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Research papers

Tidal groundwater flow and its ecological effects in a brackish marsh at the mouth of a large sub-tropical river

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ABSTRACT

Soil saturation is thought to be an important control on plant zonation in intertidal wetlands, but quantitative studies linking saturation and plant zonation in real marsh systems are few. We conducted a combined field and modeling study to examine the potential links between groundwater flow and ecological zonation in a brackish marsh in the Yangtze River estuary. The intertidal marsh transect contained two plant zones (*Phragmites australis* and *Spartina alterniflora*) and an unvegetated mud flat adjacent to the estuary. Numerical simulations were conducted to quantify soil saturation index (SSI, ratio of saturated time to the whole observation period) for analyzing plant zonation. Models considered multiple factors, including aquifer stratification, anisotropy, evapotranspiration, surface topography (particularly slope breaks), seepage face formation and tidal loading. Simulations revealed that the average SSI over the rhizosphere depth from 0.0 m to 0.3 m increased abruptly by 11.4% at the interface of the two plant zones, and by another 10.5% at the riverward boundary of the vegetated zone. The significant increase of SSI was not caused by slope breaks but seepage face was responsible for the riverward increase of SSI. Given known differences between *Phragmites australis* and *Spartina alterniflora* in their tolerances to anoxic conditions, the subsurface saturated/unsaturated conditions quantified by SSI are most probably responsible for the observed plant zonation.

1. Introduction

Tidal marshes are highly dynamic ecosystems, characterized by complex hydrologic interactions with adjacent uplands and the coastal ocean or tide-dominated estuary (Devoy, 1977; Kirwan and Megonigal, 2013). These interactions influence nutrient budgets, plant productivity and internal plant distribution in tidal marshes (Valiela and Teal, 1979).

The ecology of tidal marshes is strongly influenced by abiotic factors, particularly surface water dynamics, which control elevation-driven hydroperiod or inundation frequency and salinity (Morris et al., 2002; Silvestri et al., 2005). Groundwater dynamics are inextricably linked to surface water, although often studied separately (Winter et al., 1998). Many studies have also highlighted the ability of groundwater flow to control the position of wetlands and plant zonation (e.g., Thibodeau et al., 1998; Wilson et al., 2015; Xin et al., 2013). Therefore, identification of the interaction between surface water and groundwater is critical for effective management for marsh plants.

Previous studies consider several hypotheses regarding the causes of plant zonation in tidal marshes, including variations in soil aeration (Li et al., 2005; Marani et al., 2006; Xia and Li, 2012), interspecific competition (Pennings and Callaway, 1992; Pennings et al., 2005; Xin et al., 2013), marsh topography (Gardner, 2005) or combined influences associated with topography, sediments, species competition and vegetation heterogeneity

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Table 1
Summary of numerical modeling studies conducted in tidal marshes. The following abbreviations or symbols are used in the table:

