Tide-induced surface water and groundwater interactions in coastal wetlands: Effects of soil stratigraphy

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Introduction and Objectives

Intertidal wetlands such as salt marshes are complex hydrological systems characterized by strong, dynamic interactions between coastal surface water and groundwater, driven particularly by tides. We simulated such interactions with a focus on 3D, variably saturated pore water flow in a salt marsh with a two-layer soil configuration (a low-permeability mud layer overlying a high-permeability sandy-loam layer), which is commonly found in natural marshes. The subsurface flow processes have been linked to two important hypotheses about marsh ecosystems: nutrient outwelling [*Valiela and Teal*, 1979] and plant zonation [*Silvestri et al*., 2005]. Here we demonstrate the effect of soil stratigraphy on pore water flow in three aspects:

1) Spatial variations of pore water flow
2) Particle traces and associated travel times
3) Surface water and groundwater interactions

Conceptual and mathematical models

Physical conditions

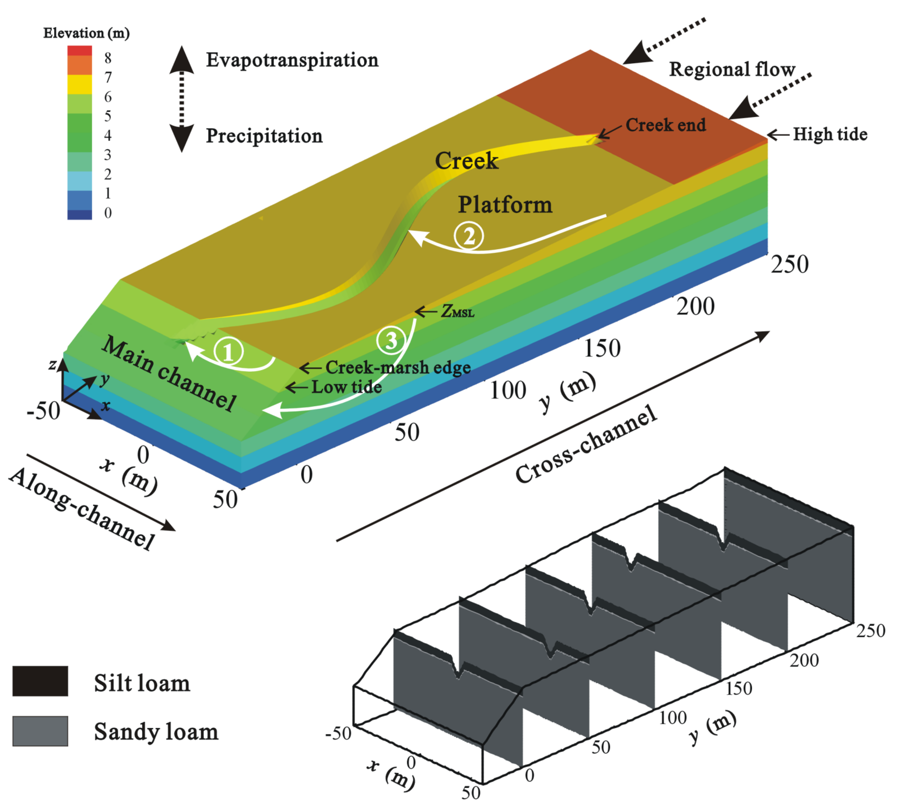

Figure 1. Diagram of the modeled creek-marsh system including major flow processes at different scales: (1) creek-induced circulation, (2) meander-induced circulation and (3) mean channel-induced circulation (after *Xin et al*. [2011]). The contours show the marsh sediment elevation. The scale of the z axis is exaggerated by a factor of 8 relative to those of the *x* and *y* axes. The layered soil stratigraphy is illustrated in the lower right corner

The creek-marsh system capturing the characteristics of some upper sections of tidal flats was characterized by topographic (slope) changes over three different scales: (1) large slope changes at the creek and main channel bank (0.2 and 0.1, respectively), (2) marsh surface elevation changes associated with the creek meander (with an maximum channel curvature of $\pi^2/500$ m^{-1}), and (3) a small uniform inclination angle (0.005 slope) of the whole marsh platform

