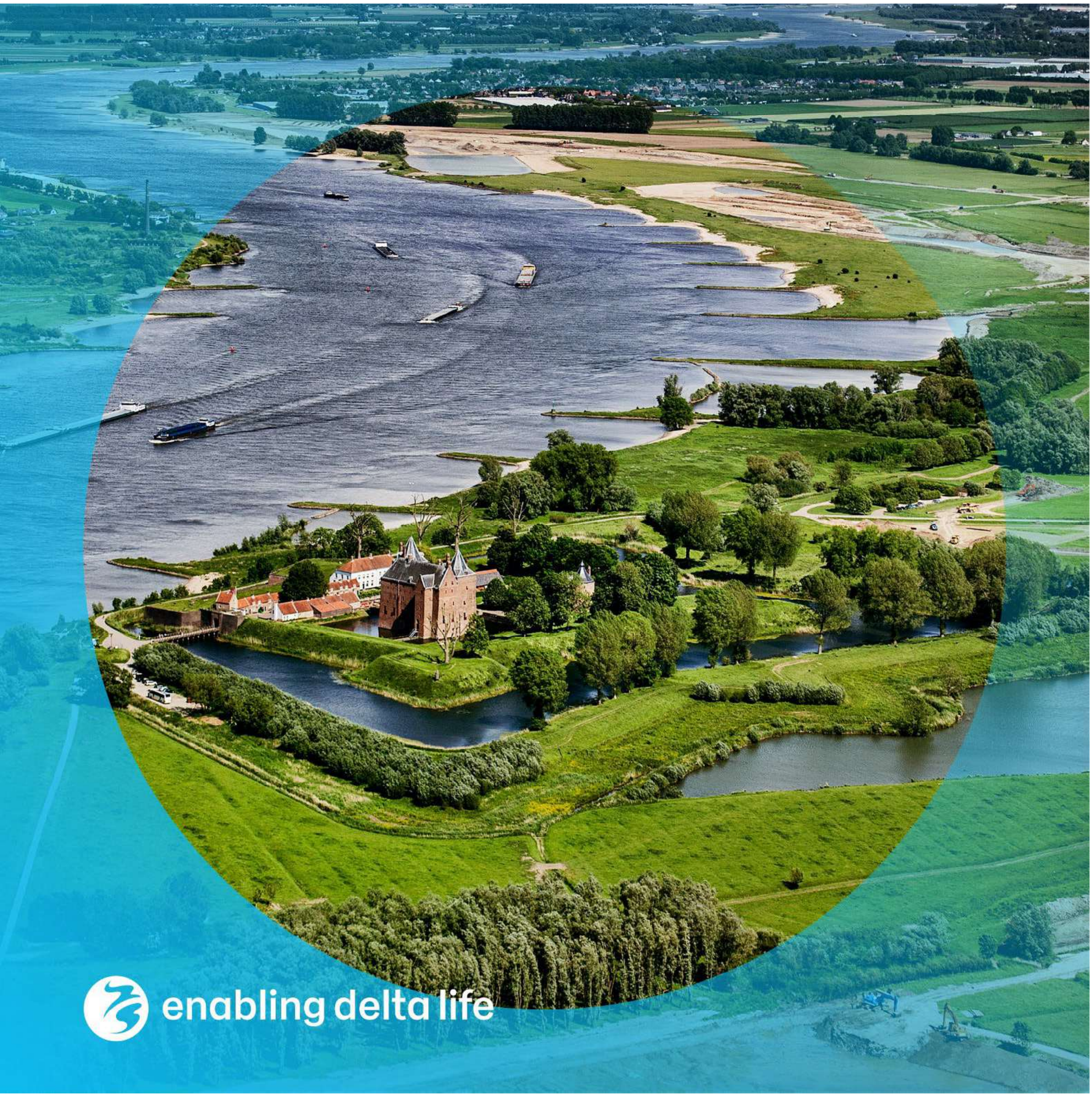
Deltares

Plastics in the water column



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Author(s)
Tobias van Batenburg

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Author(s)		
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Summary

There is a significant mismatch between the estimated amounts of plastics in the ocean and the expected plastic input by rivers. Most plastic transport monitoring data used for global modelling of plastic flux estimations is based on the number of items transported at the water surface. However, the amount of submerged plastic items transported in rivers is not accounted for or is based on approximations. Net measurements in rivers show that submerged plastic transport can exceed surface transport. Furthermore, existing numerical models have difficulty predicting plastic behaviour in rivers due to simplistic parametrisation, neglecting crucial factors like particle characteristics and free-surface interaction.

To address these knowledge gaps, a detailed laboratory measurement campaign was set up to better understand plastic behaviour in the water column. This study is combined with validation from field measurements by Rijkswaterstaat. The laboratory data is used to improve parameterization within the numerical particle tracking software Delft3D-PART, enhancing its capability to model the vertical distribution of plastic litter in riverine conditions.

The experimental work is performed in a 45-meter-long flume at Deltares, adjusted to replicate typical Dutch riverine hydraulic conditions. Large quantities of different plastic items were released close to the flume bed 30m upstream of the measurement location, where the position of each item was measured and counted to obtain a vertical distribution. These experiments incorporated various plastic types, representing commonly found plastic litter and varying in size, shape and material. Hydraulic properties were measured using Acoustic Doppler Velocimeter (ADV), and camera tracking was used to determine item positions.

In the field campaign, Rijkswaterstaat collected data on submerged riverine plastic items at three locations on the Meuse River: Sambeek (downstream of a weir), Ohe en Laak (a river bend), and Eijsden (a straight section) using three nets at different depths, alongside ADCP measurements to assess river flow conditions.

Both laboratory and field data consistently showed that increased turbulence, quantified by shear velocity, led to higher concentrations of submerged plastic. Shear velocity describes the intensity of flow acting on the riverbed and the resulting turbulence. In practical terms, it indicates how forcefully the flow mixes the water column. This study shows that at low shear velocities, plastics tend to remain near the surface, while at higher shear velocities, turbulence mixes them deeper into the water.

A transition zone was identified between shear velocities of 2.2 and 3.3 cm/s, beyond which transport shifts from near-surface dominated to substantially submerged transport. For the Meuse River, shear velocities above 3.3 cm/s occurred at average flow velocities greater than 0.7 m/s. During these flow velocities, the number of submerged plastic items was 3 to 6 times greater than at the surface.

This study also demonstrated that classical Rouse profiles are only applicable to smaller plastics (< 2 cm) or lower turbulence levels (shear velocity < 2.2 cm/s). For larger items combined with higher turbulence, measured profiles deviated from the Rouse profile. These findings were used to improve the Delft3D-PART model, enabling it to incorporate particle size and surface interaction effects. This results in a more realistic vertical plastic transport simulations and better global plastic flux estimates.

In conclusion, this study shows that neglecting submerged transport, which occurs at higher turbulence levels, can lead to an underestimation of total riverine plastic flux. Field-based measurements indicate that the flux can be underestimated by up to a factor of six. Accurately determining these vertical distributions is therefore essential for effective mitigation of riverine plastic pollution.

Contents

1 Introduction

1.1 Motivation

There is a significant mismatch between the estimated amounts of ocean plastic and the expected plastic ingress by rivers (van Sebille, et al., 2020; OECD, 2022). Rivers act as main pathways for plastic litter, facilitating transport toward the ocean. However, existing plastic transport data for global flux models relies on surface item counts (González-Fernández, et al., 2023). Submerged plastic transport in rivers is largely unaccounted for or based on approximations (Buschman & Blondel, 2022; Hurley, et al., 2023), despite evidence that it can exceed surface transport by orders of magnitude (Vriend, et al., 2023). Furthermore, numerical models often oversimplify macro-plastic transport, focusing only on rising velocity and neglecting key physical processes like particle characteristics and free-surface interaction (Wickramarachchi, Niven, & Kramer, 2024).

1.2 Research objective

This study addresses these issues by combining a detailed experimental investigation with field measurement validation. Experimental research on the vertical distribution of near-neutrally buoyant macro-plastics in a controlled laboratory environment is therefore conducted. The objective is to provide validation data to improve parameterization in the numerical particle tracking software Delft3D-PART, enhancing its capabilities in modelling vertical distributions of plastic litter in riverine conditions.

1.3 Research methodology

An experimental investigation is conducted to obtain the vertical distribution of near-neutrally buoyant macro-plastics in a controlled laboratory environment. The lab setup uses the 45 meter long Eastern Scheldt Flume at Deltares, where typical riverine hydraulic conditions were created. Various plastics varying in type, size and shape were released upstream to investigate the concentration profile 30m downstream of the releasing point. In the measurement area, Acoustic Doppler Velocimeter (ADV) measurements for flow velocity profiles measurements and camera-based particle tracking to determine the vertical plastic distributions were used.

To validate the measured vertical plastic distributions from the experiments, a comparison was made with field measurements carried out by Rijkswaterstaat. These measurements were carried out at three locations along the Meuse river: Sambeek (downstream a weir, 2023 & 2024), Ohe en Laak (river bend, 2024) and Eijsden (straight section, 2023 & 2024). During these field campaigns, a net was deployed from the vessel Stern at three different water depths to capture plastics. The net had dimensions of 4 x 1m and a mesh size of 6 mm. Further details of the field setup and data collection procedures can be found in Roozendaal (2024), Polinder (2023), and Lin (2024). In addition, vertical velocity profiles were measured using an ADCP mounted on a trailing vessel.

1.4 Report structure

This report first outlines the theoretical background for parameterizing plastic litter transport in rivers (Chapter 2). It then describes the laboratory setup and experimental results (Chapter 3 – 4) and the field measurements from Rijkswaterstaat, including plastic and flow profiles (Chapter 5). Chapter 6 discusses the improved Delft3D-PART model for simulating vertical plastic transport, followed by the conclusions in Chapter 7.

2 Theoretical background

This chapter outlines the theoretical framework for plastic transport in rivers. First, the parameterization of plastic transport based on flow and material properties are discussed. Secondly, the natural conditions under which plastic transport occurs in the Netherlands will be described. Based on these natural conditions, the parameter-space is defined for the experiments.

2.1 Characteristics of riverine plastic transport

The transport of suspended plastic pollution in rivers throughout the main part of the water column is described by the ratio between buoyancy of plastics and the turbulence in the water (Valero, et al., 2022). This layer is referred to as the *suspended transport layer*, see Figure 2-1.

