particularly for small particle sizes, which favours their maintenance in suspension. In contrast, PVC particles display an almost linear downward movement, with minimal interaction with turbulent structures, indicating a rapid and stable sedimentation process. This contrast highlights the role of material density as a determining factor in differentiating the transport and accumulation mechanisms of microplastics.

3.4. Rapid sedimentation of dense particles (PVC)

Polyvinyl chloride (PVC) particles, characterized by a density significantly higher than that of water, exhibit distinct behaviour dominated by gravitational effects. The simulated trajectories indicate an almost linear downward displacement, with rapid loss of elevation relative to the free surface and minimal interaction with the turbulent structures of the flow.

The absence of significant lateral and vertical fluctuations suggests that PVC particles rapidly decouple from the turbulent field and move almost exclusively under the action of their own weight. This behaviour is characteristic of stable sedimentation processes and indicates a high probability of accumulation of dense microplastics within bottom sediments, particularly in low-flow areas or in the vicinity of the confluence.

3.5. Implications for accumulation mechanisms in confluence zones

The comparative analysis of trajectories for the four polymer types highlights that material density and particle diameter represent the determining factors governing microplastic transport in the confluence area of the East Jiu River and the Maleia Stream. Light particles are transported predominantly within the upper layers of the flow, particles with densities close to that of water are controlled by turbulence, and dense particles tend to sediment rapidly.

These behavioural differences suggest the existence of selective accumulation mechanisms, whereby dense microplastics may concentrate within bottom sediments, while light particles remain mobile and are redistributed over long distances. Confluence zones, characterized by local variations in the velocity field and turbulence intensity, may therefore act as critical points for the separation and redistribution of microplastics within the fluvial system.

4. **Conclusion**

This study investigated microplastic transport in the confluence area of the East Jiu River and the Maleia Stream through an integrated approach combining experimental data on polymer typology with numerical modelling based on Computational Fluid Dynamics. The simulations performed in ANSYS Fluent, using the Reynolds-Averaged Navier–Stokes equations and the Discrete Phase Model within a Euler–Lagrange formulation, enabled a detailed analysis of local mechanisms governing the transport, dispersion, and sedimentation of microplastic particles.

The obtained results indicate that material density and particle diameter represent the dominant factors controlling microplastic behaviour in turbulent flow. Particles with densities lower than that of water (HDPE and LDPE) are transported predominantly within the upper flow layers, without sedimentation tendencies along the analysed reach. Microplastics with densities close to that of water (PET) exhibit pronounced dispersion controlled by turbulent structures, particularly for small particle sizes, which favours their maintenance in suspension over significant distances. In contrast, dense particles (PVC) display rapid and stable sedimentation, with minimal interaction with turbulence, indicating a high probability of accumulation within bottom sediments.

The comparative analysis of particle trajectories suggests that fluvial confluence zones may act as selective points for the separation and redistribution of microplastics, depending on particle physical properties and the local structure of the flow field. The proposed approach demonstrates the usefulness of CFD–DPM modelling for understanding the local mechanisms governing microplastic transport and provides a methodological framework applicable to similar studies in other hydrological systems. Future extension of the model toward three-dimensional domains and variable hydrological regimes could contribute to a more comprehensive assessment of microplastic dynamics in riverine ecosystems.

Acknowledgments

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