Groundwater Modeling for Assessing the Impacts of Natural Hazards in East-Central Florida

Han Xiao

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GROUNDWATER MODELING FOR ASSESSING THE IMPACTS OF
NATURAL HAZARDS IN EAST-CENTRAL FLORIDA

by

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B.S. Jiangsu University of Science and Technology, 2011
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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Civil, Environmental and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

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2017

Major Professor: Dingbao Wang
ABSTRACT

In coastal east-central Florida (ECF), the low-lying coastal alluvial plains and barrier islands have a high risk of being inundated by seawater due to climate change effects such as sea-level rise, changing rainfall patterns, and intensified storm surge from hurricanes. This will produce saltwater intrusion into the coastal aquifer from infiltration of overtopping saltwater. In the inland ECF region, sinkhole occurrence is recognized as the primary geologic hazard causing massive financial losses to society in the past several decades. The objectives of this dissertation are to: (1) evaluate the impacts of sea-level rise and intensified storm surge on the extent of saltwater intrusion into the coastal ECF region; (2) assess the risk level of sinkhole occurrence in the inland ECF region. In this dissertation, numerical modeling methods are used to achieve these objectives. Several three-dimensional groundwater flow and salinity transport models, focused on the coastal ECF region, are developed and calibrated to simulate impacts of sea-level rise and storm surge based on various sea-level rise scenarios. A storm surge model is developed to quantify the future extent of saltwater intrusion. Several three-dimensional groundwater flow models, focused on the inland ECF region, are developed and calibrated to simulate the spatial variation of groundwater recharge rate for analyzing the risk level of sinkhole occurrence in the geotypical central Florida karst terrains. Results indicate that sea-level rise and storm surge play a dominant role in causing saltwater intrusion, and the risk of sinkhole occurrence increases linearly with an increase in recharge rate while the timing of sinkhole occurrence is highly related to the temporal variation of the difference of groundwater level between confined and unconfined aquifers. The outcome will contribute to ongoing research focused on forecasting the impacts of climate change on the risk level of natural hazards in ECF region.
Keywords

Climate change, Saltwater intrusion, Groundwater modeling, Sinkhole occurrence, Recharge rate, East-central Florida
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# TABLE OF CONTENTS

LIST OF FIGURES ...................................................................................................................... xii

LIST OF TABLES ........................................................................................................................ xvii

CHAPTER 1 INTRODUCTION .............................................................................................. 1

CHAPTER 2 ASSESSING THE IMPACTS OF SEA-LEVEL RISE ON SALTWATER

INTRUSION INTO THE SATURATED ZONE ........................................................................... 4

2.1 Introduction................................................................................................................ 4

2.2 Overview of Study Area ............................................................................................ 8

2.2.1 Hydro-climatologic conditions ................................................................................ 10

2.2.2 Hydrogeology .......................................................................................................... 11

2.3 Numerical Modeling ................................................................................................ 14

2.3.1 Model development ................................................................................................. 14

2.3.2 Scenarios of SLR and precipitation change ............................................................. 15

2.3.3 Simulation code and graphical user interface ......................................................... 16

2.3.4 Spatial and temporal discretization .......................................................................... 18

2.3.5 Hydrogeologic parameters ....................................................................................... 21

2.3.6 Boundary conditions ............................................................................................... 23

2.3.7 Initial conditions ...................................................................................................... 28

2.4 Calibration ................................................................................................................ 29

2.4.1 Head calibration ....................................................................................................... 29

2.4.2 Sensitivity analysis .................................................................................................... 34

2.5 Results and Discussions ........................................................................................... 35
6.3.3 Regional-scale model ................................................................. 187
  6.3.3.1 Model domain ................................................................. 187
  6.3.3.2 Discretization ................................................................. 189
  6.3.3.3 Parameters ................................................................. 192
  6.3.3.4 Boundary conditions .................................................... 192
  6.3.3.5 Initial conditions ......................................................... 193
  6.3.3.6 Simulation results ......................................................... 194
6.3.4 Local-scale model ........................................................................ 196
  6.3.4.1 Model domain ................................................................. 196
  6.3.4.2 Discretization ................................................................. 196
  6.3.4.3 Parameters ................................................................. 200
  6.3.4.4 Boundary conditions .................................................... 204
  6.3.4.5 Initial conditions ......................................................... 205
6.3.5 Calibration .............................................................................. 205
6.4 Results and discussions .................................................................... 213
  6.4.1 Groundwater recharge ....................................................... 213
  6.4.2 Risk level of sinkhole occurrence ....................................... 213
  6.4.3 Regression analysis ............................................................ 216
6.5 Conclusion ..................................................................................... 220
6.6 References .................................................................................... 221

CHAPTER 7 SUMMARY AND CONCLUSION .................................................... 224
APPENDIX A CERTIFICATE OF COMPLETION OF THE SURVEY .................. 229
LIST OF FIGURES

Figure 1 Location of the Cape Canaveral Barrier Island Complex (CCBIC), Florida (USA)........ 9
Figure 2 Illustration of the hydrology of the CCBIC................................................................. 9
Figure 3 Description of the hydrostratigraphic units ............................................................... 13
Figure 4 Spatial discretization: (a) Plan view; (b) West to east cross-section labeled W-E
[NAVD88 – North American Vertical Datum of 1988]................................................................. 19
Figure 5 Land surface elevation of the CCBIC ........................................................................ 20
Figure 6 Specified head and concentration boundary (marked in light-blue) assigned to layer 1:
(a) Case 0; (b) Cases 1 and 2; (c) Case 3; (d) Cases 4 and 5......................................................... 25
Figure 7 (a) Land use and land cover; (b) Mean daily recharge (2010) ...................................... 27
Figure 8 (a) Location of observation wells and scatter diagram of the goodness of fit between the
observed and simulated water table elevations (W.T., m NAVD88); (b) Sensitivity of horizontal
hydraulic conductivity (K_h) and recharge ................................................................................... 30
Figure 9 Spatial variation of: (a) Water table depth; (b) ‘Sensitive’ areas ................................. 36
Figure 10 Spatial variation of: (a) ‘Influenced’ areas (plan view); (b) ‘Influenced’ areas (west to
east cross-section labeled A-A’); (c) Elevation of land surface and water table (west to east
cross-section labeled 1-1’).......................................................................................................... 39
Figure 11 Spatial variation of ‘sensitive’ areas: (a) Case 0; (b) Case 1 (13.2 cm SLR, +17%
precipitation); (c) Case 2 (13.2 cm SLR); (d) Case 3 (31.0 cm SLR); (e) Case 4 (58.5 cm SLR);
(f) Case 5 (58.5 cm SLR, -7% precipitation).............................................................................. 42
Figure 12 Spatial variation of ‘influenced’ areas: (a) Case 0; (b) Case 1 (13.2 cm SLR, +17% precipitation); (c) Case 2 (13.2 cm SLR); (d) Case 3 (31.0 cm SLR); (e) Case 4 (58.5 cm SLR); (f) Case 5 (58.5 cm SLR, -7% precipitation)................................................................................................. 43

Figure 13 (a) Growth rate of ‘influenced’ areas; (b) The relationship between increased/decreased precipitation and its impacts on alteration of growth rate............................... 48

Figure 14 Location of the Cape Canaveral Barrier Island Complex (CCBIC), Florida (USA).... 66

Figure 15 Illustration of the hydrologic conditions of the CCBIC ............................................ 66

Figure 16 Time-variant water surface elevation [m NAVD88] of the coastal lagoons and the Atlantic Ocean during the 84-hour ADCIRC simulation: (a) Before simulation; (b) 3 hours; (c) 9 hours; (d) 15 hours; (e) 21 hours; (f) 27 hours; (g) 33 hours; (h) 39 hours; (i) 45 hours; (j) 51 hours; (k) 57 hours; (l) 63 hours; (m) 69 hours; (n) 75 hours; (o) 81 hours; (p) After simulation 74

Figure 17 Steady-state spatial distribution of salinity: (a) Plan view; (b) South to north cross-sectional view......................................................................................................................... 78

Figure 18 Transient spatial distribution of salinity (plan view): (a) 09/27/2004; (b) 01/25/2005; (c) 05/25/2005; (d) 09/22/2005; (e) 01/20/2006; (f) 05/20/2006; (g) 09/17/2006; (h) 01/15/2007; (i) 05/15/2007; (j) 09/12/2007; (k) 01/10/2008; (l) 05/09/2008; (m) 09/06/2008; (n) 01/04/2009; (o) 05/04/2009; (p) 09/01/2009; (q) 09/01/2010; (r) 09/01/2011; (s) 08/31/2012; (t) 08/31/2013; (u) 08/31/2014; (v) 08/30/2016; (w) 08/30/2018; (x) 08/29/2020; (y) 08/29/2022; (z) 08/29/2024 ............................................................................................................................................ 83

Figure 19 Transient spatial distribution of salinity (cross-sectional view): (a) 09/27/2004; (b) 01/25/2005; (c) 05/25/2005; (d) 09/22/2005; (e) 01/20/2006; (f) 05/20/2006; (g) 09/17/2006; (h) 01/15/2007; (i) 05/15/2007; (j) 09/12/2007; (k) 01/10/2008; (l) 05/09/2008; (m) 09/06/2008; (n)
Figure 20 Percentage increase in the area ratios compared to the steady-state simulation .......................... 89

Figure 21 Percentage decrease in fresh groundwater storage compared to the steady-state simulation ................................................................. 89

Figure 22 Location of the study area .............................................................................................................................. 106

Figure 23 Boundary conditions assigned to the lateral boundaries ............................................................................. 111

Figure 24 Monthly mean water level and TDS concentration of the Banana River .................................................. 111

Figure 25 Monthly mean precipitation and evapotranspiration .................................................................................. 112

Figure 26 Two-dimensional and three-dimensional mesh ............................................................................................. 112

Figure 27 Calibration of the simulated heads ............................................................................................................. 117

Figure 28 Monthly variation of TDS concentrations in the vegetation root zone that are 10, 20, 30, and 40 m away from the coastline ........................................................................................................... 117

Figure 29 Spatial distribution of salinity: (a) June, 2010; (b) June, 2080 (23.4 cm SLR); (c) June, 2080 (59 cm SLR); (d) June, 2080 (119.5 cm SLR) ............................................................................................................. 120

Figure 30 Spatial distribution of salinity: (a) October, 2010; (b) October, 2080 (23.4 cm SLR); (c) October, 2080 (59 cm SLR); (d) October, 2080 (119.5 cm SLR) .......................................................................................... 121

Figure 31 Location of the study area and spatial distribution of the reported sinkholes ......................................................... 142

Figure 32 Cross-sections through the ECF region showing the hydrostratigraphic units: (a) West to East; (b) North to South. Only a small portion of the Floridan aquifer is shown since its bottom is much deeper than -75 m .............................................................................................................. 145
Figure 33 Size distribution of reported sinkholes: (a) Diameter; (b) Depth; (c) Length; (d) Depth
..................................................................................................................................................... 152

Figure 34 Frequency of monthly occurrence of the 414 reported sinkholes ......................... 153

Figure 35 Location of rain gauge and observation wells.......................................................... 154

Figure 36 (a) Monthly average rainfall (1950-1997); (b) Head difference between Well 1 and 1’;
(c) Head difference between Well 2 and 2’; (d) Head difference between Well 3 and 3’; (e) Head
difference between Well 4 and 4’; (f) Head difference between Well 5 and 5’ ......................... 159

Figure 37 (a) Spatial variation of recharge rate; (b) Sinkhole density and recharge ............... 163

Figure 38 (a) Spatial variation of head difference; (b) Sinkhole density and head difference ...

Figure 39 Location of study area (a) Map of Florida; (b) Map of Lake County and study area 183

Figure 40 Mean monthly rainfall ................................................................................................ 183

Figure 41 Model domain............................................................................................................. 188

Figure 42 Spatial discretization of regional-scale model (horizontally and vertically)......... 190

Figure 43 Boundary conditions and spatial variation of top elevation: (a) Layer 1; (b) Layer 2; (c)
Layer 3 ........................................................................................................................................ 191

Figure 44 Water table elevation simulated by the regional-scale model and the model domain of
the local-scale model................................................................................................................... 195

Figure 45 Locations of the SPT boring logs ............................................................................ 198

Figure 46 Spatial discretization of regional-scale model (horizontally and vertically)......... 199

Figure 47 Estimated hydraulic conductivity: (a) Layer 1; (b) Layer 2; (c) Layer 3; (d) Layer 4203

Figure 48 Boundary conditions applied to Layer 1 ................................................................. 206
Figure 49 Locations of the installed piezometers and the seasonal variation of water level measured from Piezometer 1-2 ................................................................................................... 206

Figure 50 Comparison between the simulated heads and the observed heads ...................... 209

Figure 51 Calibrated hydraulic conductivity: (a) Layer 1 (horizontal); (b) Layer 1 (vertical); (c) Layer 2 (horizontal); (d) Layer 2 (vertical); (e) Layer 3 (horizontal); (f) Layer 3 (vertical); (g) Layer 4 (horizontal); (h) Layer 4 (vertical)............................................................................................................. 211

Figure 52 Calibrated water table elevation ................................................................................. 212

Figure 53 Spatial variation of high resolution groundwater recharge ........................................ 214

Figure 54 Locations of relic sinkholes........................................................................................ 214

Figure 55 Relationship between sinkhole density and recharge rate......................................... 215

Figure 56 Risk level of sinkhole occurrence............................................................................... 215

Figure 57 Regression analysis .................................................................................................... 219
LIST OF TABLES

Table 1 Scenarios of SLR and precipitation change used in model simulations ......................... 17
Table 2 Input parameters ........................................................................................................ 22
Table 3 Results of the second-stage calibration ..................................................................... 33
Table 4 Growth rate of ‘influenced’ areas .............................................................................. 47
Table 5 Area ratios between the influenced areas and the total land area (511 km²) .............. 90
Table 6 Hydrogeologic parameters ...................................................................................... 110
Table 7 Fluid Properties ...................................................................................................... 110
Table 8 Percentage increase of the influenced vegetation root zones suffered from SWI ...... 123
Table 9 Descriptions of the hydrostratigraphic units ............................................................. 144
Table 10 Descriptions of the observation wells .................................................................... 153
Table 11 Sinkhole density and recharge rate ........................................................................ 165
Table 12 Sinkhole density and head difference ...................................................................... 168
Table 13 Hydrogeologic parameters ..................................................................................... 195
Table 14 Annual-averaged rainfall measured from 20 piezometers ...................................... 208
CHAPTER 1
INTRODUCTION

The impacts of climate change such as sea-level rise and intensified storm surge from tropical
storm and hurricane on east-central Florida coastal resources are projected to include changes in
surface and groundwater quality (e.g., saltwater intrusion), wetland inundation and migration,
alterations in the distribution, abundance and productivity of vegetation communities (shifts in
species composition possibly from less salt tolerant species to more salt tolerant species), and
changes in the distribution and quality of wildlife habitat. Beach erosion is likely to accelerate
and the potential for flooding and impacts to infrastructure will increase throughout east-central
Florida coastal areas.

Sea-level rise (SLR) reduces the usable water supply and results in water shortages along the
coast. Particularly, SLR affects the shallow surficial aquifer in various ways. First, the shoreline
can be inundated by saltwater from wave overtopping and subsequently the underground
interface between freshwater-saltwater can move landward, resulting in saltwater intrusion into
fresh groundwater affecting coastal water supply. Second, the shoreline is likely to erode and
low-lying coastal areas are likely to be inundated more frequently or permanently, since the
water table in low elevation areas may emerge from the land surface and create new wetlands or
expand existing ones, which may alter the distribution and abundance of vegetation communities
and change the distribution and quality of the wildlife habitat. Third, the risk of saltwater
flooding during extreme events (e.g. hurricanes) is also likely to increase with rising sea level.
Extreme weather events such as intensified storm surge can cause saltwater overtopping on coastal lowland in that waves can reach and pass over the crest of the coastal defense structures if wave run-up levels are high enough. Saltwater flooding of the inland surface occurs during the storm surge itself, and some saltwater can be trapped inland in topographic depressions following the event, acting as effective point-sources of contamination. The ponded saltwater infiltrates into vegetation root zone and percolates into groundwater, threatening the survival of coastal freshwater vegetation and water quality of the surficial aquifer.

Sinkhole occurrence is recognized as the primary geo-hazard in central Florida, which is life-threatening and can greatly damage man-made infrastructures such as buildings, roads, bridges, and pipelines. In central Florida, sinkholes are mostly classified into three categories, that is, dissolution sinkholes, cover-subsidence sinkholes, and cover-collapse sinkholes. Dissolution sinkholes and cover-subsidence sinkholes usually form very slowly and the negative effects are often negligible. However, cover-collapse sinkholes, which are very common in Central Florida, occur suddenly and cause significant civil infrastructure damage and property loss. The Florida Office of Insurance Regulation (2010) reported that insurers had received 24,671 claims for sinkhole damage in Florida between 2006 and 2010 totaling $1.4 billion, an average of $280 million per year for those 5 years; cost per year in Florida is on an increasing trend with total sinkhole losses for closed and open claims combined increasing from $209 million in 2006 to $406 million in 2009.
Groundwater recharge rate, mostly depending on water level difference between the overlying unconfined aquifer and the underlying confined aquifer and the characteristics and thickness of the overburden materials, plays a critical role in triggering sinkhole occurrence in central Florida. Sinkholes are more likely to occur in those areas that have higher recharge rate, and less likely to occur in those areas that have lower recharge rate. The probability of sinkhole occurrence is highly dependent on groundwater recharge, and a good estimation of recharge rate can make a great contribution to determine the risk level of sinkhole occurrence in central Florida sinkhole-prone areas.
CHAPTER 2
ASSESSING THE IMPACTS OF SEA-LEVEL RISE ON SALTWATER INTRUSION INTO THE SATURATED ZONE

The study described in this chapter (Chapter 2) was published in *Hydrogeology Journal* on Jun. 5th, 2016. The study was funded in part by the NASA Kennedy Space Center, Ecological Program, Climate Adaptation Science Investigators (CASI) Project (Award: IHA-SA-13-006) and the Louisiana Sea Grant Laborde Chair Endowment.

Title: Assessing the impacts of sea-level rise and precipitation change on the surficial aquifer in the low-lying coastal alluvial plains and barrier islands, east-central Florida (USA)

Authors: Han Xiao, Dingbao Wang, Scott C. Hagen, Stephen C. Medeiros, Carlton R. Hall

2.1 Introduction

In coastal aquifers, saline and fresh groundwater are in a dynamic equilibrium, and a landward shift of the equilibrium can cause landward encroachment of saline groundwater, resulting in the occurrence of saltwater intrusion (SWI) (Bear 1979). Barlow and Reichard (2010) found that SWI occurs by three main pathways including lateral intrusion from seawater, vertical upward intrusion from the deeper saline groundwater, and vertical downward intrusion from storm- or tidal-driven coastal flooding. SWI has been recognized as a global issue with detrimental effects including land salinization, reduction of available freshwater storage, and closure or forced landward relocation of pumping wells (Werner et al. 2013). The magnitude of SWI is dependent on the variability of hydrologic and hydrogeologic settings, the historical spatial and temporal distribution of salinity, and groundwater withdrawal and drainage (Bear et al. 1999).
A saltwater/freshwater transition zone is formed between inland fresh groundwater and coastal saline groundwater, and a landward migration of the transition zone is an effective indicator of the occurrence of SWI (Bear 1979). Groundwater density and salinity in the transition zone varies spatially and temporally depending on the regional hydrologic and hydrogeologic conditions (Freeze and Cherry 1979). Due to the complexity and variability of the variable-density condition, numerical methods are usually used to simulate SWI (Anderson and Woessner 1991). The SEAWAT computer code (Guo and Langevin 2002) has been successfully applied to many case studies. Langevin (2003) simulated the submarine groundwater discharge to Biscayne Bay in southeastern Florida, USA. Qahman and Larabi (2006) examined the present condition of SWI and predicted its future behavior under different pumping schemes in the Gaza aquifer in Palestine. Lin et al. (2009) evaluated the current and prospective extents of SWI in the Alabama Gulf Coast, USA. Sanford and Pope (2010) assessed the historical water level and projected the future behavior of SWI in the Eastern Shore of Virginia, USA. Nakada et al. (2011) focused on the subterranean circulation in a tidal flat by modeling the regional-scale submarine groundwater flow. Other notable case studies of additional interest are described in Cobaner et al. (2012), Dausman et al. (2010), Masterson et al. (2014) and Shoemaker and Edwards (2003).

In recent years, the impacts of climate change, such as sea-level rise (SLR) and precipitation change, have caused wide public concern (Oude Essink et al. 2010; Sherif and Singh 1999; Sulzbacher et al. 2012; Tang et al. 2013; Webb and Howard 2011). Werner and Simmons (2009) assessed the effect of SLR on a simplified, conceptual, unconfined aquifer and demonstrated that the saltwater invaded and retreated in correspondence with a lowering and elevating inland water
Interpretations of this study confirmed that inland boundary conditions are of great importance for the ‘self-reversal’ mitigation process. Chang et al. (2011) converted the above-mentioned conceptual model to a case study in the Pioneer Valley of Australia and concluded that SLR does not have as severe adverse effect as expected due to the ‘lifting’ of the entire aquifer because of SLR. Rasmussen et al. (2013) conducted a quantitative study to analyze the combined effects of SLR, precipitation change and drainage canals on an island located in the Western Baltic Sea. Likewise, it was demonstrated that the extent of SWI relied strictly on inland boundary conditions.

