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

VII JORNADA DEL I3A – XV JORNADA DE JÓVENES INVESTIGADORES

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ABSTRACT

Transport of solutes and suspended sediments in estuaries and river channels is a key parameter for environmental studies and is typically analysed within the water column. Three-dimensional (3D) models coupled with transport equations are often used for this purpose; however, they require high computational resources and, in most cases, limit the achievable mesh resolution. This study proposes the use of a GPU-based two-dimensional (2D) shallow water model coupled with a multi-layer solute transport system adapted to the water column depth. **The main objective is to assess whether this modelling approach can accurately reproduce experimental data while maintaining high mesh resolution and reducing computational time.**

GOVERNING EQUATIONS

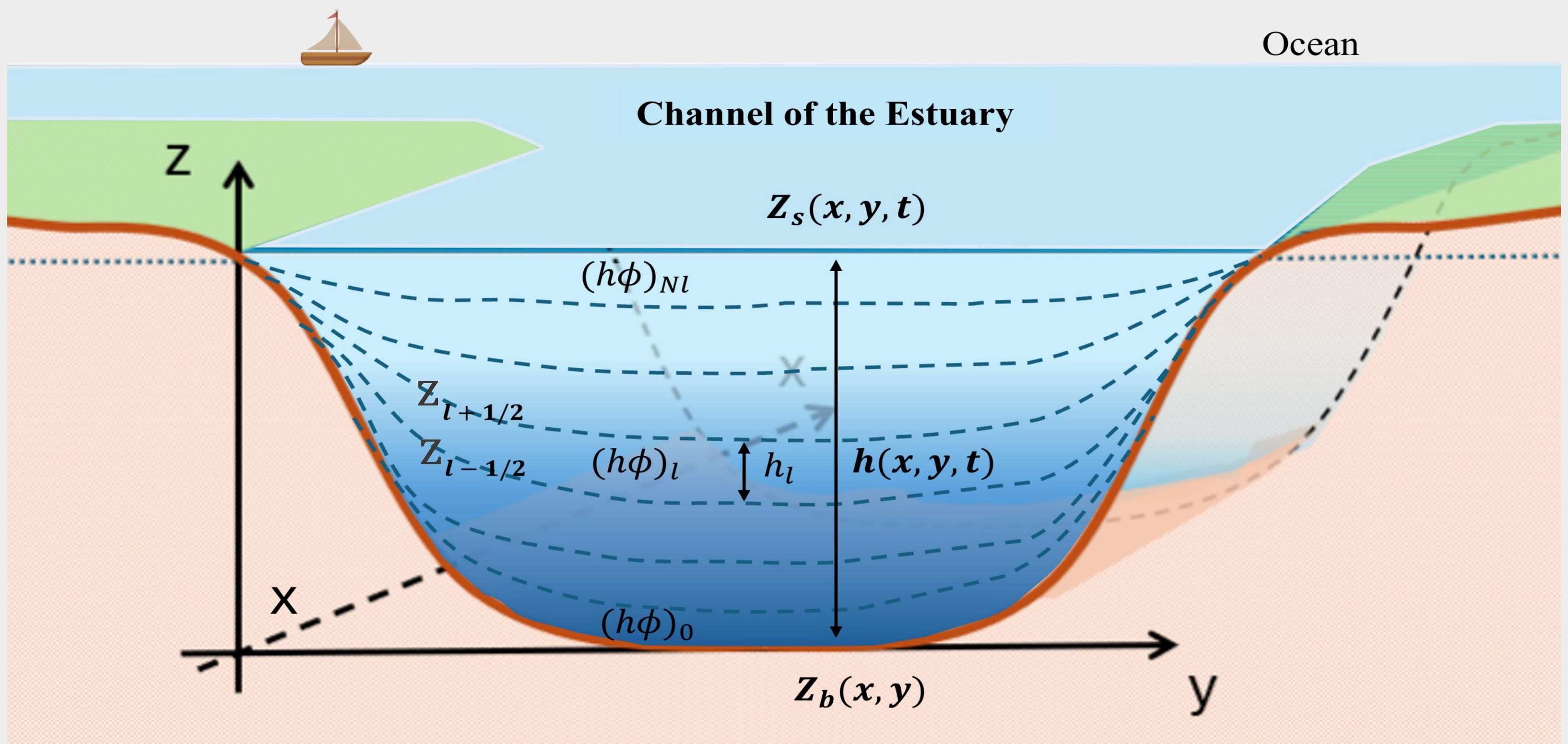
Hydrodynamic System [1]

