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Exploration of the effects of storm surge on the extent of saltwater intrusion into the surficial aquifer in coastal east-central Florida (USA)

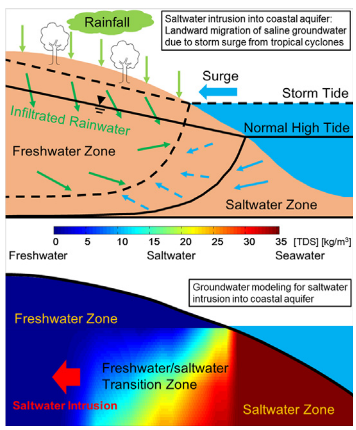
Han Xiao [a,*], Dingbao Wang [a], Stephen C. Medeiros [a], Matthew V. Bilskie [b], Scott C. Hagen [b], Carlton R. Hall [c]

[a] *Department of Civil, Environmental, and Construction Engineering, University of Central Florida, 12800 Pegasus Drive, ENGR II 324, Orlando, FL, United States of America*
[b] *Department of Civil and Environmental Engineering, Center for Computation & Technology, Center for Coastal Resiliency, Louisiana State University, Baton Rouge, LA, United States of America*
[c] *Ecological Program, Integrated Mission Support Services, Kennedy Space Center, Florida, United States of America*

HIGHLIGHTS

- Storm surge from tropical cyclones can cause saltwater intrusion into coastal aquifers.
- Infiltrated saltwater can be diluted and flushed by infiltrated rainwater.
- Recovery of groundwater quality by infiltrated rainwater might need eight years.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change such as altered frequency and intensity of storm surge from tropical cyclones can cause saltwater intrusion into coastal aquifers. In this study, a reference SEAWAT model and a diagnostic SEAWAT model are developed to simulate the temporal variation of surficial aquifer total dissolved solids (TDS) concentrations after the occurrence of a storm surge for exploration of the effects of storm surge on the extent of saltwater intrusion into the surficial aquifer in coastal east-central Florida (USA). It is indicated from the simulation results that: (1) rapid infiltration and diffusion of overtopping saltwater resulting from storm surge could cause a significant and rapid increase of TDS concentrations in the surficial aquifer right after the occurrence of storm surge; (2) rapid infiltration of freshwater from rainfall could reduce surficial aquifer TDS concentrations beginning from the second year after the occurrence of storm surge in that the infiltrated rainwater could generate an effective hydraulic barrier to impede further inland migration of saltwater and provide a downgradient freshwater discharge for saltwater dilution and flushing counteracting the effects of storm surge on the extent of saltwater intrusion; and (3) infiltrated rainwater might take approximately eight years to dilute and flush the overwhelming majority of infiltrated saltwater back out to the surrounding waterbodies, i.e., the coastal lagoons and the Atlantic Ocean.

* Corresponding author.
E-mail address: Han.Xiao@Knights.ucf.edu (H. Xiao).

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1. Introduction

Saltwater intrusion (SWI) occurs as a result of the landward shift of the dynamic equilibrium between saline and fresh coastal groundwater usually caused by coastal aquifer overexploitation, and is a significant growing problem globally with detrimental effects such as reduction of fresh groundwater storage, degradation of drinking water quality and soil salinization, deserving of close attention in coastal areas around the world (Bear, 1979; Bear et al., 1999; Freeze and Cherry, 1979; Werner et al., 2013). Recently, studies focusing on assessments of the impacts of climate change on SWI into coastal aquifers blossomed, since climate change such as sea-level rise, changing groundwater recharge rates due to changing temperature and precipitation regimes, and increases in both the frequency and intensity of extreme weather events such as tropical storms and hurricanes can further increase the extent of SWI posing a significant challenge for coastal engineering and drinking water resource management in vulnerable coastal areas (Chang et al., 2011; Chui and Terry, 2013; Colombani et al., 2016; Intergovernmental Panel on Climate Change, 2007; Kazakis et al. 2016 & 2018; Langevin et al., 2005; Oude Essink et al., 2010; Ptak et al., 2011; Rasmussen et al., 2013; Sulzbacher et al., 2012; Tang et al., 2013; Werner and Simmons, 2009; Xiao et al., 2016; Yang et al. 2013 & 2015; Yu et al., 2016). For example, Chang et al. (2011) used numerical method based on SEAWAT computer code to evaluate the short-term and long-term impacts of sea-level rise on SWI into a conceptual unconfined and confined aquifer system; Chui and Terry (2013) conducted a numerical study to investigate the effects of eustatic sea-level rise on SWI into fresh groundwater lenses on a typical atoll in the tropical Pacific Ocean; Colombani et al. (2016) used numerical method based on SEAWAT computer code to quantify the foreseeable impacts of climate change on SWI into the unconfined aquifer of the Po Delta located in the coastal floodplain of the Po River in Northern Italy; Kazakis et al. (2016) used the electrical resistivity tomography (ERT) method in conjunction with hydro-chemical data to determine the extent and geometrical characteristics of SWI into the coastal aquifer of the eastern Thermaikos Gulf located in northern Greece; Kazakis et al. (2018) used the fuzzy logic based modification of the GALDIT method to assess the SWI vulnerability of coastal aquifers of Anthemountas basin located in Northern Greece; Langevin et al. (2005) developed an integrated surface-water/groundwater flow and solute transport model and applied it to the southern Everglades of Florida (USA) to assess the effects of hydro-climatologic conditions changes on SWI into the coastal aquifer; Oude Essink et al. (2010) constructed a three-dimensional numerical model to quantify the possible impacts of climate change in combination with anthropogenic activities on increasing the salinity level of the coastal groundwater system in the low-lying Dutch Delta in coastal Netherland; Rasmussen et al. (2013) used numerical method based on SEAWAT computer code to assess the impacts of sea-level rise and changes in groundwater recharge on SWI into the coastal aquifer of an island located in the Western Baltic Sea; Sulzbacher et al. (2012) implemented a numerical, density-dependent FEFLOW model to estimate climate change impacts on increasing the salinity level of the coastal aquifer of the North Sea Island of Borkum (Germany); Werner and Simmons (2009) developed two conceptual models to explore the extent of SWI into conceptual coastal unconfined aquifers in response to sea-level rise; Yang et al. (2013 & 2015) numerically investigated the impacts of tides and storm surges on changing coastal flow dynamics and alteration of salt distribution in the coastal aquifer situated north of Bremerhaven, northern Germany; Yu et al. (2016) simulated the impacts of coastal topographic features and increases in the frequency and intensity of storm surges on groundwater salinization in a conceptual coastal aquifer in coastal Delaware (USA).