The low-lying alluvial plains and barrier islands located in the coastal areas of east-central Florida, USA, are vulnerable to flooding from the rising water table driven by SLR (Bilskie et al. 2014; Passeri et al. 2015), since the water table depth is usually shallow and can even breach land surface during and after a heavy rainfall. Water quality of the shallow coastal aquifer is also vulnerable to SLR-induced SWI, especially during prolonged drought. Hence, the low-lying coastal alluvial plains and barrier islands are dynamically influenced by climate change, and the negative effects include, but are not limited to, shoreline erosion, wetland inundation and migration, SWI, and alterations of the distribution and productivity of vegetation communities with shifts in species composition possibly from less salt tolerant species to more salt tolerant species (Foster et al. 2017).

The rate of SLR is expected to accelerate and the probability of severe weather is also expected to increase due to the effects of El Niño (Nicholls and Cazenave 2010; Parker 1991). In 2050,
local SLR projections indicated low, intermediate and high scenarios of 13.2 cm, 31.0 cm and 58.5 cm, respectively, and local precipitation projections indicated that the estimated rainfall would vary from a 7% decline to a 17% increase compared to 2010 (Rosenzweig et al. 2014). However, the effects of SLR and precipitation change on coastal groundwater flow patterns and salinity distribution are unknown and warrant investigation. Therefore, it is of great importance to develop a three-dimensional variable-density groundwater flow and salt transport model for quantitative assessment.

In inland areas, the surficial aquifer is recharged by direct infiltration of rainfall. Along the coastline, the surficial aquifer contacts the brackish water of the coastal lagoons and seawater of the Atlantic Ocean. The surficial aquifer which has its upper boundary as the water table and lower boundary as the confining unit is extremely important in that it connects the surface water system to the deeper groundwater system and supports marshes/wetlands, and receives recharge from rainfall and provides discharge to the surrounding coastal lagoons and the Atlantic Ocean. Thereby, the surficial aquifer is of primary concern for the effect of SLR and precipitation change. In this study, the SEAWAT code is applied to develop three-dimensional, variable-density groundwater flow and salinity transport models for the surficial aquifer of east-central Florida. A reference model is developed and calibrated against field-measured data to simulate the spatial variation of water table depth and salinity under steady-state 2010 hydrologic and hydrogeologic conditions. The calibrated reference model is then modified to implement five prediction/projection models based on various scenarios of SLR and precipitation change.
projected to 2050 time frame. The predicted/projected results also contribute to ongoing research that focuses on forecasting vegetation community responses to the projected climate change.

2.2 Overview of Study Area

The Cape Canaveral Barrier Island Complex (CCBIC) located in east-central Florida, consists of multiple barrier islands, saltwater lagoons, and the Atlantic Ocean coastline. The CCBIC covers an area of approximately 1000 km² 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 (Figure 1). The unique transitional geographic setting between the Caribbean and Carolinian zoogeographic provinces contributes to the area being recognized as having high biodiversity (Hall et al. 2014). The ground surface elevation varies from -0.2 to 10 m with a regional average of about 1.2 m NAVD 88 from LiDAR data – obtained from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast (https://coast.noaa.gov/digitalcoast/). The variation of topography is relatively small since the region is mainly comprised of broad and flat lowland. Surface water and groundwater flow can be influenced significantly by small changes in land surface elevation because of the flat terrain.
Figure 1 Location of the Cape Canaveral Barrier Island Complex (CCBIC), Florida (USA)

Figure 2 Illustration of the hydrology of the CCBIC
2.2.1 Hydro-climatologic conditions

The climate of east-central Florida is humid subtropical with hot/humid summers and mild/dry winters (Mailander 1990). The wet season is from May to October and the dry season is from November to April. The mean minimum temperatures are 10°C in January and 22°C in August, while the mean maximum temperatures are 22°C in January and 33°C in July. The amount of annual rainfall varies from 848 mm to 2075 mm, with a mean annual rainfall of 1366 mm.

From Schmalzer et al. (2000), the hydrology of the area is characterized by dynamic interactions between surface water and groundwater, evapotranspiration, and rainfall as shown in Figure 2 (the west to east cross-section labeled W-E in Figure 1). Much of the area is considered micro-tidal (1-2 cm) due to the narrow and distant inlet connections to the Atlantic Ocean. Mosquito Lagoon and Indian River Lagoon are connected by Haulover Canal on the north end of Merritt Island. Indian River Lagoon and Banana River are connected by a man-made navigation canal, and the canal is connected to the Atlantic Ocean through the Port Canaveral Locks. Water levels in the lagoons are dominated by the annual rise and fall of sea level with a maximum of near 0.0 m (NAVD88) in October. Water flow between the lagoons is primarily driven by wind forcing. In most places, the coastal lagoons have shallow, flat seagrass covered bottom with an average depth of 1.5 m. The Intracoastal Waterway is maintained at a depth of 4 m and several basins were dredged to depths of 9-10 m for filling materials during construction of space launch facilities. The total dissolved solids (TDS) concentration in the lagoons typically vary from 10000 to 45000 mg/L.
2.2.2 Hydrogeology

From Schmalzer and Hinkle (1990), the hydrostratigraphic units of the CCBIC are composed of, from top to bottom, the surficial aquifer system (SAS), the intermediate confining unit (ICU), the Floridan aquifer system (FAS), and the lower confining unit (LCU). The characteristics of each hydrostratigraphic unit are described in Figure 3.

As a large and productive aquifer occurring within the Ocala and Avon Park limestone, the general thickness of the FAS is greater than 600 m with mostly very high permeability and transmissivity. In general, the FAS is confined by the silt and clay of the overlying Hawthorn Formation and the underlying Cedar Keys Formation. In most places, the potentiometric level of the FAS is higher than the water table of the SAS, resulting in an upward groundwater seepage from the FAS to SAS, thereby creating a pathway for upward salinity migration. However, the upward seepage is relatively small since the overlying ICU, composed of Hawthorn sediments and Pliocene and upper Miocene deposits, has a very low permeability. The downward seepage through the LCU is extremely small. The highly mineralized water pumped from the FAS is classified as moderately to highly saline water, which greatly limits its consumptive use.

The SAS, which has its upper boundary as the water table and lower boundary as the top of the ICU, occurs in the saturated part of the moderate- to low-permeability Holocene and Pleistocene sediments of fine to medium sand, coquina, silt, shell and marl. The inflow is infiltrated rain water and upward seepage from the underlying FAS, and the outflow is evapotranspiration and discharge to surface water. The primary recharge areas are located at the relatively higher sand...
ridges on Cape Canaveral Island and east Merritt Island, and the groundwater flow directions are indicated in Figure 2. The water table rises to its highest level late in the wet season (September to October) and drops to its lowest level late in the dry season (March to April) following the annual rise and fall of sea-level (Foster et. al. 2017). The thickness and migration of the saltwater/freshwater transition zone formed in the coastal areas is mainly dependent on the characteristics of the hydrogeologic settings and the fluctuation of the inland water tables. The transition zone can move either landward or seaward in correspondence with lowering or elevating water tables.
<table>
<thead>
<tr>
<th>Geologic age</th>
<th>Stratigraphic unit</th>
<th>Hydrostratigraphic unit</th>
<th>Thickness (m)</th>
<th>Lithological character</th>
<th>Water-bearing property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene and Pleistocene deposits</td>
<td>Holocene and Pleistocene deposits</td>
<td>Surficial aquifer system (SAS)</td>
<td>0–33</td>
<td>Fine to medium sand, sandy coquina and sandy shell marl</td>
<td>Low permeability, yields small quantity of water</td>
</tr>
<tr>
<td>Pliocene</td>
<td>Pliocene and upper Miocene deposits</td>
<td>Intermediate confining unit (ICU)</td>
<td>6–27</td>
<td>Gray sandy shell marl, green clay, fine sand and silty shell</td>
<td>Very low permeability</td>
</tr>
<tr>
<td>Miocene</td>
<td>Hawthorn Formation</td>
<td></td>
<td>3–90</td>
<td>Sandy marl, clay, phosphorite, sandy limestone</td>
<td>General low permeability, yields small quantity of water</td>
</tr>
<tr>
<td>Eocene</td>
<td>Ocala Group</td>
<td>Crystal River Formation</td>
<td>0–30</td>
<td>Porous coquina in soft and chalky marine limestone</td>
<td>General very high permeability, yields large quantity of artesian water</td>
</tr>
<tr>
<td></td>
<td>Williston Formation</td>
<td>Floridan aquifer system (FAS)</td>
<td>3–15</td>
<td>Soft granular marine limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inglis Formation</td>
<td></td>
<td>21–24</td>
<td>Coarse granular limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Avon Park Formation</td>
<td></td>
<td>&gt;87</td>
<td>Dense chalky limestone and hard, porous, crystalline dolomite</td>
<td></td>
</tr>
<tr>
<td>Paleocene</td>
<td>Cedar Keys Formation</td>
<td>Lower confining unit (LCU)</td>
<td>–</td>
<td>Interbedded carbonate rocks and evaporites</td>
<td>Very low permeability</td>
</tr>
</tbody>
</table>

Figure 3 Description of the hydrostratigraphic units
2.3 Numerical Modeling

2.3.1 Model development

A reference model is implemented to simulate the spatial variation of water table depth and salinity in the SAS under steady-state 2010 hydrologic and hydrogeologic conditions. The reference model is calibrated against the field-measured groundwater levels monitored from 2006 to 2014 and the spatial distribution of marshes/wetlands classified by a land use and land cover map. The calibrated reference model is crucial in this study in that it serves as the ‘foundation’, and the prediction/projection models that incorporate various scenarios of SLR and precipitation change are developed based on it. The reference and prediction/projection models are simply developed for the SAS due to: (1) the SAS is of primary concern for climate change; (2) the SAS plays a crucial role in the interaction of surface water and groundwater, supporting marshes/wetlands and providing groundwater discharge to the surrounding coastal lagoons and the Atlantic Ocean; (3) salinity of the SAS is extremely important to the diverse ecosystem and the survival of the threatened and endangered species of wildlife; (4) the upward salinity migration from the underlying FAS to the SAS is assumed to be negligible due to the relatively small upward groundwater seepage; (5) simulation of groundwater flow and salt transport in the underlying FAS is not important since the FAS is highly mineralized which greatly limits its consumptive use. The advantages of this ‘simple’ model set-up include: (1) the capability to implement finer vertical discretization so that the vertical salinity gradient and the thickness and migration of saltwater/freshwater transition zone can be accurately simulated; (2) less computational demand; (3) reduced simulation assumptions because the hydrogeologic characteristics of the ICU and FAS are unknown due to lack of geophysical survey. The
disadvantage of it is a sacrificed accuracy of simulated salinity at local-scale since the upward SWI from the underlying FAS is not considered.

Using the calibrated reference model, five prediction/projection models are implemented by modifying the boundary conditions that represent precipitation and water levels of the coastal lagoons and the Atlantic Ocean, to quantify the effects of SLR and precipitation change, based on the assumption that all other hydrologic and hydrogeologic conditions remain unchanged from 2010.

2.3.2 Scenarios of SLR and precipitation change
Comparing to 2010, precipitation is estimated to vary from 7% decline to 17% increase, while SLR scenarios are estimated to be 13.2 cm, 31.0 cm, and 58.5 cm for the low, intermediate, and high ice melt projections, respectively. These downscaled projections for 2050 are developed using data provided by Radley Horton and Daniel Bader, Center for Climate Systems Research, Earth Institute, Columbia University as part of the NASA Climate Adaptation Science Investigators Program (Rosenzweig et al. 2014). Based on these projections, five cases (Case 1-5) are simulated (Table 1).

From a common hydrologic view, increased/decreased recharge to the SAS due to increased/decreased precipitation can alter groundwater salinity. Comparing Case 1 to Case 2, and comparing Case 5 to Case 4, it is expected that the extent of SWI of Case 1 will be less severe than Case 2, and the extent of SWI of Case 5 will be more severe than Case 4. Comparing
Case 1 to Case 0, however, it is unknown whether the 17% increase of precipitation can counteract the effect of SLR.

2.3.3 Simulation code and graphical user interface

The SEAWAT Version 4 (SEAWAT_V4) code developed by Langevin et al. (2008) is selected as the simulation code. Groundwater Vistas, a well-known graphical user interface developed by Environmental Simulations Inc., is used to create model input files.
Table 1 Scenarios of SLR and precipitation change used in model simulations

<table>
<thead>
<tr>
<th>Year</th>
<th>Case</th>
<th>SLR (cm)</th>
<th>Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2050</td>
<td>1</td>
<td>13.2</td>
<td>+17%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13.2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>31.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>58.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>58.5</td>
<td>-7%</td>
</tr>
</tbody>
</table>
2.3.4 Spatial and temporal discretization

Carefully selecting horizontal and vertical discretization that can effectively represent and identify the saltwater/freshwater transition zone and topographic variations of land surface is essential. The horizontal and vertical discretization is determined by considering enhancing simulation accuracy while maintaining reasonable computer runtimes. In the horizontal plane, the model domain is discretized into 373 rows and 646 columns with a uniform grid spacing of 100 m in both x- and y-directions (Figure 4a). In view of the variable-density condition, a finer vertical discretization in comparison to the constant-density condition is always required for accurate simulation of flow velocities and solute transport (Langevin 2003). Vertically, the model domain is divided into five layers with a uniform layer thickness of 2 m, with the exception of layer 1 (Figure 4b). The top elevation of layer 1 is set to land surface elevation and 0 m over coastal lagoons and the Atlantic Ocean. The land surface elevation is derived from LiDAR DEM data as shown in Figure 5. The bottom elevation of layer 1 is set at an elevation of -2 m (NAVD 88). The bottom elevation of the SAS is unknown due to lack of stratigraphic data. However, it was estimated by Schmalzer et al. (2000) that the thickness of the SAS is 10-12 m. Thereby, the bottom elevation of layer 5 is set to -10 m (NAVD 88). From layer 2 to 5, the layers are flat and have a uniform thickness of 2 m for the purpose of minimizing numerical instabilities. Hence, the model grids in layer 2, 3, 4, and 5 have a uniform cell volume of 100 m × 100 m × 2 m. However, the volume of each model grid in layer 1 is different because of the topographic variations.
Figure 4 Spatial discretization: (a) Plan view; (b) West to east cross-section labeled W-E [NAVD88 – North American Vertical Datum of 1988]
Figure 5 Land surface elevation of the CCBIC
Temporally, the reference and prediction/projection models are steady-state based on the assumption that climate change is gradual and the groundwater systems are in ‘equilibrium’ with climatic factors. This assumption is reasonable in that the purposes of this study are to quantify the long-term climate change impacts rather than the effects of extreme weather (e.g., hurricanes, storm surge). Besides, impacts of human activities are not significant since only a small portion is urbanized and the pumping rate from the 2 extraction wells are very low. Further temporal discretization is introduced in terms of transport time steps for better simulation of salt transport. The length of the transport time step is specified to start with 0.01 day and increased by a time step multiplier of 1.2, with a maximum transport time step of 100 days. The program does not terminate until steady-state is reached.

2.3.5 Hydrogeologic parameters
The specified hydrogeologic parameters are summarized in Table 2. The SAS is assumed to be composed of equivalent porous media, implying that the underground conduits and cavities are not explicitly simulated. This assumption is appropriate and reasonable for implementing a regional-scale numerical model since the complex hydrogeologic conditions in the study area are greatly simplified, despite limiting the interpretation of the model result to the local scale (Langevin 2003).
Table 2 Input parameters

<table>
<thead>
<tr>
<th>Hydrogeologic Parameters</th>
<th>Value [units]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Hydraulic Conductivity ($K_h$)</td>
<td>15 [m/d]</td>
<td>McGurk and Presley 2002</td>
</tr>
<tr>
<td>Anisotropy ($K_h/K_z$)</td>
<td>10 [-]</td>
<td>Blandford et al. 1991</td>
</tr>
<tr>
<td>Porosity ($n$)</td>
<td>0.2 [-]</td>
<td>Hutchings et al. 2003</td>
</tr>
<tr>
<td>Longitudinal Dispersivity ($a_L$)</td>
<td>6 [m]</td>
<td></td>
</tr>
<tr>
<td>Transverse Dispersivity ($a_T$)</td>
<td>0.01 [m]</td>
<td></td>
</tr>
<tr>
<td>Vertical Dispersivity ($a_V$)</td>
<td>0.025 [m]</td>
<td></td>
</tr>
<tr>
<td>Diffusion Coefficient ($D^*$)</td>
<td>0.00128 [m$^2$/d]</td>
<td></td>
</tr>
</tbody>
</table>
2.3.6 Boundary conditions

The model domain extends offshore to simulate the interactions between the SAS and coastal lagoons and the Atlantic Ocean with minimal boundary effects. The recharge boundary and the evapotranspiration boundary are assigned to the top of layer 1 to represent the infiltrated rainwater that recharges the SAS and the loss of groundwater due to evaporation and plant transpiration. The no-flow boundary is assigned to the bottom of layer 5 since the upward groundwater seepage from the underlying FAS is not simulated. The specified head and concentration boundary and the general head boundary are assigned to represent the lateral boundaries. The well boundary is assigned to represent the two pumping wells.

The specified head and concentration boundary is assigned to the model grids that represent the coastal lagoons and the Atlantic Ocean. In most places, the coastal lagoons are only in layer 1 because of the shallow depth. However, the Atlantic Ocean is obviously much deeper lying in one or more layers depending on depth to seafloor. Due to lack of monitored data, it is assumed that the water levels and TDS concentrations of the coastal lagoons and the Atlantic Ocean are the same. For the reference model, water levels and TDS concentrations are specified to 0 m (NAVD 88) and 35 kg/m³, respectively (Sharqawy et al. 2010). The horizontal view of the specified head and concentration boundary assigned to layer 1 is visualized in Figure 6a.

For the prediction/projection models, water levels of the coastal lagoons and the Atlantic Ocean are specified corresponding to SLR scenarios based on the assumption that water levels of the coastal lagoons rise simultaneously at the same magnitude as with the SLR, and TDS
concentrations are specified to 35 kg/m³. Further inland encroachment of the coastline is inevitable due to SLR. The new coastline is estimated by comparing the land surface elevation with the ‘new’ sea level, and the coastal lowland that has a lower elevation than the ‘new’ sea level is considered to become ‘new’ coastal lagoons or sea. Based on this criteria, the specified head and concentration boundary assigned to layer 1 for Cases 1-5 are visualized in Figure 6b, 6c, and 6d.
Figure 6 Specified head and concentration boundary (marked in light-blue) assigned to layer 1:
(a) Case 0; (b) Cases 1 and 2; (c) Case 3; (d) Cases 4 and 5
The recharge boundary is assigned to represent the spatial variation of mean daily recharge from infiltrated rain water. The mean daily recharge rate is estimated by mean daily precipitation measured from 2006 to 2014 given by Tropical Rainfall Measuring Mission (TRMM) and recharge/precipitation (R/P) ratio mainly dependent on soil type and land use and land cover (Cherkauer and Ansari 2005; Dawes et al. 2012). The map of land use and land cover provided by the St. Johns River Water Management District (SJRWMD 2009) is shown in Figure 7a. The R/P ratio is specified to 0 for urban areas and marshes/wetlands under the assumption that the land cover is comprised of impervious concrete for the former situation and the infiltration of rain water is impeded by the saturated soil in the latter situation. The R/P ratios specified to forest, upland non-forest and cropland (agriculture) are 0.87, 0.96, and 0.87, respectively (Brauman et al. 2012). The spatial variation of mean daily recharge is visualized in Figure 7b. The recharge rate is converted to zoned values and imported into the reference model in order to facilitate the calibration process.

For the prediction/projection models, the recharge rate is assumed to increase/decrease proportionally with the increased/decreased precipitation. Hence, the recharge rate is specified as 17% increase and 7% decrease in Case 1 and 5 comparing to Case 0.
Figure 7 (a) Land use and land cover; (b) Mean daily recharge (2010)
The evapotranspiration boundary is assigned to represent the spatial variation of mean daily evapotranspiration. In fact, the model input is mean daily potential evapotranspiration (PET) and vegetation extinction depth (ED), and mean daily evapotranspiration is computed by the SEAWAT code based on PET, ED, and simulated water table depth. Mean daily PET (2006-2014) is given by the USGS Florida evapotranspiration network, and ED values are specified to 2.5 m, 1.45 m, and 2 m for forest, upland non-forest, and cropland, respectively (Shah et al. 2007).

