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Abstract

Plastics are globally dispersed and reported at a growing rate and increasing concentrations in marine ecosystems. Due to their persistence in aquatic environments, the global plastic problem will last for decades. In this context, the removal of plastic at the source prior to reaching the marine environment is instrumental. Hence, plastic detection methods and plastic remediation measures are urgently needed and may become obligatory in the near future. A first prerequisite to taking effective plastic remediation measures is to know where and when action should be taken. PLUXIN addressed this challenge by developing a plastic dispersal model, integrating in situ data, experimental insights, and remote sensing to enhance our understanding of plastic distribution. To do so, PLUXIN integrated Flanders' expertise in hydrology, circular economy, and plastic-related research. Based on standardized sampling protocols, in situ sampling and remote sensing, quantifying plastic flux, identifying accumulation zones and transport routes, we identified that plastic is everywhere, that plastic moves and accumulates, and that not all plastic flows towards the sea. These groundbreaking insights from the PLUXIN project have catalyzed impactful national and international initiatives and projects (cfr. impact timeline). So, besides the scientifically oriented targets, PLUXIN also stimulated innovation in Flemish companies through future valorization efforts. Collaborative efforts have sparked new interactions, amplifying our collective impact on a broader international scale. The project's findings were disseminated through abstracts, publications, workshops, conferences, media outreach, and a short movie highlighting key results.

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1. Introduction

Plastics have become increasingly prevalent in marine ecosystems, with reports of their presence growing steadily. Given their long-lasting nature in estuarine and marine environments, it's clear that addressing the global plastic issue will require sustained efforts over many years. One key approach to tackling this problem is intercepting plastics before they reach the marine environment, highlighting the importance of developing effective plastic detection methods and remediation measures, which may soon become standard practice.

A critical aspect of implementing successful remediation measures is understanding where and when action is most needed. However, at the start of PLUXIN there was a significant gap in our knowledge regarding the distribution of plastics and their movement towards the marine environment. This information is vital for optimizing the effectiveness and efficiency of remediation efforts. To address this gap, PLUXIN developed a plastic dispersal model. Through careful calibration and validation using experimental data and field sampling, this model provides insights into the movement of plastics. Remote sensing reflectance data and advanced image recognition algorithms automate the detection of plastics. By integrating these technologies, we can enhance our understanding of plastic distribution and streamline efforts to mitigate their impact on marine ecosystems.

Project objectives

Flanders excels in hydrologic, hydraulic, and circular economy expertise, hosting leading international companies. Flemish knowledge institutes are internationally recognized for their plastics-related expertise. PLUXIN integrated this knowhow and took essential steps to further our expertise and strengthen our international position. Through remote sensing, in-situ observations, and numerical models, Flanders gained insights into plastic distribution, circulation, and fate in aquatic environments. Knowledge gaps tackled in PLUXIN were:

- Lack of standard protocol for sampling, detecting, and identifying micro- and macroplastics.
- Uncertainty regarding the quantities of plastic in rivers and harbors.
- Unquantified flux of plastic from rivers and harbors to the marine environment.
- Unclear locations of plastic accumulation zones.
- Unknown travel speed of plastic through the water column.
- Limited understanding of plastic degradation and fragmentation rates, and their impact on transport routes and fluxes

Approach

The PLUXIN project aimed to develop an optimized protocol for in situ plastic sampling, to quantify plastic flux from rivers and harbors to the marine environment, and to automatically detect plastic through remote sensing. This involved four scientific work packages:

- Experimentally assess the detection and quantification of surface plastics using **remote sensing** techniques.
- Conduct **field observations** on plastic distribution in water columns and sediments, sampling micro- and macroplastics;
- Experimentally study **plastic behavior** in water columns, including vertical flux based on various factors;
- **Model-based quantification of plastic flux** from inland waters to coastal regions, analyzing plastic movement and deposition;

The project aims to stimulate innovation in Flemish companies, with focusing on **future valorization** efforts. A specific work package was dedicated to facilitate this project objective.

2. Highlights

- Transparent state of the art protocols have been developed prior to going into the field to ensure high quality data. These sampling protocols and laboratory procedures align with the most recent methodological development in plastic research.
- Focus was on both microplastic (100 µm - 5 mm) and macroplastic (> 5mm) pollution. The integration of both size fractions is unprecedented.
- The presence of microplastics is widespread in the environment. Microplastics have been detected on all locations in the study area. Smaller sized plastics are more abundant than large plastics based on the size frequency distributions.
- Microplastic concentrations vary spatially, and the highest concentrations have been observed in the river Scheldt. Microplastic concentrations in sediment are high, indicating sediment to be sinks of microplastics. The variability between samples taken at the same location, but with a short time interval can be substantial.
- Light-weighted polymers such as polypropylene are most prominent in surface waters, whereas polymers denser than the ambient water, such as PET, are more prominent in the sediment. Polystyrene is very common in both surface waters and sediment. The majority of macroplastic items in the Scheldt estuary are foil-like non-floating plastics with a high volume-to-weight ratio.
- Remote sensing has potential to significantly contribute to the observation of plastic pollution.
- There are some conditions that need to be taken into account when remotely sensing plastic. For example, wet or submerged plastics exhibit lower reflectance, especially in the near and short-wave infrared regions.
- A machine learning tool was developed for automated detection of floating debris. Plastic detection in airborne multispectral image is proven to be feasible and different clases of litter could be distinguished with high accuracy.

- The sinking behavior of microplastics is a complex process under the influence of both plastic characteristics (e.g. polymer type, size) and environmental factors (temperature and salinity), linked to changing density of the water.
- Possible changes due to artificial weathering are too small to have a profound direct impact on the density to change the settling velocity.
- Biofilm formation on microplastics and its effect on sinking velocity is influenced by the polymer type, surface roughness and size.
- A performant hydrodynamic and wave model has been developed, as such Population Balance Equations are well-suited for plastic transport modelling
- A cross-section analysis in Vlissingen, Doel and Wintam revealed that the flow of plastic land inwards is sustained much longer than the flow towards the sea.
- The estuary reserves as a plastic reservoir. Accumulation of plastic occurs at locations with high fine-grained sediment (i.e. mud) deposition.
- Due to the data heavy population balance model, and despite the unprecedented sampling effort, there is still some uncertainty in the model results. This means that the cumulative plastic flux values can be twofold higher or lower than the mean value.
- In PLUXIN, stakeholder connectivity is the driver for innovation. Expert knowledge and stakeholders opinions have been consulted to stimulate the innovative character of the project.
- The groundbreaking insight of an estuary as a plastic reservoir has catalysed impactful national and international initiatives, as showcased by the PLUXIN impact timeline.
- Based on insights, scientific knowledge, or technological innovations from the PLUXIN project, several follow-up R&I projects and grants have been launched.
- The new insights and scientific knowledge from the PLUXIN project were presented and discussed at numerous national and international events and conferences.

3. Scientific results

3.1. Detection of plastic litter through remote sensing

Detecting plastic litter in natural waters via remote sensing poses significant challenges, mainly due to spectral signal interference from water and the diverse range of plastic materials. To address this, we have conducted various experiments under controlled lab and mesocosm conditions, employing different sensor systems (RGB, multi-spectral, hyperspectral) and sensing setups (such as UAV, fixed poles, and near-surface setups). We determined the feasibility of detecting and quantifying plastics near the water surface using remotely sensed data. We have assessed the effectiveness of different image classification methods, combining spectral feature analyses with innovative machine learning techniques.

Results

Based on the experiments and tests conducted within PLUXIN, it has been demonstrated that remote sensing technology has potential to significantly contribute to the observation of plastic pollution. Through the efforts carried out within the PLUXIN project, we have improved our understanding of both the scientific and operational facets of detecting plastics in riverine environments, and identified challenges for further investigation. The key findings are related to the spectral signature of plastics, detecting floating plastics in the river and plastics along the riverbank.

- **Conclusion 1: Dry, submerged, and weathered plastic have different spectral signatures**

Based on laboratory, mesocosm and field hyperspectral experiments, we concluded that wet or submerged plastics exhibit lower reflectance, especially in the near and short-wave infrared regions due to water absorption. Weathered plastics showed higher reflectance, potentially due to surface cracks, while biofouling affected reflectance in the visible light range. Details about this work can be found in Leone et al. (2023) and Castagne et al. (2023).

- **Conclusion 2: Machine learning algorithms detect of floating plastic objects**

A machine learning tool was developed for automated detection of floating debris, utilizing a retrained Faster R-CNN (Region-Based Convolutional Neural Network) model. The effectiveness of the AI model was evaluated using data gathered from a test fixed-camera set-up, which collected RGB and multispectral images during release-catch experiments. Floating objects were detected with very high accuracy (Average Precision at 50% threshold is 89.88%). Lower accuracies are obtained for objects which are slightly submerged. In a feasibility study performed within PLUXIN, we achieved additional categorization of detected objects into organic matter and plastics using multispectral data. This data was collected with the Micasense Dual camera covering ten spectral bands (444nm, 475nm, 531nm, 560nm, 650nm, 668nm, 705nm, 717nm, 740nm and 842nm). In addition, with a known Ground Sampling Distance (GSD), the size of the items can be derived (Figure 1).

