Numerical Analysis of Particle Trajectories Driven by Currents and Waves in an Idealized Estuarine Model

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ABSTRACT
Estuaries, which serve as critical transitional zones between riverine and marine ecosystems, are subject to complex hydrodynamic processes due to the combined influences of river inflows, tidal forces, and oceanic currents. Understanding particle trajectories within these environments is crucial for assessing the transport of sediments, pollutants, and other materials. This study utilizes a numerical modeling approach to examine nearshore circulation generated by currents around an idealized inlet configuration. The primary objective is to compare trajectories of water particles extracted using the Delft-3D software with the results obtained from a 2DH Nonlinear Shallow Water Equation (NSWE) solver. Both modeling approaches reveal dominant circulation patterns around the inlet, yet differences emerge in the particle distribution. Using a tailored Lagrangian tracker, the NSWE solver results are also used to investigate the fate of non-neutral units, with the objective to mimic the motion of plastic particles with different densities. These findings contribute to a better understanding of the hydrodynamic processes in estuarine environments, particularly in terms of pollutant particle retention and dispersion.

Keywords: Estuarine Environment; Particle dispersion; Delft-3D; Nonlinear Shallow Water Equations.

INTRODUCTION
Estuarine environments are characterized by complex and dynamic water movements, driven by the interplay of riverine inflows, tidal fluctuations, and oceanic currents. These interactions result in variable particle trajectories that influence critical processes, such as sediment deposition, nutrient dispersion, and contaminant transport (Özsoy and Ünlüata, 1892). Estuaries play a pivotal role in regulating the transport of sediments and nutrients, which can either be retained within these zones or exported to the open ocean, depending on the prevailing hydrodynamic conditions (Fontes et al., 2014). The dynamic interplay of forces within estuaries creates constantly fluctuating conditions that affect sediment transport, nutrient cycling, and ecosystem health (Jay and Musiak, 1994).
Accurately predicting particle trajectories in such environments is essential for effective estuarine management. This is particularly critical for addressing issues like sedimentation or pollution, where understanding transport pathways can inform mitigation strategies. Numerical modeling has proven to be a valuable tool for simulating the complex processes governing particle movement, providing insights that aid in the development of strategies to manage and protect these sensitive coastal areas.
In this study, a particle-tracking model integrated within a hydrodynamic framework is employed to simulate particle trajectories in a simplified estuarine environment. The primary goal is to compare two distinct methods for tracking particle movement: Delft-3D, a sophisticated hydrodynamic modeling software, and a MATLAB-based script, utilizing the hydrodynamic simulation computed by the NSWE solver's velocity field and wave as an input. This comparison evaluates the capabilities of each approach in simulating particle trajectories, highlighting their respective strengths and limitations within a controlled estuarine domain.

MATERIALS AN METHODS
Model setup – Delft-3D
To simulate the effects of currents and waves on a simplified inlet, a series of numerical simulations were conducted to examine nearshore circulation patterns. The Delft-3D software was employed for this study, providing a basis for comparison with the work of Olabarrieta et al. (2014), which offers a robust framework for understanding hydrodynamic and sediment transport processes in estuarine environments. Delft-3D, developed by Delft Hydraulics (now Deltares), is a versatile numerical modeling system capable of simulating hydrodynamic processes driven by waves, tides, rivers, winds, and coastal currents (Delft-3D, 2024).
The primary objective of this study was to explore the effects of river currents entering the sea and wave effects on particle tracking, leveraging Delft-3D's robust hydrodynamic and particle transport modeling capabilities.
For the simulations, the computational grid was created in Delft-3D, with bathymetry data sourced from an in-house NSWE solver (Brocchini et al., 2001; Melito et al., 2018) that employs a 2DH formulation suitable for shallow-water conditions. The grid dimensions were $300 \times 151\ [M \times N]$ with $\Delta x = 20,\ \Delta y = 10\ m$, covering a domain of $3 \times 3\ km$ in the cross-shore and alongshore directions. The estuarine window accounted for the current velocity, while Reimann boundary conditions were applied at the seaward boundaries.
According to Figure 1, the model domain features a maximum water depth of approximately 9 m at the offshore boundary.

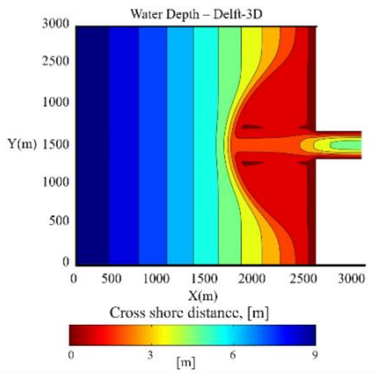

Figure 1. Water depth, Delft-3D.

This bathymetric profile aligns well with the findings of Olabarrieta et al. (2014), further validating the model's accuracy in replicating key dynamics, such as flow circulation and particle trajectory patterns.
Figure 2 presents depth-averaged velocities simulated using Delft-3D. This simulation compares well with NSWE simulation (Melito et al., 2018) and shows that the flow is primarily directed downstream, with velocity decreasing laterally as the distance from the centerline increases. Delft-

3D results display smoother and more symmetric velocity fields, characterized by a distinct jet spreading uniformly downstream. In contrast, the solver captures more intricate and turbulent flow features, including eddies and mixing zones, which become more pronounced at higher flow rates. The differences highlight the contrasting approaches of the models in resolving flow dynamics, particularly in regions with complex flow behaviour.