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{\partial hu}{\partial x} + \dfrac{\partial hv}{\partial y} = 0 \\ \dfrac{\partial hu}{\partial t} + \dfrac{\partial}{\partial x}\left(hu^2 + \dfrac{1}{2}gh^2\right) + \dfrac{\partial}{\partial y}(huv) = -gh\left(\dfrac{\partial z_b}{\partial x} + \dfrac{n^2 u\|\mathbf{u}\|}{h^{\frac{4}{3}}}\right) \\ \dfrac{\partial hv}{\partial t} + \dfrac{\partial}{\partial x}(huv) + \dfrac{\partial}{\partial y}\left(hv^2 + \dfrac{1}{2}gh^2\right) = -gh\left(\dfrac{\partial z_b}{\partial y} + \dfrac{n^2 \mathbf{v}\|\mathbf{u}\|}{h^{\frac{4}{3}}}\right) \end{cases}$$

Depth Averaged Velocity Vector $u = \frac{1}{h}\int_{z_b}^{z_s} u_x\, dz, \quad v = \frac{1}{h}\int_{z_b}^{z_s} u_y\, dz$

h water depth z_b bottom elevation z_s surface elevation n Manning's roughness

Numerical Resolution: Explicit first order upwind scheme based on Roe's linearization.



Multi-layer Solute Transport [3]

$$\frac{\partial(h_l\phi_l)}{\partial t} + \frac{\partial(h_l u_l \phi_l)}{\partial x} + \frac{\partial(h_l v_l \phi_l)}{\partial y} = \int_{zl-1/2}^{z_{l+1/2}} \frac{\partial}{\partial z}(w_s\phi_l)dz + \int_{zl-1/2}^{z_{l+1/2}} -\frac{\partial}{\partial z}\left(\epsilon_z \frac{\partial \phi_l}{\partial z}\right)dz$$

ϕ_l h_l-averaged concentration h_l layers thickness ω_s settling velocity ϵ_z turbulent eddy viscosity

Numerical Resolution:

- Explicit first order upwind scheme for the advection.
- Explicite first order upwind scheme for the settling velocity.
- Implicit scheme for vertical diffusion.

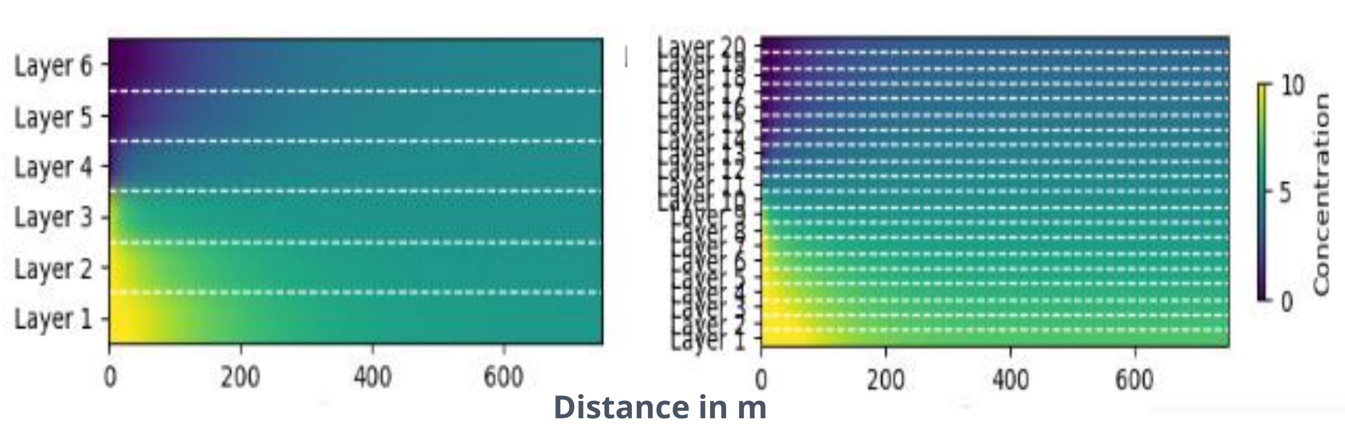
Flow velocity modulus based on the Law of the Wall [2]