2.3.7 Initial conditions

For steady-state models, it is not necessary to specify the starting water level and TDS concentration at each active model grid to be consistent with the designated aquifer properties and boundary conditions. In short, steady-state models do not require accurate starting heads and concentrations. However, reasonable estimates are required before start-up to avoid numerical instability. Thus, a steady-state one-layer SEAWAT model with a uniform grid spacing of 1000 m in both x- and y- directions is implemented under 2010 hydrologic and hydrogeologic conditions in order to approximately estimate the water level and TDS concentration at each active model grid, and the output is the initial conditions for the reference model. The output of the calibrated reference model is the initial conditions for the five prediction/projection models.
2.4  Calibration

2.4.1  Head calibration

For the first-stage calibration, the hydraulic conductivity is adjusted using the trial-and-error method to minimize the differences between the simulated groundwater levels and the field-measured groundwater levels collected from 10 active observation wells (Figure 8a). Daily groundwater levels monitored and recorded by each observation well during the period from 2006 to 2014 are averaged to represent the mean annual groundwater levels in 2010 as calibration targets. The calibration process does not terminate until the simulated groundwater levels match the observed groundwater levels to a satisfactory degree. Due to lack of observed groundwater levels from the central part of the CCBIC, the calibrated results might not accurately represent the true condition, and second-stage calibration is necessary.
Figure 8 (a) Location of observation wells and scatter diagram of the goodness of fit between the observed and simulated water table elevations (W.T., m NAVD88); (b) Sensitivity of horizontal hydraulic conductivity ($K_h$) and recharge
For the second-stage calibration, the zoned recharge rate is adjusted using the trial-and-error approach to minimize the differences between the ‘simulated’ and ‘true’ wetlands. Due to the water table approaching the land surface (shallow water table depth), wetlands are seasonally or permanently inundated. A uniform threshold of water table depth cannot be defined because wetlands are highly complex ecological systems not only dependent on water table depth. In order to perform the second-stage calibration, three conditions (Conditions 1, 2 and 3) are proposed. For Condition 1, the land areas where the simulated water table depths are less than 0.2 m are speculated to be ‘simulated’ wetlands. In contrast, the land areas where the simulated water table depths are greater than or equal to 0.2 m are deduced to be ‘simulated’ non-wetlands. Thereby, a map of ‘simulated’ wetlands and non-wetlands are plotted based on the model simulation results. For Conditions 2 and 3, the thresholds of water table depth are switched to 0.3 and 0.4 m, and two maps of ‘simulated’ wetlands and non-wetlands are plotted. The three maps are overlaid with the map of ‘true’ wetland, given by the land use and land cover map (Figure 7a) produced by SJRWMD (2009). From the overlaid maps, some parts are ‘simulated’ wetlands and ‘true’ wetlands (Situation A), and some parts are ‘simulated’ wetlands but not ‘true’ wetlands (Situation B), and some parts are ‘simulated’ non-wetlands but ‘true’ wetlands (Situation C), and some parts are ‘simulated’ non-wetlands and not ‘true’ wetlands (Situation D). For each condition, the percentages of covering areas of Situations A, B, C and D are computed, along with the percentage of consistency (the sum of percentages of covering areas of Situations A and D because Situations A and D indicate a consistency between the simulated results and the true conditions). A higher percentage of consistency is considered an indicator of better model performance.
After calibration, a Nash-Sutcliffe model efficiency coefficient (NSE) of 0.96 is achieved. From Table 3, the percentages of consistency are 64.6%, 65.3%, and 66.0% for Conditions 1, 2 and 3, respectively. The calibration results are considered acceptable. The horizontal and vertical hydraulic conductivity are calibrated to 360 m/d and 36 m/d, and the annual recharge is calibrated to vary from 846 mm to 1606 mm.

It should be noted that a good match between the simulated and observed groundwater levels is achieved. It is understandable that the simulated and observed groundwater levels from Wells 2 and 4 are slightly different, since their locations are close to the border. However, the ‘simulated’ and ‘true’ wetlands do not match very well. The discrepancies in the second-stage calibration appears to be most likely due to the definition of ‘simulated’ wetlands. In fact, wetlands are complicated and dynamic natural systems composed of swamps, marshes, and bogs dependent not only on water table depth but also topography, vegetation cover and soil type. However, the second-stage calibration is worthwhile although it is not optimal to determine wetlands only by simulated water table depth.
Table 3 Results of the second-stage calibration

<table>
<thead>
<tr>
<th>Situation</th>
<th>‘Simulated’ Wetlands</th>
<th>‘True’ Wetlands</th>
<th>Percentage of Covering Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Threshold 0.2 m</td>
</tr>
<tr>
<td>A</td>
<td>Yes</td>
<td>Yes</td>
<td>18.4</td>
</tr>
<tr>
<td>B</td>
<td>Yes</td>
<td>No</td>
<td>13.7</td>
</tr>
<tr>
<td>C</td>
<td>No</td>
<td>Yes</td>
<td>21.8</td>
</tr>
<tr>
<td>D</td>
<td>No</td>
<td>No</td>
<td>46.2</td>
</tr>
<tr>
<td>Total (%)</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Consistency (%)</td>
<td>-</td>
<td>-</td>
<td>64.6</td>
</tr>
</tbody>
</table>
2.4.2 Sensitivity analysis

Sensitivity analysis is carried out after model calibration. Sensitivity analysis is performed to explicitly determine the effects of small changes to model input on the simulated results by systematically modifying the input values within a reasonable range.

The horizontal hydraulic conductivity ($K_h$) is model-wide varied and the zoned recharge rate (Zone 1-10) is locally varied within a certain range. The sensitivity analysis results are shown in Figure 8b. It can be observed that the simulated groundwater levels are most sensitive to changes in Zones 7, moderately sensitive to changes in $K_h$ and Zones 2 and 8, and slightly sensitive to changes in Zone 3. However, the results are insensitive to changes in Zones 1, 4, 5, 6, 9 and 10. It is reasonable that the simulated groundwater levels are most sensitive to Zone 7 in that this zone lies in east-central Merritt Island (Figure 8a) which is comprised of high sand ridges serving as the primary recharge areas and the recharge rate specified to this zone determines how much freshwater is able to recharge the SAS.

However, it should be noted that the sensitivity analysis results might be biased because of the limitation of calibration targets. As mentioned earlier, the observation wells are not evenly distributed (located in the north and south Merritt Island) and no observation wells are in Cape Canaveral Island. This is partly the reason that the calibrated results are not sensitive to changes of recharge rate applied to Cape Canaveral Island.
2.5 Results and Discussions

2.5.1 Present conditions

The simulated mean water table depth in 2010 is visualized in Figure 9a. In general, the water table depth is shallow (less than 0.5 m) in west Merritt Island, but is deep (greater than 1 m) in the upland sand ridges in east Merritt Island, Cape Canaveral Island, and the northwestern coastal highlands. A positive water table depth indicates that the water table is below land surface, while a negative value represents the opposite condition. It is postulated that the areas with negative values have a high risk of being frequently or permanently inundated due to water table approaching or breaching land surface, and are referred to as ‘sensitive’ areas. These areas are highlighted in yellow-brown in Figure 9b. Based on the simulated results, it is estimated that the ‘sensitive’ areas account for 21.7% of the total land area in 2010.
Figure 9 Spatial variation of: (a) Water table depth; (b) ‘Sensitive’ areas
According to NGWA (2010), the TDS concentration of the saltwater/freshwater transition zone is between 1000 mg/L and 35000 mg/L which is higher than freshwater (less than 1000 mg/L) and lower than seawater (35000 mg/L), and the water quality is defined as slightly saline water (1000-3000 mg/L), moderately saline water (3000-10000 mg/L), and highly saline water (10000-35000 mg/L). The plan view of the transition zone is shown in Figure 10a. The simulated values of TDS concentrations are extracted from model layer 3 (the model consists of five layers and layer 3 is the middle layer). In general, the transition zone covers a larger area in west Merritt Island where the saltwater wedge toe even trespasses 3-4 km inland, indicating a greater groundwater salinity than other locations. The areas that TDS concentrations are greater than freshwater are referred to as ‘influenced’ areas shown in Figure 10a. It is estimated that the ‘influenced’ areas account for 9% of the total land area in 2010. The vertical view of the transition zone is shown in Figure 10b (the west to east cross-section labeled A-A’ in Figure 10b). The widths of the zones of slightly saline water and moderately saline water are approximately 0.5 km, and the width of the zone of highly saline water is approximately 3 km. The vertical view of land surface and water table elevation in Merritt Island is shown in Figure 10c (the west to east cross-section labeled 1-1’ in Figure 10a). In most places in west Merritt Island, land surface is low and water table depth is shallow. A heavy rainfall event might cause a rapid rising of water table above land surface resulting in overland flooding. Besides, the marshes/wetlands located there are highly vulnerable to wind-driven coastal flooding induced by storm surge and hurricanes. In addition, freshwater recharge is impeded because of the shallow water table depth. Thus, groundwater salinity in west Merritt Island is higher than other places. In Cape Canaveral Island and east Merritt Island, land surface is higher and water table depth is
deeper compared to west Merritt Island. Additionally, freshwater recharge is higher because of the high permeability of sand. Therefore, fewer areas are vulnerable to overland flooding, and groundwater salinity is lower.

It should be noted that the spatial distribution of ‘sensitive’ areas and ‘influenced’ areas might expand and shrink with the annual cycles of sea-level and rainfall. However, the dynamic expansion and shrinkage are not simulated, since the reference model assumes a steady-state condition. Future research may be able to quantify the dynamic changes of the ‘sensitive’ areas by changing the temporal scale from yearly to monthly and developing a transient model.
Figure 10 Spatial variation of: (a) ‘Influenced’ areas (plan view); (b) ‘Influenced’ areas (west to east cross-section labeled A-A’); (c) Elevation of land surface and water table (west to east cross-section labeled 1-1’).
2.5.2 Predicted conditions

Based on the calibrated reference model, five prediction/projection models are developed by modification of the specified head and concentration boundary and the recharge boundary to represent SLR and precipitation change while keeping other boundary conditions unchanged from 2010.

Cases 2, 3, and 4 represent 13.2 cm, 31.0 cm, and 58.5 cm SLR (refer to Table 1), and the predicted ‘sensitive’ areas are highlighted in yellow-brown in Figure 11c, 11d and 11e, respectively. The simulated ‘sensitive’ areas of Case 0 are also shown in Figure 11a for reference. Comparing to Case 0, the ‘sensitive’ areas of Cases 2, 3 and 4 account for 26.6%, 36.0%, and 47.2% of the total land area, with a growth rate of 4.9%, 14.3% and 25.5%. The predicted ‘sensitive’ areas are mainly found in west Merritt Island, and expand corresponding to SLR. The predicted ‘influence’ areas are shown in Figure 12c, 12d and 12e, respectively. The predicted salinity is extracted from model layer 3. The simulated ‘influence’ areas of Case 0 are also shown in Figure 12a for reference. Comparing to Case 0, the ‘influence’ areas of Case 2, 3 and 4 account for 21.8%, 34%, and 47.9% of the total land area, with a growth rate of 12.8%, 25%, and 38.9% comparing to Case 0, respectively. The landward migration of saline water mostly occurs in west Merritt Island, and the saltwater wedge toe trespasses 8-10 km inland in some locations, indicating the occurrence of SLR-induced SWI. However, it seems that the effect of SLR on Cape Canaveral Island is not significant.
Case 1 represents 13.2 cm SLR coupled with a 17% increase in precipitation, and Case 5 represents 58.5 cm SLR coupled with a 7% decrease in precipitation (refer to Table 1). In order to quantify the effect of precipitation change, Case 1 results are compared to Case 2, and Case 5 results are compared to Case 4, since the SLR scenarios of Cases 1 and 2, along with Cases 4 and 5, are the same.

The predicted ‘sensitive’ areas of Cases 1 and 5 are highlighted in yellow-brown in Figure 11b and 11f. For Case 1, the ‘sensitive’ areas account for 32.1% of the total land area, comparing to Case 0 (21.7%) and Case 2 (26.6%). For Case 5, the ‘sensitive’ areas account for 45.8% of the total land area, comparing to Case 4 (47.2%). The predicted ‘influence’ areas of Cases 1 and 5 are shown in Figure 12b and 12f. For Case 1, the ‘influence’ areas account for 18.2% of the total land area, comparing to Case 0 (9%) and Case 2 (21.8%). For Case 5, the ‘influence’ areas account for 49.3% of the total land area, comparing to Case 4 (47.9%). Similarly, the ‘sensitive’ and ‘influence’ areas are mainly found in west Merritt Island, and the coupled effects are not significant on Cape Canaveral Island.
Figure 11 Spatial variation of ‘sensitive’ areas: (a) Case 0; (b) Case 1 (13.2 cm SLR, +17% precipitation); (c) Case 2 (13.2 cm SLR); (d) Case 3 (31.0 cm SLR); (e) Case 4 (58.5 cm SLR); (f) Case 5 (58.5 cm SLR, -7% precipitation)
Figure 12 Spatial variation of ‘influenced’ areas: (a) Case 0; (b) Case 1 (13.2 cm SLR, +17% precipitation); (c) Case 2 (13.2 cm SLR); (d) Case 3 (31.0 cm SLR); (e) Case 4 (58.5 cm SLR); (f) Case 5 (58.5 cm SLR, -7% precipitation)
The predicted results indicate that the effects of SLR and precipitation change are significant in west Merritt Island. This area is particularly vulnerable because of its low-lying coastal areas with flat topography and shallow water table depth having a high risk of being inundated during and after an extreme rainfall event. Also, low land surface elevation corresponding with low potential for freshwater recharge due to shallow water table, results in a low fresh groundwater pressure head and low hydraulic head gradient between inland fresh groundwater and coastal saline groundwater, which further results in a low rate of submarine groundwater discharge. This reduces the protection from SLR-induced SWI offered by freshwater groundwater recharge. In west Merritt Island, the land cover is mainly composed of fresh marsh, intermediate marsh (less saline than brackish), brackish marsh, and saline marsh. Landward migration of saline water into the traditionally freshwater areas can cause degradation of the ecologic system and alter the distribution and productivity of vegetation communities. Increased rainfall can contribute to flushing while a prolonged drought can intensify salinity problems. Salt tolerance of plant communities is dependent on vegetation type, duration of exposure to saline water, rate of salinity increase, mineral content of soil, and degree of submergence (Webb and Mendelssohn 1996; Howard and Mendelssohn 1999). Some species can tolerate a wide range of salinity, and can recover quickly once the salinity declines. However, some species die off quickly and cannot recover. Potential consequences of exposure to salinity include, but are not limited to, shift of wetland from fresh or less saline marsh to brackish or saline marsh, vegetation species dieback and limited recovery, shift in vegetation species composition from less salinity-tolerant species to more salinity-tolerant species, and reduction in biomass production (Steyer et al. 2007). SWI not only affects marshes/wetlands, but also affects agriculture as well. Citrus is the main...
agricultural product in this area, and a reduction in citrus production due to increased groundwater salinity might be a big problem. Currently, no pumping wells are designed for human consumption in this area, and SWI does not have a negative effect on public drinking water supply.

The predicted results indicate that the effects of SLR and precipitation change are not significant in Cape Canaveral Island and east Merritt Island. This area serves as the primary recharge area due to its high elevation, deep water table depth, land cover (forest and pasture) and soil type (sand). Because of the highly permeable sand, infiltration of rainwater is facilitated, which generates a high freshwater pressure head, resulting in a high rate of submarine groundwater discharge from inland fresh groundwater zone to coastal saline groundwater zone. This builds up an effective freshwater hydraulic barrier to prevent the landward migration of saline groundwater and alleviate the negative effects of SWI to some extent. However, it is estimated that the negative effects could be noticeable if SLR and precipitation change turn out to be greater than projected.

Five additional cases (Cases 6-10) are simulated for further investigation of the effect of SLR and precipitation change on SWI, the key factors that determine whether SWI occurs and how far inland the saltwater wedge toe invades. Cases 7, 8 and 9 quantify the effect of 23.4 cm, 59 cm, and 119.5 cm SLR. Case 6 quantifies the coupled effects of 23.4 cm SLR and +16% precipitation, while Case 10 quantifies the coupled effects of 119.5 cm SLR and -11% precipitation. These scenarios are the estimated projections for 2080 (Rosenzweig et al. 2014).
The growth rate of the ‘influenced’ areas where SWI occur are computed and described in Table 4 and plotted in Figure 13a. In order to differentiate the effect of SLR and precipitation change, the growth rate of Cases 2, 3, 4, 7, 8 and 9 are plotted as red circles and the growth rate of Cases 1, 5, 6 and 10 are plotted as yellow-brown triangles. An interpolation of the growth rate based on Cases 2, 3, 4, 7, 8 and 9 (red circles) is also plotted.
Table 4 Growth rate of ‘influenced’ areas

<table>
<thead>
<tr>
<th>Case</th>
<th>‘Influenced’ Area (km²) (^a)</th>
<th>Percentage (%)</th>
<th>Growth Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>46</td>
<td>9.0</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>93</td>
<td>18.2</td>
<td>9.2</td>
</tr>
<tr>
<td>2</td>
<td>111</td>
<td>21.8</td>
<td>12.8</td>
</tr>
<tr>
<td>3</td>
<td>174</td>
<td>34.0</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>245</td>
<td>47.9</td>
<td>38.9</td>
</tr>
<tr>
<td>5</td>
<td>252</td>
<td>49.3</td>
<td>40.3</td>
</tr>
<tr>
<td>6</td>
<td>128</td>
<td>25.1</td>
<td>16.1</td>
</tr>
<tr>
<td>7</td>
<td>146</td>
<td>28.6</td>
<td>19.6</td>
</tr>
<tr>
<td>8</td>
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<td>48.1</td>
<td>39.1</td>
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<tr>
<td>9</td>
<td>344</td>
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</tr>
<tr>
<td>10</td>
<td>353</td>
<td>69.1</td>
<td>60.1</td>
</tr>
</tbody>
</table>

\(^a\) The total land area of the CCBIC was 511 km² in 2010
Figure 13 (a) Growth rate of ‘influenced’ areas; (b) The relationship between increased/decreased precipitation and its impacts on alteration of growth rate.
In Figure 13a, the growth rate increases faster at first and then slightly declines. At the beginning, the growth rate increases sharply in that west Merritt Island is vulnerable to SLR even though the amount is small due to its low elevation and flat topography. Afterwards, the growth rate slightly declines because the amount of SLR is not large enough to affect Cape Canaveral Island and east Merritt Island significantly. Using the SLR scenarios applied in this study, the growth rate of the ‘influenced’ areas under other potential SLR scenarios can be roughly estimated by the interpolation as shown in Figure 13a. For example, the growth rate might increase to 35% and 52% when SLR is 50 cm and 100 cm, indicating potential ‘influenced’ areas of 225 km² and 312 km², respectively. The growth rate is also altered by increased/decreased precipitation. Comparing to Case 2, +17% precipitation (Case 1) generates a growth rate of -3.52%; Comparing to Case 4, -7% precipitation (Case 5) generates a growth rate of 1.37%; Comparing to Case 7, +16% precipitation (Case 6) generates a growth rate of -3.52%; Comparing to Case 9, -11% precipitation (Case 10) generates a growth rate of 1.76%. The relationship between increased/decreased precipitation and its impacts on alteration of growth rate is plotted in Figure 13b. According to linear interpolation, in order to offset the effect of SLR for Cases 2, 3 and 4, an increased precipitation of 63.0%, 125.6% and 195.4% is required. This estimate is based on the assumption that recharge increases/decreases proportionally with precipitation. In fact, an increased recharge of 63.0%, 125.6% and 195.4% is required.

In order to prevent SWI, it is of great importance to minimize the effect of SLR, since its effect is clearly more influential than the effect of precipitation change. In order to ‘balance’ SLR, it is necessary to increase the inland fresh groundwater pressure head by artificial recharge. Recharge
wells could be constructed close to the coastline, along with detention ponds designed for flood control to avoid inland flooding, since the CCBIC is humid subtropical with plenty of precipitation especially in the rainy season. The designed detention ponds could be used to temporarily hold the excess rainwater while slowly draining to the coastal recharge wells. Artificial recharge is even more important in the dry season because of less precipitation. It is not necessary to shut down the two pumping wells, which are used occasionally for lawn irrigation, since the pumping rates are very low and the effect is tiny.

It should be noted that the results might be biased due to the following reasons. First, the calibration targets are limited due to a lack of observation wells, resulting in a less robust model calibration. It is expected that more observed groundwater level and salinity data would be available for future model calibration. Second, the effect of heterogeneity on the spatial variation of water table depth and groundwater salinity is not considered. Due to lack of geophysical surveys and borehole tests, the spatial variation of hydraulic conductivity is unavailable, and the SAS is assumed to be homogenous with a uniform value assigned initially to all model grids expecting to be adjusted during calibration. Third, the effects of different water levels and TDS concentrations in the coastal lagoons and the Atlantic Ocean are not considered. The mean water levels of the coastal lagoons are usually slightly higher than the Atlantic Ocean (10 cm approximately). The TDS concentrations of the coastal lagoons and the Atlantic Ocean are varied spatially, affected by climate factors and human activities. In some locations, the TDS concentrations of the coastal lagoons are higher than 35000 mg/L particularly during the dry season because of large amounts of water loss due to evaporation and drainage. The TDS
concentrations of the nearshore Atlantic Ocean might be lower than 35000 mg/L because of submarine groundwater discharge. However, due to lack of the relevant recorded water levels and TDS concentrations, water levels of the coastal lagoons are assumed to be exactly the same with the Atlantic Ocean, and TDS concentrations of the coastal lagoons and the Atlantic Ocean are assumed to be equal to 35000 mg/L. Fourth, upward migration of saline water from the underlying highly-mineralized FAS is not simulated. The situation of SWI might be even worse than predicted if the upward groundwater seepage from the FAS is considered. Fifth, the ‘new’ coastline determined for the predicted models under various SLR scenarios contain high levels of uncertainty, resulting in the predicted results being over- or under-estimated. Based on the explanations above, the results might be biased and the discrepancies are probably due to the simplification of the model implementation. Future research will take other climate change factors into consideration, including increasing the number and size of extreme weather events, such as hurricane and storm surge, and higher mean annual temperature and potential evaporation.

2.6 Conclusion

The purpose of this study is to quantitatively evaluate the impacts of climate change on water table depth and salinity distribution in the shallow unconfined coastal aquifer of alluvial shorelines and barrier island systems. The selected study site is the CCBIC region in east-central Florida, where the associated Kennedy Space Center, Cape Canaveral Air Force Station, Merritt Island National Wildlife Refuge and Canaveral National Sea Shore are located. Numerical
models using the SEAWAT code are implemented and parameterized with the relevant regional geologic, hydrogeologic and hydrologic features in order to achieve this goal.

