DEVELOPING A TRANSPORT MODEL FOR PLASTIC DISTRIBUTION IN THE NORTH SEA

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ABSTRACT

As a result of the rising plastic usage worldwide, the abundance of plastic litter in the sea and ocean has steadily increased over the last few decades. However, there is considerable uncertainty regarding the occurrence and effects of plastic litter on the marine environment. This uncertainty is visible both at the level of physical impacts but also with respect to the adaptation measures to reduce the negative environmental consequences. Aiming for a better representation of this uncertainty, the EU Marine Strategy Framework Directive was published in 2008 and requires EU member states to achieve 'good environmental status' (GES) in Europe's seas by 2020.

The present study aims to improve the knowledge regarding the distribution and possible accumulation of plastic litter in the North Sea. The litter transport in the North Sea is modeled by further development of the Delft3d software. By combining hydrodynamics with particle tracking concepts, the model calculates how the position of plastic particles evolves in time from their release (discharge from rivers such as the Rhine or the Meuse) until the end of the simulation. The settling velocity of the particles in the water system is dependent on the ambient conditions (temperature/salinity) as well as on the particle characteristics (density/size).

The results for micro-sized plastics are presented, while ongoing work is extending the concept for the larger macro-sized plastic litter items. Different types (polyethylene, polystyrene, PET, PVC) and sizes (10 μm, 330 μm and 5 mm) of plastics were simulated. The results demonstrate that density is the main determining factor for plastic settlement and that size also has an effect on the final location of accumulation. Modeling results are then compared with field measurements in sediments as a validation step. This research demonstrates that modeling can provide a regional or global overview and aid in identifying monitoring questions.

Keywords: pollution, plastic litter, modeling, probabilistic, North Sea

1. INTRODUCTION

The abundance of litter in the marine environment has steadily increased over the last few decades and recent studies have showed relatively high concentrations of microplastic particles (MPs) (particles up to 5 mm) in coastal sediments (Browne et al., 2011). By various means (e.g. transport accidents, inappropriate disposal of packing materials as well as microplastic beads used in cosmetics), different types of plastics enter the water column, with serious ecological implications for marine organisms, such as fatal entanglement in macro plastics or the ingestion of microplastics by fish and birds (Leslie et al., 2011).
However, the integral impact of plastics on wildlife and water quality is not well established. Existing studies, such as (Tanaka, 2013) state that plastic litter has the potential to cause adverse effects in wildlife and possibly humans (e.g. malformations, behavioural effects, cell damage, negative effects on growth and energy assimilation, see Leslie et al., 2011). Also, the water quality deterioration could have direct implications for the biological productivity and abundance of species. With these concerns in mind, many questions arise: Which areas probably have the highest concentrations of plastic litter (hotspots)? What are the transport routes of plastic litter in the North Sea and in which areas do they end up? How are different types and sizes of plastic behaving? The fate of the plastics in the marine environment is also uncertain: they might accumulate or degrade due to fragmentation and microbiological decay. To address these issues, an integrated approach is essential; this study highlights the role of transport and fate models to provide the means to include different processes and investigate their relative contribution.

Answers to the questions above can aid the implementation of the EU Marine Strategy Framework Directive (MSFD), which requires EU member states to achieve 'good environmental status' (GES) in Europe's seas by 2020. Within this directive, the 10th GES descriptor explicitly addresses marine litter, focusing on the need to identify trends in the amount of litter in the marine environment and on coastlines, including analysis of its composition and spatial distribution.

2. PLASTIC MODELING

Modeling is a promising approach to improve the existing knowledge regarding the litter dynamics in marine environments and obtain new insights in areas where information is lacking (Thompson et al., 2009). For example, the data regarding the abundance of plastic litter on the seabed is very limited. Also, it is assumed that substantial quantities of plastic litter has accumulated in the natural environment due to the continued input of marine litter over the last decades; however, the location of possible accumulation areas is not well delimited.
Figure 1 illustrates a schematic representation of the modeling framework for plastic transport in a marine environment. The chart incorporates a primary understanding of the processes that affect plastics: transport due to flows, settling due to the differences in density, fragmentation, microbial decay. However, little available information is available regarding the magnitudes and rates of these processes. Still, progress can be made in our understanding of the plastic behavior by making first assumptions and explore on the timescales.