- **Conclusion 3: Plastic detection in airborne multispectral image is proven to be feasible and different clases of litter could be distinguished with high accuracy**

Experiments were conducted with artificially created accumulation zones, with plastics originating from Vietnam, Port of Antwerp-Bruges and the Scheldt River, both on land and in water with observations made using multispectral drone imagery. In the first step, a binary classification was conducted (litter/no-litter) testing four different algorithms: Decision Tree (DT), Random Forest (RF), Support Vector Machines (SVM) and Gaussian Naïve Bayes (NB), and a good performance was obtained for plastic pixels (accuracy larger than 90%). In the second phase, nine classes of interest were defined, including both natural (grass, tree, soil, water) and litter classes (cement, painted surface, oxidated metal, plastics and wood; Figure 2). The classification algorithm is a machine learning algorithm based on Random Forest approaches. The performance metrics (precision, recall and F1-score) are all higher than 90% for the litter categories.

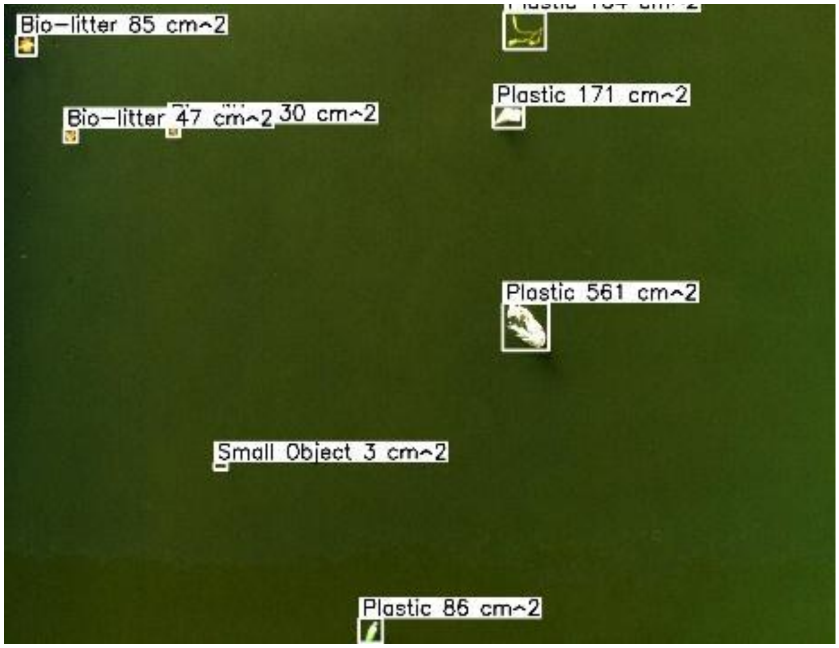


Figure 1: Floating items detected in the river through Faster R-CNN, categorized under bio-litter (organic matter) and plastics. Additionally, the sizes of the objects calculated from the image are provided.

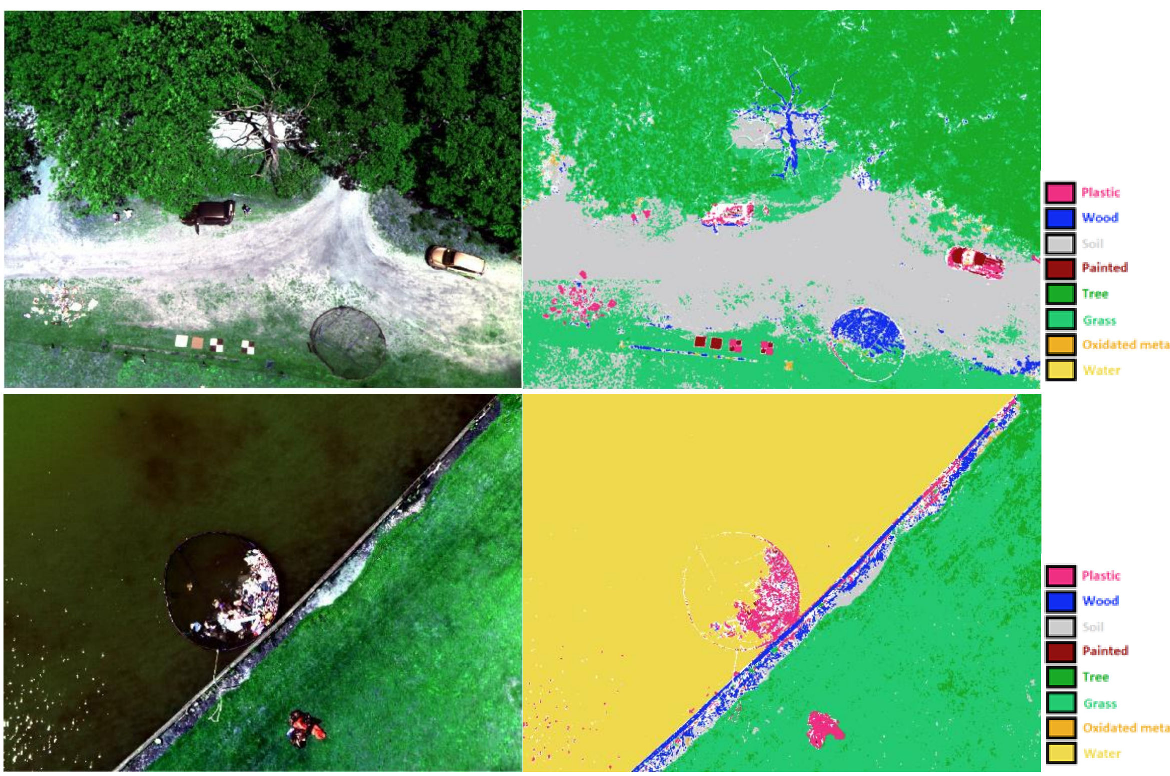


Figure 2: Classification of drone images capturing artificially created plastic accumulation zones over land (top) and water (bottom).

Despite the promising results, also four categories of limitations have been observed, related to: (1) misclassification of shadowed pixels; (2) confusions between certain classes (e.g., soil-wood); (3) classification of sun glint as plastic; and (4) exacerbated class confusions for mixed pixels. Improving the classification algorithms and developing innovative post-processing methods are promising future research directions. Furthermore, litter detection over water might be improved if the particular spectral characteristics of water pixels in the NIR/SWIR spectral regions are exploited, thus insights on the differences between the spectral responses of the litter on land and water areas can be exploited to design customized classifiers for the two cases.

Remaining challenges and recommendations

Observing floating plastics in rivers involves more than just detecting individual objects, i.e. it is about understanding the flow of plastic pollution. This means we need to infer the plastic flux, which requires careful post-processing to avoid counting objects multiple times in successive images and/or due to tidal cycles. In PLUXIN, we researched to find the optimal camera setup. Such camera setup should be tailored towards the local conditions. For example, we may either use multiple cameras to cover the full width of the river or position them strategically to allow extrapolation of the observations. In PLUXIN, we have taken the first steps towards creating a plastics flux product by using personalized segmentation, which helps identify the same objects across different images. In the follow-up INSPIRE project, we should delve deeper into the operational aspects, including optimizing camera setups, to further develop our plastic flux product.

In PLUXIN, the drone observations were centered on detecting macroplastic accumulation zones in both water and on land. Now, we are broadening our focus to include mesoplastics (pellets) and the use of body cams for observing plastics. The scientific foundation of these innovative ideas, originated within PLUXIN, will be explored further in new research projects, such as the intercluster and STEREO project (J'ADORE, proposal submitted). We are also enhancing operational aspects through the Mission Europe funded project INSPIRE (2023-2027; https://inspire-europe.org/).

3.2. In situ observations of plastic

Our primary goal was to gather essential input data for the plastic dispersal model through in situ observations of micro- and macroplastics. To enhance the accuracy of our data collection, we optimized existing protocols for sampling and processing samples. Besides training the plastic dispersal model, the field data also were used to validate the outcomes of the plastic dispersal model. One of our major challenges was to monitor both micro- and macroplastics simultaneously and select relevant sampling locations within the study area.

Results

The results of the in situ observations of plastic cluster around three topics. Besides the development of the sampling and analytical protocols, the results of our study yielded important insights into the spatial and temporal abundance of plastics in the study area. The data exploration suggests that the Scheldt estuary can retain plastics, with a delayed plastic flux towards the North Sea. This is further confirmed by the plastic dispersal model.

