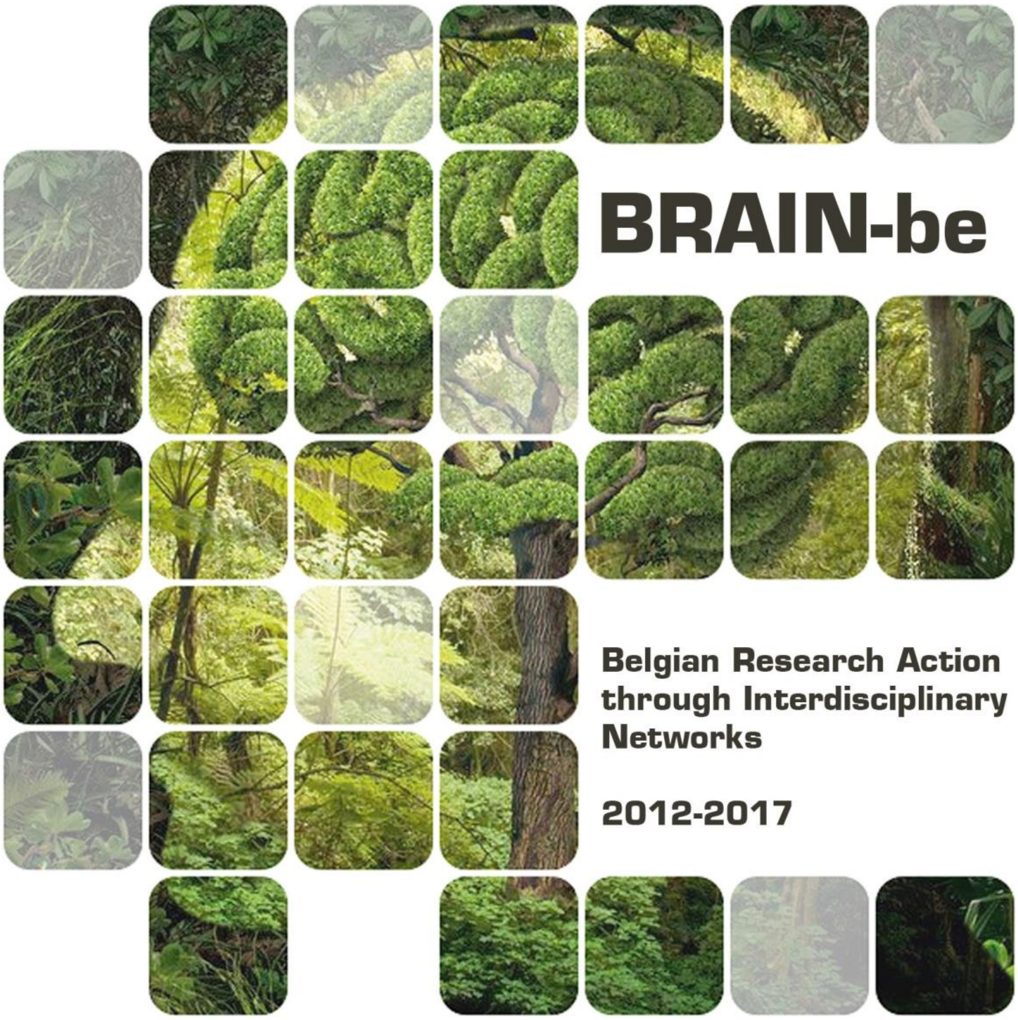

WEATHER-MIC

How microplastic weathering changes its transport, fate and toxicity in the marine environment

Erik TOORMAN, Qilong BI, Samor WONGSOREDO, Xiaoteng SHEN (KU LEUVEN)

JPI Oceans Microplastics Research Project

Axis 1: Ecosystems, biodiversity and evolution

BRAIN-be

Belgian Research Action through Interdisciplinary Networks

2012-2017

NETWORK PROJECT

WEATHER-MIC

How microplastic weathering changes its transport, fate and toxicity in the marine environment

The Belgian contribution

Contract - BR/154/A1/WEATHER-MIC

FINAL REPORT

PROMOTORS: ERIK TOORMAN (KU Leuven)

AUTHORS: ERIK TOORMAN (KU Leuven)
SAMOR WONGSOREDJO (KU Leuven)
QILONG BI (KU Leuven)
XIAOTENG SHEN (KU Leuven)

Published in 2019 by the Belgian Science Policy Office
WTCIII
Simon Bolivarlaan 30 Boulevard Simon Bolivar
B-1000 Brussels
Belgium
Tel: +32 (0)2 238 34 11 - Fax: +32 (0)2 230 59 12
http://www.belspo.be
http://www.belspo.be/brain-be

Contact person: David Cox
Tel: +32 (0)2 238 34 03

Toorman E., Bi Q., Wongsoredo S., Shen X. *WEATHER-MIC: How microplastic weathering changes its transport, fate and toxicity in the marine environment. The Belgian contribution.* Final Report. Brussels: Belgian Science Policy Office 2019 – 32 p. (BRAIN-be - Belgian Research Action through Interdisciplinary Networks)

TABLE OF CONTENTS

ABSTRACT

Context: The problem of plastic litter in the aquatic environment has recently become a trendy research topic as the result of serious concerns on the potential environmental risks. The focus of the JPI Oceans' first call is on microplastics in oceans, which are feared to end up in the food chain and may intoxicate species. This risk assessment requires the prediction of where MP particles will end up during their voyage in the seas. 3-dimensional (3D) numerical modelling is the most adequate tool for this purpose.

Objectives: The aim of the KU Leuven participation to the WEATHER-MIC project was to apply their expertise in sediment transport modelling to microplastics dispersal modelling to selected locations in the Baltic Sea area.

Conclusions: The analysis of particle settling data confirm that MP plastic particles behave as expected according to the semi-empirical drag laws known from fluid mechanics. 3D hydrodynamic models have been set up for the study areas (Oslo Fjord, Norway, and Himmerfjärden Bay, Sweden) with boundary conditions generated from a 2D depth-averaged Kattegat-Baltic Sea model. The set-up of an Eulerian particle transport model for MP particles was mainly hindered by a lack of field data on the initial distribution and composition of plastics in the study areas, as well as on the time scales of degradation and fragmentation processes. Since MP research started to boom about 5 years ago, little progress has been made to efficiently sample and characterize MP particles in the aquatic environment. This is even worse in the water column below the surface, where plastic concentrations are often surprisingly low, and on the seabed where the majority of plastics is found. Due to the presently used techniques, large-scale sampling cannot capture particles smaller than of the order of 100µm. Moreover, the change of MP properties due to weathering proved to remain too slow, even under artificially enhanced weathering, in order to deduce time-scales for process model development. Therefore, it will remain very difficult to correctly and accurately quantify plastic dispersal in the oceans until the above bottlenecks have found a solution.

Keywords: microplastics, particle settling velocity, particle dispersal modelling, flocculation, turbulence modelling

SAMENVATTING

Context: Het probleem van plasticvervuiling in het aquatische milieu is recentelijk een trendy onderzoeksobject geworden ten gevolge van de ernstige bezorgdheid over potentiele risico's voor het leefmilieu. De focus van de eerste JPI Oceans' oproep betreft microplastics (MP) in oceanen, waarvan men vreest dat zij belanden in de voedselketen en soorten zou kunnen vergiftigen. Deze risico-inschatting vereist de voorspelling van waar MP partikels terechtkomen gedurende hun reis op zee. 3-dimensionale (3D) numerieke modellering is het meest adequate werktuig voor dit doel.

Doelstellingen: Het doel van de KU Leuven deelname aan het WEATHER-MIC project was het toepassen van hun expertise in sedimenttransportmodellering op het modelleren van de verspreiding van microplastics voor geselecteerde locaties in de regio van de Baltische Zee.

Conclusies: De analyse van data van bezinkingssnelheden van MP partikels bevestigt deze partikels zich, zoals verwacht, gedragen volgens de gekende semi-empirische sleepweerstandswetten uit de vloeistofmechanica. 3D hydrodynamische modellen warden opgebouwd voor de studiegebieden (Oslofjord, Noorwegen, en Himmerfjärdenbaai, Zweden), met randvoorwaarden gegenereerd met een 2D dieptegemiddeld Kattegat-Baltische Zee-model. De opbouw van een Euleriaans partikeltransportmodel voor MP partikels werd voornamelijk belemmerd door een gebrek aan veldwaarnemingen die moesten toelaten om realistische beginvoorwaarden van samenstelling en verspreiding van plastic op de oevers, in de waterkolom en op de bodem te kunnen bepalen, evenals tijdschalen voor degradatie en fragmentatie.
Sinds het MP-onderzoek begon te boomen zo'n 5 jaar geleden is er nog maar weinig vooruitgang geboekt op het vlak van efficiënte monstername en –analyse om MP in het aquatische milieu te karakteriseren. Dit is nog erger voor de waterkolom onder het oppervlak, waar de concentraties aan MP verrassend laag blijken te zijn, en voor de zeebodem waar uiteindelijk de grootste meerderheid aan plastic wordt teruggevonden. De huidig gebruikte monsternametechnieken laten bovendien niet toe om de deeltjes kleiner dan ca. 100µm grootschalig te bemonsteren. Bovendien bleek de verandering van karakteristieken van MP deeltjes door verwering veel te traag te verlopen, zelfs onder artificieel verhoogde verwering, om daaruit tijdschalen voor degradatieprocessen te kunnen afleiden. Daarom blijft het voorlopig zeer moeilijk om op correcte en nauwkeurige wijze de verspreiding van plastic in de oceanen kwantitatief te begroten, zolang er geen oplossingen gevonden worden voor de genoemde problemen.