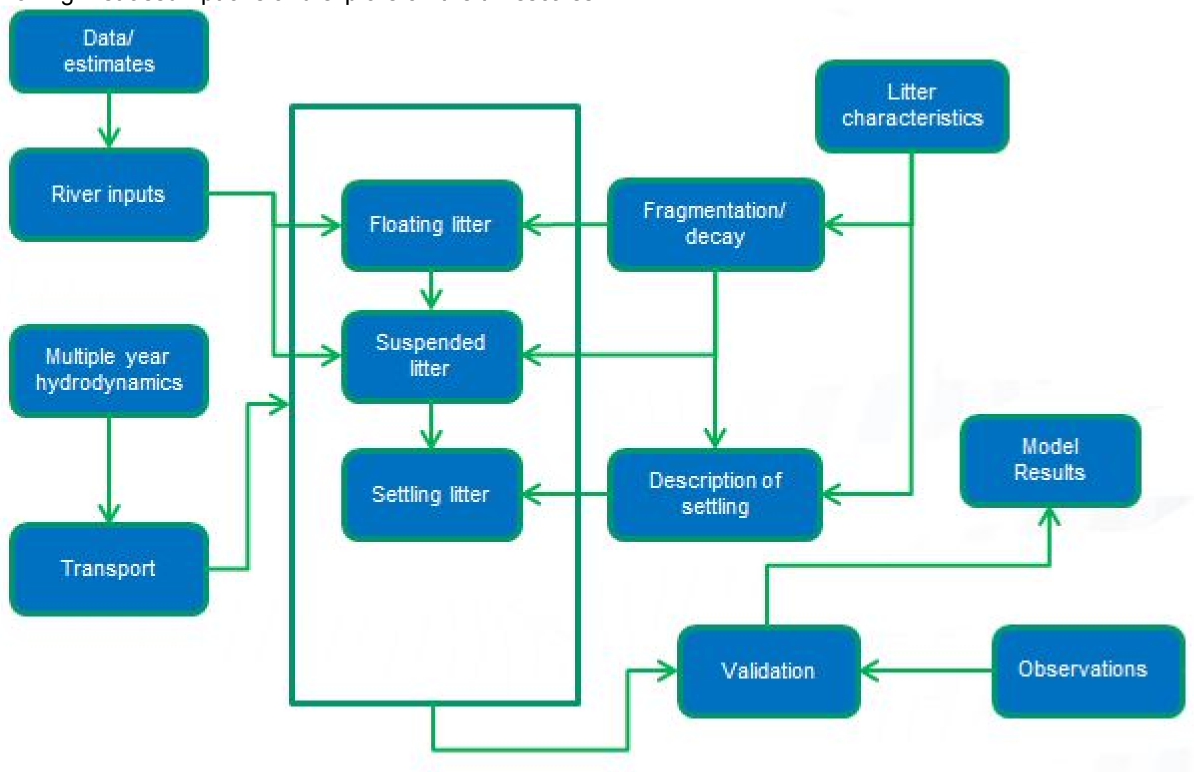

Figure 1. Modeling framework

2.1Delft3D-PART

In this study, the spatial and temporal transport patterns of microplastics are modeled using the Delft3D-PART stochastic module. This module is incorporated in an integrated modeling system (Delft3D) able to simulate water flow, sediment transport, waves, water quality, morphological developments and ecology. The PART module of Delft3D simulates transport and simple water quality processes by means of a particle tracking method. The tracks are followed in three dimensions over time, whereby a dynamic concentration distribution is obtained by calculating the mass of particles in the model grid cells. The processes are assumed to be deterministic except for a random displacement of the particle at each time step. The particle tracking method is based on a random-walk method since the simulated behavior is stochastic.