The turbulence in rivers is primarily characterized by the bed roughness, which for sand bed rivers (as commonly found in the Netherlands) mainly depends on the large-scale bedform configurations referred to as sand dunes. This description relates to natural riverine flow conditions. However, additional non-natural sources of turbulence can be present due to inland navigation and weir operations, which can significantly enhance local turbulence intensity.

The tendency of plastics to float or sink in water without flow depends on the material density. However, close to the water surface, surface tension becomes a significant factor and leads to a tendency for plastics to adhere to the free surface. This upper region is referred to as the *near-surface layer* (Valero, et al., 2022).

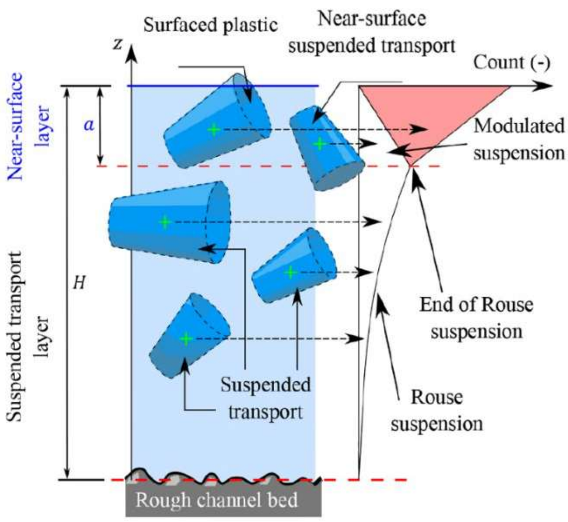

Figure 2-1 Sketch of different modes of plastic transport in turbulent rough open channel flow from (Valero, et al., 2022)

Valero, et al. (2022) proposed that the mechanics of plastic transport in rivers is best described by the following non-dimensional parameters:

- The Rouse number (β), which is defined as the ratio of the buoyant to turbulent forces acting on a particle in suspension.
- A modified Weber number, later referred to as Gamma number (Γ), which is defined as the ratio between surface tension forces and turbulent forces.

The Rouse number is defined as:

$$\beta = w/\kappa u_*$$

In which w is the vertical terminal velocity. This velocity is positive for buoyant plastics in which w is referred to as the rising velocity, while for sinking plastics w is referred to as the settling velocity. κ is the von Kármán constant and u_* is the shear velocity to express the turbulence in the flow. Large Rouse number conditions are related to plastic distribution with high concentrations at the top part of the water column, while small Rouse numbers represent suspended plastic transport in which turbulence is the dominant factor.

The Gamma number is defined as:

$$\Gamma = \frac{8\sigma}{\rho_w u_*^2} \frac{l_{max} + l_\perp}{l_{max} \cdot l_\perp}$$

In which σ is the surface tension, ρ_w is the mass density of water and l_{max} and $l_\perp$ are the lengths of the maximum main axis of a plastic material and its orthogonal counterpart respectively, as presented in Figure 2-2. For large Gamma numbers, the plastics particles are concentrated near the top of the water column as the surface tensions and plastic size play a dominant role. For small Gamma number, turbulence is again the dominant factor.

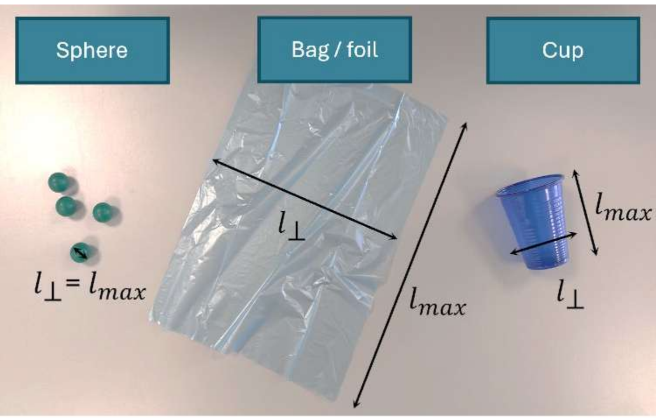

Figure 2-2 Main length-scales of plastic particles

2.2 Parameterization of plastic transport in natural riverine conditions

The dimensionless Rouse and Gamma numbers are used to quantify plastic transport within natural riverine environments. Determining these parameters necessitates knowledge of the shear velocity (u_*), particle rising velocities (w) and the particle length-scales (l_{max} & $l_\perp$). These variables are elaborated upon in this section. The values of $\kappa = 0.41$, $\sigma = 72.86$ mN/m and ρ_w = 998.2 kg/m^3 are considered constant in this research.

2.2.1 Shear velocity

As can be observed by their definitions, the Rouse and Gamma number are hydraulically solely dependent on the shear velocity (u_*). This parameter characterizes the shear-induced motion within the flow and can be used to quantify the turbulence in riverine flow. It is related to mean flow velocity (U_m) and the Darcy-Weisbach friction coefficient (f) (Tominaga & Sakaki, 2010):

$$u_* = U_m\sqrt{f/8}$$

Empirical data from field campaigns along the Meuse, Rhine, Waal, and Bovenrijn rivers were used to determine the range of shear velocities in Dutch rivers (Julien, et al. (2002), de Lange, et al. (2021) & Adriaanse (1986)). The field measurement campaigns were conducted during a broad range of river discharges. These rivers can be characterized by sandy beds and large-scale sand dunes (Julien, Klaassen, Ten Brinke, & Wilbers, 2002) and exhibited a Darcy-Weisbach friction factor range between 0.02 and 0.07. Based on this, the shear velocity under natural conditions was found to range from 0.02 to 0.13 m/s. An overview of the ranges is presented in Table 2-1.

Table 2-1 Overview of flow conditions (mean flow velocity (U_m), Darcy-Weisbach friction factor (f) and flow shear velocity (u_*) for multiple Dutch rivers.

River	U_m (m/s)	f (-)	u_* (m/s)	Reference
Bovenrijn	1.4 – 1.8	0.023 – 0.042	0.075 – 0.130	Julien, et al. (2002)
Waal	1.5 – 1.8	0.027 – 0.035	0.087 – 0.120	Julien, et al. (2002)
Rhine/Waal	0.6 – 1.0	0.022 – 0.070	0.031 – 0.094	de Lange, et al. (2021)
Meuse	0.5 – 1.1	0.030 – 0.042	0.024 – 0.071	Adriaanse (1986)

2.2.2 Riverine plastic properties

To fully parameterize plastic transport in rivers using the Rouse and Gamma numbers, particle rising velocities and length scales are required. These particle parameters were determined based on recent studies of plastic litter found in diverse river systems globally.

Rising velocities of plastics in the Santa Ana River (USA) were measured ranging from 0.2 to 20 cm/s, while settling velocities varied between 0.2 and 4 cm/s (Waldschläger, Born, Cowger, Gray, & Schüttrumpf, 2020). Other studies showed comparable ranges of settling/rising velocities for plastic films with surface areas between 0.1 and 1 cm² (Kuizenga, van Emmerik, Waldschläger, & Kooi, 2022).

Given the similarity in types and categories of riverbank plastic items found in the Rhine and Meuse regions (van Emmerik, et al., 2020) and those analysed from the Santa Ana River, we assume that the plastics in these Dutch rivers exhibit comparable rising and settling behaviours. Equivalent diameters for buoyant plastics ranged from 1 to 30 cm, and for sinking plastics, from 0.5 to 5 cm. Consequently, a rising velocity range of 0.1 to 20 cm/s is anticipated for plastics in the Rhine and Meuse rivers, corresponding to characteristic length scales of 0.5 to 30 cm.

Beyond rising velocity, plastic shape and type significantly influence riverine transport. Field measurements in the Rhine River (2021-2022) revealed that plastic films were the predominant litter type (Vriend et al., 2023). Approximately 75% of sampled items were classified as either small (<2.5 cm) or large (2.5 – 50 cm) plastic films.

2.2.3 Parameter-space of natural conditions

Combining the flow and plastic characteristics as presented in subsections 2.2.1 and 2.2.2, a range of the Rouse and Gamma number as found under natural conditions is obtained (see Table 2-2).

Table 2-2 Overview of minimum and maximum values to obtain the Rouse (β) and Gamma (Γ) number for natural conditions, characterized by shear velocity (u_*) and plastic properties (w, l_{max} and $l_\perp$)

	u_* (m/s)	w (cm/s)	l_{max} (cm)	$l_\perp$ (cm)	β (-)	Γ (-)
Min β and Γ	0.130	0.1	10	10	0.02	0.69
Max β and Γ	0.024	20	1.5	1.5	20.1	132

3 Experimental setup & conditions

The aim of the plastic transport measurements is to characterize the vertical distribution profiles of various plastic types under controlled laboratory flow conditions. This chapter details the testing facility, measurement techniques, experimental setup and materials. Finally, a comparison is made between the parameter space of natural and experimental conditions.

3.1 Experimental Setup

3.1.1 Testing facility

The experiments were conducted in the Eastern Scheldt Flume at Deltares, which is approximately 45 meters long and 1.0 meter wide. The maximum still water level is 1.0 meter and flow is generated by a pump with a maximum discharge of 550 l/s which pumps water from the underground reservoir. A weir downstream at the flume is used to control the water level. A side view of the flume is presented in Figure 3-1.

As introduced in Section 2.1, the hydraulic conditions during plastic transport are in this study solely described by the turbulence level expressed in shear velocities. To achieve the shear velocities which are comparable to those in Dutch rivers, a resistance element was introduced into the flume. While dynamic sand dune bedforms drive shear velocity in the Rhine and Meuse, replicating them with a mobile sand bed would compromise the static bed conditions necessary for reliable measurements. Consequently, a static gravel bed with a mean volume equivalent diameter of 74 mm was selected, as presented in Figure 3-1A, resulting in a similar flow and turbulence profiles in the experiment and the river.

The plastic items were inserted at 5.75m downstream of the flume inlet. Plastic types (bags, foils and spheres) were released into the flow through a transparent hose, see Figure 3-1B. For the lower water level (60 cm), the hose outlet was positioned 5 cm above the gravel bed, while for the higher water level (90 cm) it was positioned 20 cm above the bed. Plastics were pre-suspended in an elevated tank located near the flume's overflow weir, see Figure 3-1D. Air bubbles were manually removed from each plastic item before injection through the submerged inlet transparent hose. The tank was supplied with water by a pump that maintained a 60 cm water level via an overflow pipe. Its elevated position, 2.2 m above the ground, provided sufficient water head for transport into the flume. After passing the Plastic measurement zone (Figure 3-1C), bags, foils, and spheres were manually retrieved and reused if undamaged. Most items remained intact, although some bags and foils were damaged during retrieval or through contact with the rock bed. Plastic cups were manually inserted with a grabber into the flume at the same insertion location, after air bubble removal. The insertion depth of the cups was set to match the outlet level of the transparent hose.

