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Assessing sea-level rise impact on saltwater intrusion into the root zone of a geo-typical area in coastal east-central Florida

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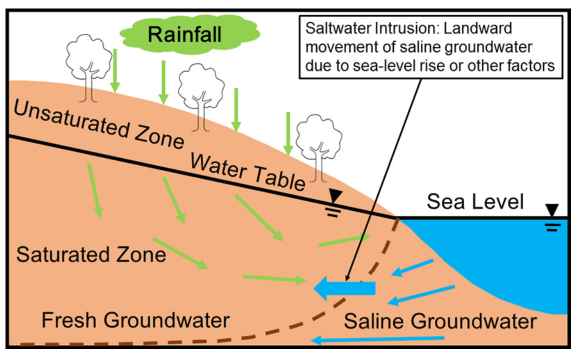
HIGHLIGHTS

- Saltwater intrusion due to sea-level rise greatly increases root zone salinity level.
- FEMWATER models can simulate the extent of saltwater intrusion.
- Root zone salinity level is highest in June and lowest in October.

GRAPHICAL ABSTRACT



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ABSTRACT

Saltwater intrusion (SWI) into root zone in low-lying coastal areas can affect the survival and spatial distribution of various vegetation species by altering plant communities and the wildlife habitats they support. In this study, a baseline model was developed based on FEMWATER to simulate the monthly variation of root zone salinity of a geo-typical area located at the Cape Canaveral Barrier Island Complex (CCBIC) of coastal east-central Florida (USA) in 2010. Based on the developed and calibrated baseline model, three diagnostic FEMWATER models were developed to predict the extent of SWI into root zone by modifying the boundary values representing the rising sea level based on various sea-level rise (SLR) scenarios projected for 2080. The simulation results indicated that the extent of SWI would be insignificant if SLR is either low (23.4 cm) or intermediate (59.0 cm), but would be significant if SLR is high (119.5 cm) in that infiltration/diffusion of overtopping seawater in coastal low-lying areas can greatly increase root zone salinity level, since the sand dunes may fail to prevent the landward migration of seawater because the waves of the rising sea level can reach and pass over the crest under high (119.5 cm) SLR scenario.

1. Introduction

Coastal aquifer water quality is of great importance for human development since more than 50% of the world's population lives within 60 km of the shoreline (Newmann et al., 2015). However, coastal groundwater contamination from saltwater intrusion (SWI) has been

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reported in many coastal areas and was deemed as a detrimental issue affecting coastal water supplies, ecosystems, and economies (Barlow and Reichard, 2010). The occurrence of SWI depends on coastal hydrogeology, hydro-climatology such as sea levels and rainfall, and anthropogenic activities such as groundwater pumping and land use change (Bear et al., 1999). In recent years, sea-level rise (SLR) has been highlighted as one of the main factors causing SWI (Chang et al., 2011; Rasmussen et al., 2013; Werner and Simmons, 2009; Werner et al., 2013), and the extent and intensity of SWI will further increase due to the increase of the rate of SLR (IPCC, 2013). This is likely to cause environmental problems including land salinization, groundwater quality deterioration, closure or relocation of water supply wells, and ecosystem degradation (Alizad et al., 2016; Bilskie et al., 2016; Hovenga et al., 2016; Huang et al., 2015; Ketabchi et al., 2016; Kidwell et al., 2017; Passeri et al. 2015a, 2015b & 2015c).

A saltwater/freshwater transition zone is formed between the fresh and saline groundwater zones, and the density and salt concentration in the transition zone varies spatially and temporally depending on local hydrologic and geologic conditions (Bear, 1979). The migration of transition zone can be simulated by numerical models, such as SEAWAT (Guo and Langevin, 2002) and SUTRA (Voss, 1984). These models have been utilized to estimate the extent of SWI by modeling the migration of the transition zone under climate change and human development (Datta et al., 2009; Hussain and Javadi, 2016; Kim et al., 2012; Langevin, 2003; Lin et al., 2009; Mzila and Shuy, 2003; Qahman and Larabi, 2006; Sanford and Pope, 2010; Xiao et al., 2016; Yu et al., 2016). For example, Xiao et al. (2016) developed a SEAWAT model to study the salinity distribution in the surficial aquifer of east-central Florida coast for assessing SLR and climate change impacts on SWI into surficial aquifer. However, note that both SEAWAT and SUTRA models can simulate the extent of SWI into saturated zone (unconfined/confined aquifer below water table), while are not capable of simulating SWI into unsaturated zone (vadose zone above water table).

Root zone salinity affected by water table dynamics in coastal east-central Florida is crucial to the survival of various vegetation species (Purdum et al., 2002) and the distribution of plant communities and habitats (Box et al., 1993; Foster et al., 2017; Saha et al., 2011; Saha et al., 2015). Root zone salinity level provides a good measurement of salt exposure to vegetation and an indication of vegetation impacts. An increasing salinity level can cause serious consequences such as vegetation species dieback and limited recovery, shift in species composition from less to more salt-tolerant species, and reduction in biomass production (Hall et al., 2014; Schmalzer, 1995; Steyer et al., 2007). Therefore, it is of great importance to quantify the spatial and temporal variation of root zone salinity and predict the extent of SWI under SLR impacts, and numerical models capable of simulating salinity transport under variable-density condition in unsaturated zone (or combined unsaturated and saturated zones), such as FEMWATER (Lin et al., 1997), are highly required.

