Impact of coastal marsh eco-geomorphologic change on the prediction of saltwater intrusion under future sea level rise

YU ZHANG[1], Daniil Svyatsky[2], Joel Carey Rowland[3], J. David David Moulton[3], ZHENDONG CAO[4], Phillip Justin Wolfram Jr.[4], chonggang xu[5], and Donatella Pasqualini[3]

[1]Los Alamos National Lab
[2]Los Alamos National laboratory
[3]Los Alamos National Laboratory (DOE)
[4]Los Alamos National Laboratory
[5]lanl

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Abstract

Coastal saltwater intrusion (SWI) is one key factor affecting the hydrology, nutrient transport, and biogeochemistry of coastal marsh landscapes. Future climate change, especially intensified sea level rise (SLR), is expected to trigger SWI to encroach coastal freshwater aquifers more intensively. Numerous studies have investigated decadal/century scale SWI under SLR by assuming a static coastal landscape topography. However, coastal marshes are highly dynamic systems in response to SLR, and the impact of coastal marsh evolution on SWI has received very little attention. Thus, this study investigated how coastal marsh evolution affects future SWI with a physically-based coastal hydro-eco-geomorphologic model, ATS (Advanced Terrestrial Simulator). Our synthetic modeling experiments showed that it is very likely that the marsh elevation increases with future SLR, and a depression zone is formed due to the different marsh accretion rates between the ocean boundary and the inland. We found that, compared to the cases without marsh evolution, the marsh accretion may significantly reduce the surface saltwater inflow at the ocean boundary, and the evolved topographic depression zone may prolong the residence time of surface ponding saltwater, which causes distinct subsurface salinity distributions. We also found that the marshland may become more sensitive to the upland groundwater table that controls the freshwater flux to the marshes, compared with the cases without marsh evolution. This study demonstrates the importance of marsh evolution to the freshwater-saltwater interaction under sea level rise and can help improve our predictive understanding of the vulnerability of the coastal freshwater system to sea level rise.

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[1]Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM, USA.

[2]Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM, USA.

[3]Advanced Engineering Analysis, Los Alamos National Laboratory, Los Alamos, NM, USA.

[4]Analytics, Intelligence & Technology Division, Los Alamos National Laboratory, Los Alamos, NM, USA.

Corresponding author: Yu Zhang (yuzhang@lanl.gov)

Key Points:

- The effect of coastal marsh evolution on future saltwater intrusion is examined for the first time
- Marsh accretion under sea level rise may significantly reduce surface seawater inflow and prolong the surface seawater residence time
- Future saltwater intrusion on the evolved marsh landscape may become more sensitive to upland groundwater inflows

Abstract

Coastal saltwater intrusion (SWI) is one key factor that affects the hydrology, nutrient transport, and biogeochemistry of coastal marsh landscapes. Future climate change, especially intensified sea level rise (SLR), is expected to trigger SWI to encroach coastal freshwater aquifers more intensively. Numerous studies have investigated decadal/century scale SWI under SLR by assuming a static coastal landscape topography. However, coastal marshes are highly dynamic systems in response to SLR, and the impact of coastal marsh evolution on SWI has received very little attention. Thus, this study investigated how coastal marsh evolution affects future SWI with a physically-based coastal hydro-eco-geomorphologic model, ATS (Advanced Terrestrial Simulator). Our synthetic modeling experiments showed that it is very likely that the marsh elevation increases with future SLR, and a depression zone is formed due to the different marsh accretion rates between the ocean boundary and the inland. We found that, compared to the cases without marsh evolution, the marsh accretion may significantly reduce the surface saltwater inflow at the ocean boundary, and the evolved topographic depression zone may prolong the residence time of surface ponding saltwater, which causes distinct subsurface salinity distributions. We also found that the marshland may become more sensitive to the upland groundwater table that controls the freshwater flux to the marshes, compared with the cases without marsh evolution. This study demonstrates the importance of marsh evolution to the freshwater-saltwater interaction under sea level rise and can help improve our predictive understanding of the vulnerability of the coastal freshwater system to sea level rise.

Keywords: Saltwater intrusion, Coastal marsh evolution, Sea level rise, Freshwater-saltwater interface, Groundwater table, Coastal aquifer vulnerability

1 Introduction

Coastal wetlands, unique landscapes that connect the terrestrial landscape and the ocean, are some of the most productive ecosystems on Earth (Tiner, 2013). Climate change, especially sea level rise (SLR) under a warming climate, is one of the biggest threats to the stability and sustainability of coastal wetland ecosystems (Burkett & Kusler, 2000). SLR-driven impacts on coastal marsh ecosystems are strongly affected by changes in coastal hydrology (Zhang et al., 2019). The rising sea level alters the balance of coastal freshwater-saltwater interaction both on coastal wetland surface and in the subsurface aquifer causing the changes in saltwater intrusion (SWI), thereby affecting soil water salinity (Guimond & Tamborski, 2021; Sorensen et al., 1984; Sousa et al., 2010), triggering the mortality of salt-intolerant vegetation (Silvestri & Marani, 2004), and eventually altering the ecosystem functions of coastal wetlands (Burkett & Kusler, 2000). Therefore, investigating the response of SWI to SLR is critical for our understanding of the SLR impact on coastal wetland ecosystems.

Numerous studies have attempted to predict and/or assess the impact of SLR on SWI for decades. These studies have aimed to track the movement of the freshwater and saltwater interface in coastal aquifers driven by SLR at global (e.g., Ferguson & Gleeson, 2012; Michael et al., 2013), regional (e.g., Oude Essink et al., 2010; Zhang et al., 2018, 2019), and local/transect scales (e.g., Ataie-Ashtiani et al., 2013; Carretero et al., 2013; Chang et al., 2011; Chen et al., 2015; Giambastiani et al., 2007; Hughes et al., 2009; Ketabchi et al., 2014, 2016; Langevin & Zygnerski, 2013; Loáiciga et al., 2012; Lu et al., 2015; Masterson & Garabedian, 2007; Mazi et al., 2013; Morgan et al., 2013; Payne, 2010; Rasmussen et al., 2013; Sefelnasr & Sherif, 2014; Sorensen et al., 1984; Vandenbohede et al., 2008; Vu et al., 2018; Watson et al., 2010; Werner et al., 2012; Werner & Simmons, 2009; Yang et al., 2015). By using analytical or numerical models, these studies examined SWI in coastal aquifers under SLR, especially under the influence of different environmental settings, such as regional-scale hydrologic connectivity, upland groundwater boundary condition, land surface inundation, groundwater extraction, and recharge. For example, *Zhang et al.* (2018, 2019) investigated the groundwater flow path and SWI of the coastal wetlands in North Carolina, USA, by considering regional-scale coastal hydrologic connectivity. They found that aquifers with the largest seasonal changes of SWI are located hundreds of meters away from the shoreline, where freshwater strongly interacts with saltwater. In terms of the effect of upland boundary conditions on SWI, *Werner and Simmons* (2009) and *Werner et al.* (2012) found that SLR impact is more extensive in unconfined aquifers with a head-controlled inland boundary, compared with confined aquifers. *Carretero et al.* (2013) found that SWI increased linearly with SLR in aquifers with a flux-controlled boundary condition, but increased nonlinearly with a head-controlled boundary condition. In terms of the effect of groundwater extraction and freshwater supply (recharge), *Loáiciga et al.* (2012) found that groundwater extraction was the predominant driver of SWI in one coastal aquifer in Monterey, California, compared with the effect of SLR. Using the coastal aquifer at the Western Baltic Sea as an example , *Rasmussen et al.* (2013) found that the SWI in flux-controlled aquifers is more sensitive to recharge than SLR. Likewise, *Ataie-Ashtiani et al.* (2013) found that surface inundation may induce significantly more extensive SWI than SLR. Each of these studies provided insights into understanding SWI under SLR in the temporal scales of decades and centuries, however, none of them considered the effect of coastal landscape topographic change, which may have a significant impact on SWI by altering flow paths and residence time.