- **Conclusion 1: Design and operation samplers and protocols**

In PLUXIN, we present an optimized protocol for preparing, acquiring, processing and reporting results of macroplastic and microplastic samples. We identified relevant sampling locations at which different sampling techniques can be jointly operated. We specified the frequency of taking samples, and how the samples are to be stored, transported, processed in the lab, and data communicated and archived. Our sampling and processing protocol aligned with existing (European) developments in microplastic research and innovations. More information, and the protocols themselves can be found here:

Macroplastic protocols

Microplastic protocols

Relying on the expertise of UA in terms of macroplastic sampling, the PLUXIN project could make use of two sampling devices – a Suspension Sampler and a Bedload Sampler to study the vertical distribution of plastics (Fig. 3 and 4).

Figure 3: The Suspension Sampler. A mechanical flowmeter is attached to the second frame of the Suspension Sampler (SUS2). This second frame also carries a 25kg hydrodynamically shaped weight. In addition, the lower frame (SUS3) also carries three such hydrodynamically shaped weights (CREDIT: Mattias Bossaer, VLIZ).

Figure 4: Left: The Bedload Sampler with the 1m long fin at the back of the cage (CREDIT: Remi Chevalier, UA). Right: The Bedload Sampler being lowered into the water at an angle of 30° (CREDIT: Mattias Bossaer, VLIZ).

- **Conclusion 2: The effort attributed to sampling campaigns and laboratory analyses was unprecedented**

For the PLUXIN project, in total we performed 51 sampling campaigns of which 13 tidal cycles and 38 spot sampling campaigns. A total of 266 manta water column samples and 88 sediment samples (micro- and macroplastic combined) have been collected and processed, resulting in 62 116 particles that have been characterized.

- **Conclusion 3: Plastic is everywhere, and their concentrations vary in time and space**

Plastic was detected in each sample. The plastic concentrations vary spatially, and the highest microplastic concentrations have been observed in the river Scheldt. On average, the surface water of the river Scheldt contained about 10 – 100 particles/m³ microplastics. In surface water of the port of Ostend (1 – 10 particles/m³) and in the river Yser in Nieuwpoort (1- 10particles/m³) the number of microplastic was five- to tenfold lower than the microplastic concentrations observed in the river Scheldt. These concentrations are in line with microplastic concentrations reported in other European rivers, estuaries and ports.

In terms of macroplastic, we observed a high spatial variation with port areas being more polluted than estuarine environments. On average, the surface water of the river Scheldt contained about 10 - 50 g/1000 m³ macroplastic. In the port of Ostend on average 1 – 10 g/1000 m³ macroplastic have been observed. As such, the mass of macroplastic in the surface water of the river Scheldt is comparable to the mass of macroplastic observed in the port of Ostend. The mass of macroplastics observed in the river Yser (0.1 – 2.02.4 g/1000 m³) is about one order of magnitude lower than the concentration observed in Ostend. Inside the port of Antwerp and in the Ghent-Terneuzen canal the mass of macroplastics is in the order of magnitude of 100 - 1000 g/1000 m³.

The majority of macroplastic items in the Scheldt are foil-like non-floating plastics with a high volume-to-weight ratio. The highest concentrations of plastic items were found near the riverbed and in the mid-layers of the water column. In general, a lower number of items per 1000m³ of water was found in the upper net (SUS1), compared to the other two nets (SUS2 and SUS3) of the Suspension Sampler. The number of plastic items per 1000m³ of water varied between weeks (Fig. 5). The variability between samples taken at the same location, but with a short time interval can be substantial.

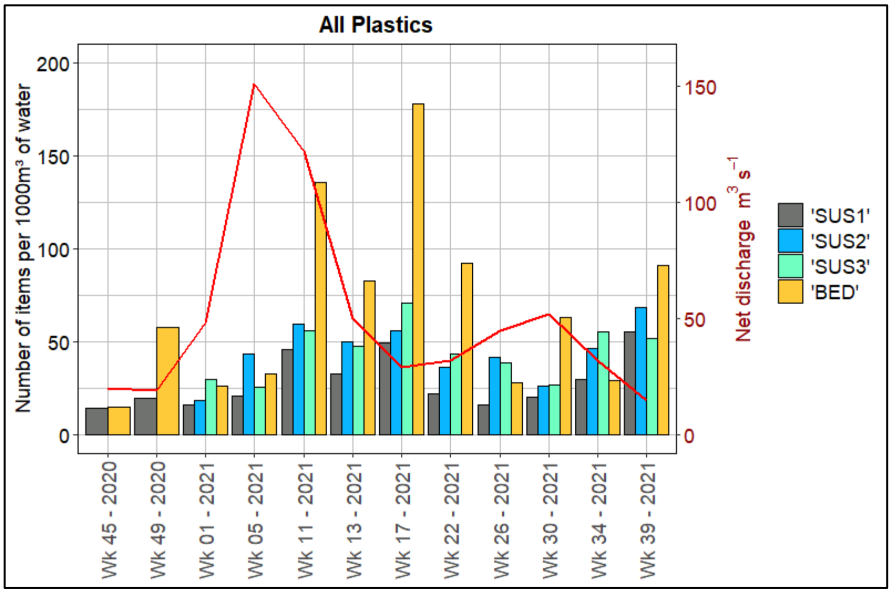


Figure 5: Plastic items per 1000m³ of water collected with the Suspension Sampler and the Bedload Sampler, between November 2020 and September 2021. Mean monthly net discharges in Temse are given in red.

Microplastic concentrations in sediment are high, indicating sediment to be sinks of microplastics. All sediment samples contained microplastics, and the concentrations ranged on average from 1000 - 5000 part kg DW^{-1} in Wintam to 100 - 1000 part kg DW^{-1} in Doel. On average, the Scheldt estuary downstream from Temse Bridge contained 1000 – 5000 part kg DW^{-1}. The sediment in the Tijdok in the port of Ostend did contain 1000 - 10000 part kg DW^{-1}, a concentration comparable to the sediment microplastic concentrations observed in Wintam. In the sediment of the river Yser, close to Portus Novus, microplastics were present at a concentration of 1000 - 5000 part kg DW^{-1}. Overall, all sediment compartments appeared to be heavily polluted with the microplastics.

Based on the size frequency distributions, small-sized particles are more abundant than larger particles. This trend was detected at each of the sampling locations in the water compartment and in the sediment, and for micro- and macroplastic. Based on the sampling and the polymer identification, all 'big five' plastics are present in different ratios in different matrices. The five big plastics refer to polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS) and PET. Detailed information is available here.

Remaining challenges and recommendations

The newly developed Suspension Sampler and Bedload Sampler were successfully deployed in the Scheldt estuary and seem suitable for studying the vertical distribution of meso- and macroplastics in other rivers and estuaries. It was determined that the optimal flow velocity range for simultaneous deployment of both samplers, was between 0.3 and 1.2m s^{-1}.

The study clearly demonstrates that most plastics in the Scheldt estuary are transported in the mid-layers of the water column. Hence, studies focusing on floating plastic items may significantly

underestimate the plastic flux in rivers and estuaries. Accurate estimates of plastic fluxes require techniques that sample the whole water column, from the water surface to the riverbed.
Future work should investigate how different types of plastic relate to specific places. Understanding these "plastic profiles" can help to pinpoint the sources of pollution and what factors affect their behavior. Once we know this, we can better assess the local risks and target cleanup efforts more effectively. For instance, areas with a lot of macroplastic items might need different cleanup strategies than those with mainly microplastic particles or pellets.

3.3. Vertical movement of plastic

Once emitted to the environment, microplastics can be redistributed to other environmental compartments (e.g. by natural elements such as wind and rain). Hydrological models suggested that transport of microplastics can also be affected by particle size, density (and thus polymer type) and shape as well as processes such as biofouling, weathering, aggregation and sedimentation. Until now, there is however little information about the three-dimensional distribution of microplastic in water bodies, including the influence of the aforementioned plastic traits and processes. Nonetheless, this information could lead to the identification of hot or cold spots and is therefore crucial to improve successful plastic remediation and removal projects. Hence, the aim was to experimentally study the behavior of microplastic in the water column by determining their vertical movement as a function of plastic type, environmental conditions (temperature and salinity), weathering and biofouling.
To do so, experiments were set up to study the vertical movement of plastics by a measurement of terminal sinking velocity using a settling column. Terminal sinking velocity was calculated using a MATLAB script (MATLAB R2020b) according to Nguyen et al. (2022). Settling velocity was calculated for different polymer types, different environmental situations and weathering status. A more in depth study was performed on the influence of biofilm formation on microplastic particles and its effects on terminal sinking velocity.

Results

Based on the performed experiment, it can be concluded that the sinking behavior of microplastics is a complex process under the influence of both plastic characteristics (e.g. polymer type, size) and environmental factors (temperature and salinity). Moreover, interactions between the environment and the plastic such as a microplastic-specific biofilm formation can also cause changes in vertical behavior and thus affect the vertical distribution and fate of microplastics in freshwater environments. Three specific conclusions of the performed experiments in the PLUXIN project are being highlighted.