Mathematical model

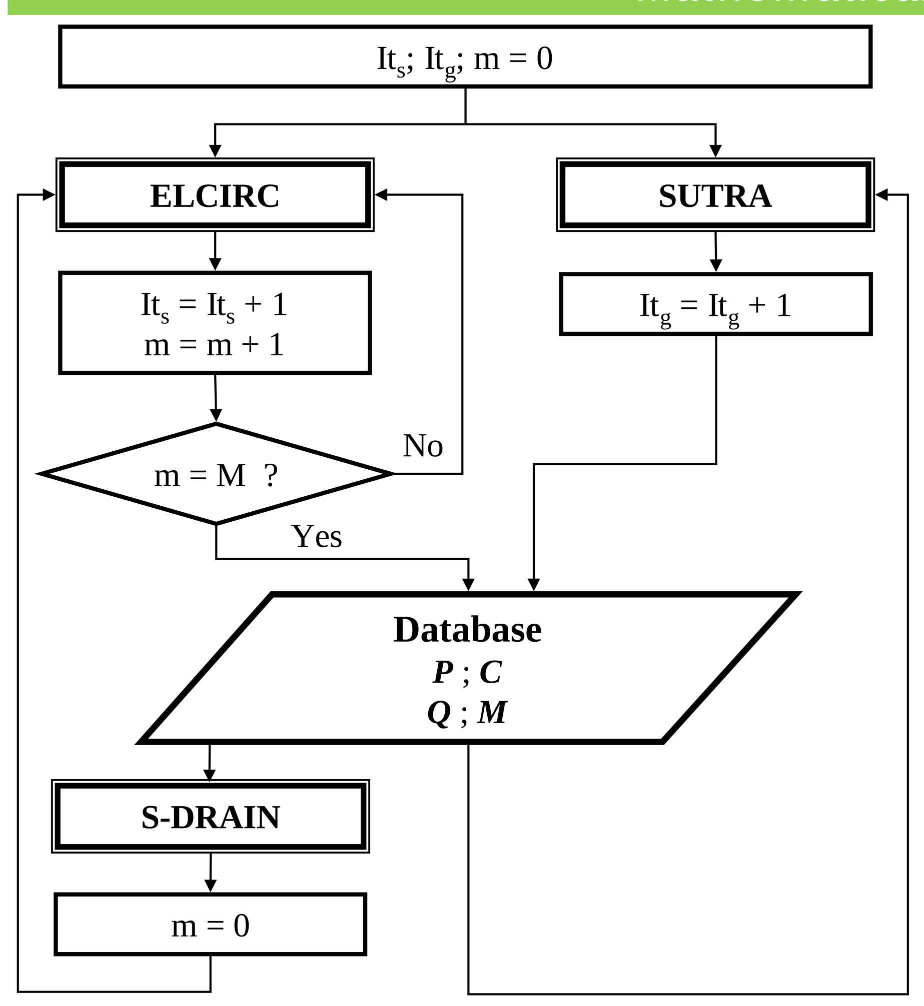

Figure 2. Schematic diagram of the coupling approach. The two coupled models run in parallel within two separate CPUs and exchange data through a common database [*Yuan et al*., 2011]

Surface water flow

ELCIRC: Three-dimensional hydrodynamic model simulating the surface water flow and solute transport in the coastal wetland system. ELCIRC uses a finite-volume/finite-difference, Eulerian-Lagrangian method to solve the shallow water equations

Subsurface water flow

SUTRA: 3D hydrodynamic model simulating variably saturated, variable-density pore water flow and solute transport in the soil

Seepage face flow

We developed a simple model, S-DRAIN, to route the drained water and associated solute flux to the nearest surface water cell through flow paths according to the local sediment surface slope (i.e., via the steepest downward slope)

Parameters values used in the simulations

Scenario	Hydraulic conductivity (m s^{-1})		Porosity (–)		Compressibility (pa^{-1})	
	Upper layer	Lower layer	Upper layer	Lower layer	Soil matrix	Water
Case 1	1.25×10^{-6}	1.23×10^{-5}	0.45	0.41	10^{-7}	4.47×10^{-10}
Case 2	1.25×10^{-6}	1.23×10^{-5}	0.45	0.41	0	0
Case 3	1.25×10^{-6}	1.25×10^{-6}	0.45	0.45	10^{-7}	4.47×10^{-10}
Case 4	1.25×10^{-6}	1.25×10^{-6}	0.45	0.45	0	0

