

## The Vertical Distribution of Riverine Microplastics: The Role of Turbulence

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# Chapter 28

## The Vertical Distribution of Riverine Microplastics: The Role of Turbulence



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### 28.1 Introduction

Owing to plastics high durability and resistance to degradation [1] alongside the high production rates [1–3], plastic pollution and its impacts have reached every aquatic and terrestrial environment [4–7]. In the water and sediments of aquatic systems, sampling campaigns confirmed and documented a plethora of microplastic (<5 mm) (e.g., [8–12]). Estimates suggest that the total amount of plastics immitted to the world oceans is approximately 4.8–12.7 MT [7], of which a high percentage is thought to reach the ocean through rivers [13, 14]. Hence, rivers are seen as a primary pathway for microplastics to marine environments. Recent observations further suggest that rivers represent a sink for plastic litter where it may be retained for prolonged periods before being released into the ocean [15]. Rivers can also act as a hosting environment for larger plastic litter (>5 mm) fragmenting into secondary microplastics. Once in rivers, microplastics can lead to a variety of ecological, economic, and hazardous impacts [16, 17]. Understanding the fate and transport of microplastics in riverine systems is, therefore, a crucial step toward establishing effective protocols to mitigate against these emerging pollutants. Accurate estimates of microplastics abundance and transport in rivers remain far from reach [18], however. Despite the abundance of water surface and sediments sampling campaigns (e.g., [19–21]), the record of microplastics occurrence along the water column is still in its infancy [22]. In fact, microplastics vertical distribution within the water column and the associated governing processes remain poorly understood [22, 23].

The general practice in estimating microplastics in rivers is through adopting a predefined distribution along the water column, hereafter a concentration depth

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profile, which is mainly linked to microplastics density. With the wide range of density covered by the plastic polymers (i.e., being positively, negatively, and neutrally buoyant) [24], plastic density assumptions vary among studies. As a result, microplastics were assumed to be either transported below the surface as bedload and suspended load [23, 25], surface load [13, 26], or neutral wash load regardless of the particle and flow field characteristics [27, 28]. On the contrary, the limited documentation of microplastics depth profiles supports microplastics transport along various levels of the water column [29–31]. Even further, the limited water column sampling campaigns landed on different conclusions, including but not limited to (i) the dominance of the surface load mode of transport with a limited suspension due to turbulence [32], (ii) a correlation between microplastic depth profile and flow conditions [31] and (iii) a correlation between microplastics density and depth profile [29].

These observations accompanied by the lack of understanding of other microplastics characteristics (i.e., size and shape) on their concentration depth profile, stress the need for further investigation to develop new models, where the governing mechanisms are taken into consideration [23]. In response, a process-based model based on the physical processes influencing microplastics concentration depth profile has been proposed [33]. The proposed model is developed from the Rouse model, hence employing principles previously adopted in sedimentological studies [34]. The concentration depth profile of microplastics is assumed to be governed by the interaction between gravity forces and turbulent mixing. Despite the extensive validation for sediments [34–37], model validation for microplastics remains missing. The primary parameters for the turbulent mixing process are the eddy viscosity and the material diffusivity [38, 39]. Their ratio (i.e., Prandtl-Schmidt number [40]), is a primary input for the Rouse model, yet it remains unknown for microplastics. Further, the Rouse model's capacity of representing real-life scenarios is challenged by its one-dimensional nature, reflecting simplified scenarios of turbulence. Examination of the impact of turbulence on the vertical distribution is, therefore, essential for the validation of the proposed Rouse model and the assessment of its potential and limitations. With this research project we aim to (i) better understand the concentration depth profile of microplastics within turbulence, (ii) validate and calibrate the Rouse model for microplastics, and (iii) explore the potential of computational numerical modelling for complex scenarios.

## 28.2 Methods

The project involves employing a combination of physical and numerical modelling. The physical modelling will allow for generating the necessary datasets, which will support a better understanding of the impact of turbulence on the vertical distributions and will help testing the Rouse model performance. The numerical modelling will allow for exploring extended scenarios of complex turbulence while potentially

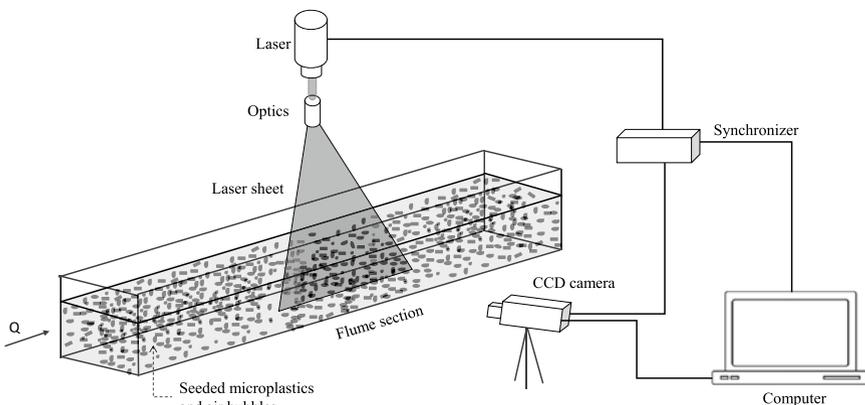
providing a prediction tool for the wide range of combinations of flow conditions and particle characteristics.