- **Conclusion 1: Changing environmental conditions such as temperature and salinity affect terminal sinking velocity of polymers, linked to changing density of the water**

In total, nine unique environmental situations were simulated in the settling column. The settling column was subsequently installed in three different temperature controlled rooms, one at 20°C (Warm), one at 15°C (Medium) and one at 5°C (Cold). In each of the rooms, the settling column was subsequently filled with seawater (31 PSU), brackish water (15 PSU) and deionized water (0 PSU) to simulate different salinities of different environments. In each of these simulated situations, microplastics of different polymer types were incubated and terminal sinking velocity was measured.

In our experiment, increasing temperature caused increasing settling velocity with a change between 0.91 % and 9.59%. Increasing salinity caused between 2.56 and 22.20 % decrease in settling velocity. The settling velocity of polystyrene particles seemed to be most sensitive to changes in the environment. The observed impact on sinking velocity is believed to be linked to changes in density of the water influenced by temperature and salinity. Warm water is less dense and more viscous than cold water causing an increase of sinking velocity. Increasing salinity is known to increase the density of the water and thus negatively impacts the terminal sinking velocity. Water with a higher density will thus result in a decrease of the terminal sinking velocity.

- **Conclusion 2: Possible changes due to artificial weathering are too small to have a profound direct impact on the density to change the settling velocity.**

Weathering, defined as a degradation or chemical change of the polymer (Andrady, 2011), is the result of an oxidation reaction that breaks down the polymer chain of plastics. Weathering causes changes in physical properties, discoloration, erosion of the polymer surface and cleavage of the polymer. These changes could also influence the terminal sinking velocity of microplastics.
In the experiments, plastics were artificially weathered using a UV weathering chamber simulating environmental weathering between 1 and 12 months. Afterwards, terminal sinking velocity was measured in the settling column. Depending on the polymer types, some slight changes were observed in terminal sinking velocity however, in general, artificial weathering for up to 12 months did not impact the vertical flux of plastics in this set up.

- **Conclusion 3: Biofilm formation on microplastics and its effect on sinking velocity is influenced by the polymer type, surface roughness and size.** Based on: (Vercauteren et al., 2024)

The process of biofilm growth over time and its subsequent effect on sinking behavior of microplastics in freshwater have been limitedly studied, but gives valuable insights on the fate and transport of various microplastics in the freshwater environment. We evaluated biofilm growth on five different polymer types (both microplastic particles and plates) which were incubated in using freshwater for nine weeks in a mesocosm experiment. After 63 days of incubation in freshwater, biofilm had formed on the surfaces of the plates (n=30), with an average of 8.37 ± 7.22 µg per mm². Polymer-specific biofilm growth was again observed. During the 63-day incubation, the amount of biofilm grew exponentially on the PET and PS particles while the LDPE and PP particles showed a rather oscillating biofilm mass. Understanding the temporal aspect of biofilm growth enabled us to refine calculations on the predicted effect of biofilm growth on the settling onset time (i.e. the time needed for the density of particles (and attached biofilm) to be equal to the density of the water which equals the time point when a particle can start sinking) and terminal settling velocity of microplastics in freshwater. According to our calculations coupled with existing knowledge, the tested polymers can primarily be categorized in three groups based on their assumed sinking behavior in freshwater and the role of biofilm growth on this process (Fig. 6). Based on that we can conclude that rivers can function as sinks for some particles. Nevertheless, for others, the likelihood of settling within river systems appears limited, thereby increasing the probability of their transit to estuarine or oceanic environments under hydrometeorological influences.

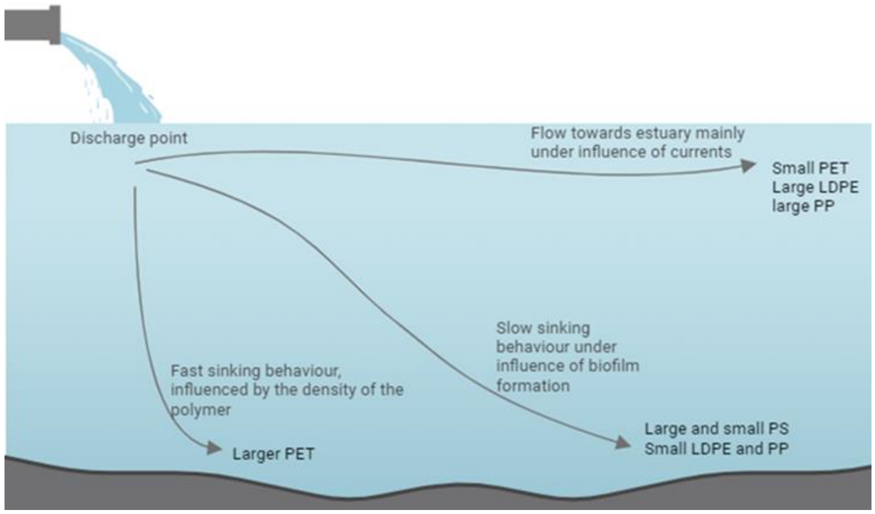


Figure 6: Overview of the three groups of microplastic particles of which the fate is differentially affected by biofilm growth

Remaining challenges and recommendations

The experiments performed in this task represent a first step in elucidating the complex interactions driving the vertical transport of virgin plastic particles in the aquatic environment. For future studies we see three challenges that are left to study. First, in the presented studies, processes such as weathering and biofilm formation were studied as independent processes, which is very interesting to understand the individual impact on vertical behavior. In the case of weathering and biofilm formation, it is expected that both processes will occur simultaneously and also affect each other as weathering can change the hydrophobicity and surface roughness of the plastics which in turn causes a higher susceptibility to biofilm attachment. Therefore, in future, more research should focus on the complex interaction between weathering and biofilm growth. Secondly, our study did not yet take into account seasonal changes. Summer-autumn periods are expected to results in more plastics in the sediment, whereas winter periods should have more MPs in the upper water layers. This is related to the lower temperatures, allowing for less growth of the planktonic ecosystem and consequently, less biofouling. Thirdly, other parameters, such as shape, are not yet taken into account in the experiments as presented here but could also affect terminal sinking velocity. Integrating more plastic characteristics and accepting microplastic heterogeneity will improve our understanding of the vertical distribution of microplastic in freshwater.

3.4. Plastic dispersal model

At the beginning of PLUXIN, understanding how plastic moves in water was challenging. We needed to know where it goes, how it gets there, and where it comes from. So, we used computer models to study how plastic travels from the Scheldt estuary to the ocean. This helped us see how plastic moves, where it ends up on shores, and how it sinks into sediment. We also investigated how different types of plastic behave during transport.

Plastic in water behaves like sediment, but it's more complicated because plastics come in all shapes and sizes. So, we came up with a new way to model plastic transport using something called Population Balance Equations. We used a software suite called openTELEMAC to do this, which considers things like tides, waves, and even changes in water density due to temperature and salt levels. We connected the plastic model with models for waves and sediment to understand how they all interact. We created a detailed model specifically for the Belgian coast and the Scheldt estuary. To make sure our model was accurate, we compared it to lots of real-world data, like water levels, flow speeds, and sediment concentrations. We even estimated how much microplastic was entering the water to start our model off.

Our combined sediment-plastic model is complex, with lots of factors that can affect the results. We focused on five key factors, like how fast plastic breaks down and how much mud is in the water. To save time and computer power, advanced sampling techniques, such as Latin Hypercube Sampling (LHS), have been devised to reduce the requisite number of model iterations.

Results

A novel modelling approach - PBE - is applied for the first time for plastic transport modelling on a large scale. The method is validated against other conventional methods. The model results of plastic concentrations are compared to the measured values over a tidal cycle. The initial condition is calibrated to achieve a similar plastic concentration as measured. Model results are processed to derive the plastic flux values at a few cross-sections to understand the net transport behaviour of the microplastics. Spatial distributions of the microplastics both in the water column and in the bottom sediment are presented to show the local transport dynamics in the coast, estuary and river. The model parameter uncertainty from 40 model simulations are presented in terms of net flux from estuary to sea and statistical analysis is performed. Three specific conclusions of the modelling efforts in the PLUXIN project are being highlighted.

- **Conclusion 1: A performant hydrodynamic and wave model has been developed - Population Balance Equations are well-suited for plastic transport modelling**

The conventional modelling approaches such as discrete classes method often do not consider the full range of plastic sizes. This means that the transport behaviour is approximated with a chosen set of discrete size classes. In the PBE method this is effectively overcome by taking into account the full size distribution. Furthermore, to address the full plastic diversity in the modelling, a settling velocity distribution is proposed in the PBE methodology.

The Belgian Coast – Scheldt model is validated against the measurement data all along the estuary and the river. This model is validated for the hydrodynamic variables free surface elevation, flow velocity and flow direction (Figure 7). The performance of the model is satisfying in all the regions of the model for the variables under consideration. The tidal amplitude shows a gradual increase in its range as moved towards the upstream boundary.