Kernwoorden: microplastics, deeltjesvalsnelheid, partikeldispersiemodellering, flocculatie, turbulentiemodellering

SOMMAIRE

Contexte: Le problème des déchets plastiques dans le milieu aquatique est un sujet de recherche récent à cause de l'inquiétude sincère sur les risques potentielles pour le milieu. Le focus de la première appelle pour des projets par JPI Oceans concerne les micro-plastiques dans les océans, desquelles on a peur qu'elles arriveraient dans la chaine de consommation et empoisonneraient des espèces. Cette estimation des risques demande la prédiction des locations d'accumulation des particules pendent leur voyage dans l'océan. Un modèle numérique en 3D est le moyen le plus adéquate pour ce but.

Objectives: Le but de la participation de la KU Leuven au projet WEATHER-MIC était d'appliquer leur expertise en modélisation du transport des particules sédimentaires sur la dispersion des particules micro-plastiques pour deux locations sélectionnées dans la région de la Mer Baltique.

Conclusions: L' analyse des dates de vitesse de chute des particules MP confirme, comme prévu, ces particules se comportent selon les lois de résistance hydrodynamique connus de la mécanique des fluides. Des modèles hydrodynamique en 3D ont été construits pour les région d'études (le fjord d'Oslo, Norvège, et la Baie d'Himmerfjärden, Suède), avec les conditions des bords générées avec un modèle 2D du Kattegat et Mer Baltique. La conception d'un modèle Eulérien de transport des particules pour MP était obstrué par le manquement des dates de champs qui devaient permettre de définir les conditions initiales et conditions des bords sur la composition et la distribution des plastiques sur les bords, dans l'eau et sur le fond, et aussi sur les échelles de temps pour la dégradation et la fragmentation.
Depuis la recherché sur les MP a commencer d'agrandir exponentiellement il y a à peu près 5 ans, peu de progrès a été fait sur des méthodes efficaces de prendre des échantillons et de caractériser les particules MP dans le milieu aquatique. C'est encore pire sous la surface, ou on trouve imprévu très peu des particules, et sur le fond de la mer, ou on trouve la majorité. Les techniques qu'on utilise pour capturer les plastiques dans le milieu aquatique en grande quantité ne permet pas de collectionner les particules de dimensions de moins de 100 µm. En plus, la variation des caractéristiques des particules par dégradation physico-chimique a prouvé de prendre trop de temps, même sous des conditions élevées, ne permettent pas de déduire les échelles de temps nécessaire pour développer les modèles des processus. Pour cette raison, il reste très difficile de quantifier la dispersion des particules MP dans les océans correctement et avec précision jusqu'à ce que ces problèmes ont trouvés une solution.

Mots clés: micro-plastiques, vitesse de chute des particules, modélisation de dispersion des particules, floculation, modélisation de turbulence

1. INTRODUCTION

WEATHER-MIC is one of the four selected projects for the first JPI Oceans call for Joint Actions on Ecological Aspects of Microplastics. This international project has been coordinated by Dr. Annika Jahnke from the Helmholtz Centre for Environmental Research GmbH – UFZ, Departments Cell Toxicology and Bioanalytical Ecotoxicology, Leipzig, Germany. The other partners were:

- Stockholm University, Department of Environmental Science and Analytical Chemistry (ACES), Stockholm, Sweden;
- Norwegian Geotechnical Institute (NGI), Oslo, Norway;
- Fraunhofer Association, Institute for Ceramic Technologies and Systems (IKTS), Dresden, Germany;
- KU Leuven (KUL), Department of Civil Engineering, Hydraulics Division, Leuven, Belgium.

As each partner received funding from their national funding agency, the present final report only describes the Belgian contribution by KU Leuven, funded by BELSPO. The position of this contribution in the entire project is clarified in the Final Report submitted to JPI Oceans, added as annex to this report.

"The overall aim of the WEATHER-MIC project is to assess how microplastic weathering changes its transport, fate and toxicity in the marine environment. Microplastic in the ocean is exposed to UV light, wave action, biofilm growth and other weathering factors. These factors lead to fragmentation, degradation, and surface modifications, changing the density and particle size distribution of the microplastic, which ultimately impacts their environmental fate and transfer in food webs. Despite the importance of these aging processes and their related impacts, the hazards associated with weathered microplastic are not well understood yet. To achieve better knowledge about how weathering influences the physicochemical properties, environmental fate and toxicity of microplastic, we carried out several research activities divided into seven scientific work packages (WPs)." (extract from the final Publishable Summary by Janhke et al., 2018)[1]

The project consisted of 8 work packages (WPs):

- WP1: Artificial aging and fingerprinting of MP debris (coordinator: ACES)
- WP2: The influence of weathering on MP aggregation and settling (coordinator: NGI)
- WP3: Effects of biofilm formation on the vertical distribution of plastics in situ and trophic transfer (coordinator: ACES)
- WP4: Modelling extension to real world environments (coordinator: KUL)
- WP5: Model validation and field evaluation (coordinator: NGI)
- WP6: Toxicological assessment of MP particles and leachates (coordinator: UFZ)
- WP7: Estimation of environmental risk posed by virgin and weathered MP, and the leachates (coordinator: UFZ)
- WP8: Project management, dissemination, communication and outreach (coordinator: UFZ)

Their specific objectives are described at http://jpi-oceans.eu/weather-mic/project-activities

[1] http://www.jpi-oceans.eu/news-events/news/final-results-four-jpi-oceans-microplastics-projects-presented

The KU Leuven coordinated WP4 and contributed to WP2, WP4, WP5 and WP8.

2. STATE OF THE ART AND OBJECTIVES

This SoA limits itself to the modelling of MP particle dispersion, which has been the main task and contribution of KU Leuven to the WEATHER-MIC project. For the entire project, the reader is referred to the Final Report submitted to JPI Oceans (added as annex to this report).

State-of-the-art on MP dispersal modelling

The transport and dispersion of microplastic (MP) particles can be modelled with particle transport models, similar to sediment transport models. Since MP research has only started to boom recently, not so many real-world modelling studies have been published so far. Initially, the focus was on floating plastics (Lebreton et al., 2012; Potemra, 2012; Ballent et al., 2013; Isobe et al., 2014; Sherman & van Sebille, 2016). When field surveys revealed that (micro)plastics are also found in large quantities on the sea bottom (Van Cauwenberghe et al., 2013; Woodall et al., 2014; Bergmann et al., 2017), attention slowly started to shift to settling behavior of MP particles. Hardesty et al. (2017) present a first review of the corresponding research needs, but it misses various aspects that we try to address.

Thus far, the majority of modelling efforts are based on Langragian particle tracking, which assumes that the plastic particles are passive tracers, i.e. they assume that the particles follow the streamlines of the water motion. This allows cheap computation of pathways, since they usually use available flow patterns from ocean models that can be found online.

On top of that, the wave field will add an important drift component to the current drag. Thus far, few studies have considered wave drift on floating particles (Isobe et al, 2014; Onink & van Sebille, 2018).

However, this modelling approach does not allow to properly take into account settling due to the excess density or rising for negatively buoyant particles that may be dragged down by the flow. Some attempts have recently been made (Bagaev et al., 2017; Wichmann et al., 2018).

Langrangian models keep evolving and are improved (e.g. Delandmeter & van Sebille, 2018; Jolan-Rojas et al., 2018), but it will remain difficult to account for all processes and to quantify the distribution of plastics in aquatic environments.

While the density of most plastics is close to that of water, the passive tracer assumption may look a good enough approximation. However, it also implies that the particles are very sensitive to Brownian motion and more importantly to turbulent dispersion. Both processes will diffuse the particles from the streamlines. A more comprehensive 3D model for the North Sea has been developed in the Netherlands at Deltares using stochastic particle tracking based on a random walk method (Stuparu et al. 2015; Scheijen, 2018). So far, no MP transport model is coupling particle motion to a turbulence model.

A key parameter in particle transport modelling is the settling velocity. A few papers have appeared that describe settling experiments and the resulting proposed settling velocity closures (Kowalski et al. 2016; Katmulliana & Isachenko, 2016; Waldschläger &

Schüttrumph, 2019). These closures either start from the empirical non-dimensional formula of Dietrich (1982) for granular sediments, or simply propose a new empirical formula with little physical background.

In our work, we propose to start from the basic laws commonly used in fluid mechanics, which express the drag coefficient as a function of the particles Reynolds number, as originating from boundary layer theory (Schlichting & Gersten, 2018)

Objectives

The main objective of the KU Leuven task is to develop a modelling framework for the 3D dispersal of microplastic (MP) particles in a coastal environment, based on the KU Leuven experience in sediment transport modelling, using en Eulerian reference frame, allowing to compute not only pathways, but also concentrations of particles.

Furthermore, closures for the settling velocity of MP particles as a function of their density (related to the type of polymer), size and shape will be sought. Since MP particles show a wide range of sizes due to fragmentation or aggregation, also these effects on the representative settling velocity will be investigated.