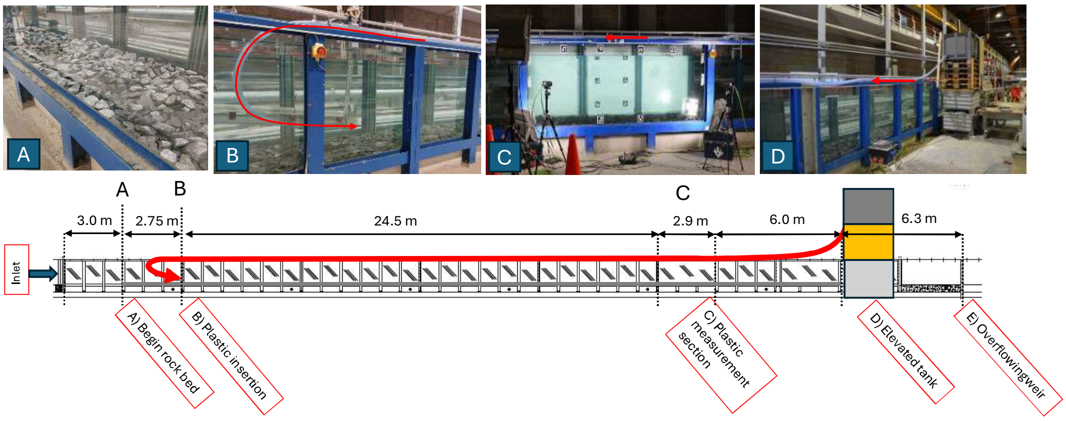

Figure 3-1: Bottom figure: Side view of Eastern Scheldt flume with trajectory of the pre-suspended plastic to the plastic insertion location marked in red.

3.1.2 Measurement equipment

For accurate plastic transport measurements, the measurement section was positioned 27.25 meters downstream from the begin of the rock bed, ensuring fully developed flow.

To characterize flow conditions within the measurement section, Acoustic Doppler Velocimetry (ADV) measurements were conducted prior to plastic introduction. Velocity profiles were obtained at the flume's centerline (28.6 meters downstream from the inlet) and 0.5 meters from the flume walls. Flow velocities were measured every 4 cm throughout the water column using an ADV probe mounted on a movable frame for precise vertical positioning.

Real-time positions of plastics within the measurement section were recorded by a multi-camera system. This system consisted of three Flir Oryx 7.1 Mpix cameras (CAM01, CAM02, CAM03) and one Flir Blackfly 5.0 Mpix camera (CAM04). Specifically, CAM01 captured perpendicular views, CAM02 and CAM03 provided lateral perspectives, and CAM04 captured a top-down view. An overview of the camera recordings is shown in Figure 3-2.

An AI-driven image analysis approach, using recordings from CAM01, facilitated the automated detection of the vertical positions of plastic items within the measurement section. The open-source Segment Anything Model 2 (SAM2) developed by Meta was used to detect and segment plastic bags and foils in the recordings. This process was fully automated for each recording using an in-house developed Python script. Following segmentation, the circumference of each detected item was determined, after which its centre of gravity was computed. The vertical distribution of the plastic items was subsequently derived from these centre-of-gravity positions

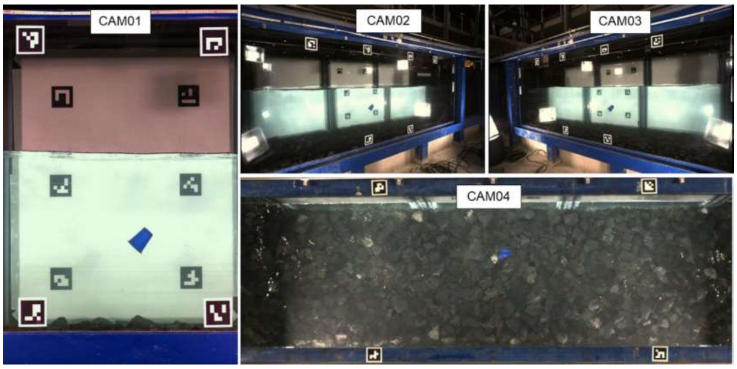

Figure 3-2: CAM01, CAM02, CAM03 & CAM04 view of the measurement section during passage of plastic cup.

3.2 Experimental conditions

3.2.1 Hydrodynamic conditions

Six different flow conditions were implemented in the plastic transport experiments, selected to generate a range of vertical distribution profiles for the plastic items. All conditions represented subcritical flow ($F < 1$) regimes with high Reynolds numbers. The measured discharge (Q) was obtained from the flume's inlet flow meter. The downstream weir was used to control the water level (H) at the measurement section. The mean flow velocity (U_m) was then calculated as $U_m = Q/H$. Table 3-1 presents the overview all hydraulic conditions used during the measurements.

Table 3-1: Hydraulic conditions during the experimental measurements.

ID	Q [m³/s]	H [m]	U_m [m/s]	$F = U_m/\sqrt{gH}$ [-]	$Re = U_m H/\nu$ [-]	u_* [m/s]	δ [m]
A1H0	0,097	0,900	0,108	0,036	9,70E+04	0,013	0,656
A3H0	0,297	0,900	0,330	0,111	2,97E+05	0,040	0,612
A5H0	0,498	0,900	0,553	0,186	4,98E+05	0,067	0,612
A1L0	0,097	0,600	0,162	0,067	9,70E+04	0,022	0,404
A3L0	0,297	0,600	0,495	0,204	2,97E+05	0,064	0,409
A5L0	0,498	0,600	0,830	0,342	4,98E+05	0,108	0,405

3.2.2 Plastic item properties

A set of five near-neutrally buoyant plastic types was selected to represent a range of commonly found plastic litter. These items varied in materials, sizes and shapes. The specific plastic items used are detailed in Table 3-2. Plastic bags and foils, frequently observed in field studies of plastic litter (Vriend, et al., 2023), were included to reflect real-world conditions. Plastic spheres were chosen to examine the effect of size on vertical distribution in the absence of shape variability. Plastic cups were incorporated to enable direct comparisons with the findings from previous studies (Valero, et al., 2022). For each plastic item, the following properties were measured in-house at Deltares: geometrical characteristics (l_{max}, $l_\perp$), plastic density (ρ_s), water density (ρ_w), item volume (V_s), rising velocity (w), and contact angle (θ_c).

Table 3-2: Plastic items used to obtain vertical distribution profiles and corresponding material properties.

ID	Item	Polymer type	l_{max} [mm]	$l_\perp$ [mm]	ρ_s [kg/m³]	V_s [ml]	w [mm/s]	ρ_{water} [kg/m³]	θ_c [deg]
B	Cups	PP	80	70	914.8 +/- 2.4	2.819	33.0 +/- 4.7	999.3	92.0 +/- 4.4
C	Bags	HDPE	320	240	971.9 +/- 3.3	1.753	7.6 +/- 1.9	999.3	87.2 +/- 3.1
D	Half bags	HDPE	320	120	971.9 +/- 3.3	0.840	6.3 +/- 1.7	999.3	87.2 +/- 3.1
G	Spheres	PP	20	20	993.7 +/- 0.6	4.138	34.5 +/- 9.4	999.2	77.8 +/- 15.5
H	Foils	HDPE	310	230	971.9 +/- 3.3	0.765	2.5 +/- 1.0	999.3	87.2 +/- 3.1

3.3 Parameter-space of experimental conditions

To compare experimental plastic transport conditions with natural riverine conditions, the dimensionless parameters Rouse (β) and Gamma (Γ) were calculated for each plastic item and hydraulic condition. The parameter space of riverine plastic transport, established in Section 2.2.3 and depicted in Figure 3-3, provides a reference range. The dimensionless parameters for the experimental plastic items, derived from the parameters presented in Section 3.2, fall within this riverine range. This correspondence indicates that the experimental conditions can be found in the Dutch rivers.

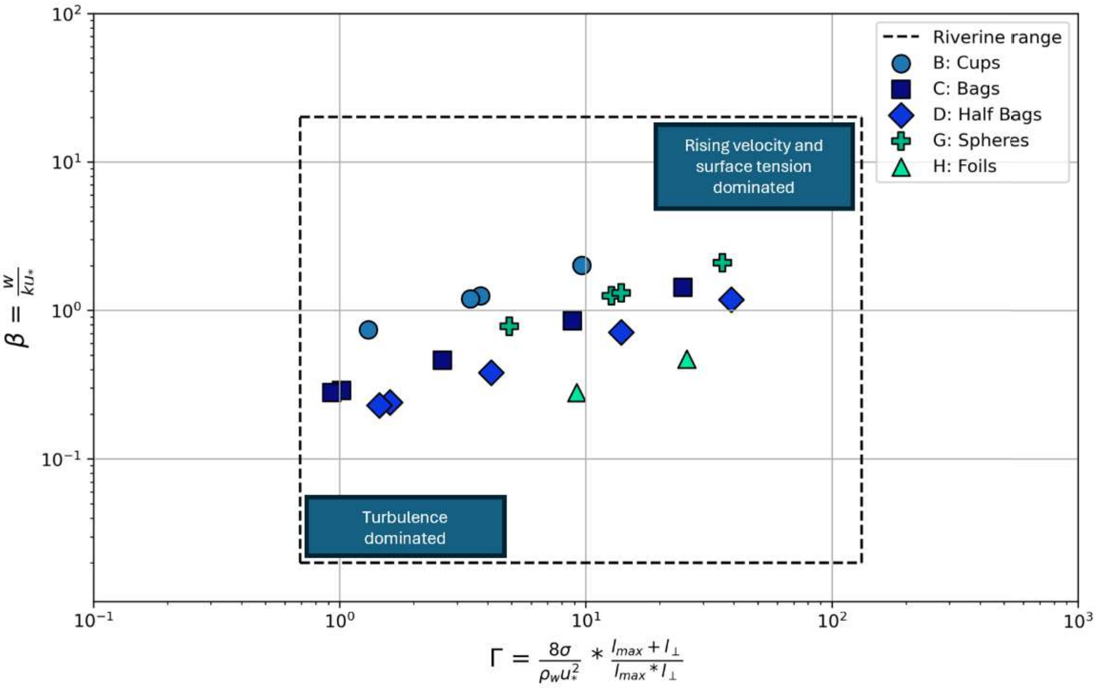

Figure 3-3: Parameter-space of experimental conditions and natural range riverine plastic transport. The black dashed line is based on the analysis described in Section 2.2.3.