The evolution of coastal marsh landscape topography under SLR has been explored extensively by the coastal geomorphologic community. Many studies have predicted coastal marsh evolution as a function of sediment erosion and deposition and found that coastal marshes are not static but dynamic landscapes. Coastal marshes are very likely to keep pace with the rates of SLR at decadal to century scales due to the net sedimentation on the marshlands (e.g., Best et al., 2018; D'Alpaos et al., 2007; Kirwan, Temmerman, et al., 2016; Kirwan, Walters, et al., 2016; Kirwan & Murray, 2007; Kirwan & Temmerman, 2009; Mariotti & Fagherazzi, 2010; Zhang et al., 2020). With the changes in marsh geomorphology, the topographic and hydraulic gradient among the land, river, and ocean will change, which will alter the seawater flow path and storage (Winn et al., 2006). However, so far, there is a critical knowledge gap on how the evolution of coastal landscape may affect the SWI under SLR. This could severely limit our capability to estimate the vulnerability of coastal aquifer to SWI under SLR. To fill this knowledge gap, in this study, we used synthetic coastal marsh transects to examine the effect of coastal marsh evolution on coastal SWI under SLR. We simulated coastal marsh evolution and SWI on the coastal marsh transects under different rates of SLR over 100 years by using a coastal marsh evolution model and a density-dependent solute transport model in the Advanced Terrestrial Simulator (ATS) (Coon et al., 2016). We evaluated the impacts of coastal marsh evolution on SWI by comparing the surface and subsurface hydrologic characteristics between the SWI simulations with and without considering coastal marsh evolution. The surface hydrologic characteristics include seawater propagation, inflow, surface salt concentration, and surface seawater penetration. The subsurface hydrologic characteristics include subsurface water salinity distribution, seawater inflow, and the displacement of the freshwater-saltwater interaction. We hypothesized that coastal marsh evolution cannot be ignored when evaluating coastal SWI under SLR at a decadal or century scale because marsh evolution may significantly affect the surface seawater inflow rate and the surface water residence time, therefore change

SWI. The insights gained from this study can help improve our understanding of the vulnerability of coastal freshwater systems to SWI.

In this paper. we first introduce the numerical model, experiment and scenario designs, and evaluation metrics in Section 2, after which we present and analyze the results from the numerical experiments for marsh evolution and SWI in Section 3. Lastly, Section 4 discusses the implication of this study for understanding SWI under SLR from a coupled hydro-eco-geomorphologic framework, its representativeness, uncertainties, and outlined future work, followed by conclusions in Section 5.

2 Materials and Methods

2.1 Mathematical models

This study used the Advanced Terrestrial Simulator (ATS) (Coon et al., 2016) to simulate SWI and coastal marsh evolution under SLR conditions. ATS is a multi-process high-performance computing simulator with process kernels (PKs) for surface and subsurface hydrology, energy balance, thermal dynamics, sediment transport, solute transport, coastal marsh evolution, and marsh vegetation dynamics. Here we used some ATS PKs to configure a saltwater intrusion model and a coastal marsh evolution model.

2.1.1 The configuration of coastal saltwater intrusion in ATS

We used the SWI configuration in ATS (hereinafter referred to as SWI model) to simulate the salinity change of surface and subsurface water by coupling surface and subsurface hydrologic processes with density-dependent solute transport processes. The integrated hydrologic processes include a two-dimensional (2-D) diffusive-wave approximation of surface flows (Vreugdenhil, 1994) and a variably saturated three-dimensional (3-D) Richards equation

(Richards, 1931) for subsurface flows. The governing system of PDEs for surface and subsurface fluid mass balance is as follows,

$$\begin{cases}\frac{\partial d\rho_1}{\partial t} = -\nabla_1(\rho_1 d\mathrm{u}) - I_w \\ \frac{\partial \theta\sigma\rho_2}{\partial t} = -\nabla_2(\rho_2 q) + I_w\end{cases} \tag{1}$$

where $\rho_1(C_1)$ and $\rho_2(C_2)$ are the surface and subsurface fluid density (kg/m^3) which are functions of surface and subsurface salt concentrations (dimensionless), C_1 and C_2, respectively; d is the surface water depth (m); θ is the subsurface water content; σ is the soil porosity; u is the depth-averaged surface flow velocity (m/s) which is, according to the diffusive wave approximation, defined as follows:

$$\mathrm{u} = -\frac{d^{\frac{2}{3}}}{n(|\nabla(z+d)|)^{\frac{1}{2}}}\nabla(z+d) \tag{2}$$

where z is surface elevation (m); n is the Manning's coefficient of roughness ($s/m^{1/3}$); q in Eq. 1 is the subsurface water flow velocity (m/s) defined by Darcy law:

$$q = -\frac{k_r K}{\mu}\nabla h \tag{3}$$

where k_r and K are a relative (dimensionless) and absolute permeabilities (m^2), respectively, μ is fluid dynamic viscosity (kg/m/s) and h is subsurface hydraulic head (m). I_w is the mass source/sink term (kg/s m^2) representing the infiltration or exfiltration (positive in the downward direction)

In Eq. 1, the density is a linear function of water concentration (Simmons et al., 2001):

$$\rho = \rho_0 + a(C - C_0), \tag{4}$$

where ρ is the fluid density for surface water or subsurface water (kg/m^3); C is the fluid salt concentration for surface and subsurface water (dimensionless); ρ_0 is the fluid density at a base concentration, C_0; a is a constant coefficient of density variability.

The generic form of saltwater concentration is calculated based on the salt mass balance equation following *Herbert et al.* (1988) and *Simmons et al.* (2001)

$$\begin{cases} \frac{\partial(d\rho_1 C_1)}{\partial t} = -\nabla_1(d\rho_1 u C_1) + \nabla_1[d\rho_1(D_0 + D)\cdot\nabla_1 C_1] - \mathrm{I}_{\mathrm{salt}} \\ \frac{\partial(\theta\sigma\rho_2 C_2)}{\partial t} = -\nabla_2(\theta\sigma\rho_2 q C_2) + \nabla_2[\theta\sigma\rho_2(D_0 + D)\cdot\nabla_2 C_2] + \mathrm{I}_{\mathrm{salt}} \end{cases} \tag{5}$$

where C_1 and C_2 are the salt concentration of surface and subsurface water (dimensionless), respectively. D_0 is the molecular diffusivity (m^2/s). $\boldsymbol{D}$ is the transverse and longitudinal dispersivities; Likewise, $\mathrm{I}_{\mathrm{salt}}$ is the mass source/sink term (kg/s m^2) representing the infiltration or exfiltration (positive in the downward direction). The capability of the SWI model in capturing saltwater intrusion through surface and subsurface flow under tidal conditions was well validated by comparing the model simulation with a lab experiment of SWI with tidal variation by *Kuan et al.* (2019) (see the validation results in the supplementary information Text S1 and Figs. S1 and S2).

2.1.2 The configuration of coastal marsh evolution in ATS

For the marsh evolution modeling, we used the coastal marsh evolution model (hereinafter referred to as Sed model) configured by the 2-D surface flow, sediment transport and marsh evolution PKs in ATS. The Sed model tracks the change of marsh surface elevation as a function of sediment erosion, sediment settling, sediment trapping by vegetation, and vegetation organic matter production. Namely,

$$\frac{dz}{dt} = \frac{1}{1-\sigma}\left(D_s + D_t + D_{org} - E\right) \quad (6)$$

where z is the surface elevation (m); t is the time (s); σ is the porosity of bed sediment; D_s is the inorganic sediment settling rate (m/s); D_t is the inorganic sediment trapping rate due to the effect of vegetation canopy (m/s); D_{org} is the organic matter production rate (m/s); E represents local sediment erosion rate (m/s).