3. METHODOLOGY

WEATHER-MIC focusses on two study areas as field cases for the development of a modelling strategy to predict transport, dispersion and fate of MP particles in a real aquatic environment. The two selected areas are Oslo Fjord (Norway) and Himmerfjärden Bay (near Stockholm, Sweden). In both cases the sources of MP plastic input into the area are from the overflow of a water treatment plant of the respective cities of Oslo and Stockholm and (probably more important) from river inputs.

Numerical modelling was performed with the open source TELEMAC code (www.openTELEMAC.org), which is systematically used by KU Leuven since 2012 for testing new process models for hydrodynamics (wave transformation processes and improved turbulence modelling) and sediment transport in large-scale applications.

3.1 Hydrodynamic modelling

A two-dimensional depth-averaged (2DH) hydrodynamic model has been set-up for the area covering the Skaggerak, Kattegat and Baltic Sea during year 1. In addition, two local 3D models with a finer mesh resolution have been set up for the two focus locations, Oslo Fjord (during year 1) and Himmerfjärden Bay (during year 2). Mesh resolutions have been adapted (i.e. coarsened) to allow faster computation. Details of the model set-ups and the data sources used are found in the detailed internal report by Bi et al. (2019).

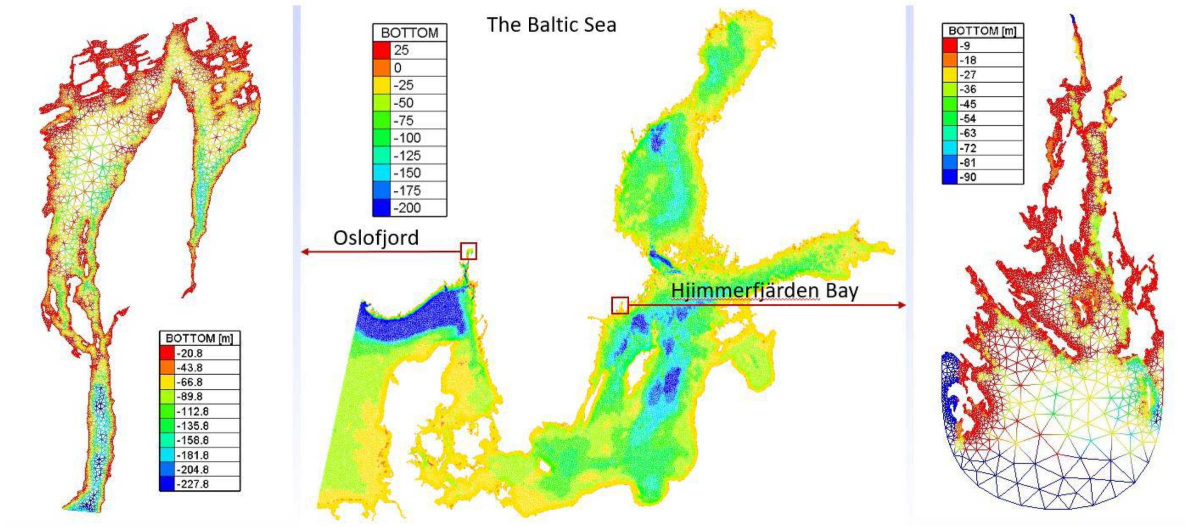

Figure 3.1: Domains, numerical grids and bathymetry for the 3 models.

The only physical driving process that was not yet available in the TELEMAC suite is Stokes drift by surface waves. Within the framework of the parallel running VLAIO-SBO funded CREST project (www.CRESTproject.be) the formulation and implementation of Stokes drift into the spectral wave model TOMAWAC (Benoit et al., 1996) has been carried, but was not yet finalized by the end of the WEATHER-MIC project. This process is expected to be of large importance to floating and pelagic plastics in the Baltic Sea, because wind induced currents and waves dominate tidal effects, which are small due to the narrow connection with the Atlantic Ocean.

The settling velocity value of individual particles is based on density and size, as for sediment particles, following the results from the analysis of settling experiments by various institutes, a major deliverable from WP2 (see section 4).
The reality of different types of plastic with different densities, as well as a wide variety of sizes, has been studied from the perspective how this is handled in sediment transport. We benefited from the parallel running BELSPO funded BRAIN.be project INID67 where one of the key problems was the modelling of flocculation of cohesive sediments in the presence of algae.

3.2 Flocculation modelling

Since MP particles are known to be captured by other suspended (cohesive organic and mineral) matter into aggregates of algae, mud flocs or marine snow, the modelling of flocculation has also been investigated in parallel with the ongoing research within the framework of the BELSPO BRAIN.be funded project INID67.
The 2-class population balance equation (2CPBE) model of Lee et al. (2012) has been extended to a 3CPBE model (Shen et al., 2018a) with simple assumptions to account for biofilm growth (Shen et al., 2019b), because it has been observed that a third size class of flocs is formed when there is much bacterial breakdown of organic matter, typically observed after an algae bloom period. This 3CPBE model has successfully been implemented into TELEMAC3D and tested and validated with a laboratory experiment and with field data from RBINS for cohesive particles in one location along the Belgian Coast with a 1DV setup of TELEMAC.
A strategy for adaptation of this model to microplastic particles has been developed during year 1. In order to apply this flocculation modelling strategy to MP particles, a different definition of the classes has to be formulated. It is proposed to formulate it is as follows:

Class 1 = pure microplastic particles
Class 2 = pure cohesive sediment particles (and their micro-aggregates)
Class 3 = aggregates (flocs) of C1 and C2
The 5 variables then are: mean size of each class, number of C1 particle in C3 and number of C2 particles in C3. The 5 corresponding equations are: 3 kinetic equations describing average growth and break-up of each class particle, and 2 mass balance equations.

The weathering of MP particles has to be included as a break-up term for class C1 in its kinetics equation. The definition of aggregation and break-up kernels in the kinetic equations requires input from the experiments, especially the column tests of WP2, providing particle size distribution evolution in time for different levels of UV radiation intensity, turbulence intensity and concentrations of organic matter, biomass and mineral particles.
Besides the capturing of MP in aggregates, the size distributions of MP particles themselves are subject to fragmentation by different weathering processes, including mechanical fragmentation (by ship propellers and wave-sand abrasion on beaches), fast degradation processes which have been too much neglected thus far.
The effective completion and application remains difficult by lack of sufficient experimental or field data of particle size distributions and on the kinetics of weathering processes and

biofilm formation. The little available data are being analysed and proposals for modelling the different processes are made, but need further study.

The possibility of modelling of biofilm formation with TELWAQ (extended with integration of the AED2 ecodynamics model library; http://aed.see.uwa.edu.au/research/models/AED/), originally scheduled for the third year, had to be postponed due to new developments in the generic TELEMAC structure by EDF's Laboratoire Nationale d'Hydraulique et Environnement (LNHE, Chatou, FR), the responsible institute for coordinating the evolution of the model structure and the release of new public versions. EDF started in 2017 with a major modification of their treatment of sediment transport, by moving suspended sediment transport out of SYSIPHE and replacing SISYPHE by a new module GAIA. This change also forced us to rethink our plans for implementation of our flocculation modelling work into the official public version of TELEMAC. This eventually has been realized with the support of Flanders Hydraulics who assigned this task to Qilong Bi (working since 2017 for FHR), for which he can spent 20% of his time at KU Leuven. During the last 10 months of the WEATHER-MIC project, he could collaborate with Xiaoteng Shen, our postdoc on the INDI67 project, and with Prof. Joon Lee, on sabbatical with us from Kyungpook University, South Korea, who developed our original flocculation modelling methodology in 2011 during his postdoc at KU Leuven. The implementation of 2CPBE and 3CPBE models in the TEMEMAC code has been done, and first tests and validations have been carried out. The work is expected to be completed within the coming months.

Another problem encountered was the poor performance of the two-equation k-epsilon turbulence model under certain conditions. A systematic analysis of the problem has revealed that this is due to the bottom boundary treatment, which proves to be incompatible with the linear interpolations used by the numerical model. Even in the most simple steady uniform flow testcase, the solution was found to deviate from the correct result. Tests with other codes (a.o. GOTM and OpenFOAM) indicate that the problem exists there as well. A new method has been designed that guarantees more accurate computation of bed shear stress, mass conservation in the bottom layer and proper values of the turbulent kinetic energy. The stability of the method and a more robust implementation is still under investigation. - For this reason, the 3D modelling for WEATHER-MIC in the meantime has been performed with the algebraic Prandtl-mixing length model.

3.3 The KU Leuven contribution in relation to the tasks and contributions of the other WEATHER-MIC partners

WEATHER-MIC is a multidisciplinary project with various partners with very different expertises. Few of the researchers involved had any previous experience in research on plastics. Therefore, the open interactions and discussions during the meetings and correspondence has been a valuable learning period, thanks to the open mindedness of everyone.

The KU Leuven model requires the following information to allow the numerical simulation of MP particles in an aquatic environment:

- **The settling velocity of plastic particles**: (which is the main characteristic of the material, needed as parameter closure). **T**his was primarily provided for individual articles by **NGI** in **WP2** through their experimental work in a settling column, and was complemented with data from the literature. In addition, a few settling experiments on PS particles caught in algae flocs were obtained by Dr. Eric Mc Givney from **ACES**.