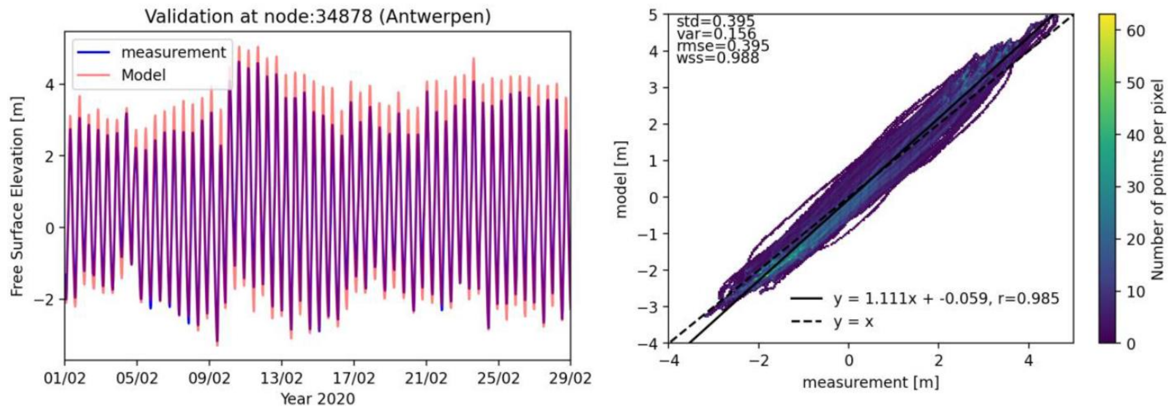


Figure 7: Validation of tide free surface elevation for the Scheldt - Belgian coast model. The time series plots (left) are shown for a duration of one month. The correlation plots (right) are derived from a three month data set.

- **Conclusion 2: Plastic movement in the Scheldt is not consistent all along the river**

A cross-section analysis in Vlissingen, Doel and Wintam revealed that the flow of plastic towards Western Scheldt is sustained much longer than the flow towards the sea (Fig. 8). As such, the Western Scheldt estuary is able to hold back the plastic longer from moving into the sea. In contrast, at the Wintam cross-section, the net flux towards the lower Sea Scheldt drastically reduces from its initial high values. This means that the initial net flux flowing downstream is counteracted subsequently by the flux moving upstream, resulting in a reduced net flux downstream. This shows that the dynamics of plastic movement in the Scheldt is not consistent all along the river. Further long-term analysis is required to establish that these trends are not only short-term but are long-lasting.

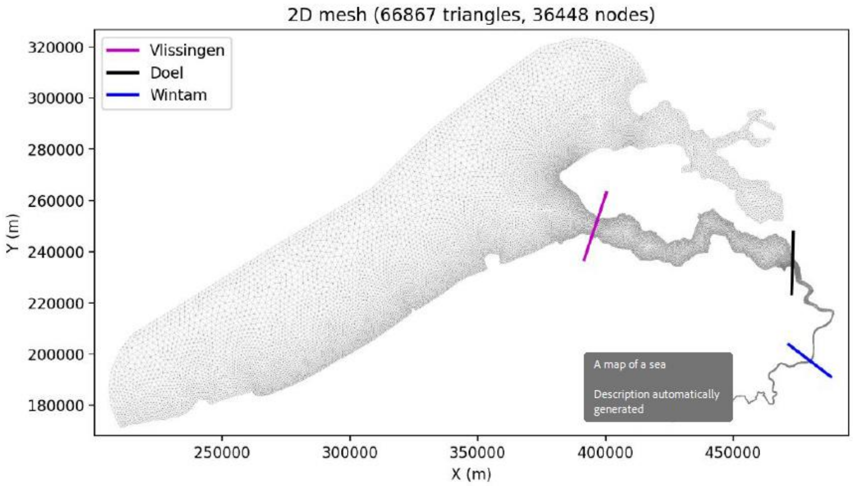


Figure 26: The cross-sections used for determining the fluxes in the Scheldt model

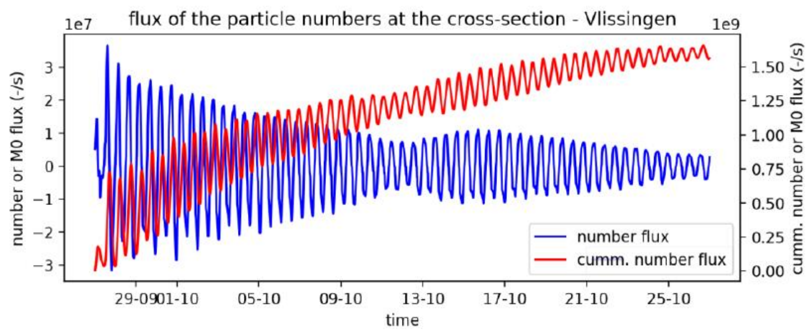
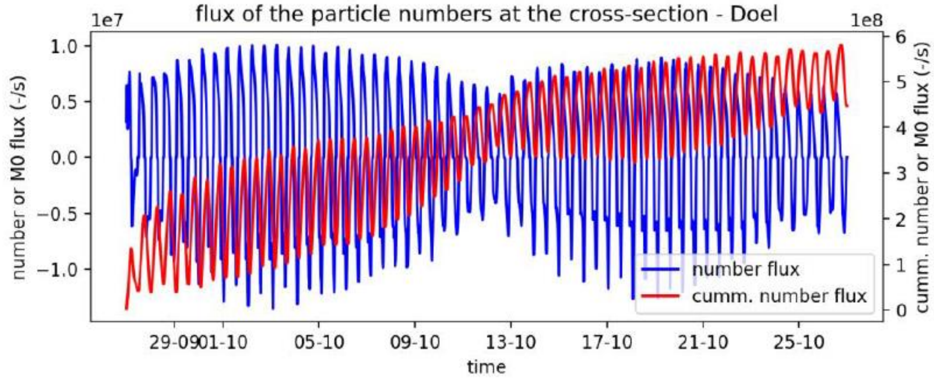


Figure 8: Microplastic number flux across the selected cross-sections



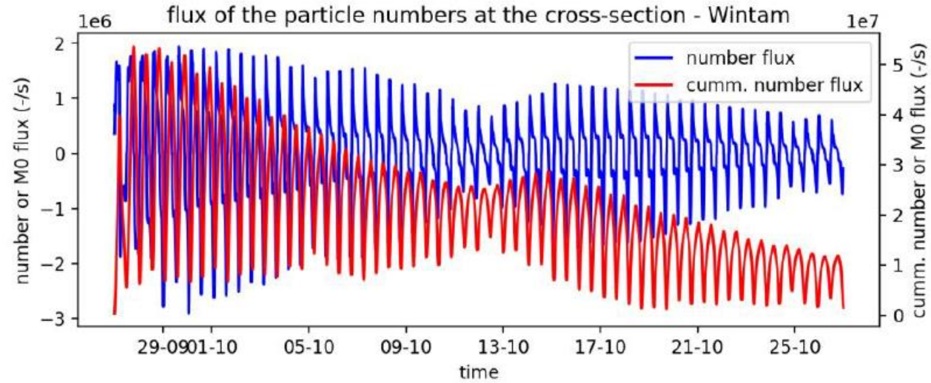
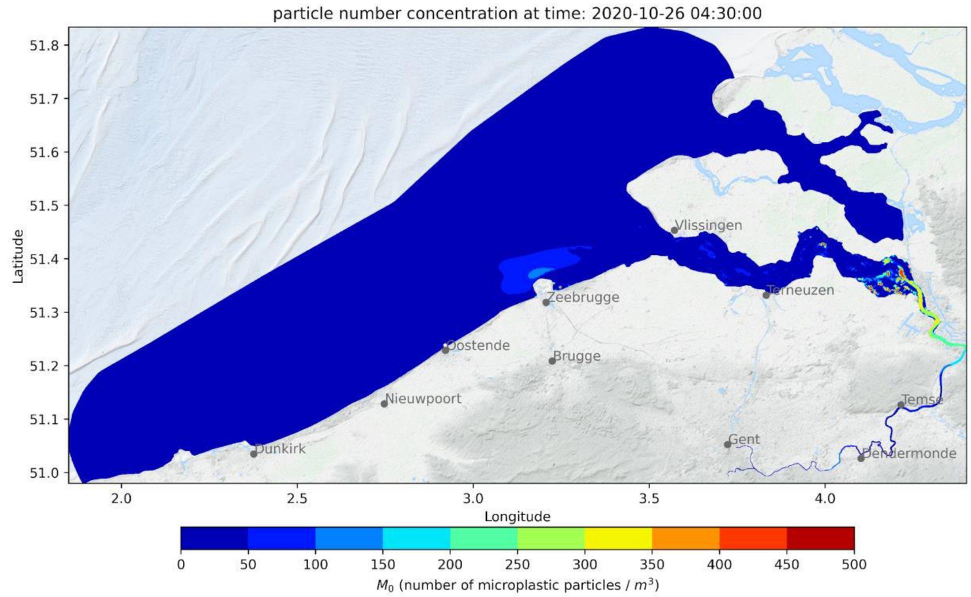