4 Experimental Results

This chapter presents the analysis and results from the measurements conducted during the experiments. First, the hydrodynamic conditions are presented and are followed by an overview of vertical plastic distribution profiles. Finally, the interpretation of the results is given.

4.1 Hydrodynamic conditions

To characterize the flow at the measurement section, vertical velocity profiles were measured using an ADV, with data points acquired at 4-centimeter intervals. The data points are presented for each condition in Figure 4-1. The flow within the flume demonstrated a boundary layer which is a common feature in riverine hydraulics. Furthermore, the measured mean velocity profile aligned with the log-wake law equation (Castro-Orgaz, 2010). This is a standard representation for turbulent riverine flow and is based on bed roughness and mean flow velocity. Using this resemblance, the shear velocities (u_*) and boundary layer (δ) were determined for each experimental hydraulic condition by fitting the log-wake law equation. These obtained parameters per hydraulic condition are presented in Table 3-1.

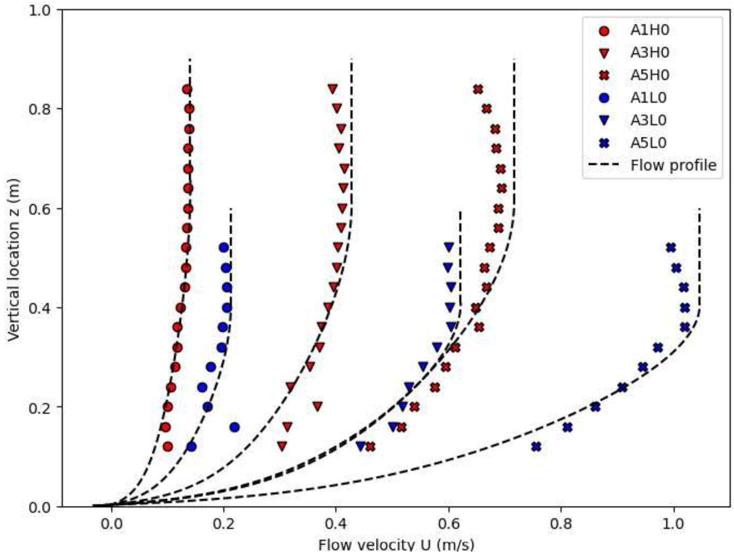

Figure 4-1: ADV flow velocity measurement per hydraulic condition marked by the corresponding ID and the theoretical flow velocity profile based on log-wake law and from boundary layer uniform.

4.2 Plastic vertical distribution profiles

Plastic centres of gravity (C.o.G.) were estimated using the multi-camera detection system. Plastics in contact or proximity to the water surface were categorized as transport within the *near-surface layer* (Valero, et al., 2022). Within this layer (denoted as “a” in Figure 4-2), the vertical profile is expected to be influenced by surface tension.

The layer beneath the near-surface layer is classified as the *suspended transport layer*. Within this layer, plastic particle transport in riverine flow is described by Valero et al. (2022) using classical particle suspension theories, specifically the Rouse profile.

Vertical distribution profiles of spheres, half bags, and complete bags are illustrated in Figure 4-2 for three hydraulic flow conditions. This figure also includes the theoretical Rouse profiles and the associated near surface layer thickness (a).

Analysis of the distribution profiles obtained from the experiments showed that under conditions of low turbulence a substantial proportion of plastic items were positioned within the near-surface layer. As turbulence increased a larger number of plastic items were observed within the suspended transport layer. However, an increased number of plastic items was still observed in the near-surface layer for all conditions.

Within the suspended transport layer, smaller solid plastic particles (e.g. spheres) exhibited a distribution that closely matched the classical Rouse profile across all tested hydraulic conditions. For larger plastic items and flexible plastics (e.g., half bags and complete bags) and increased turbulence, the distribution profile gradually deviated from the Rouse profile and developed towards a more uniform distribution.

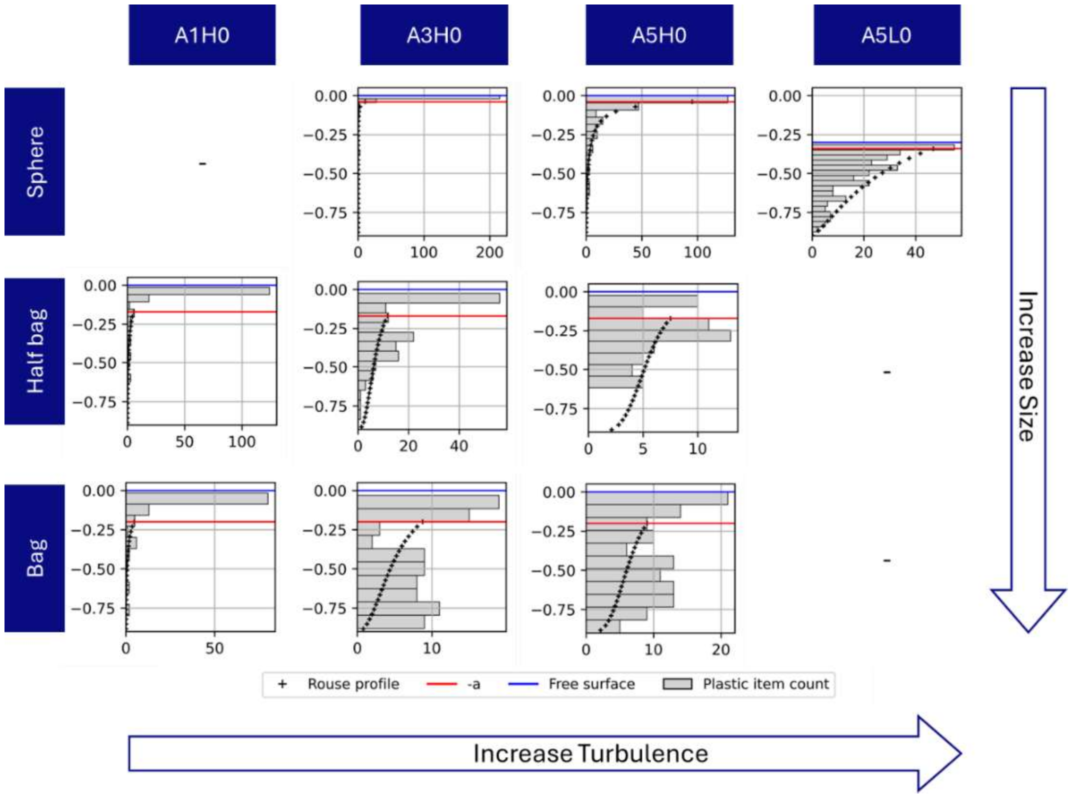

Figure 4-2: Vertical distribution profiles, showing water depth [m] on the y-axis and particle count on the x-axis.

The measured vertical distribution profiles show that turbulence and plastic particle size play crucial roles in plastic's vertical distribution. Turbulence, defined by its chaotic and irregular motion, generates eddies of varying scales. These eddies facilitate mixing and enable the transport of particles throughout the water column. When turbulence intensifies, the size and intensity of these eddies increase. This results in greater dispersion of particles across the water column. Furthermore, as particle size increases, the likelihood of direct interaction between eddies and particles rises, resulting in a profile characterized by a higher portion of submerged particles.

Also this measurement campaign confirms that the plastics near the surface are influenced by water surface interaction, resulting in an increase in items in the near-surface layer. As presented by Valero et al. (2022), the surface tension results in an extra upward force to the plastic when it is connected to the free surface. Therefore an increase of plastic items in the near-surface layer can be observed.

5 Field measurement validation

Given that the experimental measurements were designed to resemble Dutch riverine properties, a comparison with plastic field measurements was conducted to show the relevance of the experiments to real-world conditions. This chapter presents this comparison with field data collected at three locations along the Meuse River in the Netherlands by Rijkswaterstaat in 2023 and 2024.

5.1 Field measurements at Meuse

Plastic field measurements were conducted by Rijkswaterstaat using trawl nets to sample plastic litter in the water column within the Meuse River. This sampling was performed from the vessel Stern, operated by De Rijksrederij Nederland. Two nets, each with a 4 m² opening (4 m width by 1 m height) and a 6 mm mesh size, were deployed from the port and starboard sides of the vessel. The nets were positioned at three distinct depths within the water column: upper meter, the bottom meter and mid-depth. Further details and measurement procedures can be found in Roozendaal (2024), Polinder (2023), and Lin (2024).

For each captured plastic item, the circumference, area and maximum linear dimension were measured. Also the size class (meso or macro), sampling location, positions of the net and year were recorded. Furthermore, all collected plastic items were categorized following the River-OSPAR classification protocol. This dataset[1] was shared by Rijkswater with Deltares and used to obtain the vertical plastic profiles.

To characterize the hydrodynamic conditions during the field measurements, Acoustic Doppler Current Profiler (ADCP) measurements were performed from a separate vessel trailing the Stern.

The plastic field measurements were conducted at three locations along the Meuse River. Each location is shown in Figure 5-1 and Figure 5-2, which indicate its position within the river. The duration of each measurement was approximately one day. A brief description of each location is provided below:

- A) Eijsden (straight section)
  The sampling site is situated near the Dutch border where the Meuse River enters the Netherlands. This location is a relatively straight river section. Its straight morphology provides the most comparable riverine conditions to the experimental setup, as the flume is straight as well. Samples were collected at the bottom, mid-depth, and upper meter of the water column near the left bank (50°48'11.6"N 5°41'35.5"E) and right bank (50°48'12.4"N 5°41'39.4"E) during field campaigns in 2023 and 2024. Approximately six kilometres upstream of the sampling site lies the Lixhe overflow weir, which is periodically opened for short durations. These openings cause temporary increases in discharge and a corresponding rise in (mainly floating) plastic concentrations.

[1] The unpublished dataset 'Data_Meuse_items_20241203_FC_DEF.xlsx' was personally shared by Dr. Frank Collas (Ecologist, Rijkswaterstaat) on 3-12-2024.

- B) Ohé en Laak (bend)
  This sampling site is located within a river bend, characterized by the absence of shipping traffic and nearby weirs. This location minimizes the influence of unnatural disturbances on the natural flow regime. Consequently, this location allows for the observation of the effects of bend-induced currents on the vertical plastic distribution. In 2024, samples were obtained at the bottom, mid-depth, and upper meter of the water column near the right bank of the river (51°06'29.4"N 5°49'27.9"E).