The Sed model follows the forms of sediment erosion and deposition in D'Alpaos et al. (2007), but improved the representation of surface hydrodynamics, instead of using an equilibrium assumption for surface hydrodynamics. Specifically, in the Sed model, the surface hydrodynamics due to tide and SLR is represented by a depth-averaged diffusive-wave scheme (Eq. 2) considering the spatial and temporal variations of water propagation landward. Sediment erosion (E in Eq. 6) is estimated as a linear function of dynamic bed shear stress depending on surface water flow velocity. Erosion occurs when the bed shear stress (τ_0) due to water flow is greater than the critical shear stress (τ_e) for erosion. Namely,

$$E = \begin{cases} \alpha\left(\frac{\tau_0}{\tau_e} - 1\right) & if\ \tau_0 > \tau_e \\ 0 & if\ \tau_0 < \tau_e \end{cases}, \quad (7)$$

where α is the erosion coefficient. Likewise, sediment settling (D_s in Eq. 6) describes the process that particulates settle to the bottom of a liquid and form sediment due to gravity, which is also assumed as a linear function of dynamic bed shear stress. Sediment settling occurs when the bed shear stress (τ_0) is smaller than the critical shear stress (τ_d) for settling, viz

$$D_s = \begin{cases} w_s C\left(1 - \frac{\tau_0}{\tau_d}\right) & if\ \tau_0 < \tau_d \\ 0 & if\ \tau_0 > \tau_d \end{cases}. \quad (8)$$

where w_s is the settling velocity (m/s); C is the suspended sediment concentration (dimensionless). Sediment trapping by vegetation (D_t in Eq. 6) is given by

$$D_t = CU\epsilon d_s n_s \min[h_s, h_w] \quad (9)$$

where D_t is a function of water flow velocity (U), a capture efficiency of vegetation stems (ϵ), water depth (h_w), and several vegetation characteristics, such as plant stem diameter (d_s), stem density (n_s), and vegetation height (h_s). The vegetation properties are determined by vegetation biomass, which is assumed as a linear function of marsh surface elevation relative to the mean highest tide level. Also, the vegetation organic matter production (D_{org} in Eq. 6) is a linear function of vegetation biomass, viz

$$D_o = K_b \frac{B}{B_{max}}, \quad (10)$$

where K_b is the maximum production rate of belowground organic material [m/s]; B is the aboveground plant dry biomass at the current time [g/m^2]; and B_{max} is the maximum vegetation biomass [g/m^2]. In this study, we assume that the aboveground biomass of the salt-tolerant marsh vegetation linearly increases with the inundation level (Morris et al., 2002). The details of the questions are referred to D'Alpaos et al. (2007) and Zhang et al. (2020).

An offline coupling approach was used in this study to integrate the Sed model and the SWI model (an online coupling scheme is under development). Specifically, we 1) first simulate the coastal marsh evolution by using the Sed model and 2) use the simulated future surface elevation from step (1) as the initial topographic and morphologic condition to simulate future SWI until equilibrium by using the SWI model.

2.2 Numerical experiment design

To investigate the effect of marsh evolution on SWI, we designed two 2-D synthetic coastal marsh transects that include a 1 m wide coastal marshland (2000 m long) and upland region (1000 m long) with different slopes to represent real coastal marshes at the Atlantic coast, particularly the Delaware Bay and Chesapeake Bay areas (see Fig. 1). We assumed that the coastal marshland is covered by salt-tolerant marsh species, such as *Spartina (Morris et al., 2002)*. The slope of the coastal marsh (1:2500) represents an averaged slope of the coastal marsh transects in Delaware Bay, USA, measured by this study. The upland slopes of 1:1000 and 1:250 in this area are used to represent different upland controls on surface-subsurface water propagation and sediment transport (Fagherazzi et al., 2019). We assumed a homogeneous landscape with homogeneous surface roughness and homogeneous soil properties, such as surface Manning's coefficient, soil porosity, soil hydraulic conductivity, and van Genuchten water retention parameters (see the details of parameter values in Table 1). The soil thickness at the upland and the ocean boundaries are 20 m and 18.2 m, respectively, based on the measurements in *Sanford et al.* (2012).

The hydrodynamics are driven by tides and SLR at the ocean boundary. Initially, the mean sea level (MSL) is equal to 0 m, the elevation of the current coastal marsh near the ocean boundary (see Fig. 1). We adopted two widely-used future global mean SLR scenarios based on the Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 scenarios in Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Spencer et al., 2016) for our numerical experiments, including (1) a relatively low SLR rate of 0.5 m/100-yr (Da Lio et al., 2013; Ganju et al., 2020; Kirwan & Temmerman, 2009; Sefelnasr & Sherif, 2014; Spencer et al., 2016) and (2) a relatively high SLR rate of 1 m/100-yr (Carretero et al., 2013; Langevin & Zygnerski, 2013; Lu et al., 2015; Michael et al., 2013; Sefelnasr & Sherif, 2014; Watson et al., 2010; Yang et al., 2015). We applied a sinusoidal semi-diurnal tide with a tidal range of 1.6 m based on the National Oceanic and Atmospheric Administration (NOAA) tide and current observation at the Delaware Bay, USA (Cape May Station, station ID: 8536110).

Freshwater supply in the coastal aquifer is controlled by the hydrostatic groundwater table (GWT) at the upland boundary (the left boundary of the domain in Fig. 1). This study used three upland GWT scenarios to represent (1) a present-day upland GWT condition (1.3 m above the initial MSL), (2) a future GWT condition with increased groundwater extraction and/or a drier climate (0.9 m above the initial MSL), and (3) a future GWT condition with a wetter climate (1.8 m above the initial MSL), respectively. To simplify the control factors and present a more focused study on the effect of marsh evolution on SWI, we did not include the effect of rainfall recharge in this study, which will be explored in future work. We used a head-controlled upland GWT boundary condition, which may predict more SWI than the flux-controlled upland boundary condition for unconfined aquifers (Werner & Simmons, 2009). Therefore, our scenarios may represent a relatively more aggressive prediction of SWI under SLR. All scenarios are summarized in Table 2.

The 2-D model domain in Fig. 1 was decomposed into logically structured mesh with a horizontal resolution of ~5 m and vertical resolution of ~1 m (20 layers). We simulated 100-yr marsh evolution, and the SWI experiments were simulated until the freshwater-saltwater interface reached an equilibrium state.

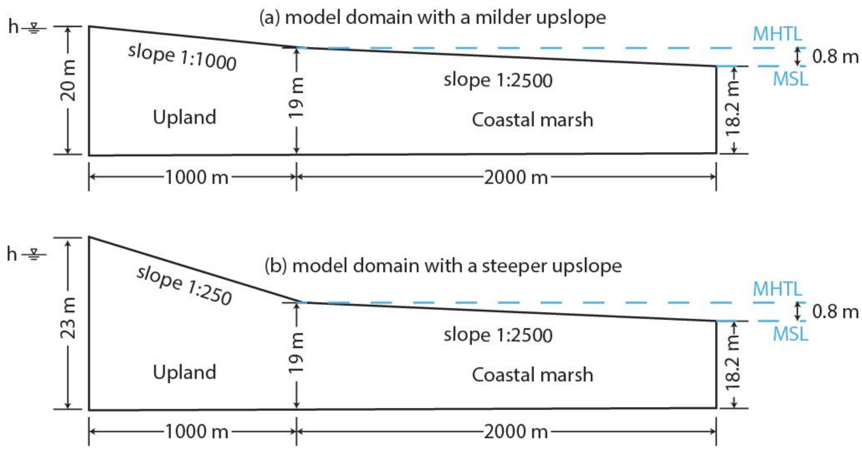

Figure 1. Sketches of the 2-D model domain. The surface elevation at the ocean boundary (right side) is 0 m. The elevation at the upland boundary is 1.8 m for the milder upslope domain and 4.8 m for the steeper upslope domain. MHTL stands for the mean highest tide level and MSL is mean sea level. The present-day MSL is at 0 m level. h at the left side of the domain indicates the upland groundwater level. Three upland groundwater level scenarios are used: h = 1.3 m (present-day level), h = 1.8 (reflecting future wetter climate), and h = 0.9 m (reflecting future drier climate or more groundwater extraction)

Table 1. Key parameter values used in the numerical experiments

	Parameters	**Values**	**References**
SWI-related parameters	Porosity	0.46	(Kuan et al., 2012)
	Hydraulic conductivity (m/day)	10	(Kuan et al., 2012)
	Manning's n (s $m^{-1/3}$)	0.06	(Arcement & Schneider, 1989)
	Diffusion coefficient (m^2 s^{-1})	1.00E-09	(Kuan et al., 2012)
	Longitudinal dispersivity coefficient (m)	0.002	(Kuan et al., 2019)
	Transversal dispersivity coefficient (m)	0.0004	(Kuan et al., 2019)
	van Genuchten α for water retention (m^{-1})	0.48	(Benson et al., 2014)
	van Genuchten n for water retention	2.54	(Benson et al., 2014)
	Residual saturation	0.1	(Kuan et al., 2012)
	Saltwater concentration in the ocean (kg salt per kg seawater)	0.0357	(Michael et al., 2013)
Marsh	Sediment concentration in the	50	(Kirwan, Walters, et al., 2016)

evolution-related parameters	ocean (mg/L)		
	Erosion coefficient ($\frac{kg}{m^2 s P_a}$)	1.12E-04	(D'Alpaos et al., 2007)
	Critical shear stress for erosion (P_a)	0.4	(Thompson et al., 2004)
	Critical shear stress for deposition (P_a)	0.1	(Parchure Trimbak M. & Mehta Ashish J., 1985)
	Sediment settling velocity ($\frac{m}{s}$)	1.00E-04	(Riazi & Türker, 2019)
	Belowground organic production ($\frac{m}{yr}$)	0.003	(Morris et al., 2016)