The Delft3D model calculates the evolution in time of the position of the particles, allowing for the particle tracks to be described in a detailed spatial and temporal pattern. The position of every individual particle can be influenced by advection (transport by water flow), diffusion/dispersion (random component) and settling. Every particle in the model is a representation of the litter particles in the reality. With this concept, the mass of a particle represents the amount of a substance attached to it. Also, the mass of a particle can be influenced by decay rate (first order decay), evaporation (of oil) or fouling. The settling velocity of each particle at a given time was calculated with the Stokes' law (Lamb, 1994):

$$V_s = \frac{2}{9}\frac{(\rho_{particle} - \rho_{fluid})}{\mu} g R^2 \qquad [1]$$

where V_s – settling velocity [m/s]

$\rho_{particle}$ – density of the particles [kg/m^3]

ρ_{fluid} – density of the sea water [kg/m^3]

μ – dynamic viscosity [kg/(s*m)]

g – Gravitational acceleration[m/s^2]

R – radius of particle[m]

Also, the density of the sea water is dependent on the ambient conditions (temperature/salinity).

2.2 The North Sea

The study area is the North Sea, which is characterized by relatively shallow water, with a bottom depth that gradually increases from less than 30m in the south to approximately 200m in the north. The North Sea is bordered by highly industrialized and densely populated countries conducting intense industrial activities, which makes it a heavily impacted ecosystem. Currently, there is limited information regarding the presence of litter in the North Sea.
The simulation domain is described by the computational grid as in the figure below. The hydrodynamics are employed from the existing long term Delft3D simulations of the North Sea (currently available for ten individual years 2003 - 2012). Computed by the Delft3D FLOW model, they are governed by tides, wind and density effects (Cronin, 2013). The plastic particles are continuously released into the system via the river discharges, as illustrated in Figure 2. We note that the plastic contribution per river is dependent on the corresponding discharge; subsequently, an assumption was made that the highest inputs originate from the river Rhine (30%), followed by the Elbe (15%) and Seine (10%). More indicatory data on the amount of particles discharged by the rivers or entering the North Sea from the Atlantic Ocean is necessary to refine these hypotheses.

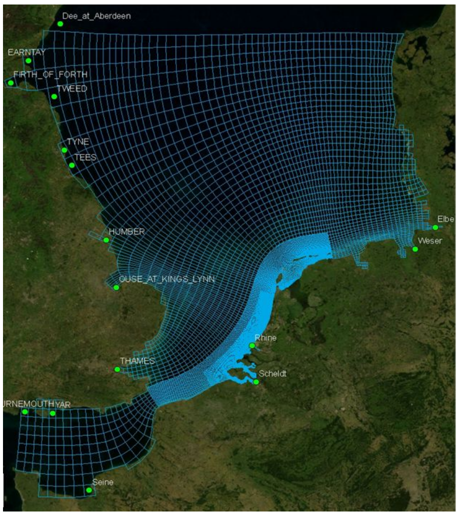

Figure 2. The North Sea

In total, 5 million particles were introduced into the model during a period of 365 days. This number has been chosen as a trade-off between numerical constraints and a pragmatic representation of the real number of plastic particles in the North Sea.

2.3 Litter characteristics

Particles of different plastic type - Polyethylene (PE), Polystyrene (PS), Polyvinylchloride (PVC) and Polyethylene terephthalate (PET) - with increasing densities and sizes (10 μm, 330 μm and 5 mm diameter) have been modeled, as shown in Table 1 and Table 2. Of course, in reality, the variety of plastics in nature is much higher, especially since many plastics are manufactured as a combination of different types of plastics. The selection of these four types is based on the study of (Andrady et al., 2009) reporting that 80% of the world's total plastic production consists of these four elements.