Bilskie et al. (2014) and Passeri et al. (2015a, 2015b) demonstrated that the low-lying coastal alluvial plains and barrier islands in coastal east-central Florida (USA) are morphologically sensitive to changing hydrologic conditions associated with sea-level rise and increased intensity and frequency of storm surge from tropical cyclones, with the dynamic impacts including coastline erosion and SWI that result in alterations of the distribution and productivity of vegetation communities such as shifts in species composition possibly from less salt tolerant species to more salt tolerant species. Thus, in order to produce climate change adaptation strategies for tackling the issue of potential SWI, it is necessary to develop knowledge on the responses of coastal aquifer salinity to sea-level rise and the increase in intensity and frequency of storm surge from tropical cyclones. The complex nature of variable-density groundwater flow and solute transport in the low-lying coastal alluvial plains and barrier islands in coastal east-central Florida requires the use of numerical methods to simulate SWI (Anderson and Woessner, 1991), and the SEAWAT computer code (Guo and Langevin, 2002) that has been successfully applied to many case studies around the world (Cobaner et al., 2012; Langevin, 2003; Lin et al., 2009; Qahman and Larabi, 2006; Rasmussen et al., 2013; Sanford and Pope, 2010) is selected as the simulation code in this study.

In the low-lying coastal alluvial plains and barrier islands in coastal east-central Florida, the effects of sea-level rise on the extent of SWI into the surficial aquifer were quantitatively simulated by the SEAWAT models developed by Xiao et al. (2016), and the simulation results indicated that sea-level rise will play a vital role causing SWI. In this study, the objective is to develop SEAWAT models to simulate the effects of storm surge from tropical cyclones on the extent of SWI into the surficial aquifer of the low-lying coastal alluvial plains and barrier islands in coastal east-central Florida as a continuous study of Xiao et al. (2016) for exploration of the impacts of climate change (e.g., sea-level rise, storm surge, etc.) on the extent of SWI. In this study, a reference SEAWAT model and a diagnostic SEAWAT model are developed for quantifying the temporal variation of TDS concentrations in the surficial aquifer from the occurrence of storm surge to twenty years after its occurrence for exploring: (1) what is the extent of SWI into the surficial aquifer and how far inland the toe of the subterranean saltwater wedge can encroach?; and (2) how long it takes for the infiltrated saltwater to be diluted and flushed from the surficial aquifer by infiltration of freshwater from rainfall?.

2. Overview of study area

2.1. Site description

The study area is the Cape Canaveral Barrier Island Complex (CCBIC) area located in the low-lying coastal alluvial plains and barrier islands in coastal east-central Florida, consisting of multiple barrier islands, saltwater/freshwater lagoons, and the Atlantic Ocean coastline. The CCBIC area covers an area of approximately 1000 km^2 bounded by the Atlantic Ocean to the east, Mosquito Lagoon to the northeast and north, Indian River Lagoon to the west, and Banana River to the southeast and south (Fig. 1a), and is recognized as having high biodiversity because of the unique transitional geographic setting between the Caribbean and Carolinian zoogeographic provinces (Hall et al., 2014). The topographic variation is relatively small since the region is mainly composed of broad flat lowlands, and the land surface elevation varies from −0.2 to 10 m with a regional average of about 1.2 m NAVD 88 (LiDAR data from the National Aeronautics and Space Administration (NASA)).

2.2. Hydro-climatic conditions

The climate is humid subtropical with hot/humid summers (mean temperature varying from 22 °C to 33 °C) and mild/dry winters (mean temperature varying from 10 °C to 22 °C) with a mean annual rainfall of 1366 mm (annual rainfall varying from 848 mm to 2075 mm) (Mailander, 1990). The regional hydrologic conditions are characterized by dynamic interactions between surface water and groundwater, evapotranspiration, and rainfall (Hall et al., 2014; Schmalzer et al., 2000) as shown in Fig. 1b. Water levels in the coastal lagoons are