Figure 8 (ctu'd): Microplastic number flux across the selected cross-sections

- **Conclusion 3: Distribution of microplastic varies in time and space, the estuary as a plastic reservoir**

The suspension concentration of microplastics during the low and high flow velocities show large variation in the coastal area of Zeebrugge and in the Western Scheldt. Large amounts of microplastics are resuspended when the flow velocities are high, while during the low flow velocities the concentrations reach near zero values (Fig. 9). The highest concentration of the suspended microplastics is seen near Doel (Belgium-Nederland border). This is the result of large flux from the upper to the lower Sea Scheldt and the particle retaining character of the estuary. These two factors together sustain the higher suspended microplastic concentration. Also, a large plume of microplastics at the Zeebrugge coast is noticeable. This coincides with the turbidity maxima that is reported in literature at the coast of Zeebrugge. It can be hypothesized that the presence of the turbidity maxima traps the microplastics, hindering their further movement into the open sea. This occurs as the deposition and erosion criteria of the microplastics are linked to that of the sediments in the turbidity maxima.

The deposition of microplastic can be observed all around the coast of Zeebrugge and up to Doel at a low energy condition (Fig. 10). In the rest of the Belgian coast the deposited material is not present as a result of the free open sea boundary from where microplastics are flushed out into the open sea and are not returning back into the domain during the tidal cycles. Large amounts of deposition are visible in the deeper channels in Western Scheldt. The lower flow velocities allow for deposition from large quantities of water resulting in higher bed concentrations. However, these depositions are resuspended again in the next high flow condition (Figure 31 (b)). Not all of the microplastics are resuspended during a high flow condition. The materials deposited on the shorelines of the coast and river and on the intertidal flats of the Western Scheldt remain in place (Figure 31 (b)). They are deposited at higher grounds away from the high flow field. Therefore, they remain in these locations for a longer duration.



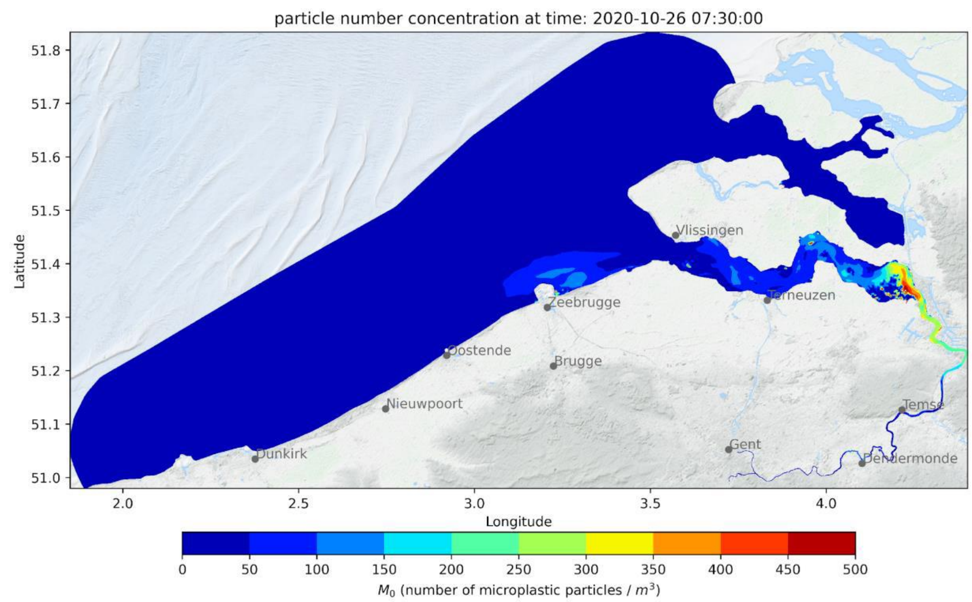
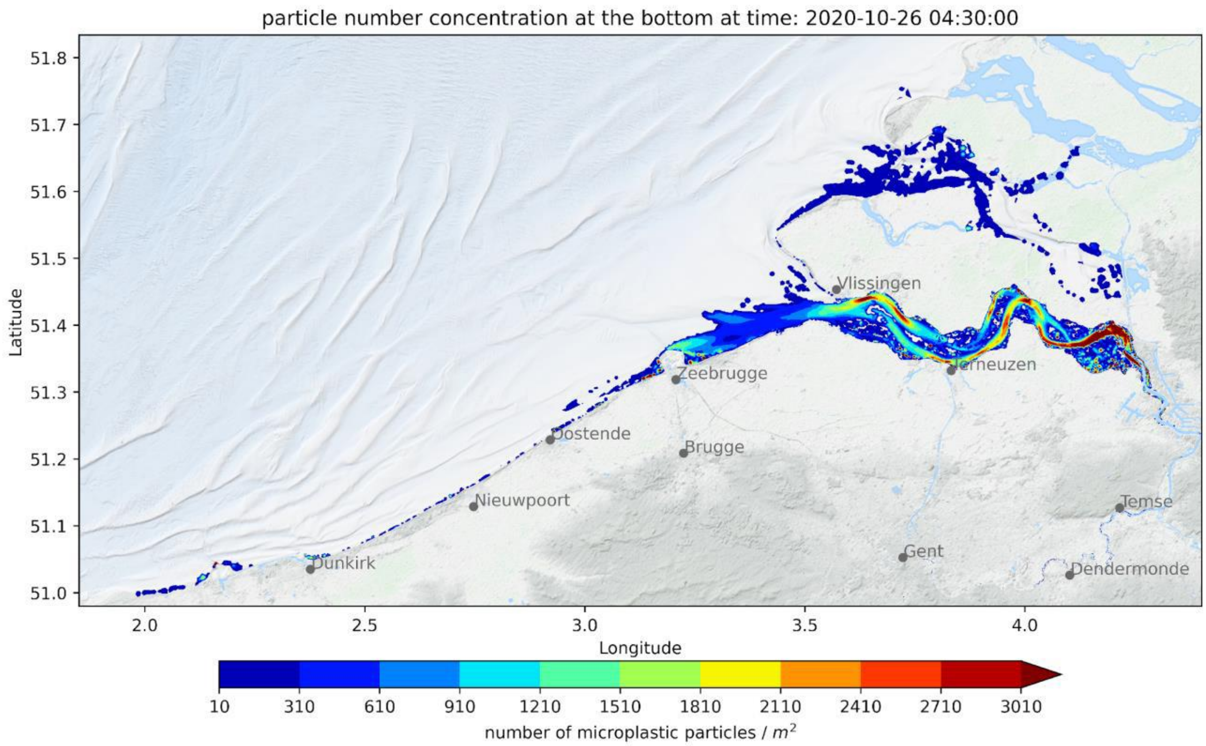


Figure 9: Spatial distribution of the microplastics in number concentration in the suspension (a) at low flow condition (b) at high flow condition