- **Data on the occurrence of plastic in the model areas:** is necessary as initial, calibration and validation data. Field data collection was the main objective of **WP5** and was carried out respectively by **NGI** for the Oslo Fjord and **ACES** for the Himmerfjärden Bay. It turned out that a big underestimation had been made in the estimation of the necessary efforts. Moreover, none of the used sampling techniques allowed for a quick enough assessment of all the necessary quantitative information (size distribution, shape characterization, polymer type fractions, biofouling, degree and types of weathering), on the plastics found.

Besides these primary data, the KU Leuven also intended to account for **variations in the particle parameters as a result of different weathering processes**, by introducing proper sink and source terms in population balance equations, following ideas used for our multiclass flocculation models (Lee et al., 2012; Shen et al., 2018a). The focus of WEATHER-MIC was on weathering due to UV radiation exposure, temperature and salinity effects, as well as on testing the hypothesis of biodegradation by bacteria.

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

4.1 SCIENTIFIC RESULTS

WP2: The influence of weathering on MP aggregation and settling (lead: Dr. H.P. Arp, NGI)

Determination of new settling velocity closures for microplastic particles

Data from settling experiments by the Norwegian partner NGI on MP particles of different nature, size and shape, of which some have been subjected to artificial or natural weathering, have been analysed and compared with available models for particle settling in the literature. In addition, all the data of similar experiments on MP particles by institutes external to the WEATHER-MIC consortium have also been collected and analysed. This extensive work eventually has led to the writing of a review paper on the MP settling and floatation, that will be submitted for publication to *ES&T Letters*. All previously proposed formulae are critically evaluated and new closures have been proposed.

The findings confirm the expected outcome that MP particles fulfil the same (non-dimensional) laws as other non-spherical particles (**figures 4.1 and 4.2**). New semi-empirical closures for the settling velocity have been proposed, which can be used in MP dispersal models. The uncertainty band on the experimental data (the yellow band in figures 4.1 and 4.2) is found to be relatively wide due to the small relative density of plastics.

Shape effects are also investigated. It is found that elongated particles with aspect ratios above 3 deviate significantly from the trend line for granular particles and fall outside its uncertainty band. It is possible to unify the trendlines through the data points into one empirical formula by adding a dependence on a shape factor.

Also settling data by the Swedish partner ACES for small spherical polystyrene particles, caught in aggregated algae, have been found to match the new general closure for granular particles (**figure 4.2**).

The previous work focusses on the settling velocity of individual particles. However, plastic particles in the aquatic environment occur in a great diversity of particle properties (density, size and shape). Little information is found in the literature on the size distribution of plastics in the aquatic environment, but the little data suggest that a log-normal distribution is a satisfying approximation (as for natural sediments and aggregate populations). The largest available dataset of MP particles from Khatmullina & Isachenko (2016), i.e. mechanically fragmented PCL, has been analysed in this perspective. This shows that the size and settling velocity show the same normalized log-normal distribution, while the settling flux shows another, which can be computed from the previous two (**figure 4.3**).

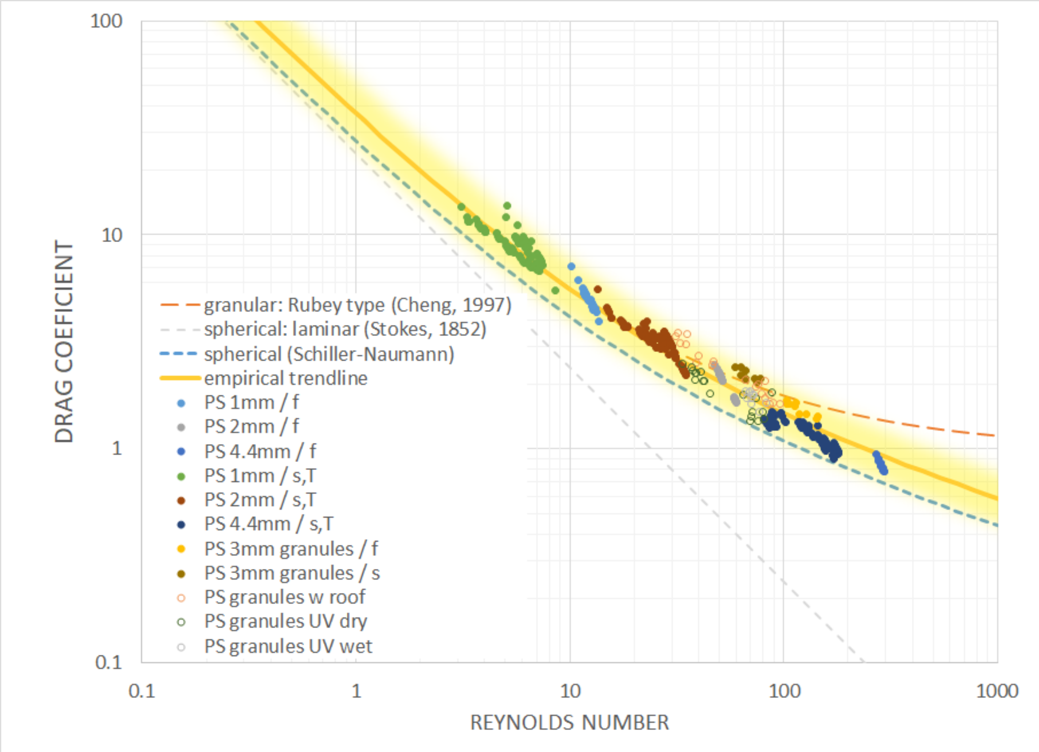

Figure 4.1 – *Drag coefficient as a function of particle Reynolds number for polystyrene spheres and pellets from settling experiments in fresh water at room temperature (f), in seawater (s) at various temperatures below room temperature (T) and weathered (w) or subjected to artificial UV exposure.*

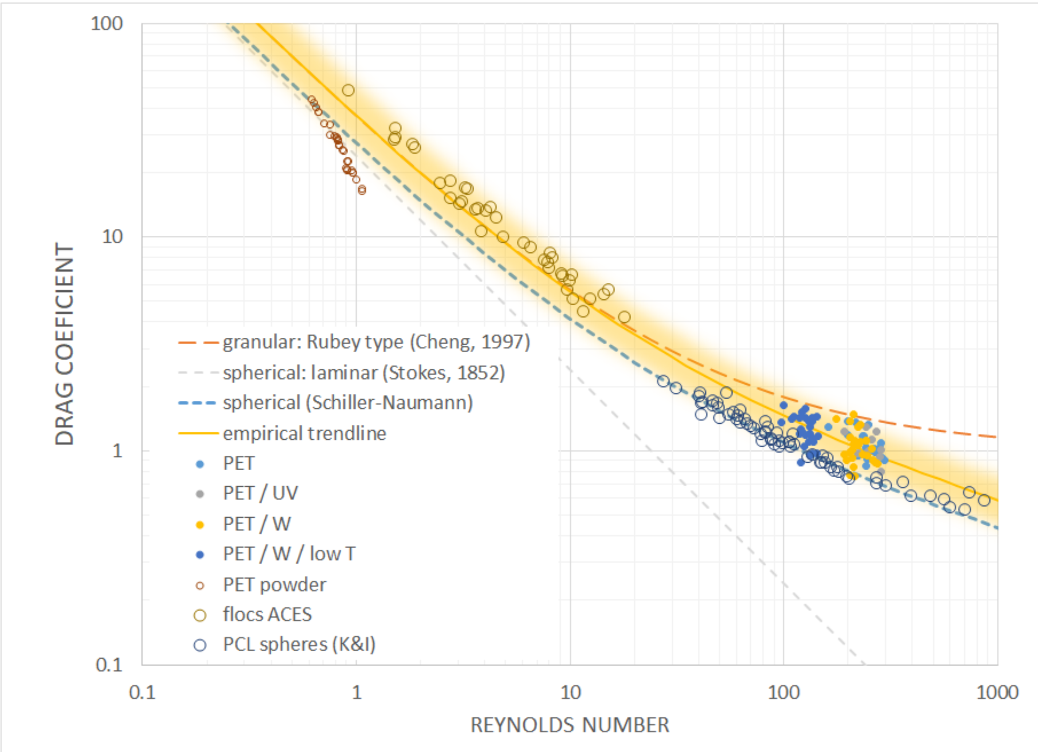

Figure 4.2 – *Experimental data for PET particles ("W" = weathered, "UV" = UV light exposed), PS in algae flocs (from ACES) and PCL spheres (from Khatmullina & Isachenko, 2016).*