Table 2. The numerical experiment cases with different upland slope, SLR, and GWT scenarios

	Milder upland slope		Steeper upland slope	
	Higher SLR	Lower SLR	Higher SLR	Lower SLR
Medium upland GWT (h=1.3 m) (present-day scenario)	Case 1	Case 2	Case 3	Case 4
High upland GWT (h=1.8 m) (wetter climate scenario)	Case 5	Case 6	Case 7	Case 8
Low upland GWT (h=0.9 m) (drier climate and/or more groundwater extraction scenario)	Case 9	Case 10	Case 11	Case 12

2.3 Evaluating the effect of marsh evolution on SWI under SLR and tides

We evaluated the effect of marsh evolution on SWI by comparing the SWI simulation with and without marsh evolution. Specifically, we created two groups of experiments. Each group consisted of all 12 experimental cases listed in Table. 2. The first group of experiments was based on the current marsh topography as illustrated in Fig. 1. SWI was simulated under different rates of SLR and different levels of the upland GWT in the future 100 years without considering coastal marsh evolution. In contrast, the second group conducted the same SWI simulations as the first group experiments but used the marsh topography from the marsh evolution simulations in the future 100 years as the topographic condition. We examined the surface and subsurface freshwater and saltwater changes in the two groups of numerical experiments. Specifically, we analyzed the changes in surface seawater propagation, inflow, concentration, and infiltration and subsurface water salinity, seawater inflow, and the displacement of the freshwater-seawater interface.

3 Results

3.1 Coastal marsh evolution driven by tidal and SLR forcing

With the SLR rates of 0. 5 m/100-yr and 1 m/100-yr, the future MSL increases to 0.5 m and 1 m in 100 years, respectively. Accordingly, the mean highest tide levels (MHTL, equal to MSL + tidal amplitude) rise from 0.8 m to 1.3 m and 1.8 m, respectively. Driven by the future SLR, our modeling results showed that the future marsh elevation rises substantially with SLR and with a larger increase near the ocean boundary and a smaller increase for the inland marsh (Figs. 2a and b) due to a gradient in sedimentation rates (Fig. 3). Therefore, a topographic depression forms in the middle of the marshland. The future elevations near the ocean boundary are close to the future MHTLs under both the higher and lower SLR rates. Correspondingly, the vegetation co-evolves with the topographic change and future inundation condition. The salt-tolerant vegetation biomass is modeled to increases with inundation level, which results in higher vegetation biomass in the middle of the domain and lower vegetation biomass at the ocean and upland sides (Figs. 2c and d). Relative to the initial marshland (the gray dashed lines in Figs. 2c and d from 1000m to 3000m from the upland boundary), there was a landward expansion of marsh vegetation that varied with SLR and upland slopes. For example, the marsh vegetation covers the entire upland region in the case with the milder slope and higher SLR rate (the light green line in Fig. 2c) because the future MHTL (1.8 m) is the same as the elevation of the upland boundary leading to an inundation condition favorable for vegetation growth. For the cases with the steeper upland slope, a large portion of the upland areas is still higher than the MHTL, therefore no vegetation presents on the upland areas (Fig. 2d).

Among sedimentation rates across the domain, the sediment settling rate is the greatest near the ocean boundary (the light blue lines in Fig. 3) because of a higher sediment concentration near the ocean boundary. Moving landward, the sediment settling rate decreases due to a lower sediment concentration, but the vegetation organic matter production rate increases because of higher vegetation biomass, which contributes more to the sedimentation of the inland marsh (the purple lines in Fig. 3). Vegetation sediment trapping is more significant near the ocean boundary where the sediment concentration and flow velocity are higher. Moving landward, due to the decrease of sediment concentration and flow velocity, the trapping effect gradually vanishes (the orange lines in Fig. 3). Due to the vegetation effect on reducing water flow velocity, sediment erosion is only observed at the beginning of the simulation when the future SLR is applied to the domain boundary (not shown). Later in the simulation, the surface elevation increases due to a higher sedimentation rate. Therefore, the seawater inflow velocity decreases because of a decrease of the hydraulic gradient between the land and the ocean, and the erosion rate drops to zero.

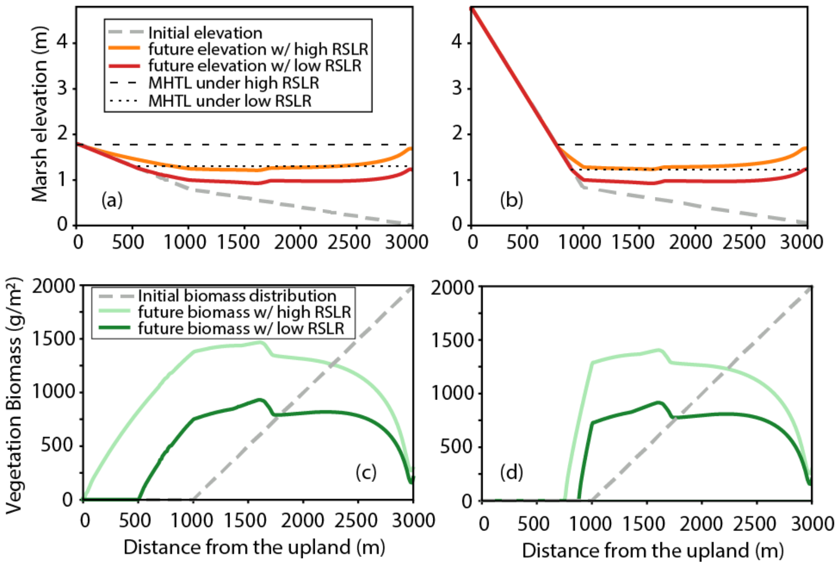

Figure 2. The distribution of future elevation and vegetation biomass of the domain with a milder upland slope (a and c) and a steeper upland slope (b and d). The gray dashed lines indicate the initial surface elevation and vegetation biomass distribution, respectively. MHTL stands for the mean highest tide level. RSLR is the rate of sea level rise.

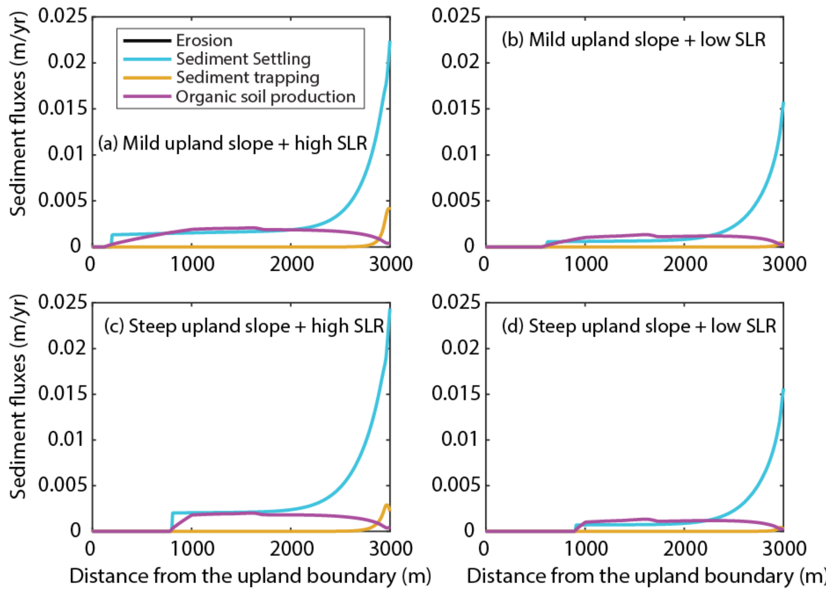

Figure 3. The spatial distribution of the sediment fluxes at the end of the 100-year simulation. The plots with various colors represent different fluxes in different scenarios.