No.	Location/Model used	Domain size in m: length $\times$ depth $\times$ width (if any)/Length of time series	Model features						Key results		Source
			Dim	Stra	Ani	ET	SF	Tle	Surface water-groundwater exchange	Zonation	
1	None/BIEM based on the Laplace equation	(17–60) $\times$ (0.86–5)/One spring-neap period	2	$\times$	$\times$	$\times$	√	$\times$	Two thirds of total discharge occurs through creek bank with other from channel bottom	Higher productivity happens in areas where marsh mud is thicker and/or creek bank slope is steeper	Gardner (2005)
2	None/TOUGH2	6 $\times$ 2.5 /one day	2	$\times$	$\times$	√	√	$\times$	Not reported	*Spartina alterniflora* grows better near creek than in inner areas	Li et al. (2005)
3	None/SUTRA	80 $\times$ 5 /60 days	2	$\times$	√	$\times$	√	√	Groundwater discharge occurred primarily on creek bank	Groundwater flushing can prevent buildup of salinity, and affect nutrient supply and redox zonation	Wilson and Gardner (2006)
4	None/FlexPDE	80 $\times$ 5 /60 days	2	√	$\times$	$\times$	√	$\times$	Sand layer beneath marsh mud enhanced drainage and limit buildup of salt in root zone caused by transpiration	Not reported	Gardner (2007)
5	None/SUTRA	80 $\times$ 5/One tidal cycle	2	√	$\times$	$\times$	√	√	Groundwater discharge increased with tidal amplitude	Not reported	Wilson and Morris (2012)
6	None/SUTRA	60 $\times$ 5/One spring-neap period	2	$\times$	$\times$	$\times$	$\times$	$\times$	Not reported	Soil saturation index (SSI) was introduced to describe soil aeration condition	Xin et al. (2010)
7	None/ELCIRC + SUTRA	250 $\times$ 8 $\times$ 100/One tidal cycle	3	$\times$	$\times$	$\times$	√	$\times$	Groundwater dynamics exhibited significant flow asymmetry with nonzero mean flow velocities. Water circulation strongly linked to marsh topography	Not reported	Xin et al. (2011)
8	None/SUTRA	250 $\times$ 8 $\times$ 100/One tidal cycle	3	√	$\times$	$\times$	√	√	The sandy layer enhances drainage during falling tides	Not reported	Xin et al. (2012)
9	None/Boussinesq or Richards' equations	200 $\times$ 5/30 days	1 & 2	$\times$	$\times$	√	$\times$	$\times$	Three-dimensional water circulation strongly linked to marsh topography	Combined influences of the intra- and inter-species competition, topography, soil hydraulic conductivity and capillary on plant zonation	Xin et al. (2013)
10	Falmouth, Massachusetts, America/ 1D unsaturated Darcy with compression	1.8 m in depth/12 h	1	$\times$	$\times$	√	$\times$	$\times$	An upward groundwater flow was needed to compensate ET	Not reported	Hemond and Fifield (1982)
11	Chesapeake Bay, America / Boussinesq equation	20 $\times$ 2/12 h	2	√	$\times$	$\times$	$\times$	$\times$	Surface water infiltrated through creek bank and discharge from the interior marsh	Not reported	Harvey et al. (1987)
12	Hunter River estuary, Australia/ SEEP/W model	36 $\times$ 2/two months	2	√	√	√	$\times$	$\times$	Surface water infiltration were about half balanced by ET	Not reported	Hughes et al. (1998)
13	The Venice Lagoon, Italy /Richards' equation	10 $\times$ 5/not reported	2	$\times$	√	√	√	$\times$	Infiltration dominates over root water uptake. Horizontal seepage is effective drainage near channels	Interspecific competition and soil oxygen controlled plant patterns	Marani et al. (2006)
14	Dongzhaigang Bay, China /MARUN model based on Richards' equation	300 $\times$ 17/3 days	2	√	$\times$	$\times$	$\times$	$\times$	Seawater infiltrated near the high intertidal zone, and discharged from the tidal river bank in the vicinity of the low tide line	Plant zonation is caused by the root respiration condition determined by the tidal groundwater hydraulics in the marsh	Xia and Li (2012)
15	The Venice Lagoon, Italy/TELEMAC 2D	70 $\times$ 2/one day	2	$\times$	$\times$	$\times$	$\times$	$\times$	Not reported	Multiple factors may be responsible for the observed plant distribution	Silvestri et al. (2005)
16	San Francisco Bay, California, USA / HydroGeoSphere	Regional model (2.2 hectares, 11 m in depth)/ 24 h	3	√	√	√	√	$\times$	Groundwater discharge mainly through the channel banks; Surface water - groundwater exchange rates were primarily influenced by hydraulic conductivities	Combined influences of topographic, sediment, and vegetation heterogeneity on plant zonation	Moffett et al. (2012)
17	The same as above	Regional model (2.2 hectares, 11 m in depth)/ Two separate days	3	√	√	√	√	$\times$	The same as above, but focusing on methylmercury distribution	Not reported	Zhang et al. (2014)
18	Estuary of Yangtze river, China / MARUN model based on Richards' equation	1338 $\times$ 25/30 days	2	√	√	√	√	√	River water recharges mainly in the upper and middle intertidal zone and groundwater mainly discharges in the low intertidal zone	Reasons for plant zonation are analyzed in terms of subsurface saturated/unsaturated conditions and groundwater-river water exchange rate	This study

Dim = Dimension; Stra = Stratification; Ani = Anisotropy; ET = Evapotranspiration; SF = Seepage face; Tle = Tidal loading effect; √ = considered; $\times$ = not considered. Salinity was not considered in numerical models listed here. Studies No. 1–9 are theoretical marsh models, and the others are models with case study sites