In this study, two research questions were addressed: (1) what is the current salinity level and where is the current saltwater/freshwater transition zone in root zone of a geo-typical coastal area located at the Cape Canaveral Barrier Island Complex (CCBIC) of coastal east-central Florida?; and (2) how will the spatial and temporal variation of root zone salinity and location of the saltwater/freshwater transition zone change under various SLR scenarios? To answer these questions, a three-dimensional finite-element variable-density FEMWATER model was developed and calibrated using 2010 hydrologic conditions to simulate the monthly variation of root zone salinity in 2010 (baseline model), and the extent of SWI into root zone under three SLR scenarios projected to 2080 were estimated by developing three "diagnostic" models based on the calibrated "baseline" model. The outcome of this study contributes to ongoing research focused on forecasting vegetation community responses to climate change (Foster et al., 2017), and serves as an effective tool for climate change adaptation planning and decision-making in the CCBIC and other low-lying coastal alluvial plains and barrier island systems.

2. Overview of study area

2.1. Site description

The study area (i.e., model domain) covers approximately 0.45 km^2 and is located in a biogeotypical coastal area located at the Cape Canaveral Barrier Island Complex (CCBIC) of east-central Florida coast, as shown in Fig. 1a. The lateral boundaries of the model domain are determined from the water table contours simulated by a developed and calibrated SEAWAT model (Xiao et al., 2016) as shown in Fig. 1b. From Fig. 1b, the lateral boundaries correspond to (1) the groundwater divide to the west; (2) the soil-water interface (coastline of the Banana River) to the east; and (3) the no-flux boundary to the north and south. Unlike the lateral boundaries, the vertical boundaries of the model domain are determined physically. The upper boundary is the land surface (see Fig. 1c) and the lower boundary is the bottom of the surficial aquifer, therefore, both the unsaturated zone (from the land surface to water table) and the saturated zone (from water table to the bottom of the surficial aquifer) are included in the model domain. The land surface elevation varies from approximately −1.28 to 5.42 m NAVD88. Variation in the local topography is relatively small since the study area is mainly composed of broad and flat lowland. The land cover is mainly comprised of shrub and brushland, grassland, and mixed scrub-shrub wetland. The climate is classified as humid subtropical with hot/humid summers (mean temperature 22 °C to 33 °C) and mild/dry winters (mean temperature 10 °C to 22 °C), and the mean annual rainfall is 1366 mm with a wet season lasting from June to October (Mailander, 1990). The primary inflow is rainfall and the primary outflows are evapotranspiration and submarine groundwater discharge to the Banana River (Schmalzer et al., 2000). The Banana River, located on the southeast border of the study area, is a coastal lagoon connected with the Atlantic Ocean through the Canaveral Lock to the east and Sebastian Inlet to the southeast, and has a shallow, flat, seagrass covered bottom with an average depth of 1.5 m, and the total dissolved solids (TDS) concentration typically varies from 10 to 45 kg/m^3 (Hall et al., 2014). The Banana River in this area is micro-tidal due to the distance to small ocean passes, and its water level varies monthly from −0.33 to −0.06 m NAVD88 approximately 4–5 cm higher than sea level of the Atlantic Ocean (Foster et al., 2017; Smith, 1990 & Smith, 1993). The unsaturated zone in the study area is mainly composed of fine sand and the water table depth varies from 0 to 2 m (Xiao et al., 2016), and the saturated zone is mainly composed of fine to medium sand (Miller, 1986; Williams and Kuniansky, 2016). The water table and local Banana River level rise to the highest elevation late in the wet season (October) and drop to the lowest elevation late in the dry season (May), mainly controlled by the temporal variation of rainfall, evapotranspiration, and the annual rise and fall of sea level (Foster et al., 2017).

2.2. Sea-level rise scenarios

The NASA Climate Adaptation Science Investigator (CASI) Workgroup established in 2010 consists of scientists and engineers from academia, private sectors, and non-governmental organizations, and developed the scientific and technical basis for climate change adaptation based on the Goddard Institute for Space Studies (GISS) global climate model (GCM) Model E (Schmidt et al., 2006). Sea-level rise projections for the coastal areas located at the Cape Canaveral Barrier Island Complex (CCBIC) of east-central Florida were regionalized and downscaled based on the GCM model as well as rapid ice-melt scenarios (low, intermediate, and high) (Horton and Rosenzweig, 2010) using the method described in Horton et al. (2011). The SLR scenarios applied to the study area were developed by the Center for Climate Systems Research, Earth Institute, Columbia University as part of the NASA CASI