The reference model is calibrated and validated against monitored heads and saltwater/freshwater marsh/wetland categorized in the land use and land cover map. Reasonable agreements between the simulated results and field-measured data are achieved, indicating that the simulation results are representative of 2010 hydrogeologic conditions. Further calibration is required for future model updates when sufficient field-measured TDS concentrations become available. Results indicate that climate change in the form of precipitation change and SLR, play an undeniable role in altering the water table depth and water quality in the surficial aquifer within the CCBIC region. The simulated salinity migration and fluctuation of water table depth can contribute to ongoing attempts at forecasting vegetation community responses to these climate change related variables. Moreover, the developed SEAWAT models can be utilized as an effective tool for coastal water resources management, land use planning, and adaptation decision making in a changing climate.
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CHAPTER 3
ASSESSING THE IMPACTS OF STORM SURGE ON SALTWATER INTRUSION INTO THE SATURATED ZONE

3.1 Introduction

Saltwater intrusion (SWI) into coastal aquifers due to groundwater overexploitation has emerged as 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 et al. 1999; Werner et al. 2013). Recently, climate change effects including sea-level rise, changing temperature and precipitation regimes, changing groundwater recharge rates, and increasing in both the frequency and intensity of extreme weather events such as tropical storms and hurricanes (IPCC 2014), are expected to further increase the risk of SWI and pose a challenge for coastal engineering and drinking water resource management in vulnerable coastal areas. However, Sea-level rise and extreme weather events such as storm surge associated with hurricanes are likely to have more direct impacts than other factors (Chang et al. 2011; Chui and Terry 2013; Langevin et al. 2005; Oude Essink et al. 2010; 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).

SWI occurs as a result of the landward shift of the dynamic equilibrium between saline and fresh coastal groundwater due to sea-level rise (Bear 1979; Freeze and Cherry 1979). However, sea-level rise is not the only cause of the landward encroachment of saltwater. An increase in both the frequency and intensity of extreme weather events such as tropical storms and hurricanes, combined with continuous sea-level rise, are expected to bring more frequent and intense storm
surge to coastal areas (Van Biersel et al. 2007), with their magnitude dependent on the dynamics of storms, coastal topography, and the position of the coastline relative to the storm track (Bruss et al. 2011). Storm surge can cause saltwater overtopping on coastal lowlands in that waves can reach and pass over the crest of the coastal defense structure (dunes) if wave run-up and storm tide levels are high enough (EurOtop 2007). Saltwater flooding of the inland surface occurs during the storm surge itself, and saltwater can remain trapped in topographic depressions following the event, acting as effective point-sources of SWI where ponding saltwater can infiltrate into soil and contaminate fresh groundwater (Vithanage et al. 2012). Water quality of coastal drinking water supply wells are particularly at risk of the negative effects of increasing salinity, and the shallow shoreline wells that are submerged during the storm surge can be rendered non-potable.

If fresh groundwater is available for flushing (sufficient precipitation and groundwater recharge), the infiltrated saltwater plume can be ‘forced’ seaward, and salinity levels can decline to ranges appropriate for drinking water over time (Steyer et al. 2007). However, this natural remediation process can take several years (Yang et al. 2013 & 2015) dependent on the hydrologic conditions and hydrogeologic setting. Conversely, salinity levels can continue to rise as a result of evaporation if precipitation and groundwater recharge are insufficient, resulting in a continuous deterioration of water quality.

Furthermore, Bilskie et al. (2014) and Passeri et al. (2015 a&b) demonstrated that the low-lying coastal alluvial plains and barrier islands in east-central Florida (USA) are morphologically
sensitive to changing hydrologic conditions associated with sea-level rise and increased intensity and frequency of storm surge, while the dynamic impacts mainly include coastline erosion and SWI. The landward encroachment of saltwater can increase salinity level in vegetation root zone, causing alterations of the distribution and productivity of vegetation communities, e.g., shifts in species composition possibly from less salt tolerant species to more salt tolerant species (Foster et al. 2017; Hall et al. 2014). Thus, in order to produce climate change adaptation strategies for tackling the issue of potential SWI, a developing knowledge on the response of coastal aquifer salinity to sea-level rise and increase in intensity and frequency of storm surge is necessary. Due to the complex nature of variable-density groundwater flow and solute transport in coastal aquifers, numerical methods are usually used to simulate SWI (Anderson and Woessner 1991), and the computer code SEAWAT (Guo and Langevin 2002) 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).

In east-central Florida (ECF), the effects of sea-level rise on SWI into the surficial aquifer were quantitatively assessed by Xiao et al. (2016) using SEAWAT computer code. In that study, one reference model and ten prediction models that incorporated various scenarios including low, intermediate and high rates of sea-level rise were developed to simulate the spatial and temporal extent of SWI, and the simulation results indicated that sea-level rise plays a vital role in inducing SWI especially in the ECF region having low elevation and flat topography. As a continuation of the previous study, the objective of the study is to simulate the effects of storm surge associated with tropical cyclones on salinity transport in the surficial aquifer of the low-
lying coastal alluvial plains and barrier islands in the ECF region. This post-hurricane assessment is conducted to study the characteristics of the temporal variation of salinity distribution in the surficial aquifer in order to investigate: (1) how far inland the toe of the subterranean saltwater wedge can encroach; and (2) how long it takes for the inland saltwater to be diluted by infiltrated rainwater and eventually flushed out of the surficial aquifer (the duration time of the natural remediation process). The model output is visualized to show the temporal variation of the spatial distribution of salinity including both the intrusion and recession of saltwater after the storm surge. The model output is also analyzed mathematically to compute the reduction in fresh groundwater storage. The aquifer water quality recovery time (the time required for inland saltwater to be diluted and flushed out from the freshwater zone) is estimated based on the model output as well. The results of this study are expected to unravel the effects of storm surge on the spatial and temporal variation of the surficial aquifer salinity in order to contribute to ongoing research focused on forecasting vegetation community responses to climate change, and to serve as an effective tool for coastal groundwater resource management, ecosystem protection and restoration, and climate change adaptation planning and decision-making in the ECF and other low-lying coastal alluvial plains and barrier island systems.

3.2 Overview of Study Area

3.2.1 Site description
The study area is the Cape Canaveral Barrier Island Complex (CCBIC) located in east-central Florida, consisting of multiple barrier islands, saltwater/freshwater lagoons, and the Atlantic
Ocean coastline. The CCBIC is recognized as having high biodiversity (Hall et al. 2014) and covers an area of approximately 1,000 km² 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 (Figure 14). The topographic variation is relatively small since the region is mainly composed of broad and flat lowland, and the land surface elevation varies from -0.2 to 10 m (NAVD88) according to LIDAR data – obtained from the National Oceanic and Atmospheric Administration (NOAA) Digital Coast (https://coast.noaa.gov/digitalcoast/). The climate as humid subtropical with hot/humid summers (mean temperature varied from 22 °C to 33 °C) and mild/dry winters (mean temperature varied from 10 °C to 22 °C) with a mean annual rainfall of 1,366 mm (Mailander 1990). The regional hydrologic conditions are characterized by dynamic interactions between surface water and groundwater, evapotranspiration, and rainfall (Schmalzer et al. 2000) as shown in Figure 15 (see the west to east cross-section labeled W-E in Figure 14). In most places, the coastal lagoons have a shallow, flat seagrass covered bottom with an average depth of 1.5 m, and the total dissolved solids concentration typically varies from 10 to 45 kg/m³ (Hall et al. 2014). The hydrostratigraphic units are composed of, from top to bottom, the surficial aquifer, the intermediate confining unit, the Floridan aquifer and the lower confining unit (Schmalzer and Hinkle 1990). The surficial aquifer is mainly composed of fine to medium sand has the water table as its upper boundary and the top of the intermediate confining unit as its lower boundary. The primary inflow is infiltrated rainwater and the primary outflow is evapotranspiration and discharge to surface water bodies including fresh/salt marshes and wetlands, coastal lagoons and the Atlantic Ocean. The water table, which rises to its highest level late in the wet season (October) and drops to its lowest level late in the dry season (April), is
mainly controlled by the temporal variation of rainfall. The saltwater/freshwater transition zone migrates either landward (saltwater intrusion) or seaward (saltwater recession) in correspondence with the lowering or rising water table. Details regarding the regional hydrologic and hydrogeologic conditions of the CCBIC are described in previous work (Xiao et al. 2016).
Figure 14 Location of the Cape Canaveral Barrier Island Complex (CCBIC), Florida (USA)

Figure 15 Illustration of the hydrologic conditions of the CCBIC
3.2.2 Storm surge associated with Hurricane Jeanne

Hurricane Jeanne, a storm of exceptionally large size and strength, was deemed the deadliest hurricane in the 2004 Atlantic hurricane season (Demotech 2014). The storm passed over the Caribbean including Puerto Rico, Dominican Republic, Haiti, and the Bahamas beginning on Sep. 13th 2004, and eventually made landfall near Stuart (approximately 150 km away from the CCBIC), Florida, on September 25th, 2004 as a Category 3 hurricane. The storm caused 5 direct deaths and $6.8 billion in property damage in the mainland US which made it the 13th costliest hurricane in US history (Lawrence and Cobb 2005) at the time. Storm surge up to 2 m associated with Hurricane Jeanne occurred along the Florida east (Atlantic) coast. Florida’s west (Gulf of Mexico) coast experienced a negative storm surge of about 1.4 m below normal tides when wind was blowing offshore, followed by a positive storm surge of about 1.1 m above normal tides when wind was blowing onshore, measured at Cedar Key, Florida (http://www.stormsurge.noaa.gov/event_history_2000s.html). The near-term effects of the storm surge associated with Hurricane Jeanne including loss of human life and property damage were devastating; however, the long-term effects on coastal water resources, vegetation communities and wildlife habitat were also catastrophic as well. Coastal saltwater/freshwater marshes/wetlands were at risk flooding both during and up to several days after the storm surge. Undoubtedly, coastal lowlands with flat topography and shallow water table depths such as those found in the CCBIC experienced saltwater overtopping during surge events that subsequently resulted in increases in groundwater salinity, surficial soil salinization and vertical SWI. Potential consequences of exposure to the overtopping saltwater also included the shift of marshes from fresh or less saline to brackish or saline marshes, vegetation species dieback and
limited recovery (or shift in vegetation species composition from less to more salt-tolerant species), and reduction in biomass production (Steyer et al. 2007).

3.3 Numerical Modeling

3.3.1 Model development

Salinity plays a critical role in evaluating both the short-term and long-term effects of storm surge associated with Hurricane Jeanne on coastal groundwater resources in the CCBIC. Therefore, it is imperative to conduct a quantitative post-hurricane assessment of salinity transport in coastal aquifers in order to determine how far the saltwater/freshwater transition zone can encroach inland and how long it takes for inland saltwater to be diluted and flushed out by infiltrated rainwater. Due to the complexity of the spatial and temporal variation of salinity under variable-density situations in coastal aquifers, as well as the limitation of field-measured salinity data from the local groundwater monitoring system, numerical modeling is used to simulate density-driven groundwater flow and salinity transport in the CCBIC coastal aquifer for the investigation of the extent of SWI due to storm surge.

In this study, a ‘simulation’ model is implemented using the SEAWAT Version 4 (SEAWAT_V4) computer code (Langevin et al. 2008) based on the ‘reference’ model developed and calibrated in the previous study (Xiao et al. 2016). In brief, the ‘reference’ model was implemented to simulate the spatial distribution of salinity under annual-average (2006-2014) steady-state hydrologic and hydrogeologic conditions in the CCBIC (climate change impacts such as sea-level rise and increase in intensity and frequency of storm surge were neglected).
using SEAWAT_V4 computer code. The role of the ‘reference’ model is to serve as the foundation and create a pathway to develop the ‘simulation’ model in this study. For the ‘simulation’ model in this study, the spatial discretization, aquifer parameters, and the boundary conditions representing recharge, evapotranspiration, lateral head-dependent and bottom no-flux hydrologic boundaries remain the same as in the ‘reference’ model. However, the constant head boundary representing the coastal lagoons and Atlantic Ocean is modified to a time-variant specified head boundary, and the assigned values of water levels are set accordingly. Moreover, the temporal discretization is converted from steady-state to transient in order to enable simulations of both rapid and long-term response of aquifer salinity to storm surge. It should be noted that the ‘reference’ model was calibrated against field-measured water levels and spatial distribution of marshes/wetlands reported in the land use and land cover map produced by the St. Johns River Water Management District, whereas the ‘simulation’ model are not calibrated due to the transitory nature of storm surge and that the rapid-response sampling of water table depth and salinity data in the influenced areas was not conducted. Therefore, to some extent the ‘simulation’ model can be deemed as a ‘prediction’ model developed based on the calibrated ‘reference’ model, and the simulation results can be considered as prediction results showing the future temporal variation of salinity after a storm surge event.

In this study, the simulation model is developed for the surficial aquifer of the CCBIC mainly because: (1) the salinity level of the surficial aquifer is of primary concern for climate change impacts and is of great importance for protection of the diverse ecosystem and survival of the vegetation communities and the threatened and endangered species of wildlife; and (2) the water
table of the surficial aquifer is crucial to supporting coastal marshes/wetlands by maintaining groundwater discharge to coastal lagoons and the Atlantic Ocean as well as acting as an effective freshwater hydraulic barrier to prevent SWI. It should be noted that the simulation model only simulates the temporal variation of salinity under the effects of storm surge overtopping flow, while the effects of sea-level rise and other climate change factors are not simulated.

3.3.2 Spatial discretization
Horizontally, a uniform grid spacing of 100 m in both the x- (373 columns) and y- directions (646 rows) is selected. Vertically, the model domain is divided into five layers with the top of Layer 1 set to the land-surface/sea-floor elevation (digital elevation model provided by NASA) and the bottom of layer 5 set to a constant elevation of -10 m NAVD88. The plan and cross-sectional view of the spatial discretization are visualized in Figure 3 from Chapter 2 (Xiao et al. 2016).

3.3.3 Parameters
Aquifer parameters such as horizontal and vertical hydraulic conductivity, porosity, specific yield, diffusion coefficient, and longitudinal/transverse/vertical dispersivity are tabulated in Table 2 from the previous study (Xiao et al. 2016).

3.3.4 Boundary conditions
Boundary conditions such as the recharge boundary, evapotranspiration boundary, general-head boundary, no-flux boundary and well boundary are described in the previous study (Xiao et al. 2016).
The time-variant specified head (CHD) boundary is used to represent: (1) coastal lagoons and the Atlantic Ocean throughout the entire simulation period; and (2) the coastal low-lying areas which were temporarily inundated by seawater during the storm surge. The assigned boundary values of time-variant water level of the coastal lagoons, sea level, saltwater overtopping depth, and saltwater retention time depend on the characteristics of the storm surge associated with Hurricane Jeanne, are computed by a two-dimensional, unstructured finite-element storm surge model implemented in ADCIRC (http://adcirc.org/). The simulation of the ADCIRC storm surge model (astronomic tides and waves not considered) with a minimum element size of 10 m within the CCBIC area started the day before Hurricane Jeanne made landfall on Florida’s east coast (Sep.23rd, 2004) and terminated after Hurricane Jeanne passed over Florida and shifted to Georgia and South Carolina (Sep.28th, 2004). During the entire six-day storm surge simulation, the ‘effective’ simulation lasted for 84 hours (3.5 days) beginning when sea level increases were observable and ending when sea levels return to their basis. The simulation results (Matthew V. Bilskie, Louisiana State University Center for Coastal Resiliency, personal communication, 2016) are visualized in Figure 16. As stated above, the simulated time-variant water levels from the ADCIRC model are utilized to assign the CHD boundary values in the SEAWAT simulation model.
(g) 33 hours

(h) 39 hours

(i) 45 hours

(j) 51 hours

(k) 57 hours

(l) 63 hours
Figure 16 Time-variant water surface elevation [m NAVD88] of the coastal lagoons and the Atlantic Ocean during the 84-hour ADCIRC simulation: (a) Before simulation; (b) 3 hours; (c) 9 hours; (d) 15 hours; (e) 21 hours; (f) 27 hours; (g) 33 hours; (h) 39 hours; (i) 45 hours; (j) 51 hours; (k) 57 hours; (l) 63 hours; (m) 69 hours; (n) 75 hours; (o) 81 hours; (p) After simulation
Due to a lack of salinity measurements, it was assumed that the total dissolved solids (TDS) concentration of the coastal lagoons, the Atlantic Ocean, and the inland overtopping saltwater is equal to 35 kg/m³ (Sharqawy et al. 2010). Due to the flat topography, it is assumed that the overtopping saltwater either evaporates or infiltrates into the soil and percolates through the unsaturated zone towards the water table, while surface runoff is negligible. It is also assumed that the residual overtopping saltwater drained out after the 3.5 day effective storm surge duration so that the saltwater ponding depth is equal to 0 m.

3.3.5 Temporal variation
The transient simulation model runs from Sep.25th, 2004 to Sep.26th, 2024, and the 20-year simulation period is divided into 15 stress periods. Stress periods 1 to 14 are within the time period of the storm surge event (3.5 days from Sep.25th, 2004 to Sep. 27th, 2004) when water levels of the coastal lagoons and the Atlantic Ocean were varied, while stress period 15 starts when water surface elevations returned back to normal (Sep.27th, 2004) and terminates 20 years later (Sep.26th, 2024). For stress periods 1 to 14, each stress period has a uniform length of 6 hours with a constant time step of 0.1 hour (6 min). For stress period 15, the stress period length is designated to be 7305 days with minimum and maximum time step length of 0.1 day and 30 days (starting from 0.1 day with a time step multiplier of 1.2), respectively.

3.3.6 Initial conditions
Unlike steady-state simulations, transient simulations require accurate initial head and concentration values for all grid cells (starting heads and concentrations should be consistent with the assigned model parameters and boundary conditions). Thus, the output from the steady-
state reference model (water levels and salinity) is used for the initial conditions of stress period 1, and the output from the previous transient simulation is used for the initial conditions of stress periods 2 to 15.

3.4 Results and Discussions

The saltwater/freshwater transition zone typically has a TDS concentration higher than freshwater (no greater than 1 kg/m$^3$) and lower than seawater (35 kg/m$^3$), and is further categorized as slightly saline (1-3 kg/m$^3$), moderately saline (3-10 kg/m$^3$), and highly saline (10-35 kg/m$^3$) based on salinity (NGWA 2010). In this study, contours of 1, 3, 10 and 35 kg/m$^3$ TDS concentration are used to delineate the location and movement of the saltwater/freshwater transition zone under the effects of storm surge. It should be noted that the simulated values of TDS concentration are extracted from model layer 1 (top layer).

The steady-state salinity distribution in the surficial aquifer (the initial state of salinity level before simulating the effects of storm surge) is visualized in Figure 17, simulated by the reference model (Xiao et al. 2016).

Stress periods 1 to 14 refer to the 3.5 days beginning from the onset of storm surge (Sep.25$^{th}$, 2004) to the ending (Sep.27$^{th}$, 2004), while stress period 15 refer to the 20 years starting immediately after the ending of storm surge (Sep.27$^{th}$, 2004). Thus, simulation results regarding both the short-term and long-term effects of storm surge on the surficial aquifer salinity are exported from the output of stress period 15. Within the first five years from Sep.27$^{th}$, 2004 to
Sep.26th, 2009, simulation results are exported every 4 months (Figure 18a-p & 19a-p). Within the second five years from Sep.27th, 2009 to Sep.26th, 2014, simulation results are exported every 1 year (Figure 18q-u & 19q-u). Within the last ten years from Sep.27th, 2014 to Sep.26th, 2024, simulation results are exported every 2 years (Figure 18v-z & 19v-z).
Figure 17 Steady-state spatial distribution of salinity: (a) Plan view; (b) South to north cross-sectional view
Figure 18 Transient spatial distribution of salinity (plan view): (a) 09/27/2004; (b) 01/25/2005; (c) 05/25/2005; (d) 09/22/2005; (e) 01/20/2006; (f) 05/20/2006; (g) 09/17/2006; (h) 01/15/2007; (i) 05/15/2007; (j) 09/12/2007; (k) 01/10/2008; (l) 05/09/2008; (m) 09/06/2008; (n) 01/04/2009; (o) 05/04/2009; (p) 09/01/2009; (q) 09/01/2010; (r) 09/01/2011; (s) 08/31/2012; (t) 08/31/2013; (u) 08/31/2014; (v) 08/30/2016; (w) 08/30/2018; (x) 08/29/2020; (y) 08/29/2022; (z) 08/29/2024
The areas that have groundwater TDS concentrations greater than 1 kg/m$^3$ are referred to as the influenced areas. From Figure 18, the influenced areas are mainly found in the northern Merritt Island area of the CCBIC. From the LiDAR DEM and land use and land cover map, the influenced areas are mainly coastal low-lying areas having an average land surface elevation from -0.1 to 0.2 m NAVD88, and are mainly covered by fresh marsh, intermediate marsh (less saline than brackish), brackish marsh and saline marsh. Due to low altitude and flat topography, storm surge can push seawater moving inland approximately 4-5 km horizontally, resulting in large amounts of areas being overtopped by saltwater. The overtopping saltwater starts to infiltrate into the shallow surficial aquifer, developing salt plumes moving vertically towards water table. In the early stage (the first five years from 2004 to 2009), the downward movement of the salt plume (development of the plume fingers observed in the cross-sectional view in Figure 19a-p) is fast because of high aquifer permeability and shallow water table depth. The dilution of the infiltrated saltwater is also fast because high rate of fresh groundwater recharge from sufficient precipitation generates a seaward groundwater flow contributing to transporting saltwater back out to the coastal lagoon – Banana River (recession of saltwater). In the middle stage (the second five years from 2009 to 2014), dilution of the infiltrated saltwater continues while the recession rate of saltwater declines from fast to intermediate. In the late stage (the last ten years from 2014 to 2024), the residual infiltrated saltwater remains in the dilution phase while the recession rate declines significantly since large amount of salt has already been removed.
Figure 19 Transient spatial distribution of salinity (cross-sectional view): (a) 09/27/2004; (b) 01/25/2005; (c) 05/25/2005; (d) 09/22/2005; (e) 01/20/2006; (f) 05/20/2006; (g) 09/17/2006; (h) 01/15/2007; (i) 05/15/2007; (j) 09/12/2007; (k) 01/10/2008; (l) 05/09/2008; (m) 09/06/2008; (n) 01/04/2009; (o) 05/04/2009; (p) 09/01/2009; (q) 09/01/2010; (r) 09/01/2011; (s) 08/31/2012; (t) 08/31/2013; (u) 08/31/2014; (v) 08/30/2016; (w) 08/30/2018; (x) 08/29/2020; (y) 08/29/2022; (z) 08/29/2024
The temporal variation of ratios between the influenced areas and the total land area is presented in Table 5, and the percentage increase in the area ratio compared to the steady-state situation is plotted in Figure 20. An increase in the ratio represents an expansion and a decrease in the ratio represents a contraction of the influenced areas. In general, the proportion curve follows a first-order exponential decay curve. The maximum percentage of 33% is found approximately eight months after the storm surge, indicating that saltwater diffusion plays an important role in the very early stages, resulting in an increase in the proportion of influenced areas. After about one year, freshwater dilution displaces saltwater diffusion and becomes the dominant controlling factor, leading to a decline in the proportion of influenced areas. A sharp drop in the proportion curve is observed from 2006 to 2014 (from 19% to 1% approximately), indicating a significant decline in the influenced areas during that 8-year time period. A small decline in the proportion from 1.09% to 0.36% is observed over the next 10-year time period (from 2014 to 2024). Therefore, the simulated natural remediation process takes approximately 10 years (from 2005 to 2014) to recover from the effects of storm surge.