Table 1. Plastic types

PLASTIC TYPE	DENSITY
Polyethylene (PE)	910 kg/m^3
Polystyrene (PS)	1050 kg/m^3
Polyvinylchloride (PVC)	1275 kg/m^3
Polyethylene terephthalate (PET)	1400 kg/m3

An important gain of this study is that it allows the evaluation of differences and similarities between the trajectories of different types of plastic, with different sizes. By studying the changes in the transport trajectories and accumulation areas, a better understanding of the possible transport processes within the study area can be obtained. This flexibility for multiple scenario analysis allows not only for coastal or global trends to be compared and highlighted, but also for new hypotheses to be explored.

3. RESULTS

Figure 3 illustrates the mean concentration of particles at the last day of a simulation run of year 2008. This concentration is calculated in the first layer of the water column, which is the closest to the water surface. The density of the PE particles is smaller than the density of sea water (approximately 1024 kg/m3), which means that these particles will generally stay at the water surface. Results show that the PE particles stay at the surface layer and accumulate according to the hydrodynamic transport processes, following the water flow to the North-Eastern part of the North Sea.

On the other hand, PS and PET particles have densities that are higher than the density of sea water and settle quite fast towards the bottom. Also, we can see that relatively little transport occurs for the PET particles and they do settle almost immediately after release with the river discharges to the bottom layer.

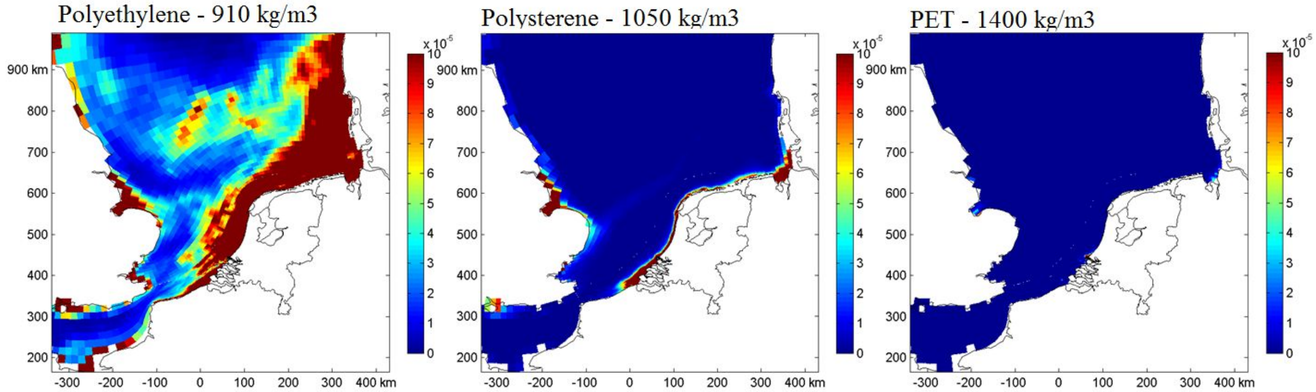

Figure 3. Mean concentration of particles in the water surface, calculated in last day of a simulation run of year 2008.
Model simulations comparison of different plastic types (polyethylene, polystyrene, PET), spherical shape, diameter ~ 330 µm

Table 2 gives an intuitive overview of the calculated settling velocities of the four particle types, considering constant seawater density equal to 1024kg/m3, spherical shape with a diameter equal to 330 µm. For negative values of the settling velocity, the particles will move upwards towards the water surface. We can see that, in shallow waters, the particles settle or move rapidly towards the surface, unless other processes affect the density of the particles in time (such as fragmentation or microbial decay, which will be added to the model in the future). We note that these values are representative for spherical particles, for other particle shapes, such as fibers, the formulation of the settling velocity can be easily adapted.

Table 2. Settling velocity

PLASTIC TYPE	SETTLING VELOCITY
Polyethylene (PE)	-38.85 m/day
Polystyrene (PS)	8.86 m/day
Polyvinylchloride (PVC)	85.54 m/day
Polyethylene terephthalate (PET)	128.15m/day

Figure 4 shows the influence of size of the particles on the plastic particle transport, by comparing the particle tracks of spherical particles with diameters sampled from normal distributions of mean 10 µm, 330 µm and 5 mm and standard deviation equal to 25% of the mean. The simulation results show that microplastics with a medium diameter mean value (330 µm) spreads out more than plastics with a smaller mean value (10 µm). Also, the transport for the 330 µm and 5 mm particles is quite similar.