3.2 SWI with and without marsh evolution

3.2.1 The influence of marsh evolution on coastal hydrodynamics

After predicting the topographic change of the coastal marsh landscapes 100 years in the future, we compared the SWI under SLR with and without considering the marsh evolution. For both SLR rates, the upland GWT is held fixed at 1.3 m above the initial MSL (0 m), but the future MSL increases (see details of the MSL rise in Subsection 3.1). Without considering marsh topographic change in the future, the rising sea level increases the hydraulic gradient between the ocean and the marshland, thus more saltwater was predicted to flow onto the marshland with a relatively larger maximum inflow rate (~0.25 m^3/s) under the higher SLR scenario and a relatively lower rate (~0.16 m^3/s) under the lower SLR scenario (the gray bars in Fig. 4). However, considering marsh evolution, the marsh surface elevation increases with SLR, especially for marshland near the ocean boundary (e.g., Fig. 2a and b), which decreases the hydraulic gradient between the ocean and the marshland. Thus, the saltwater maximum inflows are predicted to be ~0.009 m^3/s for the higher SLR rate scenario and ~0.0048 m^3/s for the lower SLR rate scenario (the black bars in Fig. 4). These rates are two orders of magnitude smaller than the maximum inflow rates without considering marsh evolution.

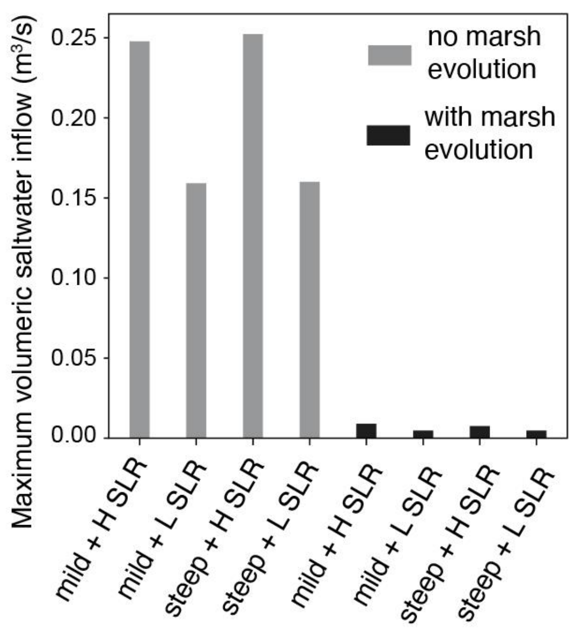

Figure 4. The maximum seawater inflows under future sea level for the simulations with and without considering coastal marsh evolution. The gray and black bars indicate the simulated seawater inflow without and with considering marsh evolution, respectively.

The marsh topographic change also affects surface seawater propagation, ponding water depth, surface water residence time, and saltwater concentration on the marsh surface. For example, Figure 5 shows the surface water propagation and saltwater concentration for the cases without considering marsh evolution (the top four plots with gray backgrounds) and with marsh evolution (the bottom four plots with white backgrounds). Without considering marsh evolution, seawater propagates landward during the high tides and causes a surface inundation with a maximum inundation depth higher than 1.3 m near the ocean boundary (the upper dashed lines in Fig. 5a, b, c, and d). During the high tides, the saltwater concentration in the ponding water is almost the same as the concentration in the ocean (3.5%; the blue dashed lines in Fig. 5a, b, c, and d), except for the upland regions, where the subsurface freshwater exfiltrates to the surface and dilutes the surface saltwater. During the low tides, the surface ponding water flows out from the marsh domain (the lower dashed lines in Fig. 5a, b, c, and d). Therefore, the residence time for surface saltwater is tightly controlled by the tidal frequency (~12 h).

In contrast, considering marsh evolution, the depression zone in the middle of the marshland significantly changes the surface water propagation. Saltwater flows onto the marshland during the high tides with a much smaller inflow rate as illustrated in Fig. 4, and then the saltwater gradually accumulates in the depression zone without flowing out from the domain during the low tides, which largely increases the residence time of saltwater (the black dashed lines in Fig. 5e, f, g, and h). A large portion of the surface ponded saltwater exits the marsh surface only through infiltration. Meanwhile, freshwater flows into the depression zone through subsurface freshwater exfiltration. In the cases with a higher SLR rate (Figs. 5e and g), the upland GWT (1.3 m) is lower than the future MHTL (1.8 m). For most of the time during a tidal cycle, fresh groundwater cannot easily flow into the marsh aquifer. Thus, at equilibrium, the surface ponding water consists almost of saltwater with very little freshwater, and the surface saltwater concentration is almost equal to the concentration in the ocean for the entire surface ponding water (the blue lines in Figs. 5e and g). However, in the cases with a lower SLR rate (Figs. 5f and h), the upland GWT (1.3 m) is at the same level as the future MHTL (1.3 m). Fresh groundwater can be more easily flow into the marsh aquifer and exfiltrate to the surface when the instantaneous sea level is below the MHTL during a tidal cycle. Thus, a larger amount of fresh groundwater accumulates in the depression zone to dilute saltwater inflow. Therefore, we only observed an increase of surface saltwater concentration near the ocean boundary (the blue lines in Figs. 5f and h).

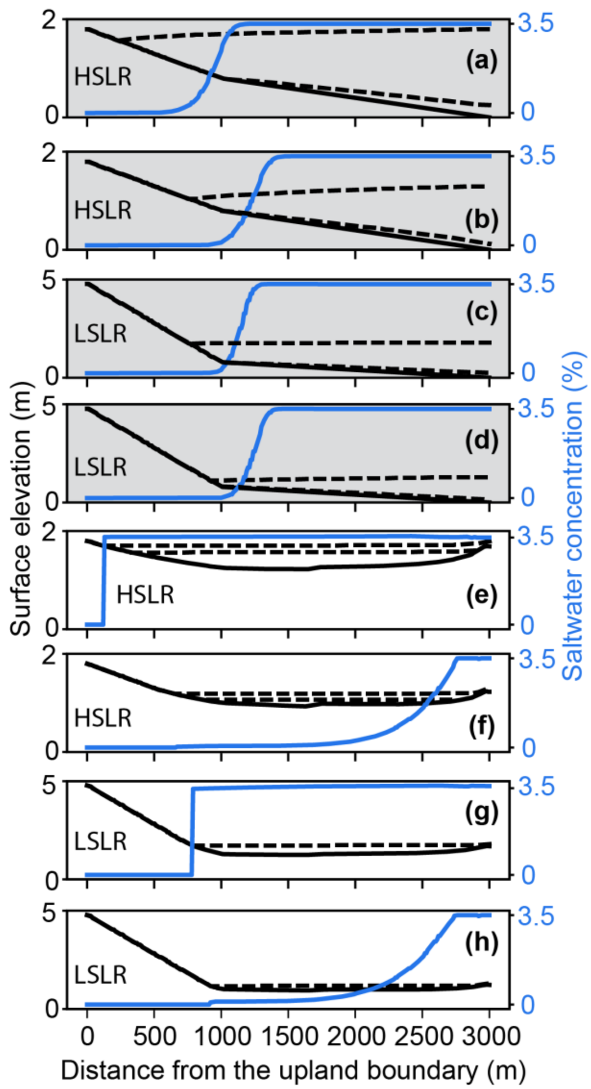

Figure 5. The surface water propagation and associated surface water concentration in the simulations with and without the considerations of marsh topographic change. (a), (b), (c), and (d) with the gray background are the cases without considering marsh evolution. (e), (f), (g), and (h)are the cases considering marsh evolution. The black solid lines are the surface elevation. The black dashed lines indicate the maximum and minimum surface water propagation under the high and low tides. The blue lines indicate the distribution of the saltwater concentration under the maximum surface water propagation conditions. HSLR and LSLR stand for the higher and lower SLR rate scenarios, respectively.

3.2.2 Subsurface salinity distribution

Under the present-day condition (upland GWT=1.3m) without SLR, Figs. 6a and b show the equilibrium salinity distribution in the aquifer with milder and steeper upland slopes, respectively. The toes and heads of the freshwater-saltwater interfaces (the interface between the blue and the cyan colors) are at ~1250 m and ~1500 m from the upland boundary, respectively.