The percentage decrease in fresh groundwater storage compared to the steady-state situation is plotted in Figure 21. From Figure 21, fresh groundwater storage is reduced by approximately 18% after about 2 years in 2006, then begins to recover at a relatively slow rate. It can be estimated from the curve that the surficial aquifer water quality recovery time might be 15-20 years, or even several decades depending on the regional hydrogeologic settings and hydro-climatologic conditions.
Figure 20 Percentage increase in the area ratios compared to the steady-state simulation

Figure 21 Percentage decrease in fresh groundwater storage compared to the steady-state simulation
Table 5 Area ratios between the influenced areas and the total land area (511 km²)

<table>
<thead>
<tr>
<th>Date</th>
<th>Covering area (km²)</th>
<th>Percentage (%)</th>
<th>Percentage Increase (%)</th>
</tr>
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<tr>
<td>Sep.27th, 2004</td>
<td>165</td>
<td>32.34</td>
<td>18.79</td>
</tr>
<tr>
<td>Jan.25th, 2005</td>
<td>168</td>
<td>32.83</td>
<td>19.28</td>
</tr>
<tr>
<td>May.25th, 2005</td>
<td>169</td>
<td>32.98</td>
<td>19.42</td>
</tr>
<tr>
<td>Sep.22nd, 2005</td>
<td>168</td>
<td>32.96</td>
<td>19.41</td>
</tr>
<tr>
<td>Jan.20th, 2006</td>
<td>168</td>
<td>32.83</td>
<td>19.28</td>
</tr>
<tr>
<td>May.20th, 2006</td>
<td>167</td>
<td>32.6</td>
<td>19.05</td>
</tr>
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<td>Sep.17th, 2006</td>
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</tr>
<tr>
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</tr>
<tr>
<td>May.15th, 2007</td>
<td>159</td>
<td>31.14</td>
<td>17.59</td>
</tr>
<tr>
<td>Sep.12th, 2007</td>
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<tr>
<td>Jan.10th, 2008</td>
<td>153</td>
<td>29.92</td>
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<td>May.9th, 2008</td>
<td>149</td>
<td>29.09</td>
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<tr>
<td>Sep.6th, 2008</td>
<td>144</td>
<td>28.13</td>
<td>14.58</td>
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<tr>
<td>Jan.4th, 2009</td>
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<td>May.4th, 2009</td>
<td>133</td>
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<td>12.51</td>
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<tr>
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<td>128</td>
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<td>99</td>
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<td>Sep.1st, 2011</td>
<td>86</td>
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<td>Aug.31st, 2012</td>
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<td>2.22</td>
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<td>Aug.31st, 2014</td>
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<td>Aug.30th, 2018</td>
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<td>Aug.29th, 2020</td>
<td>72</td>
<td>14.04</td>
<td>0.49</td>
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<tr>
<td>Aug.29th, 2022</td>
<td>71</td>
<td>13.97</td>
<td>0.41</td>
</tr>
<tr>
<td>Aug.29th, 2024</td>
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<td>13.91</td>
<td>0.36</td>
</tr>
<tr>
<td><strong>Steady-state</strong></td>
<td>69</td>
<td><strong>13.55</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>
In fact, it is difficult to determine the aquifer water quality recovery time under a changing climate due to its complexity and uncertainty. Fresh groundwater recharge, which dilutes and flushes out inland saltwater, depends on the frequency and intensity of precipitation. An increase in the infiltrated rainwater can provide more available groundwater recharge to expedite aquifer water quality recovery, while a decrease in the infiltrated rainwater, likely due to a prolonged drought, can reduce groundwater recharge and postpone the recovery. The recovery process can be further delayed by the effects of sea-level rise, or the coupled effects of sea-level rise and subsequent storm surge. Future research will be conducted to assess these coupled effects and discern whether sea-level rise or storm surge plays the key role in delaying the surficial aquifer water quality recovery process.

The simulation model used herein is developed based on several assumptions and simplifications, and is not calibrated and validated because of limitations in the necessary field-measured data. Thus, the simulation results might contain errors. However, as mentioned earlier in the explanation of the model development, the simulation model can be interpreted as a ‘prediction’ model, and the ‘prediction’ results can provide an initial post-hurricane assessment of the surficial aquifer water quality recovery under the natural remediation process, which turns out to be useful for climate change adaptation planning and management in the CCBIC and other similar low lying alluvial coastlines subject to storm surge.
3.5 Conclusion

Groundwater salinity is crucial in understanding both the short-term and long-term effects of the storm surge associated with Hurricane Jeanne on coastal groundwater resources and ecosystem. The purpose of this study is to conduct a quantitative post-hurricane assessment to examine the temporal variation of salinity distribution in the surficial aquifer in the CCBIC, with the aim of investigating the extent of SWI and estimating the time required for the natural remediation process to achieve basis conditions. In order to achieve this goal, a numerical model is developed and solved using the SEAWAT V4 computer code, and the model output is visualized and analyzed mathematically.

The simulation results indicated that: (1) overtopping saltwater infiltrates rapidly because of the high aquifer permeability and shallow water table depth producing spikes in the surficial aquifer salinity level; (2) saltwater diffusion into the freshwater aquifer results in SWI into the surficial aquifer in the early stages of a hurricane storm surge event; (3) fresh groundwater recharge from infiltrated rainwater builds up an effective hydraulic barrier that blocks further landward migration of saltwater and gradually pushes the infiltrated saltwater to move toward surrounding water bodies. (recession of saltwater); (4) saltwater recession rate reduces from high to low corresponding to continuous dilution and flushing; (5) natural remediation processes can take several years to several decades to reach baseline conditions and is mainly dependent on the regional hydrogeologic setting and hydro-climatologic conditions.
The results of this study provide a useful reference for climate change adaptation planning and decision-making in the CCBIC and other low-lying coastal alluvial plains and barrier island systems, especially with respect to coastal groundwater resource management, land use planning, and ecosystem protection and restoration in a changing climate. Specifically these results contribute to ongoing research focused on forecasting regional vegetation community responses to storm surge and climate change with a goal of maximizing endangered species habitat management activities.
3.6 References


Freeze RA, Cherry JA (1979) Groundwater. Prentice Hall


CHAPTER 4
ASSESSING THE IMPACTS OF SEA-LEVEL RISE ON SALTWATER INTRUSION INTO THE UNSATURATED ZONE

4.1 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 and this number is increasing (Newmann et al. 2015). However, coastal groundwater contamination from saltwater intrusion (SWI) into the freshwater aquifer has been reported in many coastal areas globally and is deemed a detrimental issue affecting coastal water supplies, ecosystems, and economies (Barlow and Reichard 2010). The occurrence of SWI not only depends on coastal hydrogeologic characteristics such as permeability, but is also influenced by hydro-climatological and anthropogenic factors including changes in groundwater and sea levels, changes in precipitation, and changes in groundwater pumping and land use (Bear et al. 1999). In the past several decades, most cases of SWI into coastal aquifers were attributed to over-exploitation of coastal groundwater resources resulting from the lack of proper groundwater pumping and management strategies (Bear 1979; Freeze and Cherry 1979). In recent years, sea-level rise (SLR) has become a major public focus and is highlighted as one of the main factors causing SWI (Chang et al. 2011; Rasmussen et al. 2013; Werner et al. 2013; Werner and Simmons 2009). Moreover, due to an expected increase in the rate of SLR, which greatly exceeds that of the recent past (IPCC 2001 & 2013), it is estimated that the occurrences, extent, and intensity of SWI will further increase. This is likely to create a series of environmental problems including land salinization, coastal groundwater quality deterioration, closure or relocation of coastal water supply wells, and ecosystem degradation (Alizad et al. 2016; Bilskie et al. 2016; Hovenga et al. 2016; Huang et al. 100
A saltwater/freshwater transition zone with a fluid density and salt concentration lower than typical seawater but higher than freshwater is always formed between the inland fresh groundwater zone and the coastal saline groundwater zone. The density and salt concentration in this transition zone varies spatially and temporally depending on local hydrologic and hydrogeologic conditions (Bear 1979). SWI is a complex and non-linear process of landward migration of the transition zone, and the process can be even more complex if the natural and anthropogenic factors such as SLR and groundwater pumping are taken into consideration (Freeze and Cherry 1979).

Numerical modeling is typically used to simulate this process (Anderson and Woessner 1991), and several computer programs such as SEAWAT (Guo and Langevin 2002), SUTRA (Voss 1984), and FEMWATER (Lin et al. 1997) can simulate groundwater flow and contaminant transport under variable-density conditions. These models have been widely applied to cases studies all over the world. The developed numerical models are utilized to estimate the salinity distribution over time and predict the future extent of SWI under climate change and human development impacts by modeling the location and migration of the saltwater/freshwater transition zone (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; Yu et al. 2016).
In the coastal areas of east-central Florida where the deep Floridan aquifer is highly saline and non-potable, groundwater yielded from the overlying saturated surficial aquifer is generally the dominant water supply for agricultural, industrial and domestic use (McGurk and Presley 2002; Sepulveda et al. 2012). Groundwater in the unsaturated (vadose) zone above the saturated surficial aquifer, especially in the vegetation root zone, is crucial to the survival of various vegetation species and thus the bio-diversity of the natural environment (Purdum et al. 2002). Vadose zone thickness or depth to the water table also has a significant influence on the distribution of plant communities and the habitats they support (Box et al. 1993; Saha et al. 2011 & 2015; Foster et al. 2017). Therefore, it is necessary to have a deep understanding of unsaturated and saturated zone water quality and their vulnerabilities to SWI induced by SLR and/or groundwater pumping. In an effort to achieve this understanding for low-lying alluvial plains, Xiao et al. (2016) developed and calibrated a SEAWAT model to study the salinity distribution in the saturated zone (the surficial aquifer) in the coastal areas of east-central Florida under the steady-state 2010 hydrologic conditions. The model was then used to estimate future SWI into the saturated zone under various SLR scenarios estimated for 2050 and 2080. From the modeling results, SLR was identified as the dominant factor that causes SWI into the saturated zone in that the relatively low land surface elevation and flat topography made these areas susceptible to inundation by rising sea levels with overtopping seawater infiltrating through the unsaturated zone to the saturated zone. However, the extent of SWI into the unsaturated zone was not simulated in that study.
As noted above, salinity level in the unsaturated zone especially in the vegetation root zone is crucial to plant community composition, and 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). Moreover, the salinity level in the unsaturated zone can influence the salinity level in the saturated zone primarily by the downward transport of salt via infiltrated rainwater. In order to capture the location and migration of the saltwater/freshwater transition zone in the unsaturated zone, a numerical model focusing on the unsaturated zone or including both the unsaturated and saturated zones is required, with a focus on the variation of salinity and the extent of SWI in the vegetation root zone.

In this study, two research questions were proposed: (1) What is the current salinity distribution and where is the saltwater/freshwater transition zone in the vegetation root zone of a typical area in southeast Merritt Island, Florida?; and (2) How will the salinity distribution and location of the saltwater/freshwater transition zone change under several representative SLR conditions? To answer these focused questions, a three-dimensional finite-element variable-density FEMWATER model was developed and calibrated in terms of hydraulic heads to simulate the monthly variation of salinity distribution in the study site under transient 2010 hydrologic conditions. Subsequently three diagnostic FEMWATER models were developed based on the calibrated model by modifying the boundary values that represent the rising sea level to assess the effect of SLR on SWI into the vegetation root zone under various SLR scenarios. The results will help unravel the effects of SLR on SWI into the vegetation root zone and contribute to
ongoing research focused on forecasting regional vegetation community and other system responses to climate change.

4.2 Overview of Study Area

4.2.1 Site description

The study area covers approximately 0.45 km² and is located in a biogeotypical area in southeast Merritt Island on the Cape Canaveral Barrier Island Complex (CCBIC) of east-central Florida, USA, as shown in Figure 22. The land surface elevation varies from approximately -0.40 to 3.75 m NAVD88 according to LiDAR available from the Florida Department of Emergency Management. 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 as shown in the St. Johns River Water Management District 2009 land use and land cover maps (ftp://secure.sjrwmd.com/disk6b/lcover_luse/lcover2009/lu2009_PI_Key/keylist.html). 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 1,366 mm with a wet season lasting from June to October and a dry season from November to May (Mailander 1990). The hydrologic conditions are characterized by dynamic interactions between surface water and groundwater, evapotranspiration, and rainfall (Schmalzer et al. 2000). The primary inflow is precipitation and the primary outflows are evapotranspiration and submarine groundwater discharge to the Banana River. The Banana River, located on the southeast border of the study area, 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/m³ (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 (Smith 1990 & 1993; Foster et al. 2017). The unsaturated zone in the study area is mainly composed of fine sand with the upper boundary as the land surface and lower boundary as the water table with its depth varying from 0 to 2 m (Xiao et al. 2016). The saturated zone is mainly composed of fine to medium sand with its upper boundary as the water table and lower boundary as the clay and sandy clay layer (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 drops to the lowest elevation late in the dry season (May), mainly controlled by the temporal variation of precipitation, evapotranspiration, and the annual rise and fall of sea level (Foster et al. 2017).
Figure 22 Location of the study area
4.2.2 Sea-level rise scenarios
Relative to the mean sea level in 2010, SLR scenarios in 2080 are estimated to be 23.4, 59.0, and 119.5 cm for the low, intermediate, and high ice melt projections, respectively. These projections for 2080 were developed using downscaled data provided by Dr. Radley Horton and Daniel Bader, Center for Climate Systems Research, Earth Institute, Columbia University as part of the NASA Climate Adaptation Science Investigators Program (Rosenzweig et al. 2014, Foster et al 2017).

4.3 Numerical Modeling

4.3.1 Model development
A reference model was developed to simulate the monthly variation of salinity distribution in the vegetation root zone of a biogeotypical area in southeast Merritt Island on the CCBIC under 2010 hydrologic conditions. The reference model includes both the unsaturated zone above the water table and the saturated zone below the water table. The reference model was calibrated against the hydraulic heads simulated by the SEAWAT model developed and calibrated in the previous work (Xiao et al. 2016) due to a lack of site specific groundwater level and quality monitoring data. After calibration, three diagnostic models were produced based on the calibrated reference model by modifying the boundary values representing the water levels of the Banana River according to the three SLR scenarios projected for 2080. This modeling protocol enabled assessing the effect of future SLR on SWI into the vegetation root zone, assuming all of the other hydrologic and hydrogeologic conditions remain unchanged. Another important assumption made for developing the three diagnostic models was that the water level of Banana
River rises simultaneously at the same magnitude as with SLR, since (1) no projections were made for the rising of water levels corresponding to SLR; (2) the Banana river is a coastal lagoon connected to the Atlantic Ocean at Ponce inlet and Sebastian inlet and the water level is almost the same (only 4 to 5 cm higher) with sea level. For simplicity and convenience, the term ‘sea-level rise (SLR)’ in the following paragraphs not only refers to the rising of Atlantic Ocean sea level, but also refers to the simultaneous rising of Banana River water level.

One of the main difficulties in developing the above-mentioned FEMWATER models was lack of reliable field-measured data, since no water level and water quality monitoring wells are located within the study area. Thus, data from the literature was used and reasonable assumptions were made during the model implementation procedure. Furthermore, the area is micro-tidal and storm surges were not simulated as part of this work.

4.3.2 Simulation code

The three-dimensional finite-element variable-density FEMWATER developed by Lin et al. (1997) was selected as the simulation code. Groundwater Modeling Systems (GMS), a well-known graphical user interface developed by AQUAVEO (http://www.aquaveo.com/software/gms-femwater), was used to create model input files.

4.3.3 Hydrogeologic parameters

For both the reference and diagnostic models, the specified hydrogeologic parameters such as hydraulic conductivities, porosity, and dispersivities are summarized in Table 6. For the unsaturated zone, soil moisture content curves, relative conductivity curves and water capacity
curves were generated for specified types of soil (e.g., sand, clay, silt, etc.) based on the Van Genuchten model. Throughout the entire simulation period, the hydrogeologic parameters applied throughout the study area were held constant.

4.3.4 Fluid properties

For both the reference model and diagnostic models, the specified fluid properties such as freshwater/seawater density and viscosity, and concentration dependence coefficients are summarized in Table 7.

4.3.5 Boundary conditions

For the reference model, a Dirichlet boundary condition was assigned to the lateral boundary to the southeast that represents the coastline of the Banana River (line marked in red in Figure 23). The heads and TDS concentrations specified at the Dirichlet boundary were obtained from field measurements as shown in Figure 24. The no-flux boundary condition was assigned to all other lateral boundaries (lines marked in black in Figure 23) as well as the bottom boundary. A variable flux boundary condition was assigned to the top of the model domain to represent the precipitation and evapotranspiration flux. The monthly mean values of precipitation and evapotranspiration flux were obtained from rain gauges operated by the St. Johns River Water Management District and the data collection sites of the U.S. Geological Survey Florida Evapotranspiration Network, respectively (Figure 25).
### Table 6 Hydrogeologic parameters

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<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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<td>Vertical hydraulic conductivity</td>
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<tr>
<td>Molecular diffusion coefficient</td>
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### Table 7 Fluid Properties

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<th>Parameters</th>
<th>Value (25 °C)</th>
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Figure 23 Boundary conditions assigned to the lateral boundaries

Figure 24 Monthly mean water level and TDS concentration of the Banana River
Figure 25 Monthly mean precipitation and evapotranspiration

Figure 26 Two-dimensional and three-dimensional mesh
For the diagnostic models, the heads specified at the Dirichlet boundary representing the water level of the Banana River were re-specified corresponding to the various SLR scenarios, while the TDS concentrations specified at the Dirichlet boundary remained unchanged. As mentioned previously, rising water level can cause saltwater inundation on coastal lowlands, and further inland encroachment of the coastline is inevitable wherever coastal defense structures, such as revetments or seawalls) may not be able to impede waves reaching and overtopping their crest. By comparing the land surface elevation with the new water level corresponding to each SLR scenario, the coastal lowlands that had a lower elevation than the new water level were specified as ponded by the rising Banana River. Then, the border between the inundated and the emergent areas was designated as the new Banana River coastline under SLR conditions.

4.3.6 Initial conditions
For the reference model, the initial heads and concentrations were obtained from the output of the previously developed and calibrated SEAWAT model (Xiao et al. 2016).

For the diagnostic models, the initial heads and concentrations were obtained from the output of the calibrated reference model.

4.3.7 Mesh
The criteria for the mesh design was that it: (1) represents the topographic variation of land surface; (2) simulates the freshwater/saltwater transition zone effectively; (3) maximizes simulation accuracy while maintaining reasonable computer runtimes.
Horizontally, the two-dimensional unstructured finite element mesh consisted of 932 nodes and 1674 triangular elements as shown in Figure 26. In order to increase the simulation accuracy especially in the coastal region, the average spacing for Areas (1), (2), (3), and (4) was 40, 30, 20, and 10 m, respectively. Vertically, the model domain was divided into 13 layers as shown in Figure 26. The top elevation of Layer 1 was set to the land surface elevation derived from the LiDAR data, and the bottom of Layer 13 was set to 10 m below land surface elevation, since the thickness of the surficial aquifer is approximately 10 m. The thickness of Layers 1 to 9 was 0.33 m uniformly. For Layers 10 to 13, the thickness of each layer was 1.0, 1.5, 2.0, and 2.5 m, respectively. The unsaturated zone was vertically discretized with a finer mesh than the saturated zone in order to enhance modeling accuracy and prevent oscillations in the numerical output. In total, the three-dimensional mesh consists of 13048 nodes and 21762 elements. Although simulation accuracy can further increase with finer mesh (smaller average spacing), the number of nodes and elements are required to be no greater than 25578 and 22080 for executing FEMWATER (Lin et al. 1997).