- C) Sambeek (downstream of weir)
  Positioned approximately 500 meters downstream of the Sambeek overflowing weir. This weir overflows on the left half of the river. The flow upstream is disrupted due to the hydraulic structure. This site allows for the investigation of the impact of a weir on plastic transport within a straight river section. Samples were collected in 2023 and 2024 at the bottom, mid-depth, and upper meter of the water column near the left bank (51°38'35.2"N 5°58'46.2"E) and right bank (51°38'37.4"N 5°58'46.3"E).

Figure 5-1: Locations of the performed plastic field measurements along the Meuse by Rijkswaterstaat.

Figure 5-2: Closeup view of the field measurement locations

5.2 Hydrodynamic conditions

The hydrodynamic conditions during the field measurements are characterized by using the ADCP data. This data is used to determine the flow velocity profile close to the measurement location. ADCP measurements were approximately 5 – 9 minutes in duration and are averaged over this period. This results in an average flow velocity profile, with a variation of 5 – 10%, which is used to quantify the turbulent conditions via the shear velocity (u_*). Using the log-wake law equation (as presented in Section 4.1), the shear velocities are determined based on the least square estimation. The equation was fitted by assuming fully developed flow through the measured ADCP flow velocities. The measured ADCP flow velocities, corresponding log-wake fit and determined shear velocity are presented in the next sections.

It should be noted that the ADCP measurements were short in duration compared to the plastic sampling period (approximately one day). As a result, they represent short flow conditions rather than a full-day average. This limitation is particularly relevant for the Eijsden location, which experiences increased flow velocities when the weir is open, leading to temporal variations in flow velocity. To fully capture the interplay between plastic transport and hydrodynamic variability, a more continuous flow velocity dataset would be required.

5.2.1 Eijsden

The ADCP measurements at Eijsden were performed near the left and right bank of the river in 2023 and in 2024. The log-wake fit follows a nice relation to the measured ADCP data. The obtained shear velocities based on the data from 2024 are higher compared to the one determined from the data in 2023. A potential reason for this is the higher maximum flow velocities in 2024 as well as a slightly smaller water depth.

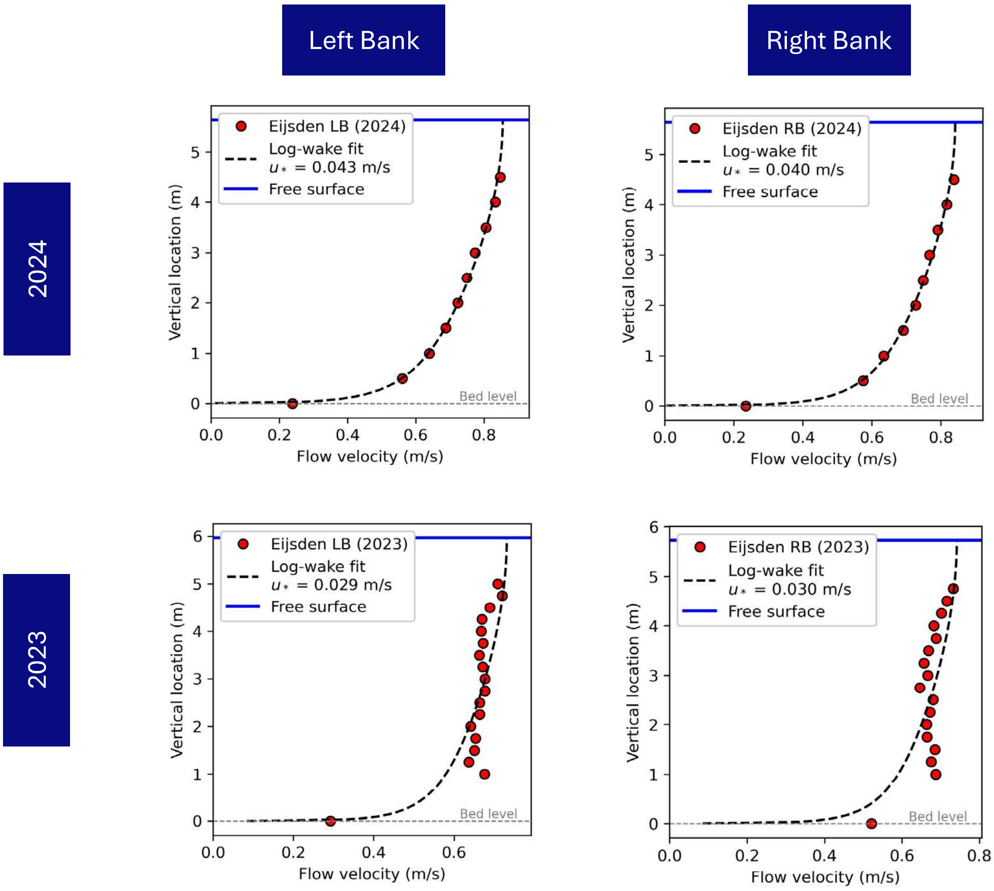

Figure 5-3: Hydrodynamic profiles during field measurements at Eijsden in 2023 and 2024

5.2.2 Ohe en Laak

The ADCP measurement at Ohe en Laak was performed near the right bank of the river 2024. The fitted theoretical log-wake velocity profile based on the flow measurements is presented in Figure 5-4. The obtained shear velocity based on the ADCP data resulted in a high shear velocity of 7.6 cm/s, indicating a higher level of turbulence during the measurement.

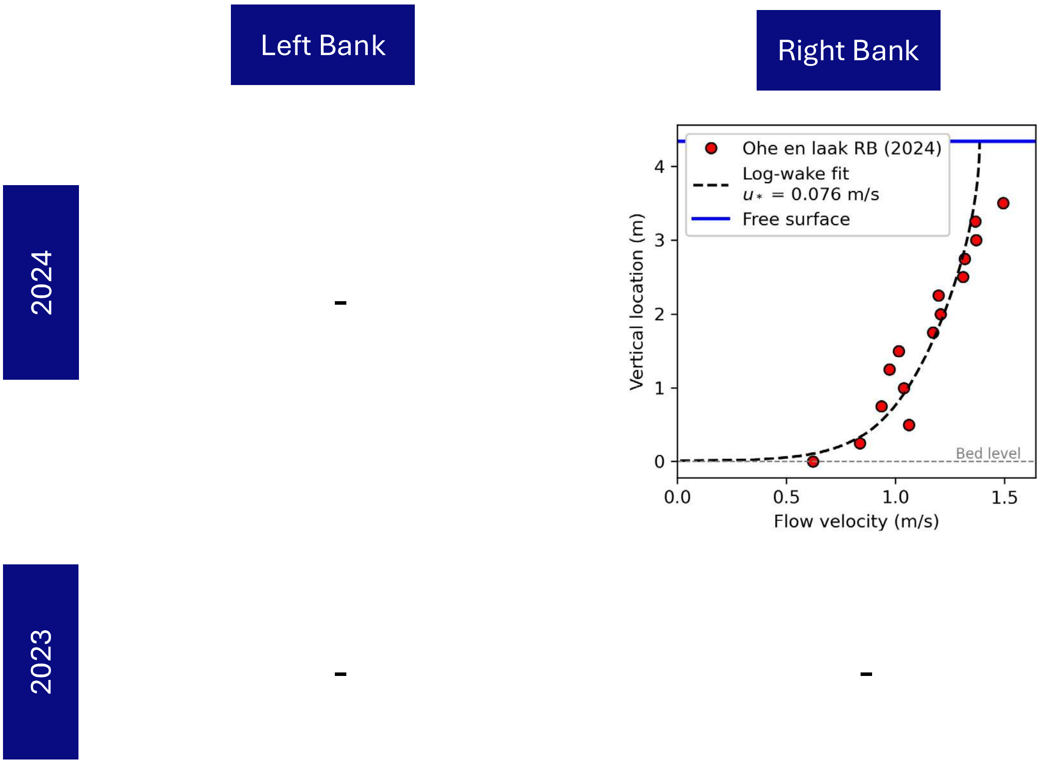

Figure 5-4: Hydrodynamic profiles during field measurements at Ohe en Laak in 2024

5.2.3 Sambeek

The ADCP measurements at Sambeek were performed near the right and left bank of the river in 2023 and near the left bank in 2024. The flow velocity profiles are presented in Figure 5-5. The obtained shear velocities showed that at the left bank a lower shear velocity occurred compared to the right bank in 2023. A potential reason for these differences can be explained by the overflow weir upstream of the measurement location. For the 2024 data, only ADCP measurement near the left bank is available.