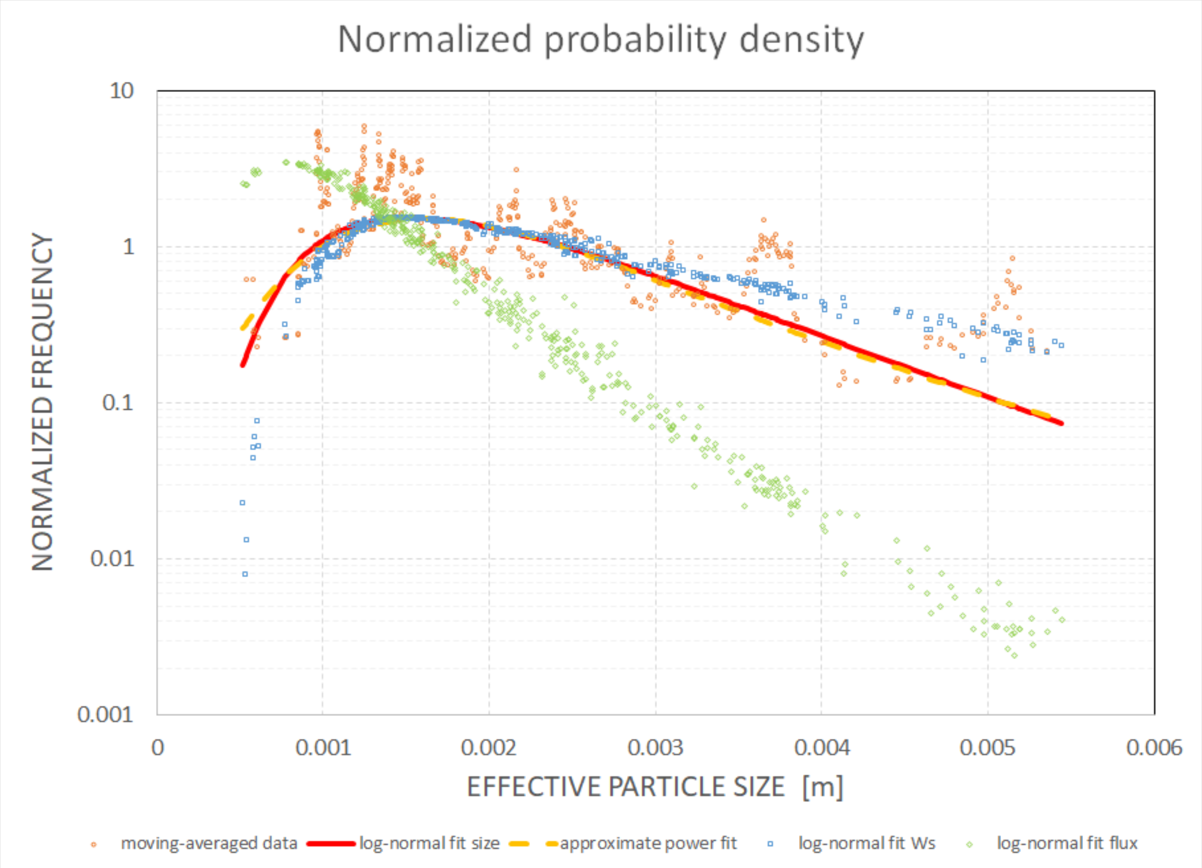

Figure 4.3 – *Normalized probability density functions for the size and measured velocity and computed settling flux for PCL particle data from (Kkatmullina & Isachenko, 2016).*

It proves to be difficult to represent the entire group of particles with a single representative of the settling velocity. Various ways result in different total fluxes. Moreover, the size distribution is expected to change in time and space due to sedimentation, aggregation and fragmentation.

Implementation of the size distribution of MP particles could be done in analogy with multifractional modelling of graded sand transport (e.g. Yang et al., 2012) which has a high computational cost.

As an alternative, in analogy to our flocculation modelling strategy (Shen et al., 2019a), our proposal is to develop a model that solves transport (i.e. advection-diffusion) equations for only two parameters, i.e. the mean size and the standard deviation of the lognormal distribution, with sink terms that represent deposition and fragmentation by bio-physico-chemical weathering and mechanical fragmentation by ship propellers and abrasion with sand (and possibly other coarse material) on beaches. One could also think of uptake of particles by animals and aggregation with organic matter and cohesive sediment particles, e.g. near the surface due to algae or near the bottom in marine snow.

Since to date there are no data available to determine the formulation of these processes, this could not be worked out into a useful model.

Much research remains needed to provide data on composition and size and shape distributions of patches of plastic pollution and its evolution in time (in an efficient way). Despite all the research efforts on marine plastic litter, we still have no reliable and fast enough method to determine the time scales of weathering and their effects on the environment.

Design of a new experimental set-up to study the effect of turbulence on the sinking behaviour of plastic particles

Figure 4.4 - *Couette type flocculation reactor, designed and built at KU Leuven, to study sedimentation and aggregation behavior of microplastic (and mineral) particles in an aquatic environment under varying shear flow conditions.*

Because of the low difference in density of MP versus ambient water, it is expected that light plastics will be very prone to turbulent drift. Since this effect has not been yet been studied systematically, a new experimental setup has been built, consisting of a Couette geometry, i.e. a rotating cylinder in a cylindrical tank (diameter = height = 0.5m) (**figure 4.4**), where shear flow can be generated, which can produce shear turbulence. The rotation can be controlled between 0 and 100 rpm, allowing the study of settling behaviour in quiescent, laminar flow and turbulent shear flow conditions.

Since the construction of the setup was delayed by late supply of ordered materials, experiments in this tank will be performed from the Summer of 2019 by visiting researchers and a MSc student in the framework of his thesis during the academic year 2019-2020.

The flow in the tank will be validated by comparison of acoustic Doppler velocity (ADV) measurements with a 3D model set up in TELEMAC. Evidently, future results with this new setup will acknowledge the BELSPO funding through WEATHER-MIC.

WP 4: Modeling extension to real world environments (lead: E. Toorman, KUL)

Two 3-dimensional (3D) models have been set up, one for the Oslo Fjord (NO) and one for the Himmerfjärden Bay (SE). Open sea boundary conditions are generated with a depth-averaged (2DH) Baltic Sea & Skagerrak model (starting from the North Sea). The 2 Class Population Balance Equation (2CPBE) flocculation of Lee *et al.* (2012), implemented by Ernst (2016) in the TELEMAC3D code, has been tested in these two models.

By lack of sufficient field data, no actual validation of the model could be performed. Only one approximate realistic scenario has been simulated, i.e. the dispersal of a flux of MP particles from the sewer treatment plant in Oslo harbor over a period of 4 weeks (**figure 4.5.a**) reveals that the material disperses very slowly because in that corner of the Fjord there is hardly any current to transport the particles. A similar simulation for the Stockholm area case is shown in **figure 4.5.b**. Longer term simulations have not yet been performed because of the long computational time and problems with the necessary turbulence model.

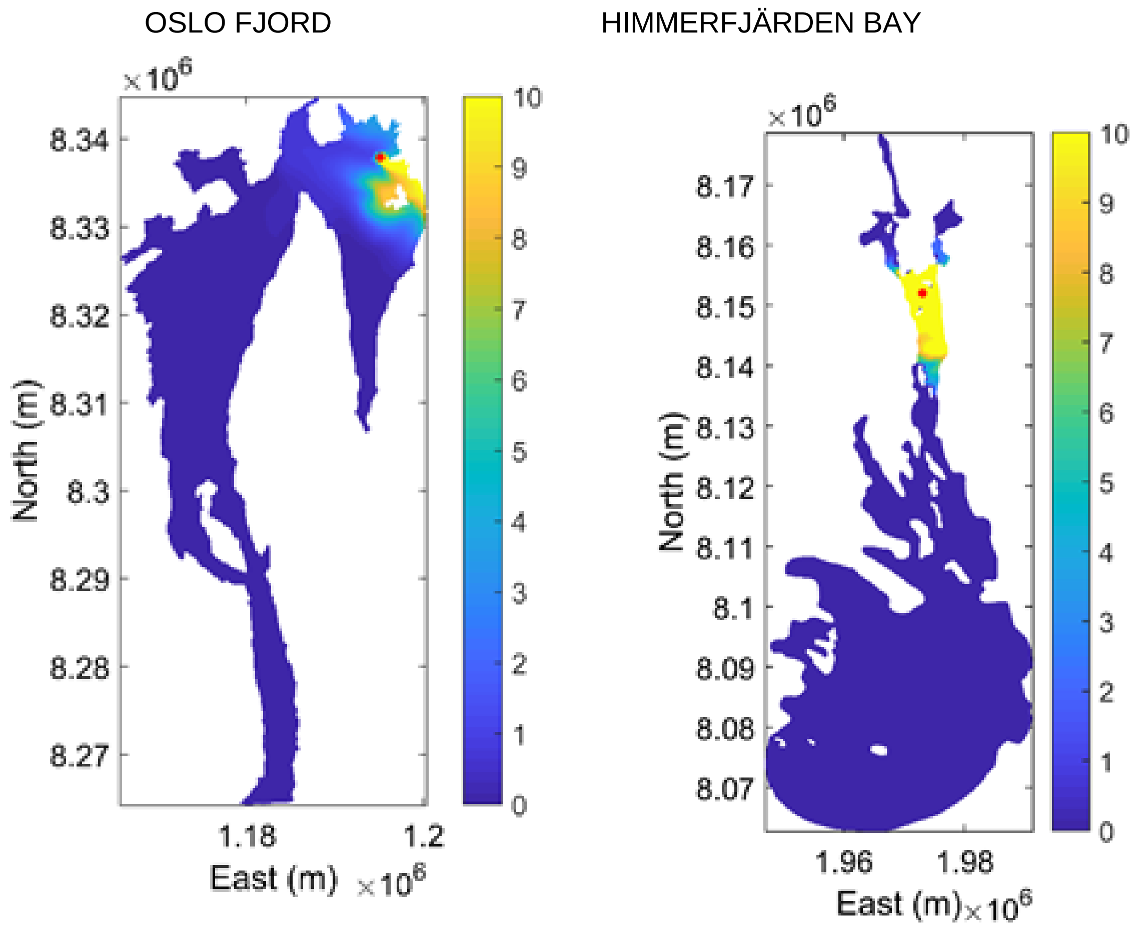

Figure 4.5 - *MP concentration at the surface [mg/l] after 28 simulated days released from a source point (red dots) situated at the location of the wastewater treatment plants.*

A major bottleneck for the advancement of the model was the observation that the preferred turbulence model, i.e. k-epsilon, did perform poorly to very bad near the bottom. The analysis of this problem eventually leads to the identification of the source and the proposal of an entirely new treatment of the near-bottom boundary conditions (Toorman et al., *in preparation*).
Once this new method has been positively evaluated and implemented into the TELEMAC source code, longer term simulations are still planned to be carried out using the HPC facilities of KU Leuven.
Furthermore, with co-funding by the BELSPO BRAIN.be project INDI67, the flocculation modelling work has been extended to include an additional population of particles aggregating with algae (Shen et al., 2018a, 2018b, 2019a, 2019b). This approach seems promising for the future application to MP particles as well, and is planned to be applied in follow-up projects.