Starting from this present-day equilibrium condition, we simulated the SWI under SLR. For the cases without considering marsh evolution (Figs. 6c, d, e, and f), we predicted an increase of SWI with the increase of SLR magnitudes. Both the toes and heads of the freshwater-saltwater interfaces are observed to move landward 500m to 1000m under the lower and higher SLR rates. The increases in SWI are attributed to the SLR-induced surface saltwater infiltration and subsurface lateral saltwater inflow. With the increased sea level, more surface seawater infiltrates to the subsurface aquifer. Meanwhile, more seawater flows into the aquifer directly through the subsurface lateral flow due to the increased hydraulic gradient between the sea level and the inland water table. We analyzed the changes in surface saltwater infiltration and subsurface lateral inflows from the beginning of the simulation to the end when the subsurface salinity distribution reached an equilibrium (see Fig. S3 and Text S2). In general, the surface saltwater infiltration had a much larger contribution to the subsurface SWI than the subsurface lateral inflow (see the blue solid lines in Fig. S3) due to the high inundation level during the high tides as illustrated in Fig. 5.

When marsh evolution was included, the depression zone formed by the marsh evolution process significantly increases surface water residence time. This occurs even though the simulated surface saltwater inflow and surface inundation depth at the ocean boundary (illustrated in Figs. 4 and 5) are much lower than the simulations without marsh evolution, Therefore, the surface ponding water accumulates seawater and prolongs the time of surface saltwater infiltration in contributing to the landward movement of the freshwater-saltwater interface. Thus, under the higher SLR rate, the equilibrium freshwater-saltwater interfaces almost reach the upland boundary (Figs. 6g and h), similar to the simulations without marsh evolution. However, under the lower SLR rate, more freshwater can flow into the domain due to a lower hydraulic gradient between the sea level (0.5 m) and the upland GWT (1.3 m), there is no significant increase in saltwater concentration in the surface ponding water (e.g., the blue lines in Figs. 5f and h). Therefore, even though the surface saltwater infiltration still dominates the SWI (the blue dashed lines in Figs. 3Sb and d), its rate is smaller than the rate under the higher SLR rate and is located only near the ocean boundary (Figs. 5f and h). We see a distinct subsurface saltwater distribution at equilibrium under the lower SLR rate: the toe of the freshwater-saltwater interface moves towards the upland boundary, but the freshwater-saltwater interface near the marsh surface moves toward the ocean boundary. More freshwater occupies the upper part of the aquifer in the middle of the marshland (Figs. 5i and j).

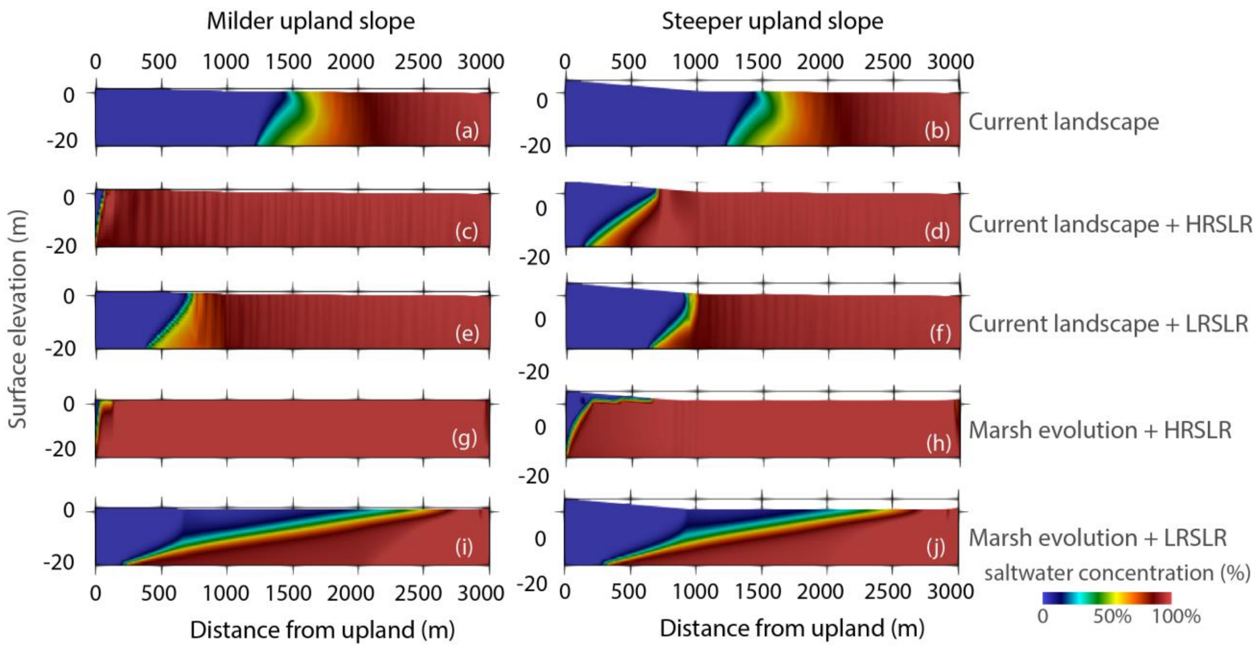

Figure 6. The distribution of subsurface saltwater concentration under the present-day sea level (a and b), future sea level (c,d, e, and f), and future sea level and topographic change (g, h, i, and j). All the simulation results are under the present-day upland GWT of 1.3 m. The left and right columns are the simulations with the milder and steeper upland slopes, respectively.

3.3 SWI under different upland GWT level

We also investigated the future SWI in response to the changes in upland GWT conditions caused by a wetter or drier future climate or intensified groundwater extraction (cases

5 to 12 in Table 2). With the same model settings and same SLR rate scenarios, a higher upland GWT (1.8 m above the initial MSL) under a wetter future climate causes a larger hydraulic gradient towards the ocean, thereby more freshwater flows towards the ocean. Therefore, the simulations predict a lower SWI for all cases under the high upland GWT (Fig. 7), compared with the cases under the present-day upland GWT (Fig. 6). Specifically, the cases without marsh evolution show slightly less SWI (Figs. 7c, d, e, and f), compared with the cases under the present-day GWT (Figs. 6c, d, e, and f). However, the cases with the marsh evolution and higher SLR rate show a larger decrease of SWI (Figs. 7g and h), compared with the corresponding cases under the present-day upland GWT (Figs. 6g and h). This is because the sufficient fresh groundwater supply from the upland pushes the saltwater back toward the ocean and dilutes the surface ponding saltwater.

However, with a lower upland GWT (0.9 m above the initial MSL) and under a drier future climate and/or increased groundwater extraction, the marshland creates a larger hydraulic gradient towards the land, compared with the present-day condition, causing more saltwater flows onto the marsh surface and into the aquifer. Therefore, more SWIs are observed in all simulation cases with the lower future upland GWT (Fig. 8). In particular, we see a larger increase of SWI for the cases with the marsh evolution and under the lower SLR rate (Figs. 8i and j), compared with the corresponding cases under the present-day upland GWT in Figs. 6i and j. This is because the upland groundwater supply is not sufficient to counteract the saltwater inflow.

