Tidal propagation into rivers influenced by salt intrusion

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Introduction

The propagation of tides into rivers is classically described as a balance between convergence-driven amplification and frictional damping (e.g., Savenije et al., 2008). In stratified estuaries, however, density gradients suppress turbulence, thereby reducing vertical mixing and altering effective bed friction (Geyer, 1993; Stacey et al., 1999). Vertical stratification can significantly alters tidal dynamics and has been shown to enhance tidal ranges (Winterwerp et al., 2009). Despite these insights, a systematic framework that quantifies how salinity-induced stratification influences tidal propagation into rivers is still lacking.

We investigate how salinity-induced stratification affects tidal water levels in rivers, and assess the adequacy of depth-averaged models to capture these effects. We address the following research questions: 1) How do salinity-induced density gradients influence tidal propagation? 2) Can physics-based parameterisations be used to improve depth-averaged model performance?

Method

The modelling software Delft3D Flexible Mesh (DFM; version 2025.01) is used. The tidal river is represented as a single channel of 250 km, a depth of 15m which slopes with 5×10^{-5} m/m. The model has a horizontal resolution of 100 m, uses 60 sigma-layers in the vertical and applies a uniform manning roughness of 0.03 $\mathrm{m}^{1/3}/s$.

At the upstream river boundary, a constant discharge q_r is applied and a background salinity of 0.1 PSU. At the river mouth, a S2 tidal range of A_0 and a salinity of 30 PSU are applied.

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Configurations & cases

Three salinity-stratification classes are considered:

- well-mixed: q_r=0.06m^2/s, A_0= 3.2m
- partially-mixed: q_r=0.6 m^2/s, A_0=1.6m
- salt-wedge: q_r=3.0 m^2/s, A_0=0.8m

Moreover, various cases are considered: depth-varying cases with and without salinity (called *Base case* and *Fresh case*, respectively), and depth-averaged cases with diagnostically derived salinity fields (*Diag. salinity*) and effective roughness fields (*Diag. Roughness*).

Results

Results per stratification class show clear differences in water levels when salinity is included. In the salt-wedge regime, tides amplify along the salt-intrusion region (0-45 km) in the Base case, but dampen throughout in the Fresh case. No significant change in tidal range is observed in the well-mixed regime (Figure 1).

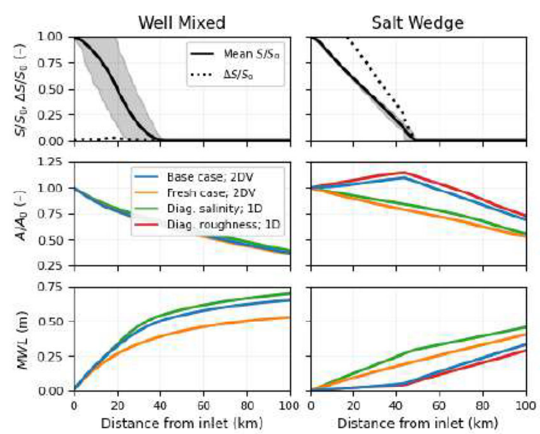

Figure 1. Hydrodynamic characteristics along the tidal river for well-mixed (left) and salt-wedge (right) regimes. Row 1: mean salinity, tidal salinity range, and stratification (Base case). Row 2: tidal range. Row 3: mean water level. Values are normalized by the value at the inlet where applicable

In the well-mixed estuary, mean water level (MWL) in the Fresh case is up to 0.20 m lower than in the Base case, reflecting a free-surface slopes induced by the depth-averaged salinity gradient. This process can be considered in a 1D model with a diagnostic salinity case (as shown in Savenije et al., 2007; Figure 1, green line).

Contrarily, in salt-wedge estuaries, neglecting salinity increases MWL, and adding a 1D diagnostic salinity field worsens agreement with the Base case. This is because in salt wedge systems, the depth-averaged density gradient is balanced internally, and does not result in a free-surface slope.

Amplification in the salt wedge regime is shown to be induced by a combination of processes. Vertical salinity stratification suppresses turbulence and lowers peak near-bed flow velocities, reducing the effective roughness along the salt-intrusion length. This weakens dampening and enhances tidal penetration. Moreover, at the salt intrusion length, the tide is partially reflected due to the sudden transition from low to high effective roughness, resulting in local amplification. A diagnostically derived reduction in effective roughness in a 1D model (*Diag. Roughness case*, red lines) mimics this, reproducing the tidal range profile successfully.

Also alternative geometries are considered, wherein the river is prismatic, tides amplifies in the Fresh case or where the river is relatively shallow. Identified findings are found to be true across all geometries considered.

Conclusion

In stratified tidal rivers, vertical density gradients weaken tidal damping and enhancing tidal penetration. Moreover, at the salt intrusion limit, partial reflection of the tide locally promotes tidal amplification, resulting in local maxima in tidal range. Together, these processes increased modelled tidal ranges by up to 30% near the salt-intrusion limit.

This has important implications for flood-risk predictions, whereby generally depth-averaged models are applied which lack (accurate) inclusion of salinity-induced effects. A substantial reduction in effective bed roughness along the stratified region allows depth-averaged models to mimic the tidal dynamics obtained when considering depth-varying salinity dynamics.

Finally, our results highlight the strong coupling between salt dynamics and tidal water levels in rivers, linking seasonal variations in river discharge to the seasonality in tidal dynamics. Moreover, large-scale interventions, such as channel deepening and narrowing, are known to substantially strengthen stratification (Siemes et al., 2025) and will therefore also enhance tidal penetration and amplification.

References

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References

Geyer, W. (1993). The importance of suppression of turbulence by stratification on the estuarine turbidity maximum. Estuaries, 16, 113–125. doi: https://doi.org/10.2307/1352769

Savenije, H. H. G., Toffolon, M., Haas, J., & Veling, E. J. M. (2008). Analytical description of tidal dynamics in convergent estuaries. Journal of Geophysical Research: Oceans, 113 (C10), C10025. doi: 10.1029/2007JC004408

Siemes, R. W. A., Duong, T. M., Borsje, B. W., & Hulscher, S. J. M. H. (2025).Salt intrusion affected by large-scale human interventions and sea level rise: A 3d modeling study of an engineered estuary. Journal of Geophysical Research: Oceans, 130 (6), e2025JC022504. doi: https://doi.org/10.1029/2025JC022504

Stacey, M. T., Monismith, S. G., & Burau, J. R. (1999). Observations of turbulence in a partially stratified estuary. Journal of Physical Oceanography, 29 (8) doi: 10.1175/1520-0485(1999)029⟨1950:OOTIAP⟩2.0.CO;2:

Winterwerp, J. C., Lely, M., & He, Q. (2009). Sediment-induced buoyancy destruction and drag reduction in estuaries. Ocean Dynamics, 59, 781–791. doi: https://doi.org/10.1007/s10236-009-0237-y.