While this work package has not fully achieved its original goal, it has resulted in a much better understanding of the actual practical and numerical problems that at this moment hamper the development of a detailed model which accounts for all processes. The final scientific report of this WP (Bi et al., 2019) therefore concludes with a focus on the lessons learnt, the identification of knowledge and (very importantly!) data gaps and recommendations for future steps in model development. The main points are summarized below in section 4.2.

WP5: Model validation and field evaluation (coordinator: NGI)
Originally, it was the aim to collect sufficient field data for the modelling task of WP4. However, the available budget for NGI was not sufficient to gather enough data in the Oslo Fjord area. Even with data collected in the framework of other project by other research institutes, not enough data could be obtained. Moreover, the majority of these datasets were incomplete, since most samplings are restricted to the determination of numbers of particles per unit volume.
Also for Himmerfjärden Bay, we only obtained limited data from ACES, restricted to qualitative estimates of beached plastic in a few places along the shore (Gewert et al., 2017).
A major issue that could not be resolved by any of the JPIO projects was the development of a new, fast and efficient method to measure and monitor quantities of MP. The model actually needs to know not just numbers of particles (per unit volume), but also their individual size, shape and density, before these data can be converted in the representative settling velocity. Therefore, this need has been identified as one of the priority research needs for the second JPIO call, launched in November 2018.

WP8: Project management, dissemination, communication and outreach (coordinator: UFZ)
The overall project management was carried out by Dr. Annika Jahnke, from UFZ.

As the only engineering research group in the JPIO projects, KU Leuven has soon developed a strategy to create eye-openers by stimulating a shift towards a more holistic approach to MP research. We noticed in the literature and at the attended conferences that many groups focus too much on small details while not placing their research focus into the wide, multidisciplinary frame of the actual problem of plastics at sea. From the response rate from participants at the JPIO conferences we deduce that the message has well been received.

The difference of our “original” modelling approach compared to the Lagrangian particle tracking method, applied by others, has also raised quite some interest at these conferences.

A list of activities and contributions in the framework of dissemination is found under the following Section 5 of this final report.

4.2 LESSONS LEARNT & RECOMMENDATIONS

The participation of the KU Leuven to WEATHER-MIC has introduced engineering science and practice into the field of research on microplastics in aquatic environments, that so far was mainly dealt with by a narrow field of expertise in environmental sciences, sometimes complemented with biologists and chemists. This became evident by our participation to the JPI Oceans and the MICRO2018 conferences and the responses we got. We have encouraged the participants to continue MP research by working in interdisciplinary

partnership with other fields of expertise, which was one of the key success factors for the WEATHER-MIC project. Our consortium concluded that the major expertise that was missing is analytical chemistry. Therefore, a new partner has been engaged for our proposal for the second call.
The content of our new proposal is based on the lessons learnt from the WEATHER-MIC project. Since all JPI Oceans projects have been invited to submit their list of research priorities for MP research, many items of our list can be found back in the second call.

The obvious first recommendation is to invest in research that finds practical, fast and efficient monitoring techniques for plastic detection, characterization and quantification (by polymer, size and density, and degree of biofouling). Ideally, one needs at least two data sets of the distribution of plastics through the entire modelling area at two different instances (at least one year apart). The first data set is necessary as initial data. The second can be used for validation.
For surficial plastics remote sensing techniques are recommended to be tested. The latter has become a main topic in a proposal for VLAIO-SBO funding in the framework of the Blue Cluster research focus on marine litter, submitted by a Flemish consortium where KU Leuven will lead the modelling work.

Measuring techniques for suspended and deposited particles will be even more challenging. A problem will be the discrimination between MP and other, i.e., mineral and organic particles.
A second recommendation is the design of methodologies to estimate weathering time-scales. The duration of typical project calls (2-4 years) is too short to notice significant changes in material densities and fractures by physico-chemical processes like UV exposure. Time scales for degradation found in the literature make estimates of the order of decades or centuries depending on the polymer. A recent paper on fractionation of plastics by cobbles and water in a concrete mill that results in the generation of MP particles in just 24 hours (Efimova et al., 2018) has raised our attention that the assumed process of abrasion and fragmentation by shear with sand on beaches subjected to wave impact, might be a much more important mechanism for rapid size changes, that we decided to investigate this in a master thesis project for the academic year 2019-2020. This research will also be continued in our follow-up project, if it will be selected by JPI Oceans. Fragmentation by ship propellers in navigation ways will also be considered in the VLAIO SBO project. How to account for the particle size distribution and its variation in space and time in the modelling framework in an efficient way also requires further investigation.

Experimental work is needed to provide detailed insights into the growth rate of biofilms on plastics and how to model this efficiently, without having to incorporate a model for the entire ecological system, which would introduce far too many parameters. (The modelling of too many processes is expected to reduce the model's accuracy because the uncertainty on the many model parameters and the measurement errors for all validation data will accumulate in excess of the theoretical gain in accuracy).

Experimental data on aggregation of MP particles with each other and other suspended matter will also be useful, in particular to understand better what is happening near the bottom in so-called benthic nepheloid layers, dominated by marine snow.

Furthermore, the critical evaluation of the numerical methods and the efficient coupling between hydrodynamic, spectral wave and particle transport models reveal several short comings, both in the poor performance of process models or the lack of certain processes, as in the numerical implementation. The discovery of the weakness in the boundary treatment for turbulent shear flow along the bottom should be further investigated in order to develop a new robust method that yields more correct results than the traditional method that is found in any CFD code, where it never has been questioned.

Perspective on the future of the marine ecosystem

Finally, it is also worth mentioning that participation in research on marine plastic litter has revealed a lot of misconceptions on the problem caused by manipulation and presentation of field data. For instance, the North Pacific Garbage Patch (NPGP) eventually has a rather low concentration of plastic particles (< 1 particle / m^2), which is much lower than the accumulation of plastics on beaches near river outflows (of which images are shown in the media for some extreme cases, often associated with storm events). The NGPG cannot be seen from aerial or satellite images.

Furthermore, recent estimates on where plastics can be found indicate that only 1% floats, 5% beaches and the remaining 94% goes to the bottom. Therefore the majority of plastic litter is expected never to be removed from the aquatic environment, since removal would imply massive disturbance of the seabed and damage to the benthic ecosystem. Fortunately, the majority of experiments on ecotoxicological effects thus far indicate lower risks than feared. But, this excludes tests with even smaller particles (<10 µm) and the leachates of often potentially toxic additives. Like with other historical pollution in sediments (e.g. of heavy metals), it seems that the best option will be to leave the plastics being buried and eventually immobilized in the sediments to generate the least harm to the fragile benthic ecosystem.

4.3 OTHER OUTCOMES & ADDED VALUE

- The TELEMAC model development by Samor Wongsoredjo is part of his PhD research program.
- The contribution of Dr. Xiaoteng Shen on flocculation and the resulting publications have played an important role in his success to become assistant professor at the State Key Laboratory of Hydrology-WaterResources and Hydraulic Engineering, Hohai University, Nanjing, China in China. We will look for new funding to continue collaboration in the field of cohesive sediments and microplastics pollution, with focus on the Yangtze River, China.
- The sabbatical stay during the academic year 2018-2019 of Prof. Byung Joon Lee, Kyungpook University, Korea, continuing our collaboration on flocculation (since 2011), has also triggered his interest to start studying the riverine plastic pollution problem in South-Korea.
- A new Flemish network on aquatic plastic litter, coordinated by the Flemish Marine Institute (VLIZ), has been initiated at the MICRO218 conference. This network is currently preparing a strategic basic research proposal to be funded by VLAIO through the Flemish Blue Cluster.
- The marine litter problem is now also introduced in lectures to the civil engineering students at the KU Leuven. The topic can now also be selected for a MSc thesis project. A first project on mechanical plastic fragmentation in aquatic environments by interaction with waves and sediments on shores is carried out during the academic year 2019-2020.