$$V_l\left(\frac{z_l}{h}\right) = \frac{u^*}{k} ln\left(\frac{30h}{k_s}\right) + \frac{u^*}{k}\ln\left(\frac{z_l}{h}\right)$$

u^* friction velocity $k = 0{,}41$ von Karman constant

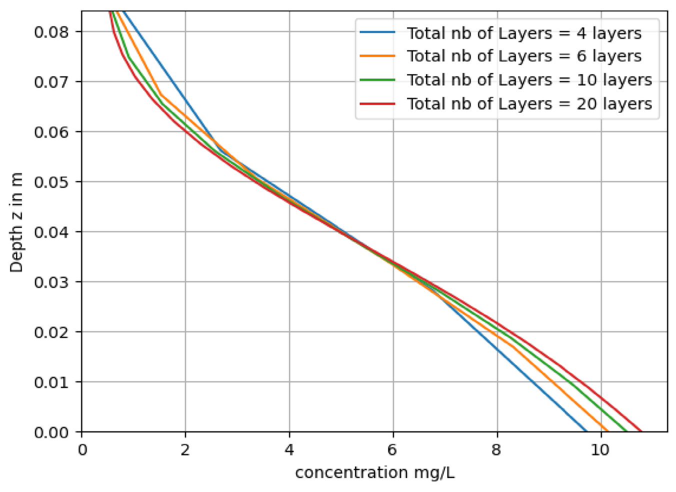
MODEL PERFORMANCE IN A TEST CASE

Vertical Plot at steady final state



Computational Times

	Squared Mesh	Unstruc. Triangular Mesh
Nb of cells	100000	199936
3layers	20.90s	84.36s
4 Layers	22.58s	91.05s
6 Layers	26.10s	108.1s
10 Layers	34.65s	140.9s
20 Layers	50.89s	225.0s