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Results

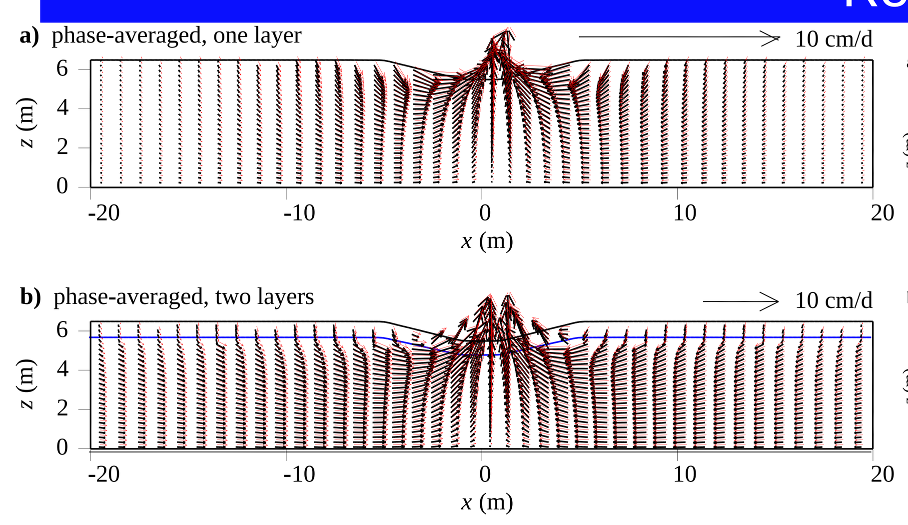

Figure 3. Flow field based on the phase-averaged result. Both figures show 2D flow in a cross-section parallel to the main channel (y = 100 m). (a) is for the one-layer marsh (Cases 3 and 4) and (b) is for the two-layer marsh (Cases 1 and 2). The black vectors are for the case without compressibility (Cases 2 and 4) and the red vectors are for the case with compressibility (Cases 1 and 3) (Note: the flow fields with and without compressibility largely overlap). The blue line in (b) indicates the interface of the two layers

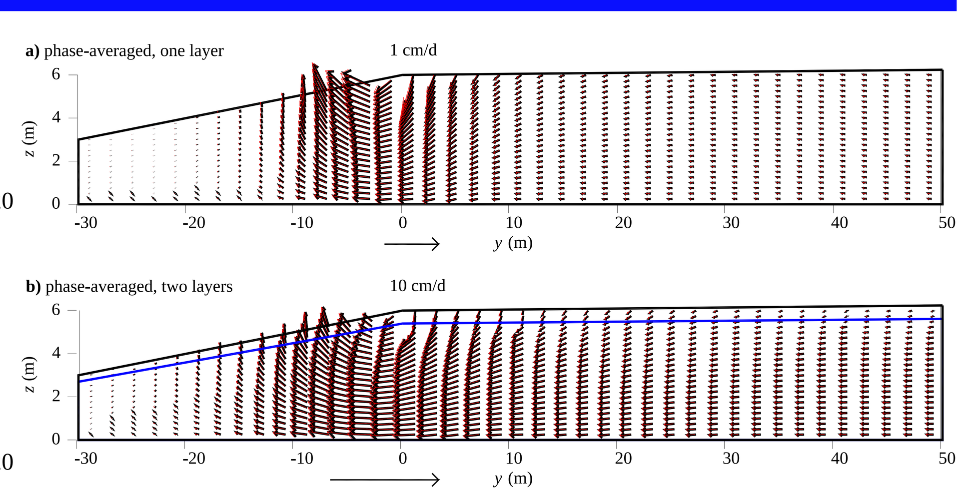

Figure 4. Flow field based on the phase-averaged result. Both figures show 2D flow in a cross-section perpendicular to the main channel (x = -40 m). (a) is for the one-layer marsh (Cases 3 and 4) and (b) is for the two-layer marsh (Cases 1 and 2). The black vectors are for the case without compressibility (Cases 2 and 4) and the red vectors are for the case with compressibility (Cases 1 and 3) (Note: the flow fields with and without compressibility largely overlap). The blue line in (b) indicates the interface of the two layers.

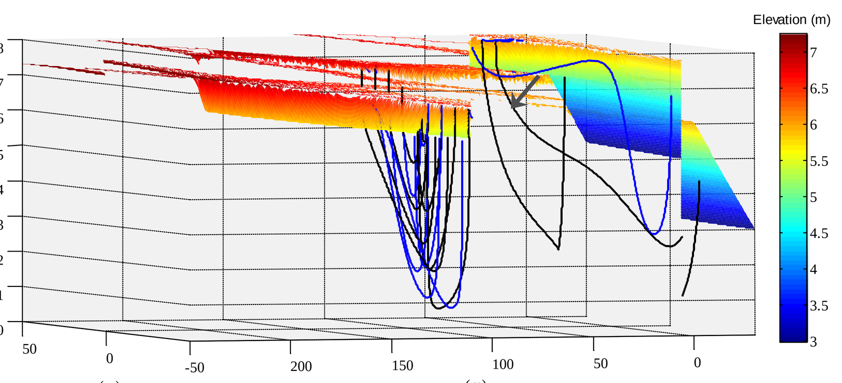

Figure 5. 3D particle traces in the marsh soil. The black lines are for the two-layer marsh (Case 1) and the blue lines are for the one-layer marsh (Case 3). The arrow indicates these particles moved out across the sediment surface in the one-layer marsh