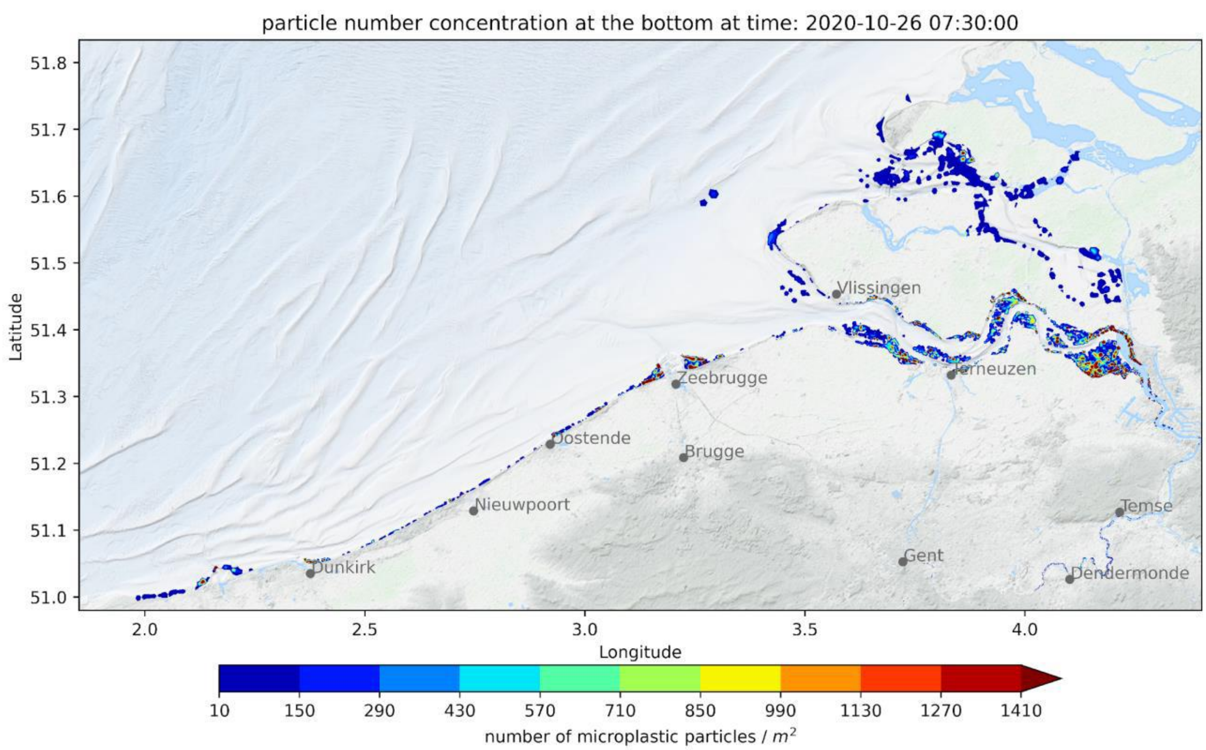


Figure 10: Spatial distribution of the microplastics in number concentration in the deposition (a) at low flow condition (b) at high flow condition

- **Conclusion 4: Remaining uncertainty**

The initial condition effect on the flux values diminishes over time and the effects of the model parameters start to dominate the outcomes. A large number of model outcomes are in concurrence with each other at the end of the three-month simulation, except for 4 or 5 results which differ significantly from the rest. This indicates that the chosen parameter uncertainties (within the range of standard deviation) do not alter the overall plastic transport dynamics in the case study. However, the cumulative microplastic flux values are sensitive to the parameter values. The cumulative flux values can be twofold higher or lower than the mean value (Figure 11) .

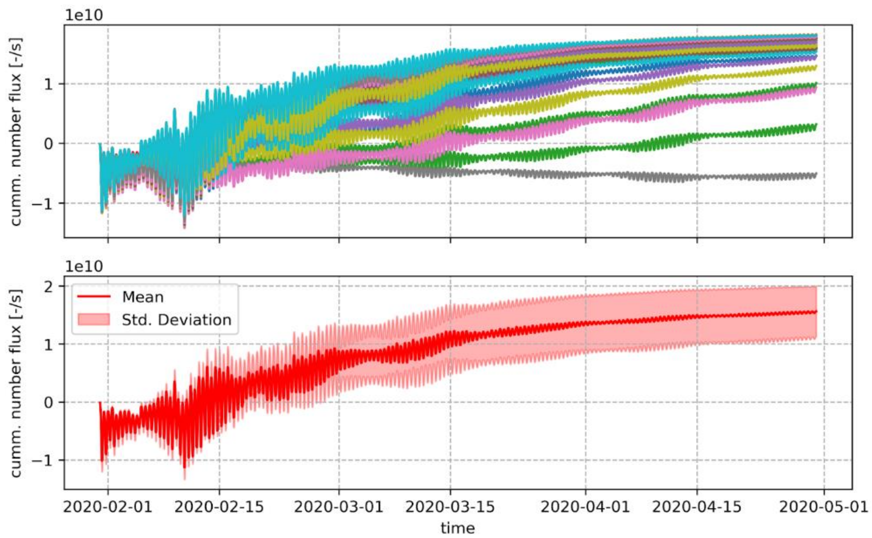


Figure 11 Model outcomes with uncertain parameter sets (N=40). Cumulative number flux values from individual model outcomes (top plot) and mean ± standard deviation of the 40 model outcomes (bottom plot), over the 3 months of the model simulation period

Remaining challenges and recommendations

Data requirements. In order to fully calibrate and validate the models, a lot of data are needed. PLUXIN is one of the most data rich plastic transport models being performed until now, but still important assumptions needed to be made. For example, the comparison of model and measurement values at Wintam, reveals a few aspects of the measurement data requirements. The temporal resolution of the measurement is not sufficient to fully reveal the tidal dynamics. As well, the measurement needs to be carried out for a longer duration at the same location, in order to fully confirm the tidal dynamics of plastic concentration. It was clearly shown that the dynamics of plastic movement in the Scheldt is not consistent all along the river. Not only more locations would need observations to confirm the patterns found, also a long-term analysis is required to establish that these trends are not only short-term but are long-lasting.

The uncertainty analysis is performed for the combined effects of five model parameters. Therefore, it is not straightforward to understand the effects of individual model parameters on the model outcome. The sensitivity of the model to the individual parameters can be analysed using a variety of methods including variance-based method, derivative-based local methods, etc. Also, large sample sets of the chosen parameters could further strengthen the confidence in the estimated uncertainties.

The PBE method with a settling velocity (instead of size) distribution will be explored to account for the complete plastic diversity including size, shape and density. It is assumed that such a distribution can be approximated with a Gaussian distribution. This would pose a challenge, considering the scalar moment quantities of the Gaussian distribution which can be negative.

3. Multiplying impact and unravelling knowledge valorisation for marine litter solutions

The issue of marine and riverine litter in Belgium has propelled responsible government bodies to the forefront of recent discussions, being high on their agenda in recent years. However, research gaps are impeding progress in developing effective solutions for Flanders' water systems. To empower policymakers and water managers in crafting strategies to reduce litter and implement preventive measures, a deeper understanding is essential. This involves comprehensive knowledge regarding primary emission sources, the quantities of (plastic) litter in water bodies and transport pathways to the sea.

In 2018, the Department EWI of the Government of Flanders (Gert Verreet) took the initiative to unite the litter and microplastic experts in Flanders, which planted the seed for the PLUXIN project (and the start of the PLUXIN impact timeline). The PLUXIN project was approved in 2020, aiming to meticulously map and quantify plastic transport from land to the North Sea. This research consortium (VLIZ, VITO, Ghent University, University of Antwerp, and KU Leuven) operates alongside a community of practice (CoP), an innovative incubator that unites science, industry (Blue Cluster members as Steering Committee), policy and society (as advisory board) with a shared ambition to collaboratively develop solutions. In this PLUXIN context, stakeholder connectivity is the driver for innovation. Based on the new scientific insights of PLUXIN, the ambition was to collaborate with the CoP and:

- To stimulate new interdisciplinary innovation projects and new business opportunities;
- To serve as a platform for future cooperation and innovation related to the plastic value chain in Flanders; and
- To stimulate knowledge transfer and international collaboration.

Recent revelations from PLUXIN indicate that lowland tidal river systems, such as the Scheldt estuary, can behave as 'plastic reservoirs.' This groundbreaking insight has catalyzed impactful national and international initiatives, as showcased by the PLUXIN impact timeline, and can be seen as a timeline of successes (considering the unsuccessful initiatives or those still in the pipeline were not included). This timeline shows different types of valorisation activities (e.g. new R&I projects, participation in event, new collaborations), thematically grouped according to the three umbrella themes determined via a CoP co-creation approach as priority innovation themes:

- Theme I. Plastic from source to seas; focusing on the behaviour and presence of plastic in aquatic systems.
- Theme II. Plastic solutions and litter management; focusing on designing advanced plastic collection and removal systems.

- ❖ Theme III. Innovative detection methods for marine and riverine litter; from the seabed to space.

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Stakeholder meeting with PLUXIN partners, steering group and strategic advisory board
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Strategic Advisory Board (SAB)

OVAM
Catalisti Cluster
VMM
POM West-Vlaanderen
Provincie West-Vlaanderen
Department of Economy, Science and Innovation (EWI)
Federal Public Service (FPS)
Centexbel-VKC (CTB)
JPI Oceans
Vlaamse Waterweg
Departement MDK

Civil Society Organisations

Zero Plastic Rivers vzw
Proper Strand Lopers vzw
DOKano vzw

Steering Committee

Xenics
Laboratorium Ecca
Colruyt
Port of Oostende
IMDC
North Sea Port Flanders
ANTEA Group
Multi NV
AQUAFIN
Enviros survey
DEME Environmental Contractors (DEC)
dotOcean NV
Port of Antwerp
Renasci (during first phase)

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PLUXIN valorisation and collaboration highligths

In the run-up to the PLUXIN project, a succesful airplane-based remote sensing experiment was conducted by VITO with support from VLIZ, in cooperation with the Province of West Flanders and the managers and operators of the Spuikom (Ostend). In April 2020, the PLUXIN project was approved, to be subsequently launched in September 2020. Immediately after approval, a new collaboration was established between OVAM (FostPlus) and the PLUXIN consortium with the aim of strengthening each other in mapping plastic flux to the sea. This data is available as a data publication and was also submitted to EMODnet Chemistry.