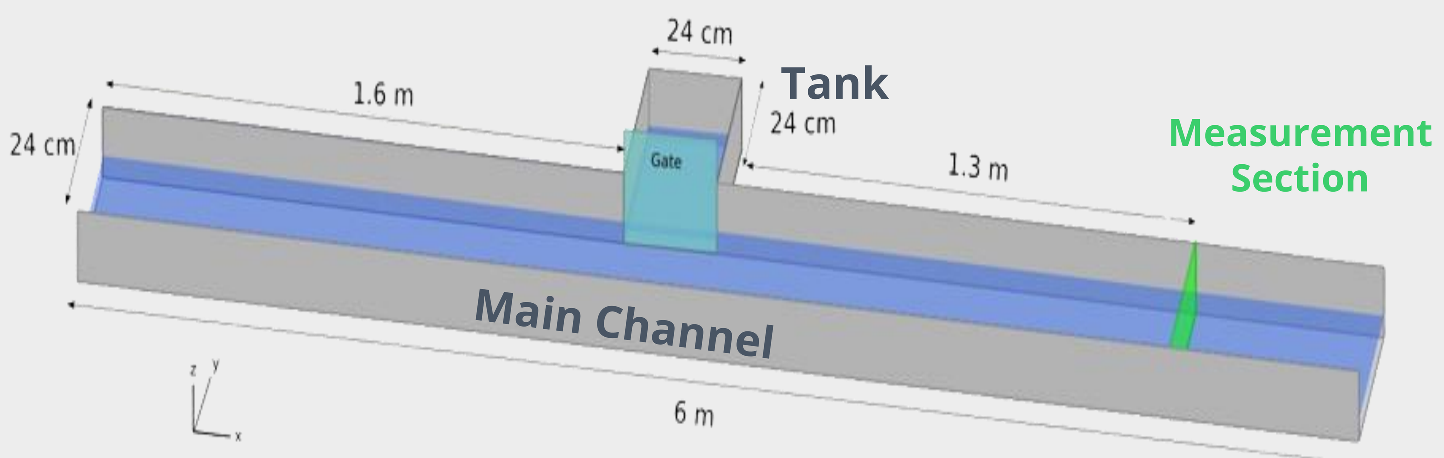


The model was calibrated using a simple channel with inlet concentration of 10 mg/L at the bottom layers. The number of layer is increased from 3 to 20 layers.

LABORATORY EXPERIMENT

Tank:
0.24 mg/L of fluorescien
h = 0.85cm

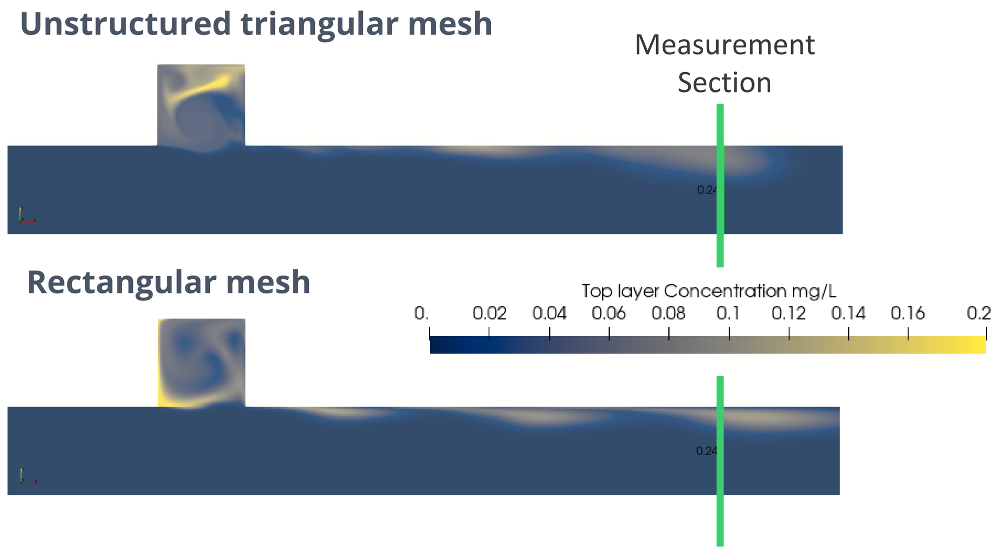
Model Parameters:
12 Layers
$\omega_s = 0$ m/s
$\epsilon_z = 5 \times 10^{-6}\ m^2/s$



Experimental study of the mixing and dispersion of fluorescein [5]. Q=2.4 m^3/h in the channel. A tank containing a solution of fluorescein is separated from the channel by a gate. The simulation/experiment starts when the gate is opened.

The GPU based multi-layer model is tested using an unstructured triangular mesh (809,211 cells) and a rectangular mesh (115,200 cells).