## 28.2.1 Physical Modelling

### 28.2.1.1 Experimental Setup

The FC 300 flume (5 m long with a cross-section of 450 mm × 300 mm) at the laboratory of water and sediments dynamics at Wageningen University is employed for the experimental setup. The flume allows for continuous and separate circulation of solid and liquid phases with an adjustable channel slope. The effective section is set within the middle 3 m of the flume length to minimise the inlet/outlet impacts. The experiment includes three series, mimicking three different flow conditions. Using the sediment circulation system, homogeneous microplastic particles are circulated (particles of the same size, shape, and density). For each run, microplastics supply rate is gradually increased, up to a point where the depth distribution (i.e., microplastics concentration) can be obtained. However, the upper limit of the supply rate is constrained by the limit for interparticle interactions [41], as such processes are unlikely in the light of microplastics concentration reported in rivers (see [42]). Three repetitions are carried out of each experimental run to assess the results' reproducibility. Once hydrodynamic equilibrium conditions are established (i.e., uniform flow) measurements are recorded using a particle image velocimetry setup (PIV) (Fig. 28.1).

In comparison to traditional approaches (e.g., acoustics devices and suction sampling), PIV systems represent a non-intrusive technique with no interference or alteration of the flow within the flume [43, 44]. The setup targets tracking two phases.



**Fig. 28.1** Experimental setup of the physical modelling

Information about microplastic concentration depth profile and rate of transport are gathered by tracking microplastics (i.e., the solid phase), employing a Lagrangian analysis of the collected images. The tracer phase refers to the water flow monitored through a tracer (air bubbles in the case of this setup), which is analysed employing a Eulerian analysis to infer the flow characteristics (i.e., the instantaneous and mean of the three components of the flow velocity). The turbulent shear stresses and strain rates needed to determine the eddy viscosity are obtained from the Eulerian analysis, while the concentration depth profiles and microplastics diffusivity are determined by the Lagrangian analysis. Finally, the ratio between the eddy viscosity and particle diffusivity (i.e., Prandtl-Schmidt number) is obtained.

The image analysis is carried out employing the open source PIVview software [45]. As the images are collected instantaneously, a pre-processing of the collected images is needed to disintegrate the two phases prior to analysis. Different methods are adopted in literature to separate the tracer from the solid phase (e.g., spot size [43], grey level [46], and colour/fluorescence [47]). The spot size approach is deemed suitable for the setup as it reduces the complexity of the needed PIV setup.

### 28.2.1.2 Material

For plastic litter (including microplastics and macroplastics), the shape, size and density of the objects are key factors determining their transport in rivers [48]. A systematic variation of microplastics characteristics (i.e., shape, size, and density) is conducted to assess the impact of each property individually. Nevertheless, the selection of a representative set of microplastics, mimicking riverine microplastic, remains challenging due to the diversity of the material properties. Previous research on microplastics in riverine systems is, therefore, used to guide the selection of the microplastics for the experiment. The work of Liu et al. [22] and Kumar et al. [49] offers an insight into the dominant shapes and polymer types (i.e., density) of microplastics based on sampling campaigns in rivers worldwide. Inferring the dominant sizes of microplastics in rivers is hindered by the variation in sampling methods among studies (e.g., the net mesh size). Therefore, the commonly used size range incorporating microplastics is considered (i.e., 5 mm–1  $\mu$ m) [50]. The targeted microplastics in the present study are summarised in Table 28.1.

In comparison to density, where the property is linked to a discrete numeric value, the size and shape properties are connected and linked to multiple identification challenges [51–53]. An alternative to the commonly used categorization of microplastics has been proposed by Melkebeke et al. [54], employing descriptive shape factors. In the present study, shape factors (namely Corey shape factor, sphericity, circularity, elongation, flatness and aspect ratio) are reported and examined for the microplastics in the experimental setup.

**Table 28.1** Microplastics for the experimental set-up (selected based on Liu et al. [22], Duis and Coors [55] and Kumar et al. [49])

Polymer	Density (g cm <sup>-3</sup> )	Shapes
Polyethylene (PE)	0.89–0.98	Fibres, fragments, films, foams, pellets, and micro-beads
Expanded polystyrene (Styrofoam) (EPS)	0.01–0.04	
Polystyrene (PS)	1.04–1.1	
Polypropylene (PP)	0.83–0.92	
PEST (Polyester)/ Poly(ethersulfone) (PES)	1.24–2.3	
Polyethylene terephthalate (PET)	0.96–1.45	
Polyvinyl acetate (PVA)	1.2–1.3	
Polyvinylchloride (PVC)	1.16–1.58	

### 28.2.2 Numerical Modelling

Due to feasibility and technical limitations of the physical modelling, the range of particles and flow characteristics is limited. Reynolds-averaged Euler–Lagrange formulations, previously explored for sediment transport, are planned for the numerical modelling exercise. The open-source coupled CFD-DEM scheme CFDEM-EIM software is adopted, where previous applications in sedimentological studies can offer guidance [56, 57]. In the present research, the intergranular interaction is not included considering microplastic concentrations in rivers. Yet, the discrete element method built within the software offers room for model adaptation to higher concentrations, where inter-particle interactions might be relevant. Datasets obtained from the physical model feed into the model validation, where the model capacity to regenerate lab observations can be tested. Once the model is validated, it can be used to explore combinations of flow conditions and particle characteristics beyond the laboratory experiment.

An additional step is to assess the performance of the Rouse model proposed by Cowger et al. [33] for the concentration depth profile of microplastics against observed concentration depth profiles at the lab and the model output.

### 28.3 Anticipated Outcomes

The anticipated project results will be useful to amend the limitations of water column sampling campaigns and could help understand the driving factors causing the variations between the findings of the documented water column observations. The unique

gathered dataset can be used to parameterise the influence of turbulence on microplastics transport and vertical distribution. Further, the numerical model can produce a prediction tool for microplastics occurrence and concentration in rivers. Ultimately, the result translates into a better quantification of microplastics occurrence in rivers, which could lead to (i) more efficient and accurate sampling practices, (ii) better estimation of the exposure dose along the water column for toxicology studies, and (iii) targeted and efficient mitigation measures for microplastics in rivers.

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