4.3.8 Simulation period and time step

Both the reference model and the diagnostic models developed in this study were transient (non-steady-state).

For the reference model, the 12 month simulation period was divided into 12 stress periods. Each stress period was specified to 30 days so that the monthly variation of salinity distribution could
be simulated. Within each stress period, further temporal discretization was introduced in the form of a time step specified to start at 0.1 day and increasing by a multiplier of 1.1.

For the diagnostic models, the temporal discretization was the same as the reference model.

4.4 Calibration

The reference model was calibrated in terms of the hydraulic head. In order to calibrate the simulated heads, field-measured groundwater levels from groundwater monitoring wells were required to serve as calibration targets. As above-mentioned, however, there are no active monitoring wells within the model domain. Therefore, the heads simulated by the previously developed and calibrated SEAWAT model (Xiao et al. 2016) were utilized as calibration targets as an alternative approach. However, it should be noted that the SEAWAT model was a steady-state model that simulated the annual-average heads and TDS concentrations only in the saturated zone under steady-state 2010 hydrologic conditions. In contrast, the FEMWATER model developed in this study was a transient model that simulates the monthly-averaged heads and TDS concentrations in both the unsaturated zone and the saturated zone under transient 2010 hydrologic conditions. Thus, before initiating the calibration procedure, the simulated monthly-averaged heads from the FEMWATER model was converted to the annual-averaged heads to be consistent with the simulated heads from the SEAWAT model. The simulated heads from the bottom layer of the FEMWATER model and the SEAWAT model were exported for comparison. However, the simulated heads from the top layer of the FEMWATER and SEAWAT models were not exported for calibration because the top layer of the FEMWATER
model belonged to the unsaturated zone above the water table while the top layer of the SEAWAT model belonged to the saturated zone below the water table.

The locations of the 24 calibration targets are shown in Figure 27. From the SEAWAT model, the simulated heads were most sensitive to changes in hydraulic conductivity. Thus, the horizontal and vertical hydraulic conductivity were adjusted iteratively in order to minimize the difference between the simulated heads from the FEMWATER model and the simulated heads from the SEAWAT model until a satisfactory agreement is reached and then the FEMWATER model can be considered calibrated.

After calibration, a Nash-Sutcliffe model efficiency coefficient of 0.99 was achieved (Figure 27), indicating a strong correlation between the hydraulic heads simulated by the FEMWATER and SEAWAT models. The horizontal and vertical hydraulic conductivities were calibrated to 6 [m/d] and 0.022 [m/d], respectively.

It should be noted that the reference model was calibrated in terms of the hydraulic heads only, while calibration against the simulated TDS concentrations was not performed. The simulated TDS concentrations produced by both the FEMWATER and SEAWAT models at 21 out of 24 calibration targets (87.5 %) were approximately equal to zero, implying that it is not necessary to calibrate the simulated TDS concentrations.
Figure 27 Calibration of the simulated heads

Figure 28 Monthly variation of TDS concentrations in the vegetation root zone that are 10, 20, 30, and 40 m away from the coastline
4.5 Results and Discussions

The calibrated reference model was aimed at modeling the monthly variation of salinity distribution in the vegetation root zone under transient 2010 hydrologic conditions. The diagnostic models developed based on the calibrated reference model were aimed at tracking the movement of the saltwater/freshwater transition zone and determining the extent of SWI into the vegetation root zone under various SLR scenarios estimated for 2080. Since salinity level in the vegetation root zone is the focus of this study, the simulated TDS concentrations from the top layer (Layer 1) is exported.

The saltwater/freshwater transition zone typically has a TDS concentration higher than freshwater (no greater than 1 kg/m³) and lower than seawater (around 35 kg/m³), and water quality is further classified as slightly saline (1-3 kg/m³), moderately saline (3-10 kg/m³), and highly saline (10-35 kg/m³) according to NGWA (2010). Thereby, contours of 1, 3, 10 and 35 kg/m³ TDS concentration were used to delineate the boundary of each category of the transition zone.

In 2010, the monthly variation of TDS concentrations in the vegetation root zone that was 10, 20, 30, and 40 m far away from the coastline are visualized in Figure 28. In general, the monthly variation was not significant and the range of the variation was mostly within 1 to 2 kg/m³, indicating that the TDS concentrations in each month were almost constant. However, it can be observed from Figure 28 that: (1) the annual highest salinity level was found in June and the annual lowest salinity level was found in October; (2) the salinity level tended to decrease from
July to October and increase from November to June. As above-mentioned, the wet season is from June to October with its precipitation accounting for approximately 70% of annual total, while the dry season is from November to May with relatively scarce precipitation (Figure 25). Hence, the salinity level started to decrease beginning in July and reached its annual minimum in October likely due to dilution and flushing of saltwater by sufficient infiltrated rainwater. The salinity level to increase from November and reached its annual maximum value in June was due to lack of sufficient infiltrated rainwater for dilution and flushing of saltwater. Since salinity level in the vegetation root zone was highest in June and lowest in October, the spatial distribution of salinity in June and October are considered representative and can be used to identify the location and track the movement of the saltwater/freshwater transition zone due to SLR.

In 2010, the spatial distribution of salinity in June and October were shown in Figure 29a and 30a, respectively. Projected to 2080, the diagnosed spatial distribution of salinity in June under low (23.4 cm) SLR, intermediate (59.0 cm) SLR, and high (119.5 cm) SLR were shown in Figure 29b, 29c, and 29d, respectively. Besides, the diagnosed spatial distribution of salinity in October under those three SLR scenarios were shown in Figure 30b, 30c, 30d, respectively.
Figure 29 Spatial distribution of salinity: (a) June, 2010; (b) June, 2080 (23.4 cm SLR); (c) June, 2080 (59 cm SLR); (d) June, 2080 (119.5 cm SLR)
Figure 30 Spatial distribution of salinity: (a) October, 2010; (b) October, 2080 (23.4 cm SLR); (c) October, 2080 (59 cm SLR); (d) October, 2080 (119.5 cm SLR)
From Figure 29a, water quality of only a small area (1.05%) of the vegetation root zone was categorized as slightly, moderately or highly saline and had a TDS concentration greater than 1 kg/m³ (i.e. contaminated by SWI); the majority of the vegetation root zone was categorized as freshwater. From Figure 29b and 29c, the effects of low (23.4 cm) and intermediate (59.0 cm) SLR are not distinctly different, since the vegetation root zone that is contaminated by SWI only increased by 0.16% and 0.38% from 1.05% to 1.21% and from 1.05% to 1.43%, respectively. However, from Figure 29d, the effect of high (119.5 cm) SLR was significant, since the vegetation root zone that is contaminated by SWI increased by 12.89% from 1.05% to 13.94%. Similarly, as shown in Figure 30a, 30b, 30c, and 30d, the effects of low (23.4 cm) and intermediate (59.0 cm) SLR were not distinctly different, while the effect of high (119.5 cm) SLR was significant (1.01% to 13.83%). The analysis of the results focused on the area percentage of the vegetation root zone contaminated by SWI due to SLR are tabulated in Table 8.
Table 8 Percentage increase of the influenced vegetation root zones suffered from SWI

<table>
<thead>
<tr>
<th>SLR Scenarios</th>
<th>Percentage (%)</th>
<th>Percentage increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June, 2010 (0 cm)</td>
<td>1.05</td>
<td>-</td>
</tr>
<tr>
<td>June, 2080 (23.4 cm)</td>
<td>1.21</td>
<td>0.16</td>
</tr>
<tr>
<td>June, 2080 (59.0 cm)</td>
<td>1.43</td>
<td>0.38</td>
</tr>
<tr>
<td>June, 2080 (119.5 cm)</td>
<td>13.94</td>
<td>12.89</td>
</tr>
<tr>
<td>October, 2080 (0 cm)</td>
<td>1.01</td>
<td>-</td>
</tr>
<tr>
<td>October, 2080 (23.4 cm)</td>
<td>1.15</td>
<td>0.14</td>
</tr>
<tr>
<td>October, 2080 (59.0 cm)</td>
<td>1.37</td>
<td>0.36</td>
</tr>
<tr>
<td>October, 2080 (119.5 cm)</td>
<td>13.83</td>
<td>12.82</td>
</tr>
</tbody>
</table>
In general, the simulation results agreed with the findings from the previous SEAWAT model (Xiao et al. 2016) that the extent of SWI due to eustatic SLR (without considering tides, storm surges or event driven geomorphology) on southeast Merritt Island is not significant if the rising sea level is no greater than approximately 65 to 70 cm higher than the 2010 MSL. For SLR scenarios lower than 65 to 70 cm, the coastal defense structure prevents saltwater from migrating inland to cause land surface inundation. Lower SLR scenarios also permit infiltrated rainwater from the sand ridges in southeast Merritt Island that serve as the primary recharge areas of Merritt Island (Schmalzer et al. 2000) to act as an effective inland fresh groundwater barrier that impedes the landward migration of coastal saline groundwater. Nevertheless, for SLR scenarios greater than 65 to 70 cm, overtopping of seawater in coastal areas and further inland encroachment of coastline are inevitable in that the man-made coastal defense structure may not be able to block waves reaching and passing over its crest without future augmentation. As noted above, the land surface is relatively low and the topography is relatively flat. Therefore, the horizontal encroachment of the coastline associated with high (119.5 cm) SLR is drastic and subsequently greatly amplifies SWI into the vegetation root zone as shown in Figure 29d and 30d. This is considered a key component of SWI associated with SLR since the infiltration of overtopped seawater plays an important role in increasing the salinity level in the vegetation root zone, although it can be buffered by the dilution and flushing by infiltrated rainwater, especially during the wet season. Further, since SWI into the vegetation root zone is mainly due to overtopping of seawater by SLR, it is estimated that heightening and strengthening of the artificial coastal defense structure will be able to effectively control SWI in the study area.
Groundwater serves as a large subsurface water reservoir and is an important source of water to support surface water bodies such as creeks and wetlands, and the contribution of groundwater to surface water weighs more in the dry season (November to May). As above-mentioned, water table within the study area is very shallow and can be at or near the land surface in many places. Thus, surface water and groundwater are highly interconnected. From the model output, an inevitable gradual rise of water table occurs with respect to SLR, although the rate of water table rise is very slowly. Surface water and groundwater is becoming more and more interrelated, and the risk of surface water being contaminated by the saline groundwater is increasing. The porous and permeable surficial soil (primarily composed of sand) tends to transmit groundwater and certain types of contaminants such as chloride to surface water bodies, resulting in an increase of salinity level in natural creeks, artificial ditches, and wetlands. An increase in chloride concentration in surface water bodies can create problems for plants and animals by altering their metabolic pathways and rates of activities, and the influence on coastal ecosystem can be at small or large scales dependent on the magnitude of the changes in chloride concentration. Therefore, further research will be concentrated on evaluating the climate change and SLR effects on potentials for altering human and ecosystem exposure pathways to changes in chloride and other toxic or non-toxic contaminant concentrations by transmitting groundwater contaminants to surface water bodies, with a focus on sites located at coastal alluvial plains in Florida and all around the USA.
4.6 Conclusion

The purpose of this study was to diagnose the effect of SLR on saltwater intrusion into the vegetation root zone of a typical low lying coastal alluvial area. Salinity in the vegetation root zone is crucial for the survival of vegetation species and maintaining high biodiversity in the natural coastal environment. The selected study area is a biogeotypical area in southeast Merritt Island on the CCBIC of east-central Florida covers an area of approximately 0.45 km².

Numerical models were implemented and parameterized with relevant regional hydrologic and hydrogeologic features to achieve the objective. A three-dimensional finite-element variable-density transient FEMWATER model was developed and calibrated in terms of hydraulic heads to simulate the monthly variation of salinity distribution in the vegetation root zone and identify the location of the saltwater/freshwater transition zone under transient 2010 hydrologic conditions. The calibrated FEMWATER model was then modified by adjusting the boundary conditions to simulate the effects of three progressive SLR scenarios to diagnose the location and movement of the saltwater/freshwater transition zone and determine the extent of SWI into the vegetation root zone under the effect of SLR.

It is indicated from the simulation results that effects of the low (23.4 cm) and intermediate (59.0 cm) SLR on SWI into the vegetation root zone are not significant as infiltrated rainwater can act as an effective hydraulic barrier to obstruct the landward migration of saltwater. However, effect of the high (119.5 cm) SLR is significant, mainly due to the downward infiltration of overtopping saltwater into the vegetation root zone, since the land surface is relatively low and
the topography is relatively flat and saltwater inundation is inevitable due to the rising sea level in that the elevation of the local man-made coastal defense structure (roadbed) cannot withstand waves reaching and overtopping its crest. Therefore, maintaining a nearly-constant submarine fresh groundwater discharge as well as heightening and strengthening of artificial coastal defense structures could be feasible and effective approaches to mitigate and minimize the occurrence of SWI into the vegetation root zone of low-similar low-lying coastal alluvial plains. However, the authors caution that astronomic tides as well as storm surges and changes in geomorphology through erosion or accretion were not considered in this study and are known to dynamically interact with SLR causing non-linear effects. The outcome of this study contributes to ongoing research focused on forecasting regional vegetation community and other resources responses to climate change and the discussion of impact minimization strategies.
4.7 References


Smith NP (1990) An introduction to the tides of Florida’s Indian River Lagoon. II. Currents. Florida Scientist. 56:216-225


CHAPTER 5
ASSESSING THE IMPACTS OF GROUNDWATER RECHARGE AND HEAD DIFFERENCE ON SINKHOLE OCCURRENCE

The study described in this chapter (Chapter 5) was published in Environmental Earth Sciences on Sep. 10th, 2016. The study was funded in part by Florida Department of Transportation (FDOT).

Title: Investigation of the impacts of local-scale hydrogeologic conditions on sinkhole occurrence in East-central Florida, USA

Authors: Han Xiao, Yong Je Kim, Boo Hyun Nam, Dingbao Wang

5.1 Introduction

Sinkholes are widely distributed in Florida karst terrains (Rupert and Spencer 2004; Gray 2014). Sinkholes can cause property damages and structural problems for buildings, roads, bridges, power transmission lines and pipelines, and can also cause environmental problems such as degradation of groundwater quality in that open sinkholes can create pathways for transmitting contaminated surface water directly into the underlying groundwater aquifer (Chen 1993; Lindsey et al. 2010). However, plugged sinkholes can create new wetlands and lakes by capturing rainfall and surface runoff, thereby causing localized flooding. Due to a rapid increase in the discovery and reporting of sinkhole occurrence in populated cities and rural areas since the 1950s, sinkholes have been recognized as the primary geologic hazard for destruction of human life and property resulting in massive financial losses to society (Wilson and Shock 1996; Brinkmann et al. 2008). From Kuniansky et al. (2015), the Florida Office of Insurance Regulation (2010) reported that insurers had received 24,671 claims for sinkhole damage in
Florida between 2006 and 2010 totaling $1.4 billion, an average of $280 million per year for those 5 years; cost per year in Florida is on an increasing trend with total sinkhole losses for closed and open claims combined increasing from $209 million in 2006 to $406 million in 2009 (The Florida Senate 2010).

In Florida, a generalized generic framework of sinkhole formation and karst topography development was explained in detail by Beck (1986) and Waltham et al. (2005). Dissolution of carbonate bedrock (highly permeable continuous sequences of limestones and dolostones capped by the overlying clayed surficial soils) is the primary and ultimate cause of sinkhole formation and development of karst topography. The carbonate bedrock is slowly recharged by infiltrated weakly acidic rainwater through the thick overlying clayed sediments. Rapid recharge occurs through cracks and sand-filled pipes where the overlying sediments are partly or completely breached. Soluble limestones and dolomites on top of the carbonate bedrock are dissolved and washed away extremely slowly (on the order of millimeters per thousand years) on a geologic time-scale, creating small cavities/voids. As time goes on they grow larger and the overlying surficial soils move downward to fill in the cavities/voids, resulting in upward raveling/erosion of soil particles beginning from bottom of the overlying surficial soils. As time progresses, the enlarging cavities/voids coalesce and become hydraulically interconnected which increase local groundwater flow rate and cavities/voids growth rate. Eventually, sinkhole occurs when surface soils fall into the subterranean cavities/voids due to a loss of compaction. Note that the hydraulically interconnected cavities and voids can: (1) form extensive conduit systems that convey large amounts of groundwater flow with high velocities on a local scale; (2) create highly
productive karst aquifers in regional scale, such as the Floridan aquifer with large areas of high transmissivity ranging from 500 to 100,000 m²/day (Kuniansky et al. 2012; Kuniansky and Bellino 2016). The impact factors of climate and human activities that can induce sinkhole occurrence in Florida were reviewed and summarized by Tihansky (1999). Climate factors such as heavy rainfall and prolonged drought, and human activities such as groundwater pumping, urbanization (land use change), surface water impoundment, well drilling, and mining can play a critical role in altering local and regional scale hydrogeologic conditions and triggering sinkhole occurrence in a relatively short period of time. Aggressive pumping and prolonged drought can lower the potentiometric level and cause a great loss of fluid pressure support from the limestone aquifer, and land use change (e.g., construction of detention ponds for managing surface water runoff and wastewater effluent) might bring more weight on the surficial soil. Hence, the probability of sinkhole occurrence increases during and after a heavy rainfall due to a sudden increase in stresses on surficial soils that is exacerbated by a loss of buoyant support from the limestone aquifer.

In Florida, detected sinkholes are classified as dissolution, cover-collapse and cover-subsidence sinkholes primarily based on the composition, physical characteristics, and thickness of the overlying sediments (Sinclair and Stewart 1985). The impact of dissolution and cover-subsidence sinkholes can be insignificant since their occurrence might be unnoticeable, while the impact of cover-collapse sinkholes are usually catastrophic since they usually occur suddenly without warning. Although sinkhole occurrence (especially cover-collapse sinkholes) might only take a short period of time, sinkhole formation is a complicated geologic process occurring over time as
part of a broader karstification process which has been happening in Florida for several thousands of years (Brinkmann 2013). Thereby, sinkhole occurrence is only a small event in a broader landscape evolution. In Florida, the carbonate bedrock is relatively young, but the geologic history is complex with cycles of deposition and erosion from periods in which the Florida Plateau was submerged and subsequently emerged. Sinkholes start and suspend formation periodically corresponding to repeated lowering and rising of sea level. During periods of high sea level, seawater inhibits limestone dissolution, and karstification process is inactive in areas covered by seawater. After a recession of the sea the karstification process recovers and becomes active again. Accordingly, sinkholes are filled with marine sediments deposited during high sea level stands, and then restart formation when sea level is low. Therefore, sinkholes detected in Florida might be new sinkholes that formed recently or paleo-sinkholes that formed tens of thousands of years ago.

In Florida, the occurrence frequency of sinkholes varies seasonally. Jammal (1982) assessed the seasonality of sinkhole occurrence in Winter Park, Florida, and found that most sinkholes occurred during May and June when potentiometric levels were usually at an annual low. Wilson et al. (1987) studied the hydrogeologic factors associated with recent sinkhole development in Orlando, Florida and pointed out that sinkhole occurrence is due to changes and transmissions of underground hydraulic and mechanical stresses and its seasonality is because of the seasonal alteration of local and regional hydrogeologic conditions caused by seasonal changes of climate and human activities such as precipitation and groundwater pumping. Wilson and Beck (1992) studied the seasonality of newly identified sinkholes that occurred in the Greater Orlando area in
Florida, and indicated that the downward groundwater recharge from the overlying unconfined aquifer to the underlying confined aquifer through the confining unit between them and the hydraulic head difference between the water table of the unconfined aquifer and the potentiometric level of the confined aquifer are critical to sinkhole occurrence. In the beginning of wet season (May and June), both the water table and the potentiometric level fall to their annual lowest point. During and after a heavy rainfall, the response of the unconfined aquifer is rapid and water table can rise promptly in a relatively short period of time, while the response of the confined aquifer is much slower and the potentiometric level might remain unchanged for some time and then start to rise gradually. The rapidly rising water table generates a fast increase in weight while the unchanged or slowly rising potentiometric level provides a near constant buoyant support, resulting in an increased probability of sinkhole occurrence since the downward force and the upward buoyant force are not ‘balanced’ and the downward groundwater seepage can facilitate the down-washing of surficial soils to the underlying cavities/voids. In the beginning of dry season (November and December), potentiometric level recovers to its annual highest point and provides a solid buoyant support, resulting in a lower probability of sinkhole occurrence.