2D Upper Layer t = 10.76 s

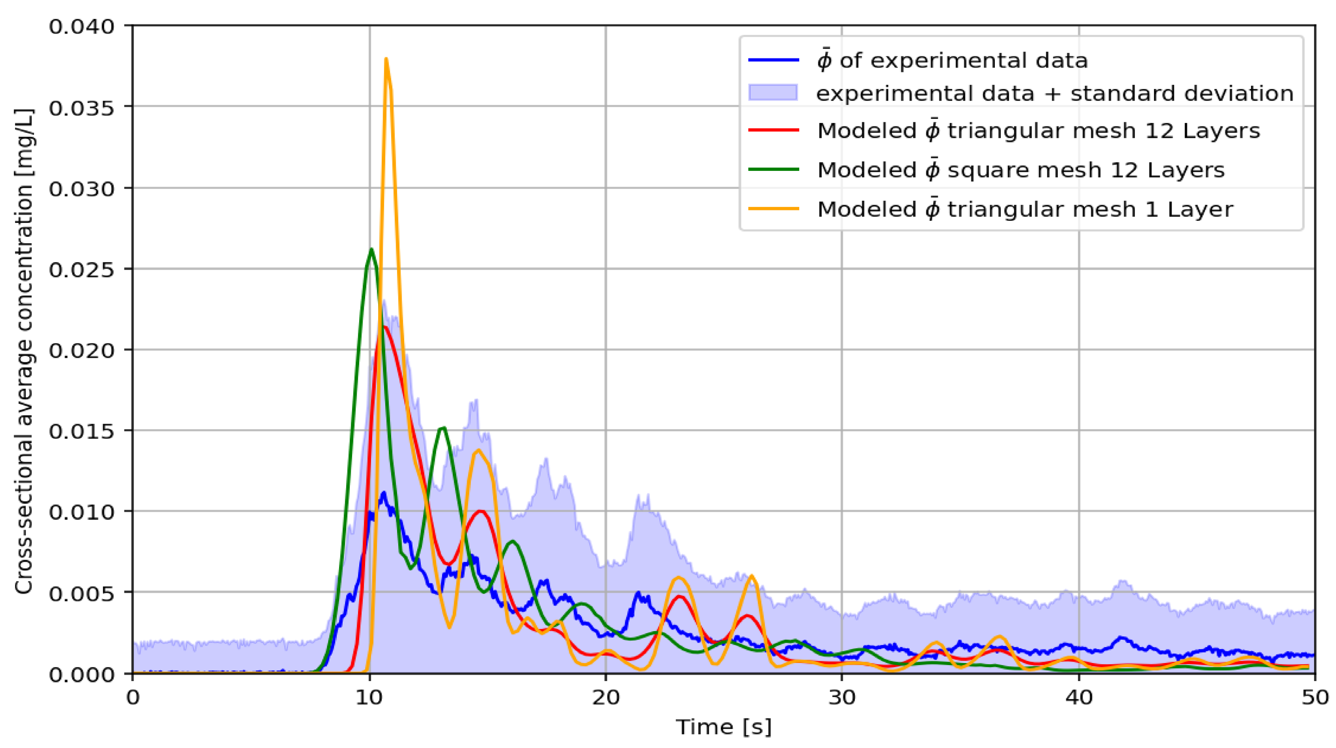


Total of Simulation: 1,546.97 s (25 min 46 s)