The presence of an underlying sandy-loam layer modifies not only exchange between surface water and groundwater but also the particle paths and associated travel time. The soil stratigraphy plays an important role in the chemical exchange between the marsh soil and coastal surface water. The lower sandy-loam layer may decrease the temporal scale and lead to weakened modifications of chemical composition of the pore water and chemical fluxes driven by circulation linked to the creek and main channel. In particular, chemicals contact/interact mainly with the lower high-permeability soil layer rather than the upper low-permeability layer. We suggest that chemical characteristics of the lower soil layer are particularly significant for chemical transport and reaction in a layered marsh

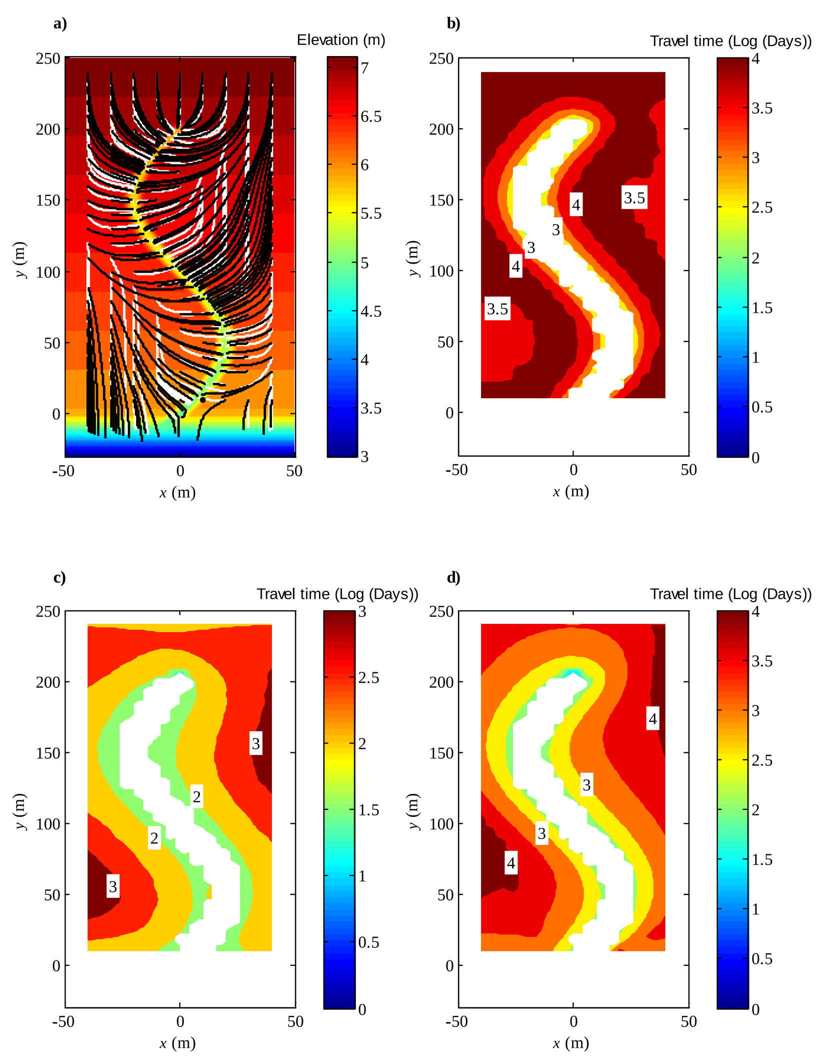

Figure 6. (a) Traces of particles initially released uniformly on the sediment surface (0.1 m soil depth): black lines are for the two-layer marsh (Case 1) and white lines are for the one-layer marsh (Case 3). (b) Associated particle travel times with Case 3 while (c) and (d) are for Case 1. (c) Travel times for particles travelling in the upper mud layer and (d) is for particles travelling through the whole marsh sediment. Note: for (b) and (d), the upper-bound is set to 10000 d. The color bar in (a) shows the sediment surface elevation, and color bars in (b), (c) and (d) show the travel time in log(days)