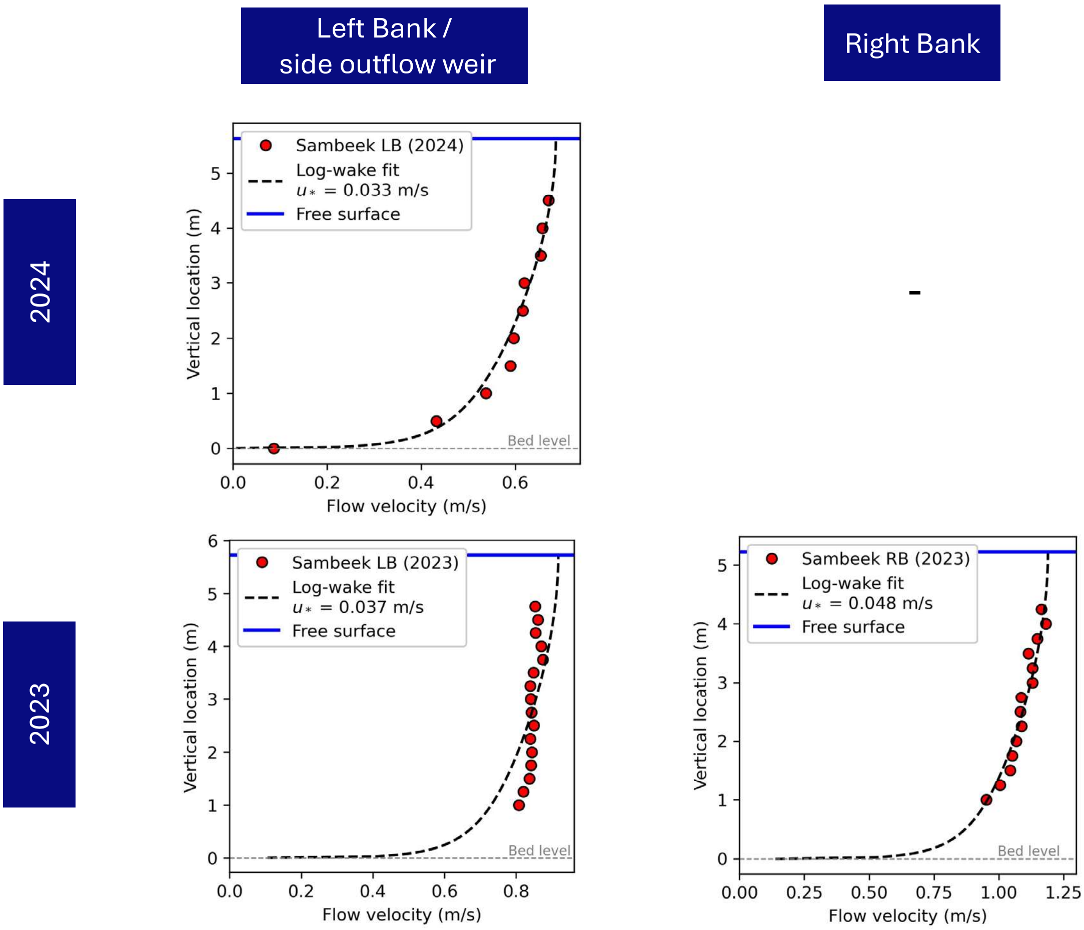

Figure 5-5: Hydrodynamic profiles during field measurements at Sambeek in 2023 and 2024

5.3 Plastic vertical distribution profiles

5.3.1 River-OSPAR

The captured litter during the field measurements are categorized by the river-OSPAR classification. This methodology provides a standardized way to collect data on the amount and types of litter present on riverbanks. This allows for comparable data collection across different locations. It involves categorizing collected litter into a large number of specific subcategories, which are further grouped into broader material categories: plastic and styrofoam, rubber, textiles, paper, wood, metal, glass, sanitary, medical and pellets.

During the data analysis in this report, only data of the material category ‘Plastic and Styrofoam’ was used. In the next sections the vertical plastic profiles from the field measurements are presented including the shear velocities obtained from the ADCP measurements as presented in Section 5.2.

5.3.2 Eijsden

The vertical distribution of plastic litter, as determined by field measurements in 2023 and 2024, is illustrated in Figure 5-6. The 2024 profiles demonstrate a relatively uniform distribution across the water column at the left bank, while the right bank indicated an increasing concentration towards the surface. These profiles were obtained by a shear velocity of 4.3 and 4.0 cm/s. The 2023 plastic measurement data indicate a significant concentration of plastic litter near the free surface, with fewer items at lower depth. The measurement at the left bank in 2023 was performed by a shear velocity of 2.9 cm/s, and 3.0 cm/s at the right bank. This increase in near-surface plastics in 2023 may be related to the lower shear velocities or to a temporary opening of the Lixhe overflow weir, which can release stored floating plastics. Both factors may have influenced the observations.

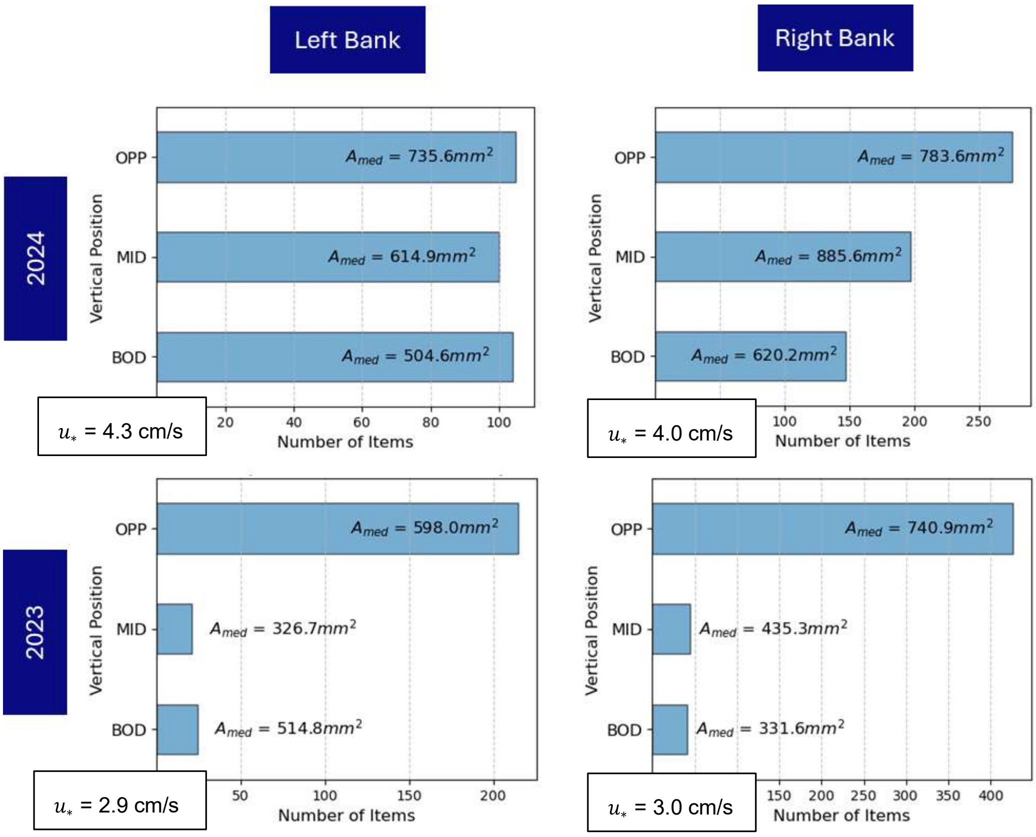

Figure 5-6: Vertical distribution profiles of plastic litter measured during field measurements in 2023 and 2024 at the location Eijsden near the left and right river bank.

5.3.3 Ohe en Laak

The vertical distribution of plastic litter at Ohé en Laak was assessed through field measurements performed on the right bank of the Meuse river in 2024. The resulting profile, presented in Figure 5-7, indicates a relatively uniform distribution throughout the water column, with a subtle increase in the number of items observed near the water surface. This measurement was performed during high shear velocity of 7.6 cm/s.

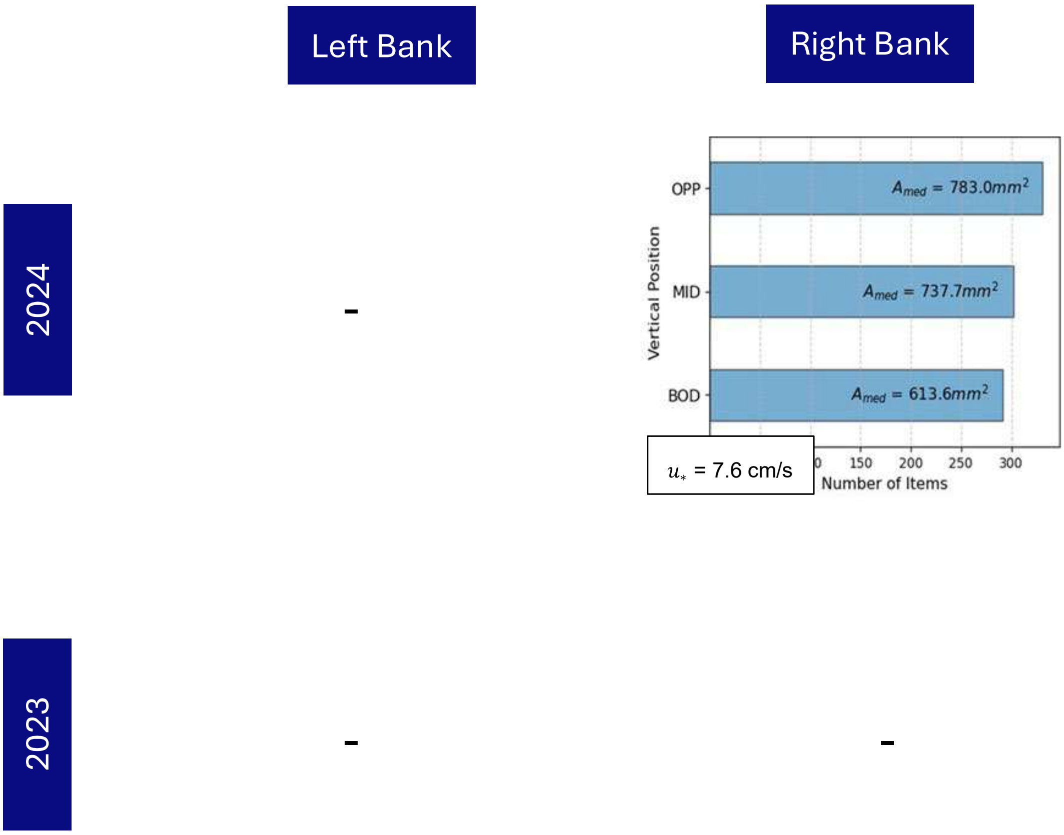

Figure 5-7: Vertical distribution profiles of plastic litter measured during the field measurement in 2023 at Ohe en Laak near the right river bank.

5.3.4 Sambeek

Vertical distribution profiles for plastic litter at the location Sambeek are presented in Figure 5-8. Measurements were performed in 2023 and 2024 at the left and right bank of the river. The nearby upstream weir overflows at the left side of the river, as presented in Figure 5-2. In the vertical distribution profiles, it can be observed that the profile at the left bank shows different profiles compared to the profiles at the right bank. In 2024 the shear velocity at the left bank was 3.3 cm/s. No velocity measurements were carried out at the right bank. The ADCP data from the measurements at the left and right bank in 2023 resulted in a shear velocity of 3.7 and 4.8 cm/s.