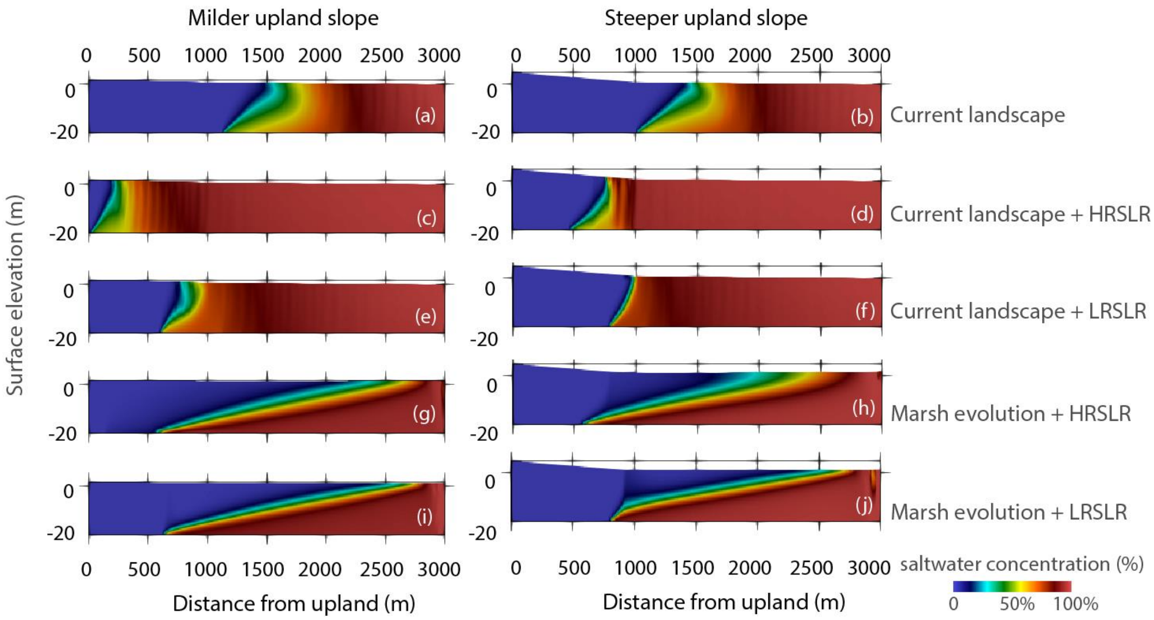

Figure 7. The distribution of subsurface saltwater concentration under the present-day sea level (a and b), future sea level (c,d, e, and f), and future sea level and topographic change (g, h, i, and j). All the simulation results are under the upland GWT of 1.8 m. The left and right columns are the simulations with the milder and steeper upland slopes, respectively.

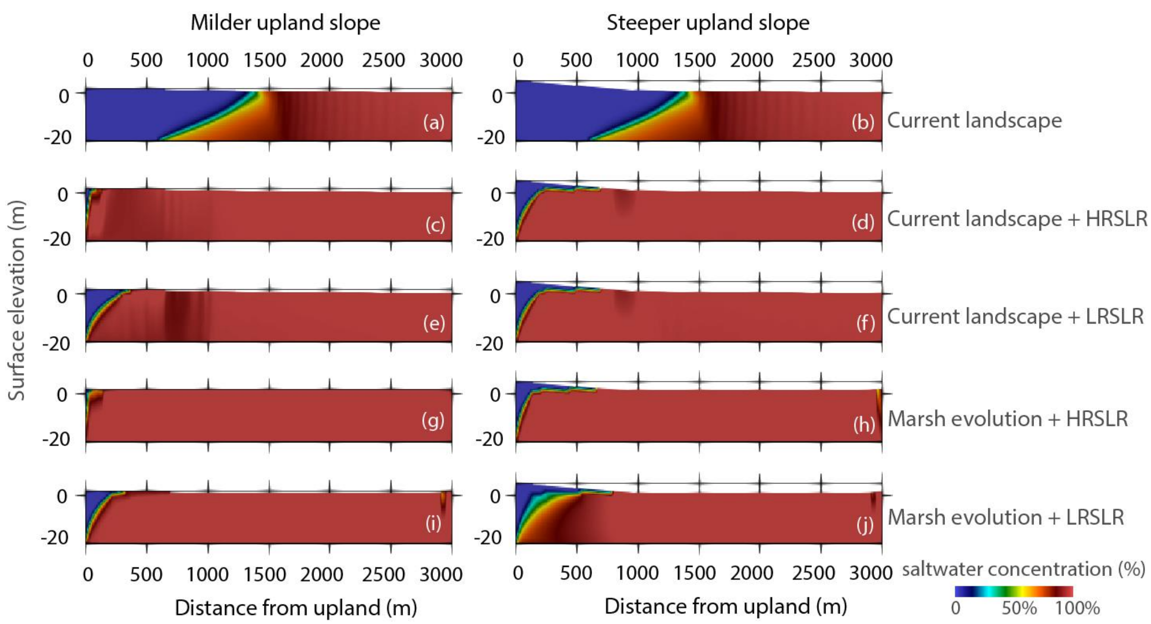

Figure 8. The distribution of subsurface saltwater concentration under the present-day sea level (a and b), future sea level (c,d, e, and f), and future sea level and topographic change (g, h, i, and j). All the simulation results are under the upland GWT of 0.9 m. The left and right columns are the simulations with the milder and steeper upland slopes, respectively.

4 Discussion

4.1 Effect of coastal marsh evolution on coastal SWI

This study used a representative coastal marsh landscape to investigate the effect of coastal landscape evolution on coastal SWI under SLR. Our marsh evolution simulations confirmed that coastal marsh landscapes are dynamic, and the evolution of coastal marsh is very spatially heterogeneous in response to SLR (Fig. 2). We found that the future marsh topography has an important influence on coastal SWI, especially on the saltwater surface inflow, surface saltwater residence time, and saltwater infiltration. Firstly, the future evolved marsh topography significantly reduces the seawater inflow on the marsh surface because the increased marsh elevation near the ocean boundary reduces the hydraulic gradient between the marshland and the ocean (e.g., the saltwater inflows in Fig. 3). The predicted seawater inflow can be up to two orders of magnitude smaller than the inflow without considering marsh evolution implying that the seawater inflow may be overestimated in the studies that do not consider marsh evolution. Secondly, the depression zone formed during the marsh evolution processes can accumulate seawater, which significantly increases the saltwater residence time on the marsh surface and prolongs infiltration time. Therefore, with the evolved marsh landscape, the hydrologic regime may be very different from that without considering marsh evolution as we demonstrated above (e.g., Figs. 4, 5, 6, and S3). In addition, our numerical experiments show that the surface saltwater infiltration contributes more to the SWI than subsurface saltwater lateral inflow through ocean boundary. This finding is consistent with several previous studies, such as *Ataie-Ashtiani et al* (2013) who discussed the predominant effect of surface inundation on subsurface SWI.

4.2 The sensitivity of future SWI to upland groundwater supply

Our simulations under future SLR show that the upland GWT effect is more significant in the cases with marsh evolution because the exfiltrated freshwater can stay longer in the surface depression zone so that it has a larger influence on counteracting with surface saltwater inflow. For example, with the different upland GWTs, the cases with marsh evolution show larger variations in the displacements of the freshwater-saltwater interface (e.g., Figs 6, 7, and 8). Quantitatively, by compiling all the cases with the different upland GWTs in Figs. 6, 7, and 8, we found that the difference between the upland GWT and MHTL (GWT-MHTL) can be a good metric to understand the effect of marsh evolution on SWI under future SLR. Specifically, Figure 9 shows the mean distance between the freshwater-saltwater interface and the ocean boundary as a function of GWT-MHTL based on the cases in Figs. 6, 7, and 8. When GWT-MHTL is greater than zero (a hydraulic gradient towards the ocean), we found that the cases considering marsh evolution predict the shortest SWI distance (the orange dots and circles in Fig. 9). However, if GWT-MHTL is less than zero (a hydraulic gradient towards the inland), we observe a slight difference of SWI between the cases with and without marsh evolution. Therefore, as marshes evolve, the system may become more sensitive to the upland GWT variation, highlighting the importance of protecting upland groundwater resources to prevent intensified SWI in the future.

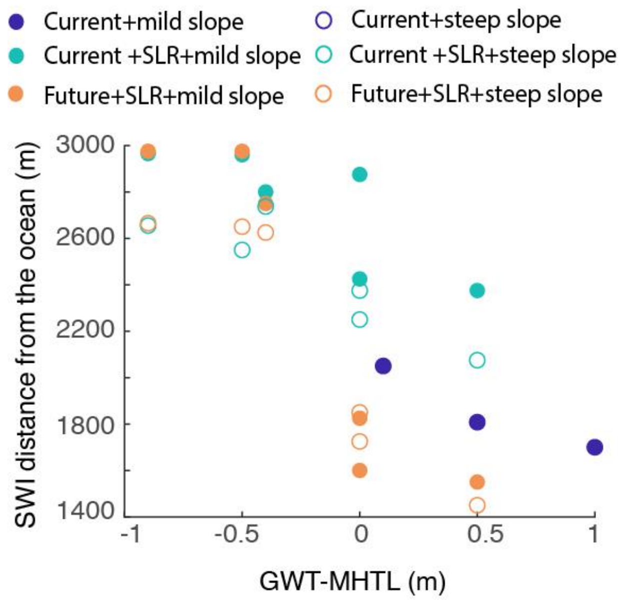

Figure 9. SWI distance as a function of GWT-MHTL under different SLR scenarios and upland slopes. The SWI distance was computed as the mean distance of the freshwater-saltwater interfaces from the ocean boundary. The terms, "current" and "future" in the legend, stand for current landscape topography and future marsh topography after marsh evolution. The circles and dots indicate the simulations under the milder and steeper upland slopes, respectively. Note: the blue circles and dots are overlapped when GWT-MHTL>0, so the blue circles are not visible.