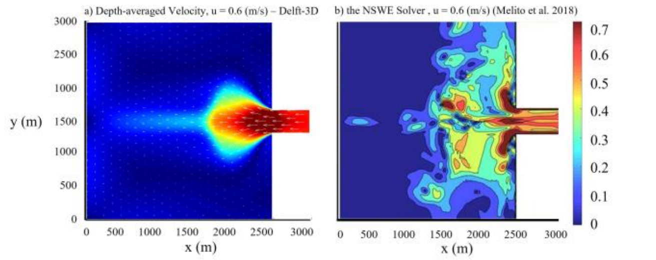

Figure 2. Comparison of depth-averaged velocity obtained using Delft-3D (left panel) and NSWE solver (right panel).

Releasing particles from the estuary into the sea is a common method for studying particle transport dynamics in coupled estuarine-coastal systems. To simulate particle transport, the Delft-3D model separates motion into two components: advection (representing large-scale flow) and dispersion (random spreading). Advection is solved analytically using a linearly interpolated velocity field, while dispersion is computed using Euler-type numerical scheme that incorporates wind-driven effects and settling processes (Delft3D-Part, 2024). In this study, to focus on horizontal transport mechanisms, particle settling is excluded in this analysis. This approach isolates the effects of flow velocity on particle trajectories, emphasizing the critical role of flow dynamics in controlling particle distribution and spread.

Model Setup- MATLAB Script

A custom MATLAB script has been implemented to simulate particle trajectories. This script tracks the particle movement by interpolating flow fields around particles. The hydrodynamic input data was sourced from the NSWE solver to analyze the effects of combined waves and current actions on particle pathways. Executing the NSWE solver requires the prior generation of a meshing domain. This process utilizes the code developed by Melito et al (2018), specifically designed for this purpose. The meshing domain is the same as that for Delft-3D. A series of numerical simulations were performed using the NSWE solver to investigate nearshore circulation induced by current around an idealized inlet configuration. The simulation results were then utilized as input for a MATLAB script. In this study, a single particle is transported by the flow velocity field derived from hydrodynamic simulations, with river-imposed current velocities of 0.6 and 1.6 m/s and no waves, weak waves and strong waves regime ($H_s = 0, 0.5, 1.5\ m$).

RESULTS AND CONCLUSION

In both models a single particle is released at different locations, allowing it to move according to the local flow field for 3600 seconds. Initially, the estuarine flow primarily governs the particle's motion. However, as the particle reaches the open sea, coastal currents become the dominant force. Increased momentum transfer from the river to the sea, driven by velocity, significantly influences the transport pathways.

Figure 3 displays the positions of a single particle with a time interval of 600 seconds and a flow velocity of 0.6 m/s at four different release points. As can be observed in Figure 2, the estuary channel has higher velocity, indicating strong flow. The Delft-3D simulation indicates that momentum drives the particle further into the coastal ocean, highlighting a strong influence on coastal dynamics. In contrast, the NSWE simulation shows that circulation limits greater particle dispersion, resulting in more localized transport.

In Figure 3-a, the particle is released at (x,y)=(270,75)m within the estuary channel, where the velocity is moderate to high. Based on the velocity field, the particle is expected to move seaward toward the estuary mouth. Upon reaching the high-velocity jet at the estuary mouth, it may be carried further offshore into the open sea.

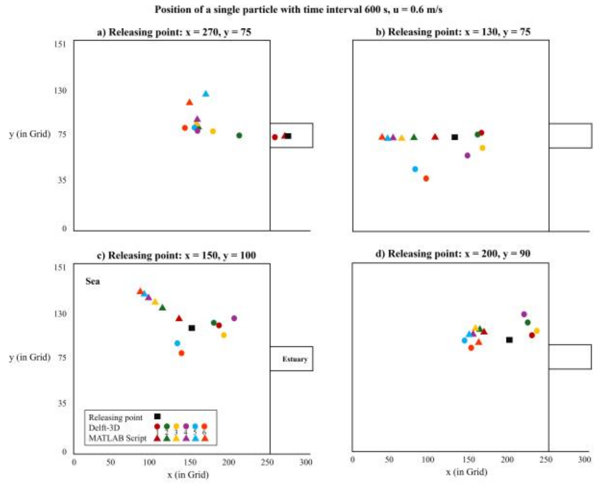

Figure 3. Comparison of single-particle trajectories in Delft-3D and MATLAB script: Influence of release location

Further results will be illustrated at the conference about the impact of waves on the particle motion, as well as the role of particle density.

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REFERENCES

Özsoy, E., & Ünlüata, Ü. (1982). Ebb-tidal flow characteristics near inlets Estuarine, Coastal and Shelf Science, 14(3), 251-IN3.

Fontes, R.F.C., & Miranda, L.B, F.P.A. (2014). Estuarine Circulation, Springer Science +Business Media Dordrecht.

Olabarrieta, M., Geyer, W.R., & Kumar, N. (2014). The role of morphology and wave-current interaction at tidal inlets: An idealized modeling analysis, *Journal of Geophysical Research: Oceans*. 119(12), 8818–8837.

Delft3D-Flow and WAQ PART User Manual. (2024). Deltares, Delft, The Netherlands.

Melito, L., Brocchini, M., Darvini, G., Lenci, S. (2018). On the hydro-morphodynamics of river mouths: the role of waves, Università Politecnica delle Marche. Faculty of Engineering, Civil Engineering Department.

Brocchini, M., Bernetti, R., Mancinelli, A., & Albertini, G. (2001). An efficient solver for nearshore flows based on the WAF method, *Coastal Eng*. 43(2), 105–129.