Brinkmann and Parise (2009) studied the relationship between the frequency of monthly occurrence of sinkholes found in Tampa and Orlando (Florida, USA) and monthly rainfall, and mentioned that the frequency of sinkhole occurrence increases with increased rainfall. From the previous studies, rainfall, groundwater recharge from/to and head difference between the overlying unconfined / underlying confined aquifer are the key impact factors and their
seasonal variations are crucial to the seasonality of sinkhole occurrence. However, the relationships between sinkhole occurrence and the impact factors have not been quantitatively investigated. Thereby, quantification of the relationships between spatial and temporal distribution of observed sinkholes and spatial and temporal variation of the impact factors and determination of how much rainfall, groundwater recharge and head difference can induce sinkhole occurrence are the focus of this study. In this study, the East-Central Florida region that is highly vulnerable to sinkhole hazards, is selected as the study area due to relatively abundant available data. The purposes of this study are to quantitatively examine: (1) the relationship between temporal distribution of observed sinkholes and temporal variation of rainfall and groundwater level; (2) the relationship between spatial distribution of observed sinkholes and spatial variation of groundwater recharge and head difference. Note that the groundwater recharge mentioned herein is the downward groundwater seepage (inter-aquifer flow) from the overlying unconfined aquifer to the underlying confined aquifer, which might be different from other studies (groundwater recharge is defined as infiltrated rainwater that percolates through unsaturated zone to water table). Recharge rate is the downward seepage rate, and mainly relies upon head difference between water table of the unconfined aquifer and potentiometric level of the confined aquifer as well as permeability and thickness of the confining unit that separate the two aquifers. It is assumed that: (1) seasonal variation of head difference plays a crucial role and sinkholes are most likely to occur when local-scale head difference stays unchanged at a peak value after a sharp increase over a short period of time; (2) sinkhole density (the ratio of numbers of reported sinkholes per unit area) increases linearly with the increase in recharge rate and head difference.
5.2 Overview of Study Area

The East-Central Florida (ECF) region study area is shown in Figure 31. The ECF region includes Orange and Seminole counties, most of Brevard, Lake, and Osceola counties, and portions of Marion, Polk, Sumter and Volusia counties. The study area spans approximately 150 km from its western to eastern boundaries and approximately 130 km from its northern to southern boundaries, covering an area of approximately 16,740 km². From west to east, land surface elevation gradually decreases from greater than 60 m (NAVD 88) to sea level. Surface water bodies include rivers and their tributaries, lakes/reservoirs, marshes/wetlands, coastal lagoons and sea. The highland is mostly covered by well-drained sandy soils and characterized by well-developed karst topography, consisting of numerous karst features.

5.2.1 Hydro-climatologic conditions

The climate is humid subtropical with hot/humid summers and mild/dry winters. The wet season is from June through October. The mean maximum temperatures usually exceed 30°C in summer, while the mean minimum temperatures are around 10°C in winter (Tibbals 1990). The approximate mean annual rainfall is 1,200 mm, estimated from daily rainfall recorded by rain gauges operated by the St. Johns River Water Management District (SJRWMD). However, the temporal variation of rainfall is uneven because of the frequently-occurring tropical storms and hurricanes. The approximate mean annual evapotranspiration varies from 760 to 1,200 mm (Tibbals 1990).
Figure 31 Location of the study area and spatial distribution of the reported sinkholes
5.2.2 Hydrogeology

From top to bottom, the hydrostratigraphic units are composed of the surficial aquifer system (SAS), the upper confining unit (UCU), and the Floridan aquifer system (FAS) as shown in Figure 32a and 32b and described in Table 9. Descriptions of the hydrogeologic framework and each hydrostratigraphic unit are as follows from Miller (1986), Kuniansky et al. (2012), Kuniansky and Bellino (2016), and Williams and Kuniansky (2016).

The unconfined SAS is the uppermost hydrostratigraphic unit occurring in the saturated part of the moderate to low permeability Holocene to Pleistocene sediments composed mostly of fine to medium sand and locally contains gravel and sandy limestone of Pliocene to Holocene age. The SAS has its upper boundary as water table and lower boundary as the top of the subjacent UCU. Water table can approach land surface in low-lying areas, and can be several meters deep in upland areas. The thickness of the SAS varies from less than 5 m in the low-lying areas to as much as 50 m in the upland ridge areas. The SAS can be relatively thin due to erosion of surficial sediments; while it can be relatively thick where the karst depressions have already been filled in by surficial materials. The inflow is infiltrated rain water, and the outflow includes evapotranspiration, lateral flow to surface water bodies, and downward seepage to the underlying FAS.
Table 9 Descriptions of the hydrostratigraphic units

<table>
<thead>
<tr>
<th>Geologic Series</th>
<th>Age</th>
<th>Hydrogeologic Unit</th>
<th>Thickness</th>
<th>Composition</th>
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</thead>
<tbody>
<tr>
<td>Surficial Sediments</td>
<td>Pliocene to Holocene</td>
<td>Surficial Aquifer</td>
<td>5-50 [m]</td>
<td>Sand, Silt, Clay, Gravel</td>
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<td>Hawthorn Group</td>
<td>Miocene</td>
<td>Upper Confining Unit</td>
<td>0-70 [m]</td>
<td>Sand, Silt, Clay</td>
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<tr>
<td>Uppermost</td>
<td>Eocene to Miocene</td>
<td>Upper Floridan Aquifer</td>
<td>60-150 [m]</td>
<td>Sand, Silt, Clay</td>
</tr>
<tr>
<td>Permeable Zone</td>
<td>Avon Park</td>
<td>Middle Eocene</td>
<td></td>
<td>Carbonate Limestone and Dolostone</td>
</tr>
<tr>
<td></td>
<td>Uppermost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lithium</td>
<td>Middle Eocene</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Ocala</td>
<td>Upper Floridan Aquifer</td>
<td>60-150 [m]</td>
<td>Sand, Silt, Clay</td>
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<td></td>
<td>Ocala Avon Park</td>
<td>Lisbon-Avon Park Composite Unit</td>
<td>100-350 [m]</td>
<td>Carbonate Limestone and Dolostone</td>
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<td>Avon Park</td>
<td>Middle Avon Park Composite Unit</td>
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<td></td>
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<tr>
<td></td>
<td>Lower Avon Park</td>
<td>Lower Floridan Aquifer</td>
<td>200-350 [m]</td>
<td>dolomites and Anhydrite</td>
</tr>
<tr>
<td></td>
<td>Oldsmar</td>
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<tr>
<td>Cedar Keys</td>
<td>Paleocene</td>
<td>Lower Confining Unit</td>
<td>-</td>
<td>Dolomite and Anhydrite</td>
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<tr>
<td>Formation</td>
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</tbody>
</table>
Figure 32 Cross-sections through the ECF region showing the hydrostratigraphic units: (a) West to East; (b) North to South. Only a small portion of the Floridan aquifer is shown since its bottom is much deeper than -75 m.
The underlain UCU overlies and confines the FAS. The UCU includes all low-permeability late and middle Miocene beds, and locally includes low-permeability post-Miocene beds if present. The UCU is predominantly comprised of sand, silt and clay, while early Miocene carbonate rocks are locally included. The UCU is the primary confining unit that impedes vertical groundwater flow between the SAS and FAS in areas where the UCU is thick. However, the UCU can be breached locally by sinkholes and other openings, forming permeable zones and dissolution pipes that open pathways for groundwater flow between the overlying SAS and the underlying FAS. Downward seepage occurs when and where water table is higher than potentiometric level, and upward seepage occurs when and where the reverse is true. The thickness varies from 0 to 70 m, and can differ markedly because of the local-scale karst features. In general, the UCU is absent or very thin in Volusia County in the northeast, and relatively thick (greater than 30 m) in Osceola County and South Orange and Brevard County in the south and southeast.

The FAS is a huge productive aquifer with high transmissivity serving as the primary source of fresh groundwater supply for agricultural, industrial, and municipal use, primarily because of dissolution of carbonate bedrock and development of secondary porosity and karst features. The FAS consists of a relatively thick sequence of mostly Tertiary-age predominantly carbonate rocks including continuous sequence of interconnected limestone and dolostone that have high permeability. The FAS consists of the upper and lower FAS separated by several confining and semi-confining units. The top of the upper FAS is marked by the start of a vertically continuous sequence of carbonate rocks located beneath the UCU or SAS, indicating by a distinct change in
water level in the drilling annulus or an increase in artesian flow. The upper FAS includes the permeable zones composed of Suwannee permeable zone (if present), Uppermost permeable zones (including all of the permeable zones between the top of FAS and the top of Ocala permeable zone), Ocala permeable zone (OCPZ), Ocala-Avon Park permeable zone (OCAPLPZ) and the uppermost part of Avon Park permeable zone (APPZ). In general, the APPZ is thicker than other permeable zones, and is comprised of several permeable zones at different levels instead of a single zone. The APPZ consists of thick beds of permeable, fractured, cavernous dolostone with interbedded lower permeability limestone, dolomitic limestone, and dolostone, where fracture systems and cavernous zones exist and dissolution along fractures and bedding planes create extremely permeable zones. The base of the upper FAS is marked by two composite units in the middle part of the FAS. The two composite units are the Lisbon-Avon Park composite unit (LISAPCU) and Middle Avon Park Composite Unit (MAPCU). The LISAPCU consists mostly of fine-grained carbonate rocks and lower permeability clastic confining beds and the MAPCU consists of evaporite-bearing rocks and stratigraphically equivalent non-evaporite-bearing carbonate units. The thickness and permeability of the composite units control the rate of groundwater exchange between the upper and lower FAS. The lower FAS consists of all permeable and less-permeable zones below the MAPCU, including the lowermost part of the APPZ, lower Avon Park permeable zone (LAPPZ), and Oldsmar permeable zone. The base of the lower FAS is the lower confining unit (LCU) composed of the Cedar Keys Formation. The thickness of the FAS, defined as all rocks between the overlying UCU and underlying LCU, gradually increases from 600 to 750 m southward. The FAS is confined by the overlying UCU in most places. However, the FAS can be unconfined and
hydraulically interconnected with the SAS where the UCU is absent due to erosion, and can even approach land surface where the SAS is very thin (some areas in Volusia County). Due to high heterogeneity and anisotropy, the transmissivity varies from 500 to 100,000 m²/day depending upon localized hydrogeologic conditions. The inflow is downward groundwater seepage from the overlying SAS when and where the water table is higher than the potentiometric level, whereas the outflow is groundwater pumping, submarine groundwater discharge, groundwater discharge to springs and rivers, and upward groundwater seepage when and where the water table is lower than the potentiometric level.

5.2.3 Karst features of the FAS
Karst features including sinkholes, sinking streams and springs are present over most of the extent of the FAS, causing the FAS to be a highly productive aquifer with relatively high transmissivity (Williams and Kuniansky 2016). Karstification and degree of confinement are critical controlling factors of regional groundwater flow. In general, transmissivity is higher in those areas where the FAS is unconfined or thinly confined because infiltrated weakly acidic rain water can easily moves downward and dissolves the carbonate bedrock (Kuniansky and Bellino 2012). The reverse is true where the FAS is thickly confined.

Sinkholes are the most common karst features developed in areas where soluble limestone and dolostone are at or near land surface. The developed open sinkholes can connect the groundwater aquifer to surface water drainage. However, the openings can be ‘closed’ and water exchange can be impeded if less permeable sediments fill in the sinkholes and the associated conduits.
The karst terrain is a well-known distinctive landform, which is sculpted by the weathering of soluble carbonate bedrock. In Florida, the mantled karst is often seen where carbonate bedrock is mostly buried and capped with sanded and clayed overburden sediments (Tihansky 1999). In the mantled karst areas, the carbonate bedrock is not exposed at land surface and the unconsolidated and insoluble covering sediments vary in composition and thickness. However, the presence of the mantled karst can be indicated by sinkholes and the hummocky topography (covering sediments follow the shape of the underlying depressions). Sinkholes are either small dry depressions, or large lakes and ponds if they have been filled in with water. Sinkhole lakes receive water directly from rainfall, overland runoff and groundwater discharge, and lose water by evaporation and leakage. Many sinkhole lakes are not connected to major surface water drainage systems so water may not flow in or out freely. Water level fluctuations in those sinkhole lakes are usually higher than other lakes since the inflow and outflow are not always balanced (Schiffer 1996).

5.3 Reported Sinkholes in Florida

5.3.1 Spatial distribution of sinkholes

In Florida, sinkhole events are recorded in Florida Subsidence Incident Report from the Florida Geological Survey (FGS), which is a primary publicly-accessible sinkhole database. Within the ECF region, more than 500 land subsidence incidents have been reported since the 1950s, and 414 of them have been fully recorded, including occurrence time, location, shape, dimensions, soil type, side slope and land use and land cover. The spatial distribution of the 414 reported land subsidence incidents is plotted in Figure 31.
The following study of sinkholes is based on these 414 land subsidence incidents that have been reported and well-documented, although some of these settling events might have not been verified as ‘true’ sinkholes by geologists. It should be noted that sinkholes that occurred in the study area might be under-reported since reporting of sinkhole events to the FGS is voluntary. Some sinkholes might be filled in and properties might be repaired individually without notifying the FGS due to the concern of negative effects on property values. However, the reporting bias is not a serious problem and the FGS sinkhole database is valid to use (Fleury et al. 2008).

5.3.2 Size distribution

Based on the morphologic characteristics of the 414 reported sinkholes, 76.6% are circular-shaped, 16.9% are elongated-shaped, and 6.5% are irregular-shaped. Circular-shaped sinkholes are predominant in that sinkholes occur when roof (cover) fails and soil surface collapses, while dome-shaped roof is most likely to be formed during raveling and erosion of surficial soils since it is the most stable configuration (Gutierrez 2013).

Sinkhole size (diameter/length, depth) is an important and useful engineering design criterion since it determines the minimum distance that has to be bridged over. Sinkholes vary in diameter and length from meters to hundreds of meters, and depth from several centimeters to several meters. The diameter and depth distribution of reported circular-shaped sinkholes are plotted in Figure 33a and 33b, respectively. The distribution is log-normal, and circular-shaped sinkholes,
whose diameters and depths are no greater than 5 m, are predominant. It is estimated that 50% of the circular-shaped sinkholes have their diameters and depths no greater than 3.3 m and 1.8 m, and 90% no greater than 10.7 m and 9.2 m, respectively. The length and depth distribution of reported elongated-shaped sinkholes are plotted in Figure 33c and 33d, respectively. It is estimated that 50% elongated-shaped sinkholes have their diameters and depths no greater than 2.9 m and 1.4 m, and 90% no greater than 7.6 m and 6.1 m, respectively. In general, circular-shaped sinkholes are larger in diameter or length and deeper in depth in comparison to elongated-shaped sinkholes.

5.4 Timing of Reported Sinkholes

The frequency of monthly occurrence of the 414 reported sinkholes is plotted in Figure 34. In general, it can be observed an increasing trend starting from December through May while a decreasing trend beginning from June to November. Sinkholes occurred mostly in May (70 reported sinkholes) while least in November (14 reported sinkholes), which accounts for 16.9% and 3.4% of total reported sinkholes, respectively. Fifty-three percent of the 414 reported sinkholes occurred within the period of time from May to August. In the following analysis, the relationship between temporal distribution of observed sinkholes and temporal variation of rainfall and groundwater level is studied using hydrologic data measured from rain gauges and observation wells operated by the SJRWMD.
Figure 33 Size distribution of reported sinkholes: (a) Diameter; (b) Depth; (c) Length; (d) Depth
Figure 34 Frequency of monthly occurrence of the 414 reported sinkholes

Table 10 Descriptions of the observation wells

<table>
<thead>
<tr>
<th>ID</th>
<th>Number</th>
<th>Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Observed Value</th>
</tr>
</thead>
<tbody>
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<td>28.535</td>
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<td>W.T.E.</td>
</tr>
<tr>
<td></td>
<td>09252090</td>
<td>L-0062</td>
<td></td>
<td></td>
<td>P.S.E.</td>
</tr>
<tr>
<td>2</td>
<td>30442915</td>
<td>L-1018</td>
<td>28.508</td>
<td>-81.750</td>
<td>W.T.E.</td>
</tr>
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<td>L-1024</td>
<td></td>
<td></td>
<td>P.S.E.</td>
</tr>
<tr>
<td>3</td>
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<td>OR-0894</td>
<td>28.708</td>
<td>-81.488</td>
<td>W.T.E.</td>
</tr>
<tr>
<td></td>
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<td>OR-0893</td>
<td></td>
<td></td>
<td>P.S.E.</td>
</tr>
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</tr>
<tr>
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<td>S-1257</td>
<td></td>
<td></td>
<td>P.S.E.</td>
</tr>
<tr>
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<td>V-0197</td>
<td>28.911</td>
<td>-81.304</td>
<td>W.T.E.</td>
</tr>
<tr>
<td></td>
<td>05601057</td>
<td>V-0196</td>
<td></td>
<td></td>
<td>P.S.E.</td>
</tr>
</tbody>
</table>

a W.T.E. – water table elevation
b P.S.E. – potentiometric surface elevation
Figure 35 Location of rain gauge and observation wells
Several rain gauges have continuous records of daily rainfall, and rainfall data measured from one of them is used to represent the temporal variation because data measured from other gauges is quite similar. The location of the ‘representative’ rain gauge is shown in Figure 35 and the temporal variation of rainfall (monthly average) is plotted in Figure 36a (data collected from 1950 to 1997). From Figure 36a, annual average rainfall is 1,296 mm, and rainfall in wet season (from June to October) is 796 mm (61.4%). In general, the seasonality of sinkhole occurrence (refer to Figure 34) is similar to the seasonal variation of rainfall.

Ninety-one and one hundred and thirty-eight observation wells have continuous records of daily or monthly water tables and potentiometric levels, respectively. Unlike rainfall, temporal variation of groundwater levels cannot be represented using only one or a few observation wells, since local scale groundwater levels vary spatially due to the mantled karst features and groundwater pumping and temporally due to the seasonality of rainfall and groundwater pumping. Thus, it is necessary to determine the site-specific temporal variation of groundwater level especially a few months before the specific sinkhole occurred, since groundwater level is different at each sinkhole site. Appropriate observation wells are selected for further analysis based on the following criterion: (1) distance to the ‘target’ sinkhole is within 2 km so that the observed groundwater levels are representative; (2) continuous water tables and potentiometric levels are both available from at least six months before to one month after the ‘target’ sinkhole occurred. Based on the above-mentioned criterion, five pairs of observation wells (one records water table and the other one records potentiometric level) are selected. The locations are plotted in Figure 35, and the detailed information is described in Table 10. Meanwhile, five ‘target’
sinkholes are chosen. In order to describe the criterion of selecting the ‘target’ sinkholes, Sinkhole 3 is taken for example (shown in the zoom-in figure on the top-right corner of Figure 35). Sinkhole 3 and three other sinkholes are located adjacent to Wells 3 and 3’ in which water table and potentiometric level data are available from 2008 to 2016. Sinkhole 3 occurred on Sep. 23rd, 2012 when observed data is available, whereas three other sinkholes occurred before 2008 when observed data is unavailable. Therefore, Sinkhole 3 is defined as a ‘target’ sinkhole. Similarly, Sinkholes 1, 2, 4 and 5 are selected. It should be noted that water table and potentiometric level data from Wells 1 and 1’, 2 and 2’, and 3 and 3’ was measured daily in the year when Sinkhole 1, 2 and 3 occurred, while the observed data from Wells 4 and 4’ and 5 and 5’ was measured monthly in the year when Sinkhole 4 and 5 occurred.

The temporal variations of site-specific head difference of the specific year when Sinkholes 1, 2, 3, 4 and 5 occurred are shown in Figure 36b, 36c, 36d, 36e and 36f, respectively. The head difference refers to the difference between water table (monitored by Wells 1, 2, 3, 4 and 5) and potentiometric level (monitored by Wells 1’, 2’, 3’, 4’ and 5’). A positive value indicates that water table is higher than potentiometric level (downward groundwater seepage), while the reverse is true (upward groundwater seepage) if the value is negative. Again, Sinkhole 3 is taken for example. From Figure 36d, the head difference near Sinkhole 3 continued to decline from January to August and dropped to the lowest annual level (0.4 m) by the end of August, then increased at a significant rate to 1.8 m in a very short period of time (about half a month). Afterwards, head difference stayed almost unchanged from late September to late November, then increased another 0.1 m in December and reached its highest annual level in 2012. Sinkhole
3 occurred on Sep. 23rd when head difference reached the peak value after a sharp increase. From Figure 36e and 36f, the situations of Sinkholes 4 and 5 are quite similar. From Figure 36c, Sinkhole 2 also occurred when head difference reached the peak value and remained almost unchanged after a sharp increase in a very short period of time (less than one week), although the increase was not as significant as the times when Sinkholes 3, 4 and 5 occurred. From Figure 36b, the fluctuation of head difference over the year was relatively small. Sinkhole 1 occurred when the head difference reached a peak value, although the peak was not as significant as those found in late August and early September.

From Figure 36c, 36d, 36e and 36f, the increases in head difference before Sinkholes 2, 3, 4 and 5 occurred were year-round most significant, implying that a sharp increase of head difference could play a critical role in triggering sinkhole occurrence. From Figure 36b, the most significant increase of head difference was found in late August, while Sinkhole 1 occurred almost one month later on September 26th. It is assumed that head difference was not the primary cause of the occurrence of Sinkhole 1 due to the relatively ‘stable’ head difference in 1986. It is demonstrated from the analysis above that the occurrence time of sinkholes is highly dependent on a sharp increase of local-scale head difference, probably caused by heavy rainfall and/or aggressive groundwater pumping.
Figure 36 (a) Monthly average rainfall (1950-1997); (b) Head difference between Well 1 and 1’; (c) Head difference between Well 2 and 2’; (d) Head difference between Well 3 and 3’; (e) Head difference between Well 4 and 4’; (f) Head difference between Well 5 and 5’
5.5 Spatial Distribution of Reported Sinkholes

In the previous decades, the bottleneck of quantifying groundwater recharge and head difference had a high level of uncertainty in estimation due to insufficient field-measured data from geophysical surveys. Nowadays, with the rapid development of computation power and simulation codes, groundwater recharge and head difference can be simulated and predicted using groundwater models (Zhou and Li 2011).

Within the ECF region, two regional-scale groundwater models have been developed in the previous years, including the ECF model (McGurk and Presley 2002) and ECFT model (Sepulveda et al. 2012). Temporally, the ECF model is steady-state simulating annual average, steady-state groundwater flow in 1995 while the ECFT model is transient with 144 monthly stress periods from 1995 to 2006 simulating monthly variation of groundwater levels and surface water / groundwater interactions. The purpose of this study is to quantify the relationship between spatial distribution of sinkholes and spatial variation of recharge rate and head difference, while the temporal variation is not considered. Therefore, the annual average recharge rate and head difference simulated by the ECF model are used for further analysis instead of using the monthly average recharge rate and head difference simulated by ECFT model. A brief description of the ECF model is as follows.