4.3 Marsh evolution and its representativeness

Under the external drivers of SLR and tidal current, our marsh evolution simulations show that coastal marsh elevation is very likely to increase with a higher increase near the ocean boundary and a smaller increase landward due to a gradient in inorganic and organic sedimentations. Although the future marsh topographies predicted by our study are the results of the combined effect of the specific tidal amplitude, SLR rates, sediment concentration in the ocean, tidal period, and sediment diffusivity, the predicted topographic features (higher increase at ocean boundary and lower landward) are consistent with many previous marsh evolution studies (e.g., D'Alpaos et al., 2007; Kirwan, Walters, et al., 2016; Kirwan & Temmerman, 2009; Zhang et al., 2020). The formulations used in the Sed model to represent the dominant processes were selected from broadly-used sedimentation, erosion, and vegetation dynamic equations. The parameters used in this study were established in the literature from field measurements (Fagherazzi et al., 2013; Kirwan, Temmerman, et al., 2016; Morris et al., 2002; Mudd et al.,

2004) and were within the parameter range in the parametric sensitivity study by Zhang et al. (2020). Thus, our simulation results of marsh evolution are representative of the future marshland topographic change of some real-world coastal marshes under SLR.

4.4 The influence of future SWI on vegetation dynamics

Subsurface water salinity has a direct impact on vegetation growth, species richness, species distribution, and migration (Antonellini & Mollema, 2010; Silvestri & Marani, 2004). In previous studies that did not consider marsh evolution, the subsurface SWI was predicted to occupy a larger area of the coastal aquifers (e.g., Kuan et al., 2012; Michael et al., 2013), which exert larger stress on vegetation growth. However, our experiments show that the subsurface salinity may decrease, especially for the upper part of the aquifer, under the cases with a higher upland GWT and lower SLR rate (e.g., Figs. 6i and j and Figs. 7g, h, i, and j). Therefore, the surface ponding freshwater dilutes saltwater providing a favorable condition for salt-intolerant vegetation, which indicates that the vegetation species and distribution may be significantly different from the previous studies without considering marshland evolution.

4.5 Uncertainties and future work

In this study, we chose to focus on certain elements, including sea level, tide, upland groundwater table, and topographic change, which we felt were critical to our analysis of the coastal eco-geomorphologic impact on SWI. However, several factors may affect the SWI prediction, such as the vegetation dynamic representation, types of upland groundwater boundary condition, precipitation, evaporation, waves, and the land-river-ocean interaction. Specifically, our marsh evolution simulation assumed a linear relationship between the *Spartina*-dominant vegetation biomass and the coastal inundation level based on the field observation by *Morris et* *al.* (2002). However, there are also other schemes to represent the relationship between vegetation biomass and inundation level for different marsh landscapes, such as the *Spartina*-nonlinear function (Mariotti & Fagherazzi, 2010) and mixed vegetation species linear function (D'Alpaos et al., 2007). Zhang et al. (2020) evaluated the topographic outcomes from these three vegetation schemes and found that all of the schemes predicted a higher elevation increase near the ocean boundary and a lower increase landward. However, these schemes also showed differences in marsh elevation relief and unvegetated-vegetated ratio. Therefore, it is worth exploring SWI under future topographic change with different vegetation dynamic representations. Our ongoing development of a physically-based vegetation dynamic configuration on ATS will better link surface and subsurface water conditions, including salinity, soil moisture, nutrient content, and inundation level, with vegetation growth. Therefore, the newly developed model will better capture the vegetation dynamic features under different subsurface salinity conditions, instead of only tracking the impact of surface inundation on vegetation growth.

In addition, a constant GWT boundary condition is used in this study, which is suitable for the coastal landscapes with a relatively small slope such as the slopes in our experiments (Ketabchi et al., 2016). However, the freshwater supply from the upland can also be controlled by continuous groundwater fluxes. Previous numerical and analytical modeling studies found that SLR-induced saltwater intrusion has a larger impact on head-controlled coastal aquifers rather than flux-controlled coastal aquifer (Rasmussen et al., 2013; Werner et al., 2012; Werner & Simmons, 2009). Therefore, our study made a more aggressive prediction of SWI under SLR based on the head-controlled systems. The SWI in a flux-controlled system will be explored in future studies.

Precipitation and evaporation may also affect surface and subsurface saltwater transport and distribution (Geng et al., 2016; Payne, 2010; Werner & Simmons, 2009). To conduct this focused study, we reduced the complexity by limiting external drivers. We acknowledge that precipitation and evaporation would play an important role in changing water salinity on land surface and in the upper subsurface zone, yet they do not affect our conclusion on the role of marsh evolution in controlling the saltwater inflow and surface water residence time. However, to have a more realistic prediction of SWI for a real-world coastal marshland, it is necessary to take precipitation and evaporation into account in future studies.

Additionally, we did not consider erosion due to waves because marsh vegetation can mitigate waves if the waves are caused by the regular tidal variation and wind speed (D'Alpaos et al., 2007; Marani et al., 2007). However, under climatic extreme events, like hurricane and storm surge, the large waves may not be effectively mitigated by the marsh vegetation, and marshland erosion may occur and exceed the rate of sediment deposition. In this case, marsh elevation may decrease, especially near the ocean boundary as predicted by *Mariotti and Fagherazzi* (2010). The decrease of marsh elevation may increase surface saltwater inflow, thereby stimulating SWI. Also, hurricanes may directly cause distinct surface and subsurface water salinity distribution due to a dramatic increase in seawater level (Yu et al., 2016). Although it is not the scope of this study, it is worth exploring the effect of marsh evolution on SWI under these extreme climatic events in future studies.

Last, this study used transects that do not allow for surface water drainage paths connecting the marshland and marsh drainage network, which may facilitate the drainage of the surface ponding water to channels. This will require a 2-D simulation that captures the complex topography of marshes with channels and drainage pathways. Also, the role of 3-D hydrodynamics is not considered and worthy of additional future study as it would incorporate baroclinic effects that can contribute to tidally-driven sedimentation.

5 Conclusions

In this study, we investigated the impact of coastal marsh evolution on SWI prediction under future SLR by using a physically-based coastal hydro-eco-geomorphologic model, ATS (Advanced Terrestrial Simulator). Using a representative coastal marsh landscape, we first predicted the marsh landscape change with different upland slopes and under two SLR scenarios. We found that the coastal marsh landscape is not static but dynamic in response to SLR. The marsh elevation increases with the rising sea level due to the organic and inorganic sedimentation and created a higher elevation near the ocean boundary and a depression zone in the middle of the marshland. The marsh accretion is projected to cause a significant reduction of saltwater inflow at the ocean boundary because of the decrease of the hydraulic gradient between the land and ocean. Also, the evolved topographic depression zone prolongs the residence time of surface ponding water, which affects surface saltwater infiltration, therefore causes distinct subsurface salinity distributions. With the evolved marsh landscape, we also tested the impact of different upland groundwater conditions on SWI under SLR, reflecting the impact of future drier/wetter climate conditions and human groundwater extraction on fresh groundwater dynamics. We found that with the topographic change in the future, SWI is more sensitive to the upland groundwater supply because of the more intensified freshwater-saltwater interaction in the depression zone. Therefore, when predicting future SWI on coastal marsh landscape, if we do not consider marsh evolution, we are very likely to overestimate SWI under future SLR if the upland GWT is higher than the MHTL, whereas we may underestimate SWI if the future upland GWT is lower than the MHTL.

This study highlighted the importance of considering coastal marsh landscape change in predicting SWI under SLR, which was not investigated in previous studies. Over the decadal and century scales, changes in coastal landscape topography can significantly affect the temporal and spatial distributions of SWI under SLR. The insights gained from this study can help improve our understanding of the vulnerability of coastal freshwater systems under SLR, marsh landscape dynamics, and changes in upland groundwater resources, where these interconnections have been previously ignored but warrant greater consideration.

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This study is a model-based study that uses the ATS model and synthetic experiments. The model source code is available in the model repositories from the Community Surface Dynamics Modeling System (CSDMS) https://csdms.colorado.edu/wiki/Model_download_portal. Model parameters are listed in the tables above.

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