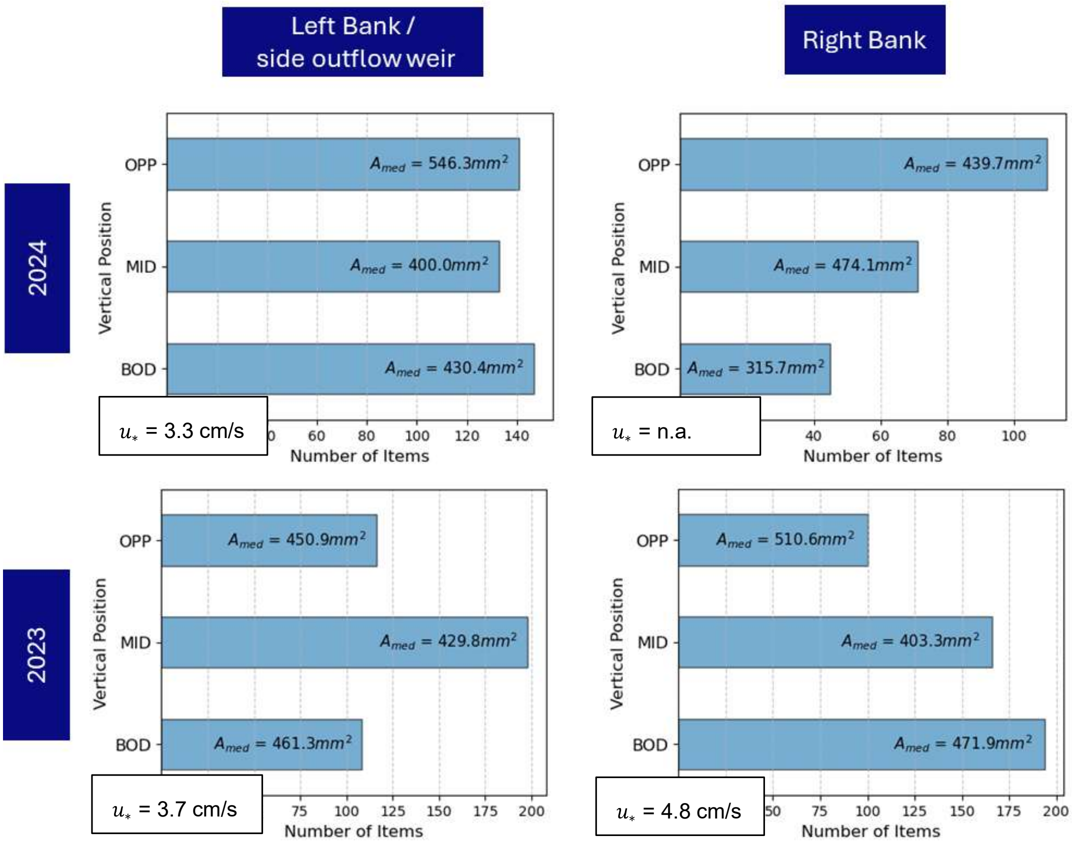

Figure 5-8: Vertical distribution profiles of plastic litter measured during field measurements in 2023 and 2024 at the location Sambeek at the left and right river bank.

5.4 Comparison field measurement with experiment

Although the ADCP measurements at the plastic sampling locations were of relatively short duration (5–9 minutes) compared to the approximately one-day plastic sampling period, they still provide valuable insight into the occurring hydraulic conditions. Despite this temporal limitation, the determined theoretical flow velocity profiles and corresponding shear velocities aligned well with those measured during the experimental campaign. Specifically, shear velocity during the field measurements ranged from 2.9 to 7.6 cm/s, while experimental values spanned 1.3 to 10.8 cm/s. This overlap indicates that, even within the short measurement window, similar hydrodynamic conditions were captured as those reproduced in the controlled experiments.

The plastic vertical distribution profiles from field measurements showed an increase in submerged plastic items with increasing shear velocity, a trend also observed in the experimental campaign. This also indicates that the experimental tests produced accurate and comparable results to the field observations.

For the experimental measurements, a significant number of submerged plastics were observed for shear velocities greater than 4.0 cm/s. The first experimental condition with lower shear velocities, specifically at 2.2 cm/s, showed significant numbers of plastic items mostly at the surface. This suggests a transition zone for plastic items that results in a shift from surface transport to include submerged conditions, which occurs for shear velocities between approximately 2.2 cm/s and 4.0 cm/s.

The shear velocities of this transition zone were also observed in the field measurements. A significant number of plastic items were found in submerged conditions when the shear velocity was greater than 3.3 cm/s. Lower field shear velocities showed mostly surface plastics with negligible submerged amounts, consistent with experimental results. By combining the transition zone of the experimental measurement and the field measurements, the transition zone is set to be between approximately 2.2 cm/s and 3.3 cm/s.

Table 5-1 presents an overview of the ratios of plastics captured in the upper and lower nets during the field measurements, categorized according to the predominant mode of transport.

Table 5-1: Range of ratios of sampled plastic items in the Meuse river in upper net (OPP) compared to middle (MID) plus bottom (BOD) nets for turbulent conditions and corresponding predominant mode of transport.

Predominant Mode of transport	Turbulence condition	Ratio Plastic OPP-net	Ratio Plastic MID & BOD - net
Surface	$u_* \leq 2.2\ cm/s$	n.a.	n.a.
Transition zone	$2.2 < u_* < 3.3\ cm/s$	81 – 82%	18 – 19%
Submerged	$u_* \geq 3.3\ cm/s$	22 – 43%	57 – 78%

Based on the depth-averaged flow velocity of the Meuse River, the number of submerged plastic items becomes significant when the velocity is greater than 0.7 m/s. Interpolations of the vertical profiles from the field measurements indicate that under these conditions, the amount of submerged plastics can be three to six times higher than that of surface plastics.

On the contrary, while experiments indicated that plastic item size played a role in vertical distribution, the field data presented here cannot confirm or deny this finding. This limitation resulted from the fact that the field measurements were conducted under different hydrodynamic conditions, which prevented a direct comparison of size-related effects.

Moreover, local factors such as flow curvature, turbulence induced by hydraulic structures and vessel traffic, and the operational dynamics of these structures may also have influenced the results. The three measurement locations were situated in a straight river section, a river bend, and behind an overflow weir. Each location resulted in distinct hydraulic characteristics that are difficult to isolate based on the current available dataset.

To address these limitations, future studies should extend the duration of ADCP measurements to capture a wider range of hydraulic events and temporal variability. Furthermore, additional measurement campaigns under different flow conditions and at various river sections would help to better distinguish the influence of local hydraulic factors on plastic transport and vertical distribution. Ideally, the exact time of capture for each net measurement should also be recorded, allowing for direct comparison with ADCP measurements and the operational status of nearby hydraulic structures.

6 Numerical validation

Numerical models are frequently employed to understand plastic transport in rivers (e.g. (Wickramarachchi, Niven, & Kramer, 2024). However, these models often rely on approximations and simplified processes, such as neglecting plastic particle size and surface interactions. This chapter presents a methodology for enhancing the Deltares numerical particle tracking software, Delft3D-PART, using data from the experimental campaign by recreating the experiment with Delft3D-FLOW (hydrodynamics) and Delft3D-PART (particle tracking). The obtained numerically determined plastic profiles are than optimized based on the measured profiles from the experiment. This will ultimately result in more realistic vertical plastic transport simulations and better global plastic flux estimates.

6.1 Delft3D-FLOW hydrodynamic conditions

A numerical model of the experimental flume was created using Delft3D-FLOW to simulate the hydrodynamic conditions during the measurements. The model was designed to accurately reproduce the experimental hydrodynamic conditions, incorporating all flume and gravel bed dimensions and simulating the required water levels and discharge.

To ensure consistency with the experimental setup, the measurement section was positioned at the same downstream location within the numerical model. For each experimental hydraulic condition, a corresponding numerical simulation was performed to generate hydrodynamic data. A comparison of the flow velocity profiles obtained numerically and experimentally is presented in Figure 6-1. As can be observed is that there is a close agreement between these profiles. This indicates that the Delft3D-FLOW hydrodynamics accurately replicate the measured flow conditions and that the simulations can be used to validate the plastic transport in Delft3D-PART.

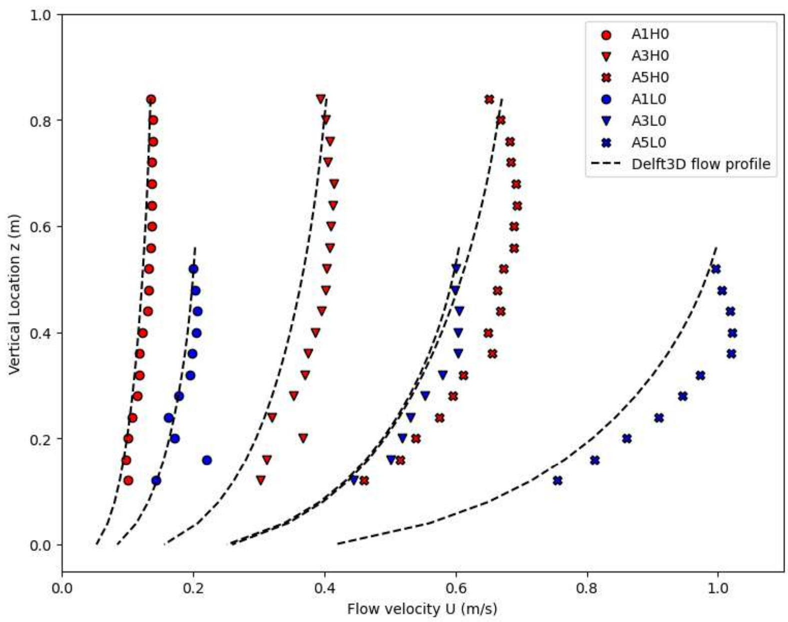

Figure 6-1: Measured vertical velocity profiles for the 6 experimental conditions and simulated vertical velocity profile with the Delft3D numerical model of the flume.

6.2 Delft3D-PART plastic vertical distribution profiles

6.2.1 Current particle tracking

Delft3D-PART relies on specific input parameters to accurately simulate particle tracking. The most important input parameters are the ones related to hydrodynamic conditions, dispersion and particle characteristics. The particle tracking approach followed here focuses in particular on the vertical transport and the (equilibrium) vertical particle distribution.

Hydrodynamic conditions are obtained from Delft3D-FLOW simulations and provide the basis for the (vertical) dispersion of particles. Dispersion coefficients regulate particle spreading and influences their horizontal and vertical distributions. The balance between the vertical dispersion process and the vertical velocity due to buoyancy will determine the steady-state vertical particle distribution profile. The vertical dispersion coefficient is provided by the hydrodynamic model output. This vertical dispersion process can be adjusted by changing a scaling factor (f). For transport of particles in the water column without any interference of additional forces which can restrict the spreading, the scaling factor is set to 1.0. The particle properties are represented by its settling or rising velocities and directly influence the transport as well. At this point, the particle sizes and shapes, or the influence of surface interaction are not taken into account.