Number of output: 241 vtk Images

GPU used: NAVIDIA GeForce RTX 4070

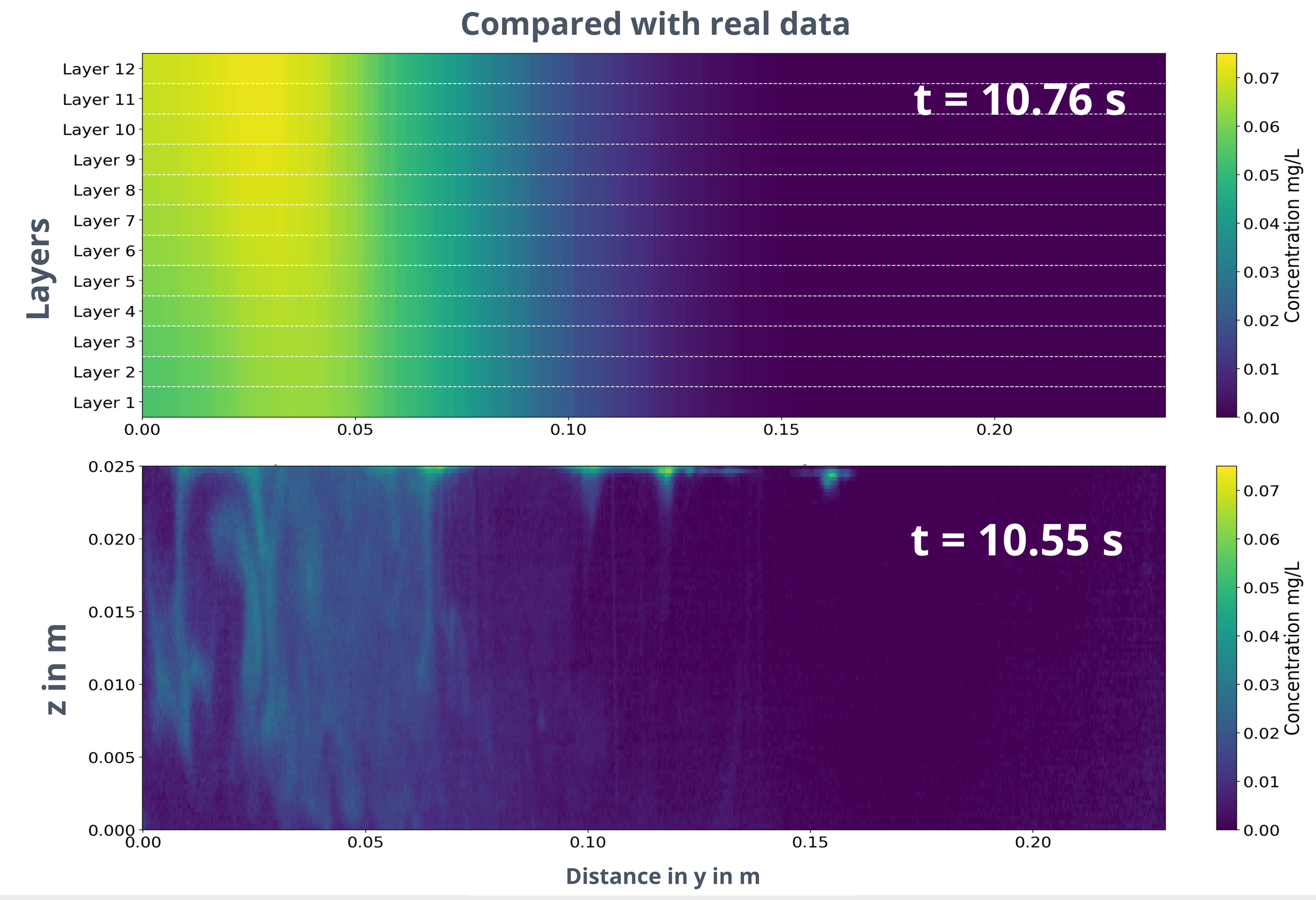
1st Peak



Vertical plot

Results from multi-layer model at the measurement section

Compared with real data



CONCLUSION AND FUTURE WORK

The model demonstrated its effectiveness through the combined use of a multi-layer approach and GPU-based computation. The results show good agreement with the experimental data, with a root mean square error (RMSE) of 0.002 mg/L. However, it is important to note that mesh geometry plays a significant role in the accuracy of this type of study. Future work will focus on improving the representation of turbulence by allowing the eddy viscosity to vary within the water column, particularly in estuarine environments. In addition, a more accurate vertical velocity profile will be implemented, accounting for variations in salinity, temperature, and water depth.

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