5. DISSEMINATION AND VALORISATION

The following **dissemination activities** have been undertaken:

- Oral and poster presentations at JPI Oceans conferences (Lisbon, 2016 and Lanzarote, 2018)
- Poster presentation at INTERCOH2017 (Montevideo, Uruguay)
- Oral and poster presentations at MICRO2018 (Lanzarote)
- Oral presentation at the TELEMAC-MASCARET Scientific Committee (Chatou, 2019)
- Participation in the EPHEMARE (one of the other three JPI Oceans MP projects) stakeholder meeting (Antwerp, 2017).
- WEATHER-MIC Stakeholder meeting at KU Leuven 2019.
- Interview published in the KU Leuven newspaper *Campuskrant* (in Dutch & English): https://nieuws.kuleuven.be/en/content/2019/ku-leuven-weather-mic-hydraulics-engineers-microplastics. Its main message (in Dutch) published by the Belgian national news agency Belga in their news overview of April 11, 2019.
- Our microplastics research will also be featured in the *KU Leuven Corporate Brochure* for the coming academic year 2019-2020.
- Two interactive lectures on marine plastic litter were given to final year primary school children in Leuven, Belgium.

Furthermore, the results of the KU Leuven team have also been included in various conference presentations by international partners of the WEATHER-MIC consortium (see the publication list), and overall project results summaries have recently been presented by the project coordinator at the Japanese-American-German "Frontiers of Science" Symposium in Kyoto, September 2019, and the 40th SETAC North America Conf., Toronto, 3-7 November 2019.

The dissemination has already resulted in a few opinion questions by journalists from national newspapers.

Valorisation:

- Although the implementations of improvements in the TELEMAC code have not yet been finalized within the time frame of the project, this is ongoing work, implying that that will be implemented in the near future, making them available to the entire TELEMAC user community through the website www.OpenTELEMAC.org. The flocculation model is expected to become available by 2020.
- The new closure for settling velocity will be published soon.
- The results of our participation to WEATHER-MIC have already been used to write new research proposals for two project calls: the 2nd JPI Oceans MP research call (*submitted February 2019, but eventually not selected*) and the Flemish Blue Cluster call for Strategic Basic Research (*submitted May 2019 and invited for a final, revised full proposal to be submitted by December 2019; selection on April 4, 2020*).

6. PUBLICATIONS

The following publications with KU Leuven researchers as **lead-author** have been published or are in preparation:

Journal papers

1. Shen X, Lee BJ, Fettweis M, Toorman EA (2018a). A tri-modal flocculation model coupled with TELEMAC for estuarine muds both in the laboratory and in the field. *Water Research*, 145: 473-486. https://doi.org/10.1016/j.watres.2018.08.062
2. Shen X, Toorman EA, Lee BJ, Fettweis M (2018b). Biophysical flocculation of suspended particulate matters in Belgian coastal zones. *Journal of Hydrology*, 567(12): 238-252. https://doi.org/10.1016/j.jhydrol.2018.10.028
3. Shen X, Toorman EA, Lee BJ, Fettweis M (2019a). Simulating multimodal floc size distributions of suspended cohesive sediments with lognormal subordinates: Comparison with mixing jar and settling column experiments. *Coastal Engineering*, 148(6): 36-48. https://doi.org/10.1016/j.coastaleng.2019.03.002
4. Shen X, Toorman EA, Lee BJ, Fettweis M (2019b). An approach to modeling biofilm growth during the flocculation of suspended cohesive sediments. *J. Geophysical Research – Oceans*, 124(6): 4098-4116. https://doi.org/10.1029/2018JC014493
5. Toorman EA, Olsen LMB, Berrojalbiz N, Issler D, Oelschlägel K, Arp HPH (2019). On the settling behavior of microplastic particles. *ES&T Letters* (*in preparation*).
6. Toorman EA, Wongsoredjo S, Bi Q (2019). A new wall-boundary treatment for the *k-ε* turbulence model for fine and coarse meshes. (*in preparation*)

Posters

1. Toorman E, Bi Q, Shen X, Jahnke A, Monbaliu J (2017). Modelling microplastics dispersal: anthropogenic cohesive particles and their fate in coastal waters. Poster presentated at INTERCOH2017, Montevideo (UY), 13-17 Nov.2017.
2. Wongsordjo S, Toorman EA (2018). Three-dimensional numerical simulation of microplastics dispersal from point sources in the Baltic Sea region. Poster presentated at MICRO2018, Lanzarote (ES), 19-23 Nov.2018.

Reports

1. Wongsoredjo S., Bi Q. & Toorman, E. (2019). *Baltic Sea model development report*. Internal Report HYD19-JPIO-1, Hydraulics Division, Dept. of Civil Engineering, KU Leuven, 68+ pp. (*in preparation*)

The following publications with KU Leuven researcher as **co-author** have been written:

1. Jahnke, A.; Arp, H.P.H.; Escher, B.I.; Gewert, B.; Gorokhova, E.; Kühnel, D.; Ogonowski, M.; Potthoff, A.; Rummel, C.; Schmitt-Jansen, M.; **Toorman, E.**; McLeod, M.. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. *Environmental Science & Technology Letters* **2017**, 4, 85–90.
   This paper received a best-paper award for papers published in this journal in 2017.
2. MacLeod, M.; Arp, H.P.H.; Gorokhova, E.; **Toorman, E**.; Potthoff, A.; Schmitt-Jansen, M.; Kühnel, D.; Jahnke, A. "WEATHER-MIC. How microplastic weathering changes its transport, fate and toxicity in the marine environment" at the "MICRO2016 - Fate and Impact of Microplastics in Marine Ecosystems: From the Coastline to the Open Sea" meeting, Lanzarote, Spain, May 2016
3. Brekke Olsen, L.M.; Berrojalbiz, N.; Issler, D.; **Toorman, E**.; Arp, H.P.H. The sinking behavior of fresh and weathered microplastics in surface water. International Conference on Chemistry and the Environment. Oslo. 19.06.2017.
4. Jahnke, A.; MacLeod, M.; Arp, H.P.H.; Potthoff, A.; **Toorman, E.** WEATHER-MIC - How MICroplastic WEATHERing changes its transport, fate and toxicity in the marine environment. JPI Oceans conference. Lisbon. 26.10.2017.
5. Jahnke, A.; Arp, H.P.H.; Escher, B.I.; Gewert, B.; Gorokhova, E.; Kühnel, D.; Ogonowski, M.; Potthoff, A.; Rummel, C.D.; Schmitt-Jansen, M.; **Toorman, E.**; MacLeod, M. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. JPI Oceans conference. Lisbon. 26.10.2017.
6. Arp, H.P.H.; Brekke Olsen, L.M.; Berrojalbiz, N.; Issler, D.; **Toorman, E.** The Influence of Weathering on the sinking behavior of microplastic. JPI Oceans conference. Lisbon. 26.10.2017.
7. Jahnke, A.; Arp, H.P.H.; Escher, B.I.; Gewert, B.; Gorokhova, E.; Kühnel, D.; Ogonowski, M.; Potthoff, A.; Rummel, C.D.; Schmitt-Jansen, M.; **Toorman, E.**; MacLeod, M. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. SETAC North America Meeting. Minneapolis. 12-16.11.2017.
8. Arp, H.P.H.; Brekke Olsen, L.M.; Issler, D.; Berrojalbiz, N.; Oelschlägel, K.; Potthoff, A.; **Wongsoredjo, S.; Shen, X.; Toorman, E.** The influence of weathering on the sinking behavior of microplastic in freshwater and all surface waters. SETAC Europe 28th Annual Meeting, Rome, Italy, 13.-17.05.2018.
9. Arp, H.P.H.; Knutsen, H.; Brekke Olsen, L.M.; Issler, D.; Berrojalbiz, N.; Oelschlägel, K.; Potthoff, A.; **Wongsoredjo, S.; Shen, X.; Toorman, E.** The influence of weathering on the sinking behavior of microplastic in freshwater and all surface waters. Emcon Oslo, 26.06.2018.
10. Jahnke, A.; MacLeod, M.; Arp, H.P.H.; Potthoff, A.; **Toorman, E.** WEATHER-MIC – how microplastic weathering changes its transport, fate and effects in the marine environment. JPI Oceans conference. Lanzarote. 20.11.2018
11. Nybakk A.W., Arp, H.P., Knutsen, H., Olsen, L.M., Mahat, S. Wade, E.J., Lilleeng, Ø., Issler, D., Berrojalbiz, N. Pettersen, A., Oelschlägel, K., Potthoff, A., **Wongsoredjo,**

S., Shen, X., Toorman, E., Laugesen, J., Møskeland, T. The sinking behavior of microplastic and their presence in various coastal environments. 11th Int. SedNet Conf., 3-5 April 2019, Dubrovnik, Croatia.

12. Arp, H.P., Knutsen, H., Olsen, L.M., Mahat, S. Wade, E.J., Lilleeng, Ø., Issler, D., Berrojalbiz, N. Pettersen, A., Oelschlägel, K., Potthoff, A., **Wongsoredjo, S., Shen, X., Toorman, E.**, Laugesen, J., Møskeland, T. Microplastic in sediments from the arctic to the tropics. Batelle 2019 Sediment Conference. 11-14 February 2019, New Orleans, USA.

Additional publications by the project partners can be found in the full final report to JPI Oceans.

7. ACKNOWLEDGEMENTS

This project has been funded by BELSPO in the framework of the first JPI Oceans call for Joint Actions on Ecological Aspects of Microplastics. We would like to thank JPI Oceans for the organization of the joint meetings of all four selected projects which encouraged and enabled interactions between the projects in an effort to increase the efficiency in data collection and exchange of ideas and methodologies.
KU Leuven's contribution to WEATHER-MIC has also benefitted from the BELSPO funded BRAIN.be project INID67 (contract nr. BR/143/A2/INDI67), the VLAIO funded SBO project Climate Resilient Coast (CREST), and a Flanders Hydraulics Research project on the implementation of the KU Leuven multiclass flocculation model in TELEMAC, which shared the collaboration between researchers to further develop and improve the TELEMAC software.