As demonstrated in Section 4.2, the plastic item size is influencing the vertical distribution profile. For small particles, rising velocities effectively represent particle-specific properties and are following a Rouse-like profile. Therefore, Delft3D-PART is able to recreate profiles for the smaller particles (spheres), as Delft3D-PART doesn’t require size and shape input. However, because of the lack in size and shape input, Delft3D-PART is less accurate in determining the vertical distribution for larger sized particles. Furthermore, Delft3D-PART neglects surface interaction which influences vertical profiles.

6.2.2 Improvement particle tracking

To improve the accuracy in modelling the vertical distribution of plastic litter, an improvement has been developed for the Delft3D-PART module. The improvement takes the particle size and surface interactions into account. This results in a more accurate concentration of plastic particles within the near-surface layer, due to surface tension forces acting upon particles encountering the free surface. Consequently, the concentration of items in submerged conditions are more accurate as well.

To replicate this phenomenon within the Delft3D-PART simulations, the scaling factor (f) was adjusted within the near-surface layer based on the dimensions of the plastic particle. The scaling factor is kept at its maximum of 1.0 in the suspended transport layer. When the scaling factor is reduced, it lowers the likelihood of particles changing their vertical position in the near-surface layer. This mimics the effect of plastic items getting attached to the surface.

As demonstrated in Section 4.2, Γ is used to describe this effect. Therefore, the dispersion coefficient is expressed as a function of Γ. To capture this dependency, an empirical relationship, simplified from Valero et al (2020), was obtained for the scaling factor in the near-surface layer:

$$f = \min\left(a * \ln(\Gamma) + b, 1.0\right)$$

where a = -0.201 and b = 0.969 are empirical fitting parameters.

The procedure for determining these parameters consisted of several steps. First different fixed scaling factors (f = 0.3, 0.5, 0,7 & 1.0) were applied in the near-surface layer in the Delft3D model. The resulting profiles were then compared against the experimentally measured profiles. From this comparison, an optimum scaling factor was identified for each profile which gave closest agreement with the experimental in the near-surface layer.

In the next step, the set of optimum scaling factors was related to the corresponding values Γ. By fitting the equation to these values using the least squares method, the parameters a and b were determined.

By implementing this relation to the Delft3D-PART module, an increase in accurately describing the vertical profiles is achieved. This was performed by comparing the vertical concentration of plastics in the near-surface layer measured during the experiment ($C_{surf,exp}$) to the vertical concentration determined by Delft3D-PART with ($C_{surf,part,new}$) and without ($C_{surf,part,cur}$) using the scaling factor relation. Figure 6-2 shows this comparison and presents that $C_{surf,part,new}$ has an improved accuracy (R^2 = 0.707) in predicting the concentration in the near-surface layer compared to the $C_{surf,part,cur}$ (R^2 = 0.401). Furthermore, by using the scaling factor relation, the vertical profiles will show a better alignment with the vertical profiles measured during the experiments, as presented in Figure 6-3.

It must be noted that the presented adjustment of Delft3D-PART uses a gamma factor to incorporate plastic item size into the near-surface layer, applying it as a scaling factor. However, the core numerical computations of Delft3D-PART itself do not account for particle size and therefore follow a Rouse-like profile. As demonstrated in Section 4.2, vertical profiles for larger items and higher turbulence deviated from the theoretical Rouse profile, indicating the necessity for developing or applying alternative distribution models that account for these more complex interactions. Further software development in Delft3D-PART is required to include these conditions.

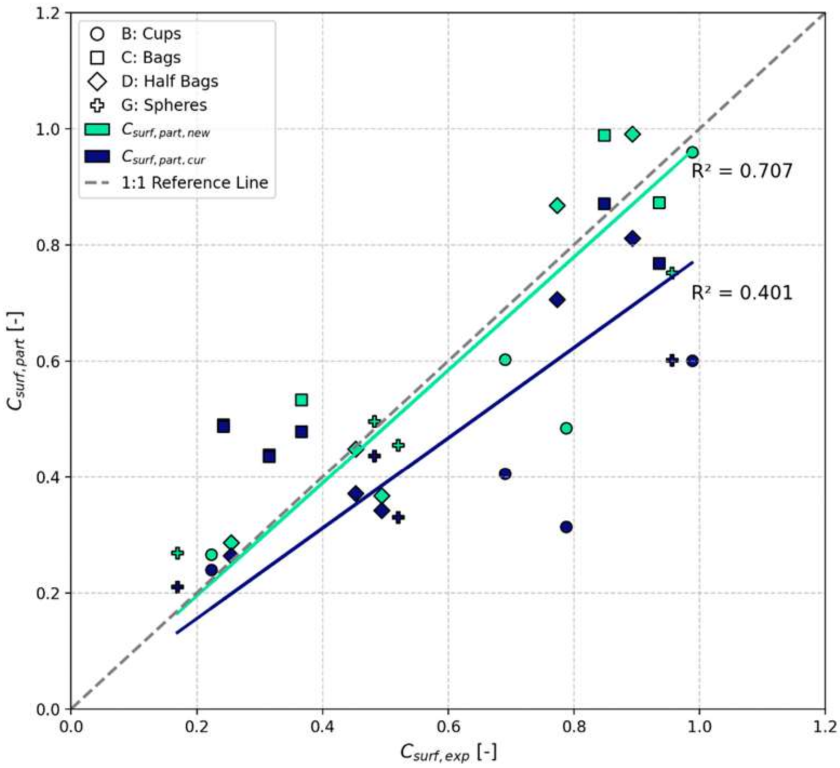

Figure 6-2: Relation between the vertical concentration of plastic items in the near surface layer measured during the experiments ($C_{surf,exp}$) and simulated by Delft3D-PART ($C_{surf,part}$).

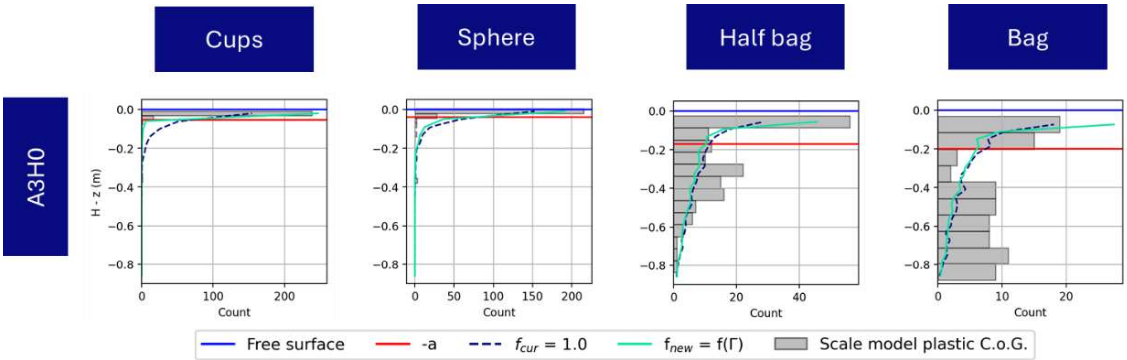

Figure 6-3: Influence of scaling factor (f=1.0) in current Delft3D-model and scaling factor as function of Γ for four different plastic items during the one flow condition.

7 Conclusion and recommendations

7.1 Conclusion

This study addressed the knowledge gap in the vertical distribution of submerged macro-plastic litter in rivers, an often overlooked but crucial component of the global plastic transport. By combining controlled laboratory experiments at Deltares with field measurements performed by Rijkswaterstaat, validation data was obtained for improving numerical particle tracking software Delft3D-PART.

The combined experimental and field data consistently showed that increased turbulence, as quantified by shear velocity, led to an increased number of submerged plastics in riverine environments.

Both field and experimental measurements showed the trend, with a transition observed for shear velocities between approximately 2.2 cm/s and 3.3 cm/s. Within this range, plastic transport shifts from mostly near-surface transport to transport with significant submerged quantities.

In terms of the average flow velocity of the Meuse river, it is observed that the number of submerged plastics starts to be significant when the depth averaged flow velocity is greater than 0.7 m/s. During those conditions the number of submerged plastic items was 3 to 6 times higher than that of plastics in the near-surface. This highlights that relying solely on near-surface observations can lead to a substantial underestimation of total plastic flux, potentially neglecting up to six times the actual amount of macro-plastics in rivers.

Furthermore, experimental measurements revealed that increased plastic size also contributes to a higher number of submerged plastics within the water column. This finding underscores the dynamic interaction between river hydrodynamic conditions and plastic particle characteristics in determining vertical distribution. However, direct confirmation of this size-related effect from field data was not possible due to variations in hydrodynamic conditions during data collection, which prevented a direct comparison.

This study also demonstrated that the vertical distribution based on the classical Rouse profiles are only applicable to smaller sized plastics (< 2 cm) or lower turbulence levels (< 2.2 cm/s). For larger items and higher turbulence, the measured profiles deviated from the theoretical Rouse profile, indicating the need for developing or applying different distribution models that account for these more complex interactions.

The vertical plastic distribution profiles obtained from the experiments have been used in improving Delft3D-PART, allowing for the incorporation of plastic particle size and surface interaction effects. These improvements facilitate more accurate simulation of vertical plastic transport for lower turbulence levels (< 2.2 cm/s), thereby contributing to more realistic estimates of global plastic flux. For higher turbulence levels additional improvements has to be made in Delft3D-PART.

In conclusion, this study demonstrates that near-surface measurements alone can underestimate total macro plastic concentrations in rivers by up to a factor of six. Accurately capturing vertical plastic distribution is therefore critical for developing effective mitigation strategies against riverine plastic pollution.

7.2 Recommendations

In this research, validation data on the vertical distribution of plastic items was collected to improve the numerical particle tracking software Delft3D-PART. In this report, the dataset was used to account for surface tension effects and particle size under lower turbulence conditions (shear velocity < 2.2 cm/s), where the vertical distribution can be represented by a Rouse profile within Delft3D-PART.

At higher turbulence levels, which frequently occur in Dutch rivers, the vertical distribution deviates from the Rouse profile. For these conditions, Delft3D-PART has not yet been updated and further improvements are required. The same validation dataset can by used to develop these improvements.

Once the updated Delft3D-PART includes both lower and higher turbulence conditions, the model can be validated against field measurements to demonstrate its improved ability to predict plastic transport in rivers.

Following these steps, Delft3D-PART can be developed into a validated tool capable of reliably representing vertical plastic transport in riverine conditions.

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