A GPU based model for multi-layer scalar transport in open channels

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Introduction

Scalar transport models derived from the two-dimensional depth averaged shallow water equations are frequently applied to a wide range of environmental flow conditions. A scalar may represent a dissolved solute, a pollutant, or fine sediment transported in river channels, estuaries, or ocean waters. However, these depth-averaged scalar transport models do not provide detailed information about the vertical distribution of the solute. The vertical distribution of a scalar could be computed from the 3D shallow water equations but is complex to compute numerically. One possible approach is to implement a multi-layer transport system, in which exchanges between layers determine the vertical concentration distribution of the transported scalar depending on the velocity of deposition, vertical eddy viscosity, and flow velocity. The model presented is a GPU-based multi-layer scalar transport model implemented in C++/CUDA and coupled with an existing two-dimensional shallow water (SWE-2D) model. The SWE-2D framework is designed to handle three types of mesh topology: structured quadrilateral meshes, structured triangular meshes, and unstructured triangular meshes. The aim of this study is to study the performances of the multi-layer model qualitatively and computationally talking. To assess the viability of the multi-layer model, a series of synthetic channel test cases are implemented, in which the vertical eddy viscosity and the settling velocity are systematically varied but the vertical velocity considered as constant in depth. In addition, an experimental study by García J.A et al. [1], investigating the vertical concentration distribution of a passive solute in unsteady laboratory channel flow (Figure 2), is reproduced using the multi-layer framework.

Model Description

The multi-layer system is implemented using an implicit scheme that accounts for inter-layer exchanges [2]. The layers are uniformly distributed in the vertical direction, with the total water depth divided by the number of layers, however, layer thickness varies in time and space with the water depth. Flux exchanges between layers depend on the vertical eddy viscosity, flow velocity, and the scalar deposition (settling) velocity (Figure 1).

$$\frac{\partial(h_l\phi_l)}{\partial t}+\frac{(h_l u_l\phi_l)}{\partial x}+\frac{(h_l v_l\phi_l)}{\partial y}=\int_{zl-\frac{1}{2}}^{zl+\frac{1}{2}}\frac{\partial}{\partial z}(\omega_s\phi_l)dz+\int_{zl-1/2}^{zl+1/2}\frac{\partial}{\partial z}(\epsilon_z\frac{\partial\phi_l}{\partial z})dz \quad (1)$$

The scalar transport in the vertical is illustrated by the equation (1), being $h_l$the layers thickness, the scalar flux in each layer and ω_s, ϵ_z the settling velocity and the eddy viscosity respectively.

Different types of vertical eddy viscosity models have been developed (linear and constant), and the vertical flow velocity model implemented is a simple logarithmic wall low model, characterized by(u_l, v_l) [3].

Results and Discussion

Different sensitivity tests were performed to assess the model response to changes in eddy viscosity and settling velocity, allowing their calibration using a simple case study (uniform flow in a synthetic straight channel). Different mesh types and sizes were tested, as well as different numbers of layers. These additional tests also enabled evaluation of the differences in computational time. The model proved to be both conservative and stable. Moreover, the computational time did not increase significantly with an increasing number of layers.

A laboratory case was also studied using the multi-layer model with different mesh types. The results from the laboratory experiments and the numerical model were first compared using depth-averaged concentrations and, secondly, using the multi-layer system with a depth-varying vertical velocity profile. A 2D depth-averaged shallow-water scalar transport model was also applied to the same case, and its results were compared with both the experimental data and the multi-layer model results. Comparison of these different models with the experimental data demonstrates that the model is capable of reproducing the overall vertical evolution of scalar concentration. In addition, the multi-layer model results are closer to the experimental observations than those obtained using a single-layer model (Figure 3).

Conclusion

The model demonstrates a good representation of the horizontal solute distribution. Vertically, when the flow velocity varies with depth, the multi-layer system captures the solute global distribution, however, the lack of precision is due to the eddy viscosity vertical models that must be adapted to the specific flow conditions and environmental context. Moreover, physical turbulent diffusion was neglected in this study to simplify the analysis. However, previous studies using the same laboratory case have shown that the diffusion coefficients strongly influence the model results and therefore must also be calibrated [4].

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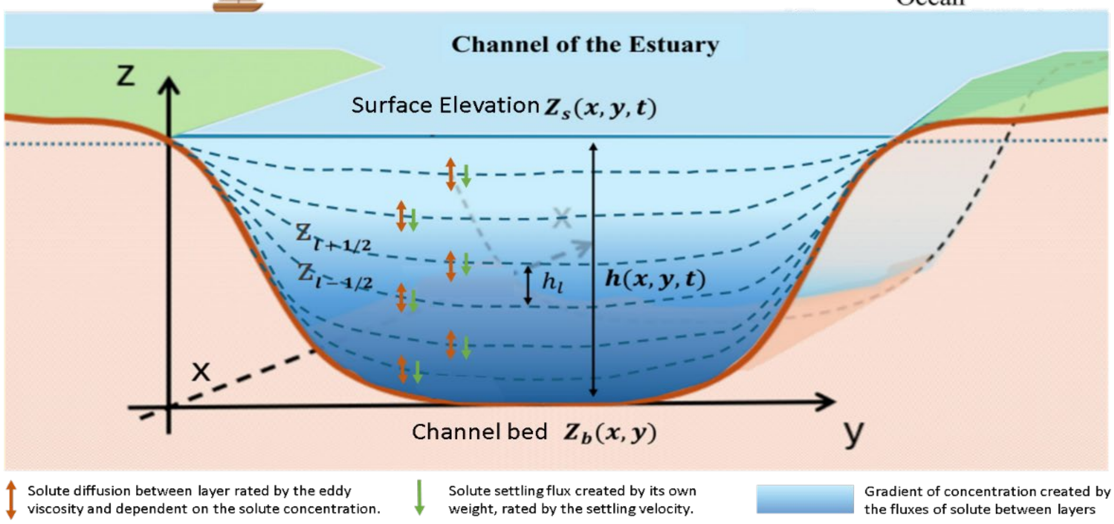

Figure 1: Schematic representation of the multi-layer model and its function in a river/estuary channel.

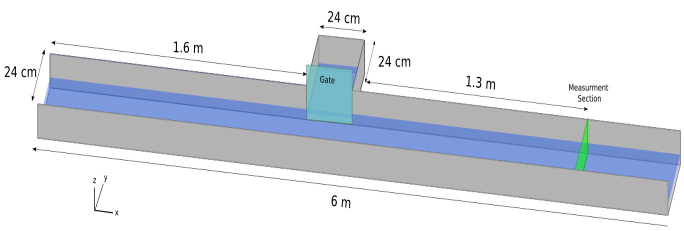

Figure 2: Schematic representation of the laboratory channel used to get experimental data.

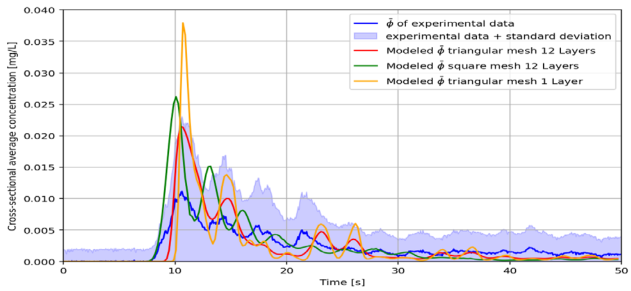

Figure 3: Comparison of the cross-averaged experimental data with the different multi-layer modeled used: a single-layer model, a triamgular mesh 12-layer model and a rectangular mesh 12-layer model.