The experimental data published in (Kkatmullina & Isachenko, 2016) have kindly been made available by Igor Isachenko (Atlantic Branch of the P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Kaliningrad, Russia). The recent experimental published in (Waldschläger & Schüttrumph, 2019) have kindly been made availabe by Dr. Kryss Waldschläger (Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University). The experimental data published in (Kowalski et al., 2016) were kindly made available by Prof. Joanna Waniek (Leibniz Institut für Ostseeforschung Warnemünde, Germany), but proved to be incomplete for a full analysis.

The KU Leuven contribution of the project has benefited a lot from the interactions with the other WEATHER-MIC partners:

- Annika Jahnke, Dana Kühnel, Mechthild Schmitt, Beate Escher and Christoph Rummel from the Helmholtz Centre for Environmental Research GmbH – UFZ, Departments Cell Toxicology and Bioanalytical Ecotoxicology, Leipzig, Germany.
- Hans Peter Arp and Deter Issler from Norwegian Geotechnical Institute (NGI), Oslo, Norway;
- Matthew McLeod, Elena Gorokhova, Eric McGivney, Martin Ogonowski, Berit Gewert and Zandra Gerdes from Stockholm University, Department of Environmental Science and Analytical Chemistry (ACES), Stockholm, Sweden;
- Annegret Potthoff and Kathrin Oelschlägel from Fraunhofer Association, Institute for Ceramic Technologies and Systems (IKTS), Dresden, Germany;

We would like to thank the following institutes and persons for being part of our stakeholder group:

- Flemish Marine Institute (VLIZ: Dr. Jan Mees)
- Flemish Institute for Agriculture and Fisheries (ILVO: Johan Robbens)
- Flemish Environmental Agency (VMM: Lieve Jorens, Saskia Vangaever)
- VITO (Dr. Els Knaeps)
- OVAM (Annelies Scholaert)
- Aquafin (Greet Degueldre)

- UGent (Prof. Colin Janssen, Prof. Carl Van Colen)
- UAntwerpen (Dr. Camilla Carteny)
- Plastics Europe
- Norner Research AS, Norway (Thor Kamfjord, Ravindra Chowreddy)

REFERENCES

Bagaev, A., Mizyuk A., Khatmullina L., Isachenko I. & Chubarenko I. (2017), Anthropogenic fibres in the Baltic Sea water column: field data, laboratory and numerical testing of their motion, *Sci. Total Environ.,* 599–600: 560–571.

Ballent A., Pando, S., Purser A., Juliano M.F. & Thomsen L. (2013), Modelled transport of benthic marine microplastic pollution in the Nazaré Canyon, *Biogeosci.,* 10: 7957–7970.

Benoit M., Marcos F. & Becq F. (1996), Development of a third generation shallow-water wave model with unstructured spatial meshing. *Proc. 25th Int. Conf. on Coastal Engineering*, 465-478.

Bergmann M., Wirzberger V., Krumpen T., Lorenz C., Primpke C., Tekman M.B. & Gerdts G. (2017), High quantities of microplastic in Arctic deep-sea sediments from the HAUSGARTEN Observatory, *Environ. Sci. Technol.,* 51: 11000–11010.

Bi, Q., Wongsoredjo S. & Toorman E.A. (2019). Internal Report, Hydraulics Division, Dept. of Civil Engineering, KU Leuven.

Delandmeter, Ph. & van Sebille, E. (2018). How do different physical processes affect the pathways of floating microplastic? The Parcels Lagrangian Ocean analysis framework. *Conference Proceedings, MICRO2018* (Lanzarote), p.81.

Dietrich W.E. (1982). Settling velocity of natural particles, *Water Resources Research*, 18(6): 1615–1626.

Efimova I., Bagaeva M., Bagaev A., Kileso A. & Chubarenko I.P. (2018). Secondary microplastics generation in the sea swash zone with coarse bottom sediments: laboratory experiments. *Front. Mar. Sci.* 5:313.

Ernst S. (2016). Implementation of a flocculation model in TELEMAC-3D. MSc thesis KU Leuven, Dept. of Civil Engineering, 151 pp.

Gewert B., Ogonowski M., Barth A. & MacLeod M. (2017). Abundance and Composition of near Surface Microplastics and Plastic Debris in the Stockholm Archipelago, Baltic Sea. *Marine Pollution Bulletin*, 120: 292–302.

Hardesty B.D., Harari J., Isobe A., Lebreton L., Maximenko N., Potemra J., van Sebille E., Vethaak A.D. & Wilcox C. (2017), Using numerical model simulations to improve the understanding of micro-plastic distribution and pathways in the marine environment, *Front. Mar. Sci.,* vol. 4, p. 30, 2017.

Isobe A., Kubo K., Tamura Y., Kako S., Nakashima E. & Fujii N. (2014), Selective transport of microplastics and mesoplastics by drifting in coastal waters, *Mar. Pollut. Bull.,* 89: 324–330.

Jalon-Rojas I., Fredjk E. & Wang X.H. (2018). Numerical Model Simulation to improve the understanding of Micro-Plastics Debris in marine environments: sensitivity of microplastics fate to particles physical properties and behavior. *Conference Proceedings, MICRO2018* (Lanzarote), p.84.

Khatmullina L. & Isachenko I. (2016). Settling velocity of microplastic particles of regular shapes. *Marine Pollution Bulletin*, 114: 871–880.

Kowalski N., Reichardt A.M. & Waniek J.J. (2106), Sinking rates of microplastics and potential implications of their alteration by physical, biological, and chemical factors, *Mar. Poll. Bull.,* 109: 310–319.

Lebreton L.C.-M., Greer S.D. & Borrero J.C. (2012), Numerical modelling of floating debris in the world's oceans, *Marine Poll. Bull.,* vol. 64, p. 653–661, 2012.

Lee B.J., Toorman E.A., Moltz F. & Wang J. (2011). A two-class population balance equation yielding bimodal flocculation of marine or estuarine sediments. *Water Research*, 45: 2131-2145.

Onink V. & van Sebille E. (2018). Why does floating microplastic accumulate in the subtropical gyre of the North Atlantic Ocean? *Conference Proceedings, MICRO2018* (Lanzarote), p.86.

Potemra J.T. (2012), Numerical modeling with application to tracking marine debris," *Mar. Pollut. Bull.,* 65: 42–50.

Scheijen N. (2018). Plastic litter in the ocean: Modeling of the vertical transport of micro plastics in the ocean, BSc Thesis, TU Delft, the Netherlands.

Schlichting H. & Gersten K. (2018), Boundary-Layer Theory (9th Edition), Berlin: Springer-Verlag.

Shen X., Lee B.J., Fettweis M., Toorman E.A. (2018a). A tri-modal flocculation model coupled with TELEMAC for estuarine muds both in the laboratory and in the field. *Water Research*, 145: 473-486.

Shen X., Toorman E.A., Lee B.J. & Fettweis M. (2018b). Biophysical flocculation of suspended particulate matters in Belgian coastal zones. *Journal of Hydrology*, 567(12): 238-252.

Shen X., Toorman E.A., Lee B.J. & Fettweis M. (2019a). Simulating multimodal floc size distributions of suspended cohesive sediments with lognormal subordinates: Comparison with mixing jar and settling column experiments. *Coastal Engineering*, 148(6): 36-48.

Shen X., Toorman E.A., Lee B.J., Fettweis M. (2019b). An approach to modeling biofilm growth during the flocculation of suspended cohesive sediments. *J. Geophysical Research – Oceans*, 124(6): 4098-4116.

Sherman P. & Van Sebille E. (2016), Modeling marine surface microplastic transport to assess optimal removal locations, *Environ. Res. Lett.,* 11, 014006.

Stuparu D., van der Meulen M., Kleissen F., Vethaak D., Serafy G. (2015), Developing a transport model for plastic distribution in the North Sea, *Proc. 36th IAHR World Congress*, The Hague, the Netherlands.

Van Cauwenberghe L., Vanreusel A., Mees J. & JanssenC.R. (2013), Microplastic pollution in deep-sea sediments, *Environ. Poll.,* 182: 495–499.

Waldschläger K., Schüttrumph H. (2019), Effects of particle properties on the settling and rise velocities of microplastics in freshwater under laboratory conditions," *Environmental Science & Technology*, 53: 1958-1966.

Wichmann D., Delandleter Ph. & van Sebille E. (2018). The role of vertical mixing on the global distribution of near-surface microplastic. *Conference Proceedings, MICRO2018* (Lanzarote), p.80.

Woodall L.C., Sanchez-Vidal A., Canals M., Paterson G.L.J., Coppock R., Sleight V., Calafat A., Rogers A.D., Narayanaswamy B.E. & Thompson R.C. (2014), The deep sea is a major sink, *Royal Society Open Sci.,* 1, 140317.

Yang C., Jiang C. & Lin B. (2012). Modelling graded sediment transport and bed evolution in a tidal harbour, *Journal of Coastal Research* 29(3): 736-744.

ANNEXES

The final report of the WEATHER-MIC project, submitted to JPI Oceans, comprising the overview of the contributions of all five partners, is sent as a separate annex.