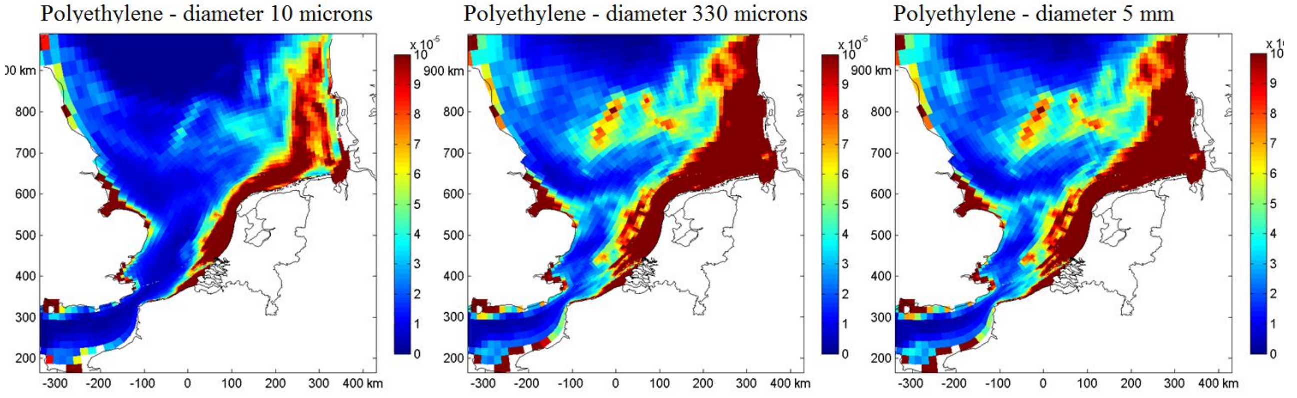

Figure 4. Mean concentration of particles in the water surface, calculated in last day of a simulation run of year 2008
Model simulations comparison for different polyethylene sizes, spherical shape, diameter ~10 µm, 330 µm and 5 mm

The model suceeds in describing the expected physical behavior of microplastic litter and can provide large scale information on transport trends. Current efforts are directed towards expanding the model to larger macro-sized plastic litter, include other processes and defining suitable scenarios to identify accumulation areas in the North Sea.

4. CONCLUSIONS

It is expected that the quantity of plastics in the marine environment will increase in the future due to the continuous input into the marine environment and the almost non-existent removal rate. However, this prediction has not been yet simulated at a large scale. The Delft3D-Part model gives the possibility to compare possible future scenarios regarding the presence of plastics in the marine environment and provide input to monitoring programs to identify areas of interest.

In the North Sea, model simulations show that the lighter microplastic particles (i.e. polyethylene) tend to stay on the sea surface and follow the hydrodynamics towards the North-Eastern part of the North Sea while the heavier microplastics (PS, PVC, PET) tend to sink towards the sea-floor and accumulate. The accumulation areas are mainly in the coastal zone, and vary depending on the size and type of plastics. There are many uncertainties associated with the modeling of microplastics due to a lack of data for validation and the complex processes (aging, degradation, fragmentation, etc.) that have not yet been incorporated in the model. Nevertheless, models are a first step to integrate all the different processes affecting particles in the marine environment. The current model will provide an overview of the plastic distribution and can link the sources (rivers, ships, beaches) to the data found in the field. However, further work is required, in particular on the processes that affect the fate of the plastics, such as the settling, fragmentation and degradation.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the CleanSea project, funded by the European Union Seventh Framework Programme ([FP7/2007-2013] [FP7/2007-2011]) under grant agreement n° 308370. We would like to offer special thanks to all of the parties involved in the CleanSea project, in particular, to Heather Leslie, the coordinator, for her help in bringing all the involved parties together.

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