A Lagrangian Model for Microplastics Transport in Rivers

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Summary

Microplastics are a serious problem due to their high presence in drinking water. This implies a high probability of being ingested by humans, which can cause serious health problems. This work presents a Lagrangian model to simulate the evolution of microplastics in rivers, to analyze possible solutions to this problem.

Introduction

Currently, the transport of debris by water flows, such as rivers, is the main cause of many natural and environmental disasters [1]. These disasters can range from the transport of cars or large objects in floods, to the transport of pollutants in rivers such as plastics or microplastics. In fact, in recent years, numerous studies have shown a high concentration of microplastics in water for domestic use and rivers [2]. The presence of microplastics in our daily life is a threat to public health as they can be ingested and cause serious diseases in humans and animals [3].

The transport of microplastics, as well as the evolution of the flow, can be represented mathematically by complex systems of equations that require computational solutions. In fact, numerical simulation is a valuable technology for analyzing, understanding, and preventing natural hazards, as it allows risk assessment based on various hypotheses and scenarios [4].

The present work is a first step to study the spatial and temporal evolution of the transport of microplastics using a Lagrangian model. Material elements are entrained and transported based on the hydrodynamic forces, computed with appropriate coefficients, or following a kinematic approach. This model is driven by an Eulerian model based on the Shallow Water Equations (SWE) to describe the evolution of the flow. The implementation of these new techniques is part of an ongoing initiative to develop a modelling framework based on physically-based surface hydrodynamics: the SERGHEI (Simulation Environment for Geomorphology, Hydrodynamics and Ecohydrology in Integrated form) model [5]. The Lagrangian Particle Tracking module has been seamlessly integrated into SERGHEI, which empowers researchers and practitioners to comprehensively study the spatial and temporal evolution of microplastics transport.

Methodology

The hydrodynamic model implemented in SERGHEI is based on the SWE. These equations and their solution by means of an explicit numerical method in finite volumes based on the Aug-Roe solver are presented in this work, all developed in more detail in [4]. Subsequently, the equations corresponding to passive particle transport are presented, which are solved using a Euler explicit method.

Hydrodynamic Model

The mathematical model that describes the surface flow is given by the hyperbolic 2D SWE based on mass and momentum conservation [6]:

$$\frac{\partial}{\partial t}\begin{pmatrix} h\\ hu\\ hv\end{pmatrix} + \frac{\partial}{\partial x}\begin{pmatrix} hu\\ hu^2+\frac{gh^2}{2}\\ huv\end{pmatrix} + \frac{\partial}{\partial y}\begin{pmatrix} hv\\ huv\\ hv^2+\frac{gh^2}{2}\end{pmatrix} = \begin{pmatrix} 0\\ gh(S_{ox}-S_{fx})\\ gh(S_{oy}-S_{fy})\end{pmatrix}$$

in terms of the water depth, h, the depth averaged unit discharges hu and hv in the x and y directions respectively. The slopes S_{ox} and S_{oy} are the two components of the bottom surface gradient and S_{fx} and S_{fy} represent friction slopes.

Lagrangian Microplastics Transport Model

The Lagrangian model for the microplastics transport is based on the main effects that the microplastics suffer into the water: the transport based on the advection, the turbulence of the flow, the sinking/deposition and the degradation. For a particle $\mathbf{p}$ located in a cell i, the discretized version of its trajectory is as follows:

$$\mathbf{r}_{\mathbf{p}}^{n+1} = \begin{cases} x_{\mathbf{p}}^{n+1} = x_{\mathbf{p}}^{n} + u_i^n \Delta t^n + \delta_x^n \\ y_{\mathbf{p}}^{n+1} = y_{\mathbf{p}}^{n} + v_i^n \Delta t^n + \delta_y^n \\ z_{\mathbf{p}}^{n+1} = z_{\mathbf{p}}^{n} + \omega_s^n \Delta t^n + \delta_z^n \end{cases}$$

where u_i^n and v_i^n are the x and y components of the advection velocity in the cell i at the iteration n; Δt^n is the time step; δ_x^n, δ_y^n and δ_z^n are the turbulence terms for each spatial component calculated as a random-walk model [7]; and ω_s^n is the sinking velocity, that depends on the microplastics form, being for a cylinder of diameter D_0 and length L_0:

$$\omega_s^n = -\frac{\pi}{2\nu_w} \frac{g(\rho_{\mathbf{p}} - \rho_w)}{\rho_w} \frac{D^n L^n}{55.238L^n + 12.691}$$

and for a sphere of diameter D_0:

$$w_s = -\frac{\nu_w}{D^n} {d_*^n}^3 \left(38.1 + 0.93 {d_*^n}^{12/7}\right)^{-7/8}, \; d_*^n = \left(\frac{{D^n}^3 g(\rho_{\mathbf{p}} - \rho_w)}{\rho_w \nu^2}\right)^{1/3}$$

being ν_w the water kinematic viscosity, $\rho_{\mathbf{p}}$ the microplastic density and ρ_w the water density. The degradation is added to the reduction of the microplastic size as follows:

$$D^n = D_0 - \alpha_D^n, \; L^n = L_0 - \alpha_L^n$$

where α_D^n and α_L^n are the degradation ratio of diameter and length at the iteration n.

Results

The Lagrangian model is validated simulating a test case. This test case is a rectangular channel with length $L = 10\text{m}$ and width $B = 4\text{m}$, where there are two different water depth levels ($h = 4\text{m}$ in the left region and $h = 1\text{m}$ in the right region of the channel) as the initial condition. There is not any boundary condition, therefore, the flow suffer a collision against the walls, producing periodic oscillations. There are 200 microplastic spherical particles, with $R = 1\text{mm}$ and $\rho_{\mathbf{p}} = 900\text{kg/m}^3$. The duration of the simulation is 1000s, therefore, the degradation is not considered because it is negligible for a short period of time. The results are shown in Figure 1. As can be seen in this figure, the flow displaces the particles by means of advection and turbulence. In addition, it can be observed how the particles rise to the surface because they have a lower density than water.

Conclusions

As it can be seen in the Figure 1, the results provided by the microplastics model can be useful to understand the behaviour of microplastics in rivers and hydrological regions. Moreover, the possibility of simulating the microplastics transport provides the search of potential solutions to reduce the concentrations of microplastics in these areas, leading to the conclusion that the model implemented can be combined with the SERGHEI framework as a tool for environmental risk prediction. However, more experiments should be sought/performed to further validate the model, so that it can be corrected and improved. Future work is planned to simulate real events and to extend the model to large debris, such as cars, waste containers or boulders.

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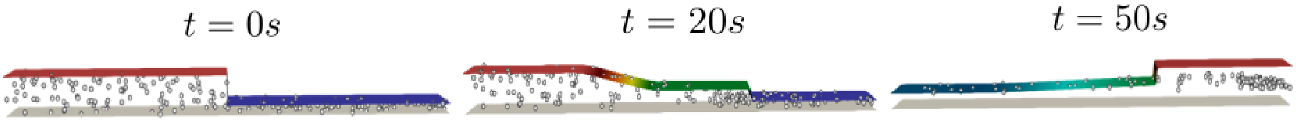

Figure 1: Three states of the dambreak case with 200 particles where the upper surface is the free water surface, and the lower surface is the bottom elevation.