An initial umbrella theme of PLUXIN focused on mapping existing systems to collect and remove plastic from the environment, resulting in a workshop, a policy informing brief, scientific publications and a case study in the North Sea Ports area. The PLUXIN valorisation activities resulted in a collaboration (TREASURE) in which a plastic catcher of Belgian convenience will be deployed in Nieuwpoort. A second umbrella theme focused on underwater plastic detection technologies, and a review paper was published in collaboration with ICES. A follow-up project for this is currently in the pipeline via an intercluster track Blue Cluster - Flanders Space. For the business model of plastic litter, a Blue Session was organised by the Blue Cluster and a possible collaboration with the Catalisti cluster is being explored at this moment.

The new insights from the PLUXIN project supported the activities of the Federal Marine Litter Action Plan (FPS), the Flemish Integrated Marine Litter Action Plan (OVAM), the Flemish Plastics Implementation Plan (OVAM) and were mentioned in documents of the Government of Flanders (e.g. committee meeting, exchange of views, public hearing). These insights were also included in the annual update of the policy informing brief on litter and microplastics in Belgium (Devriese and Janssen, 2023).

Follow-up R&I projects

In the time frame of the PLUXIN project, collaborations were established with European research projects (or grants) such as:

- ❖ Brilliant Marine Research Idea Grant (BMRI): UAntwerp obtained a 2019 BMRI on tracking marked plastic items on their journey through the Scheldt estuary, using the Permanent Belgian Acoustic Receiver Network (PBARN) (Teunkens, 2021).
- ❖ t0-measurement (OVAM): Immediately after the PLUXIN project was approved, a collaboration was established in the framework of Objective 9 from the Flemish integral action plan on marine litter (VLIZ, UAntwerpen, KULeuven, UGent) to strengthen each other (Everaert et al. 2022).
- ❖ Labplas: Shortly after the launch of the PLUXIN project, KULeuven capitalised on a first European collaboration through the H2020 Labplas project on understanding the sources, transport, distribution and impacts of plastic pollution.
- ❖ DeMARC: Through steering committee members IMDC and Multi.engineering, a collaboration was established with the DeMARC project (JPI Oceans), which formed the backbone for the follow-up project TREASURE.
- ❖ SOS-Zeropol2030: the HE Source to Seas Zero Pollution 2030 (SOS-Zeropol2030) project with VLIZ as a Belgian partner aims at developing a holistic framework towards ending pollution in

European Seas by 2030, and supported the policy framework for litter and microplastics during PLUXIN.

- Plastic Pirates Belgium: An initial collaboration with the Plastic Pirates - Go Europe! initiative was established in 2022, and eventually the Belgian wing of this initiative was launched in early 2024 (coordinated by VLIZ).

Based on insights, scientific knowledge or technological innovations from the PLUXIN project, several follow-up R&I projects (or grants) were launched:

- MARLISE: the Marine Litter Mission Conceptual Design Study (ESA PRODEX) of VITO to test the feasibility of using satellite data for marine litter observations.
- DIOS: Drone based Infrared Imaging for Oil Spill detection (DIOS) is a Blue Cluster follow-up project testing 'plastic detection imaging' for oil spill detections by partners VITO, UAntwerpen and steering group members Xenics, dotOcean and Port of Antwerpen.
- FWO Grant: the FWO grant of Giulia Leone focusses on a decision support framework for plastic clean-up technologies in rivers and estuaries.
- SWIPE: the SWIR and drones for early detection of oil spills in ports (SWIPE) project is a Belspo Stereo 4 project of VITO, UAntwerpen and Port of Antwerp.
- Waste Watchers: the Waste Watchers project (amai! Projecten) started in January 2023 and launched a public campaign to encourage citizens to participate and collect litter data (by VITO).
- INSPIRE: the HE Innovative Solutions for Plastic Free Europen Rivers (INSPIRE) project is coordinated by VLIZ supported by VITO and River Clean-up as partner, and builds on the PLUXIN insights with the Scheldt as BE focus area.
- TREASURE: the Interreg North Sea Targeting the reduction of plastic outlflow into the North Sea (TREASURE) validates the PLUXIN insights for the North Sea area, in which VLIZ is collaborating with IMDC and Multi.engineering to design solutions.

Collaboration with expert groups and networking

Collaborative efforts have sparked new interactions with entities such as the International Council for the Exploration of the Sea (ICES WGML), the North Sea Commission (CPMR NSC), International Scheldt Commission, various business clusters (blue cluster, Flanders space, catalisti), and diverse user groups and initiatives (e.g. Plastic Pirates), amplifying our collective impact on a broader international scale. Attendees will grasp the pivotal role small-scale collaborations play in fostering international innovation and propelling positive change. At national level too, the results flowed through various expert groups (e.g. PIO on removal of litter in yacht harbours, informal stakeholder dialogue and initiatives from OVAM and FPS Marine Environment).

Example for Theme I. Blue Session organized by the Blue Cluster (2022)

Example for Theme II. Online workshop on plastic catchers

Example for Theme III: collaboration with the ICES working group on marine litter (ICES WGML)

The new insights and scientific knowledge from the PLUXIN project were presented and discussed at numerous national and international events and conferences, e.g. Sediment Management in Ports (KULeuven), MICRO2020 conference (VLIZ), GEO AquaWatch lightning talk (VITO), Better off Blue event

(VLIZ), SETAC Europe (VLIZ), NON-STOP2 (VLIZ), VLEVA Green Week event (VLIZ), Optical sensors and sensing congress (VITO), Ocean Decade Laboratory (VITO), Embassy of the Kingdom of the Netherlands (VLIZ), VLIZ Marine Science Day (VLIZ, VITO, KULeuven), ESA Living Planet Symposium (VITO), Blue Session Day (VLIZ), International Marine Debris Conference (VITO), Telemac User Conference (KULeuven), Rijkswaterstaat en Deltares (VLIZ), MICRO2022 (KULeuven, VLIZ), Microplastics 2022 (VLIZ), Dag van de Wetenschap (VLIZ), NRC seminar (VITO), IAHR World Congress (KULeuven), RMSL Workshop (VITO), Erasmus Maris Days (UGent, VLIZ), IOCS (VITO). This is a non-exhaustive list of events were PLUXIN has been presented.

Movie

A short movie was prepared to highlight the main results of the project.

Bekijk een fimplje over de resultaten van het PLUXIN-project

https://www.blauwecluster.be/projecten/pluxin-plastic-flux-for-innovation-and-business-opportunities-in-flanders

4. Conclusion

Plastics are increasingly found in marine ecosystems, posing a long-lasting global problem. Removing plastic before it reaches the ocean is crucial, and detecting and cleaning it up are becoming urgent. PLUXIN tackled this challenge by creating a model that combined field data, experiments, and satellite imagery to track plastic movement. PLUXIN found that plastic is widespread, accumulates in certain areas, and even remains stored in the Scheldt estuary. PLUXIN's findings led to national and international efforts to address plastic pollution, and also stimulated innovation in Flemish companies. Through collaborations and outreach efforts, PLUXIN's impact extended internationally.

5. References

Andrady A.L. (2011). Microplastics in the marine environment. Mar Pollut Bull. 62, 1596-605. doi: 10.1016/j.marpolbul.2011.05.030

Castagna, A.; Dierssen, H.; Devriese, L.; Everaert, G.; Knaeps, E.; Sterckx, S. (2023). Evaluation of historic and new detection algorithms for different types of plastics over land and water from hyperspectral data and imagery. Remote Sens. Environ. 298: 113834. https://dx.doi.org/10.1016/j.rse.2023.113834

Everaert, G.; Asselman, J.; Bouwens, J.; Catarino, A.I.; Janssen, C.R.; Shettigar, N.A.; Teunkens, B.; Toorman, E.; Van Damme, S.; Vercauteren, M.; Devriese, L. (2022). Plastic baseline (t0) measurement in the scope Flemish Integral Action Plan on Marine Litter (OVAM). Plastic t0 study 2020-2021. Flanders Marine Institute: Ostend. 112 pp. https://dx.doi.org/10.48470/26

Leone, G.; Catarino, A.I.; De Keukelaere, L.; Bossaer, M.; Knaeps, E.; Everaert, G. (2023). Hyperspectral reflectance dataset of pristine, weathered, and biofouled plastics. ESSD 15: 745-752. https://dx.doi.org/10.5194/essd-15-745-2023

Vercauteren, M.; Lambert, S.; Hoogerwerf, E.; Janssen, C.; Asselman, J. (2024). Microplastic-specific biofilm growth determines the vertical transport of plastics in freshwater. Sci. Total Environ. 910: 168399. https://dx.doi.org/10.1016/j.scitotenv.2023.168399

Nguyen, T.T.; Kieu-Le, T.C; Tang, F.H.M.; Maggi, F. (2022). Controlling factors of microplastic fibre settling through a water column. Sci. Total Environ. *838* , 156011. https://doi.org/10.1016/j.scitotenv.2022.156011