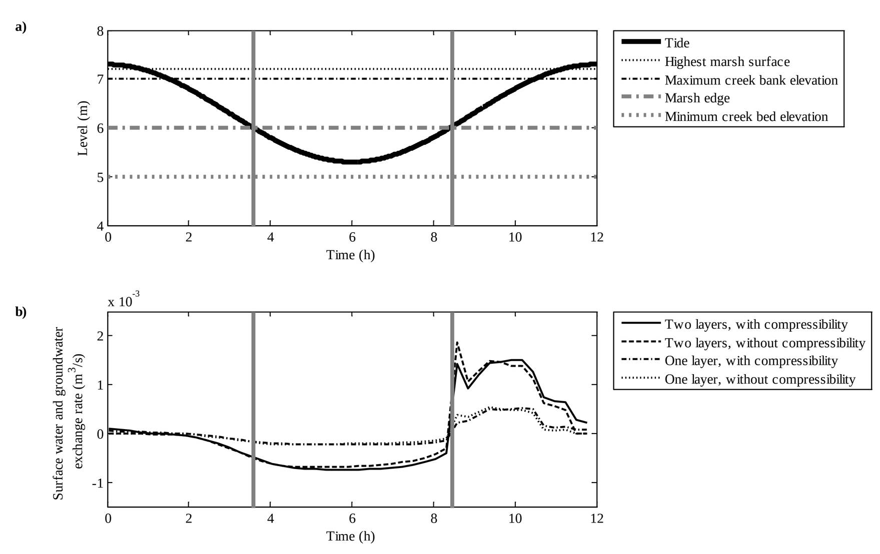

Figure 7. (a) Temporal changes of the tidal water level relative to local marsh surface elevations at various locations. (b) Surface water and groundwater exchange rate (net flux). For (b), negative values are for outflow and positive values are for inflow. The period between the two vertical lines is during the exposure of the local marsh platform

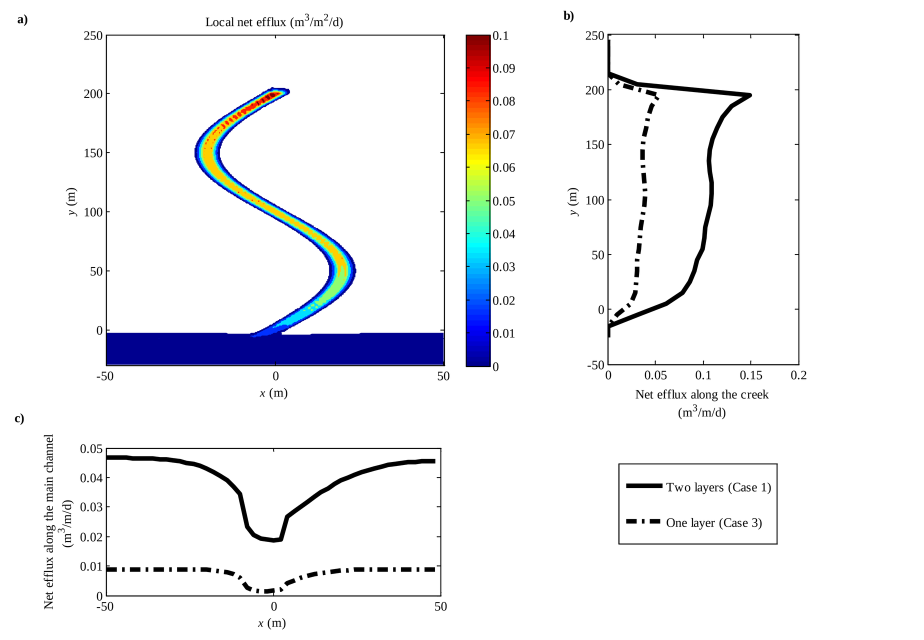

Figure 8. (a) Local net efflux (per unit area) across the interface of surface water and groundwater (in m^3/m^2/d). Variations of net efflux (b) along the creek and (c) along the main channel

Conclusions

- Multiple scales were evident in the simulated pore water flow. Under the influence of the marsh topography, the pore water circulation occurs over a wide range of spatial and temporal scales
- With the presence of an underlying sandy-loam layer of high permeability, the overall flow was increased, resulting in reduced particle travel times
- With the presence of this lower sandy-loam layer, the total exchange between surface water and groundwater also increased significantly

References

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