The ECF model simulates annual average, steady-state water tables and potentiometric levels, recharge rate, groundwater velocity, spring discharges, and seepage from and to rivers and lakes under 1995 hydrologic conditions using the finite-difference MODFLOW-1996 computer code.
(Harbaugh and McDonald 1996). Within the ECF region, the complicated hydrogeologic framework are simplified into a conceptual model, consisting of three aquifers separated by several confining units (refer to Table 9). The three aquifers (SAS, UFA and LFA) are then discretized into four model layers. Layer 1 stands for the unconfined SAS, and the simulated water levels represent the elevations of water table. Layer 2 represents the upper part of UFA including the uppermost permeable zone, the OCPZ, and the OCAPLPZ, and the simulated water levels represent the elevations of potentiometric level of the upper part. Layer 3 represents the lower part of UFA including the dolostone zone within the APPZ. Layer 4 represents the LFA including the lowermost part of the APPZ, the LAPPZ, and the Oldsmar permeable zone. Groundwater flow is conceptualized as quasi-three-dimensional assuming that horizontal flow occurs only within the aquifers and vertical flow occurs only within the confining units. The confining units (UCU, LISAPCU and MAPCU) act as membranes to transmit flow vertically between the aquifers above and below. Noted that groundwater recharge is the downward vertical flow from layer 1 to 2, and head difference is the difference between the water levels of layer 1 and 2. Groundwater recharge occurs and head difference value is positive when/where the water level of layer 1 is higher than layer 2. Similarly, groundwater discharge (concentrated at springs) occurs and head difference value is negative when the reverse is true.

It is assumed that the ECF region does not encounter significant changes in groundwater pumping and land cover and land use and the groundwater systems are always in an equilibrium with climate and human activities. It is also assumed that the climate and hydrologic conditions in 1995 is representative of the long-term conditions of the ECF region. Hence, the spatial
variation of recharge rate and head difference can be extracted from ECF model output. The model output is visualized using ArcGIS. In accordance with the horizontal resolution of the ECF model, the maps of recharge rate and head difference are displayed in the raster file format with a uniform grid spacing of 762 m × 762 m. The GIS map, showing the spatial distribution of reported sinkholes, is then overlaid on the recharge rate and head difference maps to collect and extract the point values of recharge rate and head difference at each sinkhole site for the following analysis.

5.5.1 Sinkholes and recharge rate

The spatial variation of groundwater recharge rate rooted in the ECF model output is visualized utilizing ArcGIS and plotted in Figure 37a. Based on the varied recharge rate, the study area is divided into high-recharge areas (annual-averaged recharge greater than 100 mm), intermediate-recharge areas (annual-averaged recharge ranges from 50 to 100 mm), low-recharge areas (annual-averaged recharge ranges from 0 to 50 mm), and discharge areas (annual-averaged recharge smaller than 0). The analyzed result indicates that the percentages of sinkholes found in high-recharge areas, intermediate-recharge areas, low-recharge areas, and discharge areas are 54.1%, 22.1%, 22.1%, and 1.7%, respectively.
Figure 37 (a) Spatial variation of recharge rate; (b) Sinkhole density and recharge
In order to unravel the relationship more specifically, the study area is further divided into 10
categories based on recharge rate, including 9 recharge categories (Category 1-9) and 1 discharge
category (Category 0) described in detail in Table 11. It can be seen that sinkholes are most
likely to occur in Category 2 where annual-averaged recharge rate varies from 25 to 50 mm.
However, it should be noted that the covering area of each category is different, and the areas
that have high groundwater recharge rates only cover a small portion of the study area. In order
to ‘equalize’ the covering area of each category for further meaningful analysis, the term
‘sinkhole density’ is hereby introduced. Sinkhole density is defined as the ratio of the number of
reported sinkholes within a specific category to the covering area of that category. For example,
Category 2 covers an area of 1520.8 km² with 59 reported sinkholes, then sinkhole density of
Category 2 is 3.88 per 100 km² accordingly. The analyzed result is described in Table 11 and
plotted in Figure 37b. Sinkhole density is smallest in Category 0 and largest in Category 8. From
Category 0 to 8, sinkhole density increases with the increasing of recharge rate. However, a
noticeable decline of sinkhole density can be observed in Category 9. This abnormality is
probably due to underreported sinkholes occurred in the Ocala National Forest located at the
northwest of ECF region where the groundwater recharge rate is high because of the sandy soils.
A linear relationship between sinkhole density and recharge rate with the correlation coefficient
R² of 0.98 is indicated from the analyzed result (Category 9 not included in the regression
analysis).
### Table 11 sinkhole density and recharge rate

<table>
<thead>
<tr>
<th>Category</th>
<th>Covering Area [km²]</th>
<th>Recharge Rate [mm/yr]</th>
<th>No. of Sinkholes [-]</th>
<th>Sinkhole Density [No. per 100 km²]</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>6</td>
<td>0.1</td>
</tr>
<tr>
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<td>5398</td>
<td>0-25</td>
<td>36</td>
<td>0.67</td>
</tr>
<tr>
<td>2</td>
<td>1521</td>
<td>25-50</td>
<td>59</td>
<td>3.88</td>
</tr>
<tr>
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<td>954</td>
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<td>5.45</td>
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<td>Total</td>
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<td>-</td>
<td>414</td>
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</tr>
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</table>
5.5.2 Sinkholes and head difference

The spatial variation of head difference originated from the ECF model output is visualized using ArcGIS and plotted in Figure 38a. A positive value of head difference indicates that the water table is higher than the potentiometric level and groundwater in the SAS seeps downward to recharge the FAS, whereas the reverse is true if the value is negative.

In order to unravel the relationship more specifically, the study area is further divided into 10 categories based on head difference values, including 9 categories that have positive values (Category 1-9) and 1 category (Category 0) that has negative values. The analyzed result of sinkhole density with respect to head difference is described in Table 12 and plotted in Figure 38b. Sinkhole density is the smallest in Category 0 and the largest in Category 8. From Category 0 to 8, sinkhole density increases with the increasing of head difference. A significant decline of sinkhole density in Category 9 is probably because of the underreported sinkholes which occurred in rural areas. From the analyzed result, a straight line is fitted and a linear relationship between sinkhole density and head difference is demonstrated with the correlation coefficient $R^2$ of 0.88 (Category 9 not included in the regression analysis).
Figure 38 (a) Spatial variation of head difference; (b) Sinkhole density and head difference
Table 12 Sinkhole density and head difference

<table>
<thead>
<tr>
<th>Category</th>
<th>Covering Area [km²]</th>
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<th>No. of Sinkholes [-]</th>
<th>Sinkhole Density [No. per 100 km²]</th>
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5.6 Results and Discussions

The relationships between the spatial distribution of sinkholes and spatial variation of recharge rate / head difference are quantitatively investigated. The results indicate that sinkhole density increases linearly with the increase of recharge rate and head difference. At the local scale, groundwater recharge can facilitate the process of raveling/erosion and down-washing of surficial soils into the carbonate cavities and voids. During this process, thickness of overburden materials becomes thinner due to loss of surficial soils, and recharge rate is then accelerated because of reduced resistance and shortened retention time. Increasing rates of groundwater recharge can cause more surficial soils being unraveled and eroded and eventually results in sinkhole formation.

The correlation coefficients of 0.98 and 0.88 demonstrate a satisfactory fit of linear relationship, indicating a stronger correlation between sinkhole density and recharge rate than head difference. However, there are some limitations of the findings regarding data collection and analysis. First, not all of the land subsidence events that reported to the FGS and recorded in FGS Florida Subsidence Incident Report have been verified as ‘true’ sinkholes by professionals. Second, the Florida Subsidence Incident Report is incomplete due to the underreporting of observed sinkholes. As mentioned previously, some sinkholes that occurred in rural areas (e.g., the Ocala National Forest in Central Florida) might have not been found, and some sinkholes that occurred in urbanized areas might be repaired individually without notifying the FGS due to the concern of negative effects on property value. Third, recharge rate and head difference simulated by the ECF model might not be able to represent the exact real situations to a satisfactory degree in
some places because of the ‘coarse’ spatial discretization (762 × 762 m) and the drawbacks of
the simulation code (MODFLOW-1996), especially in those places where local hydrogeologic
conditions are complicated (e.g., great hydraulic head gradient caused by groundwater pumping,
topographic change, elevation change and surface features change). Although finer spatial
discretization is always recommended to reduce error and uncertainty, however, the modelers
have to sacrifice the accuracy to some extent in order to maintain a reasonable computation time
for simulation since the covering area of the ECF region is extremely large. Besides, the
carbonate bedrock in ECF region is highly karstified composed predominantly of limestone and
dolomite with high permeability and transmissivity because of the inter-connected cavernous
conduits and caves and underground drainage channels. From Faulkner et al. (2009),
groundwater flow in the porous media (diffuse-flow dominated system) is slow (laminar flow)
and can be described by Darcy’s law, while groundwater flow in the conduits and caves
(conduit-flow dominated system) is fast (can even be turbulent flow) and Darcy’s law is not
applicable if no adjustment is made for the energy loss that occurred with the onset of turbulence
and turbulent flow. Although the simulation of turbulent flow for karst aquifers have been
incorporated as an option into MODFLOW-2005 (Kuniansky et al. 2008; Shoemaker et al. 2008;
Kuniansky 2014), however, the ECF model is simulated using an older version of MODFLOW.
From Scanlon et al. (2003), although MODFLOW-1996 is applicable to quantify spring
discharge and regional groundwater flow in highly karstified aquifer, it cannot accurately
simulate direction and flowrate of groundwater flow in local scale because of the complexity of
karst systems. Thereby, the simulated recharge rate and head difference might be deviated from
field observations in highly karstified areas, resulting in the simulation results not 100% representative.

5.7 Conclusion

In this paper, the relationships between temporal distribution of observed sinkholes and temporal variation of rainfall and groundwater level, and the relationships between spatial distribution of observed sinkholes and spatial variation of groundwater recharge / head difference are quantitatively investigated. It is illustrated from the results that sinkholes are more likely to occur when local-scale head difference is peaked and remains at the peak after a sharp increase of head difference within a short period of time probably caused by heavy rainfall and/or aggressive pumping. It is also demonstrated from the results that sinkhole density increases linearly with an increase in recharge rate and head difference, and higher recharge rate and head difference can result in higher frequency of sinkhole occurrence. In addition, sinkhole diameter/length and depth distribution are analyzed to determine the minimum distance that has to be bridged over and the minimum amount of soil that has to be reinforced. In general, the distribution is log-normal and most sinkholes have the diameters/lengths and depths no greater than 7 m and 4 m, respectively.

Sinkhole formation is part of a broader karstification process that has been happening in Florida for thousands of years, indicating that one sinkhole formation is a small event in a broader landscape evolution. The study of sinkholes occurrence in Florida is in its early stage. The temporal scale of future research will be switched from short time period (a few months or years
before sinkhole occurrence) to long time period (hundreds/thousands of years) in order to expand the understanding of sinkhole formation, and the spatial scale will be enlarged to the entire state of Florida (if data is available) to improve the knowledge of the complicated karstification evolution.

It is widely acknowledged that Florida is the riskiest state for potential property damage caused by sinkhole hazards. Due to climate change and further urbanization, it goes without saying that climate and human activities will play a crucial role in inducing ‘new’ sinkhole occurrence in future. In order to reduce the probability of ‘new’ sinkhole occurrence and minimize the negative effects, a better understanding of the relationship between sinkhole occurrence and local-scale hydrogeologic conditions is of great importance. Findings in this study can provide water resources managers and land use planners with scientific understandings of sinkhole development and the related local-scale hydrogeologic conditions. Furthermore, outcomes from this study can provide the basis for sinkhole risk assessment and follow-up scientific studies.
5.8 References


Kuniansky EL (2014) Taking the mystery out of mathematical model applications to karst aquifers – a primer, in Kuniansky EL and Spangler LE (eds), U.S. Geological Survey karst interest group proceedings, Carlsbad, New Mexico, April 29 – May 2, 2014, 69-81p


CHAPTER 6
ASSESSING THE RISK LEVEL OF SINKHOLE OCCURRENCE BASED ON GROUNDWATER RECHARGE: A CASE STUDY IN A SINKHOLE-PRONE AREA IN CENTRAL FLORIDA, USA

6.1 Introduction

Sinkholes are a common, naturally occurring geologic feature and one of the pre-dominant landforms in central Florida (Gray 2014; Rupert and Spencer 2004). Sinkholes can cause structural problems for roads and constructions, and can also cause environmental problems for groundwater aquifer in that open sinkholes can create pathways for transmitting polluted surface water to groundwater (Chen 1993; Lindsey et al. 2010). Sinkholes occur when surficial soil gradually subside or suddenly collapse into subsurface cavities and voids due to raveling and erosion of surficial soils caused by dissolution and washing-off of underlying soluble carbonate bedrock (Beck 1986). Most places in central Florida is prone to sinkhole occurrence in that (1) the underlying carbonate bedrock mainly composed of limestone is vulnerable to dissolution by circulating slightly acidic groundwater; (2) groundwater withdrawal from the confined upper Floridan aquifer lowers groundwater level resulting in a reduction or loss of buoyant support from the carbonate bedrock (Tihansky 1999). Due to a rapid increase in sinkhole occurrence frequency in populated cities and rural areas since the 1950s, sinkholes have been recognized as the primary geologic hazard in Florida for resulting in huge financial loss to society, and payouts for sinkhole insurance claims have been increasing in the last decades for increased reporting of sinkhole occurrence (Brinkmann et al. 2008; Maroney et al. 2005). However, it is estimated that the situation can be even worse, since groundwater withdrawal from the Floridan aquifer for agricultural, industrial and municipal use can still increase due to population growth in fast-
growing Florida State while a continuous lowering of groundwater level and reduction of buoyant support is inevitable (Tihansky 1999; Kuniansky 2014; Kuniansky et al. 2015).

In central Florida, carbonate bedrock (mainly composed of weathered limestone) dissolution is the primary and ultimate cause of sinkhole formation and karst topography development, while sinkhole occurrence is influenced by many natural and anthropogenic factors (Beck 1986; Waltham et al. 2005). For example, aggressive pumping and dewatering for mining can significantly lower groundwater level resulting in a great loss of fluid pressure support from the limestone aquifer, and intensified storm and runoff storage in man-made impoundments can create a significant increase in the load bearing on the surficial soil, causing sinkholes to occur.

Many researchers conducted several statistical and experimental studies focused on sinkhole formation and occurrence in central Florida karst terrains, and demonstrated that groundwater recharge rate plays a critical role in sinkhole occurrence while other hydrologic factors such as rainfall intensity and temporal variation of difference of groundwater level between water table and potentiometric level are also important as well (Jammal 1982; Wilson et al. 1987; Wilson and Beck 1992; Brinkmann and Parise 2009). Based on the previous studies, Xiao et al. (2016) conducted a statistical analysis focused on the reported sinkholes found in east-central Florida area and quantitatively investigated the relationship between sinkhole density and spatial distribution of long-term annual-averaged groundwater recharge rate, and indicated a very strong linear relationship between sinkhole density and recharge rate that sinkhole density increases linearly with an increase recharge rate. Xiao et al. (2016) also found that the risk level of
sinkhole occurrence in high recharge areas is much higher than that in low recharge areas or discharge areas in that the reported sinkholes tended to occur in higher recharge areas in a long-term time scale, although this trend is not very obvious in a short-term time scale.

Demonstrated from the previous studies, sinkhole occurrence is strongly related to recharge rate in long-term time scale, and the long-term risk level of sinkhole occurrence can be diagnosed based on long-term annual-averaged recharge rate. Namely, the long-term risk level of sinkhole occurrence in a certain area can be estimated by understanding the long-term pattern of local- or regional-scale groundwater recharge. However, the bottleneck of determining recharge rate has high uncertainty usually due to lack of sufficient observed data from geological and geophysical surveys, since it is not an easy task to implement and maintain a regular groundwater monitoring system.

In recent years, groundwater modeling has been playing an important role in the development and management of groundwater resources and simulation codes developed for various objectives blossomed, and groundwater modeling has successfully become an appropriate technique to simulate one-, two- or three-dimensional groundwater system dynamics and groundwater flow patterns, largely because of the wide use of computers and fast-development of computation power in the past several decades (Zhou and Li 2011). Groundwater modeling has been applied to many case studies worldwide for quantifying groundwater recharge (Anderson et al. 2015; Sanford 2002; Scanlon et al. 2002). In this study, regional-scale and local-scale groundwater flow models are developed to simulate the spatial variation of long-term...
annual-averaged groundwater recharge rate in a sinkhole-prone area in central Florida. The developed model is calibrated against field-measured water table elevations from multiple in-situ installed piezometers. After calibration, the simulated recharge rate is used for further analysis of the risk level of sinkhole occurrence. Based on the simulated recharge rate, as well as rainfall, evapotranspiration, overburden materials thickness and soil property, a simple regression model is developed and a linear regression equation is derived to unravel the relationship between recharge rate and its key controlling factors. It is expected that the developed regression model can be applied to other sites estimating recharge rate and risk level of sinkhole occurrence without the need for development and calibration of a groundwater model. It should be noted that the procedures of conducting a comprehensive assessment of sinkhole risk is very complex, including a great understanding of many controlling factors in many aspects. This study, however, is a simple assessment only focused on recharge rate which is the key controlling factor, while other controlling factors are not considered. It should also be noted that the assessment only reveals the long-term averaged sinkhole risk since the assessment is based on long-term annual-averaged recharge rate, while the timing of sinkhole occurrence is not included in the assessment.

6.2 Overview of Study Area

The study area is at the cross section of Wekiva Pkwy Bridge (SR 429) and SR 46 located near Mt. Plymouth located at the very east portion of Lake County (near the border of Lake and Orange County) in central Florida as shown in Figure 39a and 39b (boundary marked in red). The study area spans approximately 600 m from its western to eastern boundaries and 600 m
from its northern to southern boundaries, covering an area about 0.36 km$^2$. The proposed SR 46 Connector and Wekiva Parkway (SR 429) Interchange which consists of three bridges and four ramps as shown in Figure 39b is located within the study area. Due to subsurface karst conditions encountered in previous studies, it is necessary to conduct a sinkhole evaluation to provide geotechnical recommendations to guide the design and construction of the proposed bridge structures with consideration to the moderate to high risk of future sinkhole occurrence at the location of the proposed SR46 Connector Road with Wekiva Parkway. It should be noted that the recommendations given herein are designed to provide Florida Department of Transportation (FDOT) additional time to respond and take remedial action before occurrence of sinkholes, rather than prevent the occurrence of sinkholes within the study area.

6.2.1 Hydro-climatologic conditions

Within the study area, the mean maximum temperatures usually exceed 30°C in summer, while the mean minimum temperatures are around 10°C in winter (Tibbals 1990). The climate is humid subtropical with hot/humid summers and mild/dry winters. The wet season is from June through October. Rainfall is varied monthly and the mean monthly rainfall is obtained from daily rainfall recorded by the rain gauge SR 46A (No. 30153088) operated by the St. Johns River Water Management District (SJRWMD) as shown in Figure 40.
Figure 39 Location of study area (a) Map of Florida; (b) Map of Lake County and study area

Figure 40 Mean monthly rainfall
6.2.2 Hydrogeologic conditions

From top to bottom, the hydrostratigraphic units are composed of the surficial aquifer system (SAS), the upper confining unit (UCU) and the Floridan aquifer system (FAS). Detailed descriptions of the hydrogeologic framework and each hydrostratigraphic unit are from Chapters 1 and 4.

6.3 Numerical Modeling

6.3.1 Model development

In this study, the assessment of risk level of sinkhole occurrence is based on recharge rate. In fact, the mechanisms of sinkhole formation and the principles of sinkhole occurrence in highly karst sinkhole-prone areas are very complex and thereby the risk level of sinkhole occurrence requires a comprehensive assessment based on knowledge and data including geology, soil mechanics, lithology, hydrology, and so on. In this study, however, the risk level analysis is based on recharge rate, while other controlling factors are not taken into consideration. Therefore, the risk level evaluation is based on hydrologic perspective.

In order to evaluate sinkhole occurrence, it is very important and necessary to develop a groundwater flow model which is able to simulate the recharge rate from the overlying unconfined surficial aquifer to the underlying confined Floridan aquifer. The main difficulties in developing the target groundwater model is lacking of sufficient historical hydrologic data to define the boundary of the groundwater model. It is very important to define the model boundary before collecting model input files to build up the model.
In order to define the model boundary, it is necessary to understand the spatial and temporal variation of water table and the general patterns of groundwater flow within the study area and its vicinity. Thus, a regional-scale groundwater flow model was developed in this study before the development of the groundwater flow model for the study area. The model domain of the regional-scale groundwater model was much larger than the study area. The objective of developing the larger scale regional-scale groundwater flow model was to simulate the spatial variation of water table and identify the general pattern of regional groundwater flow within the study area and its vicinity. The output of the regional-scale groundwater model, especially the water table elevation and contours, was considered as model input and was used to build up the target groundwater flow model. The target groundwater flow model developed for the study area was named as local-scale model with higher spatial resolution. Therefore, in this study, two groundwater models were developed, including a regional-scale model and a high resolution local-scale model.

The regional-scale model including the surficial aquifer, the upper confining unit and the Floridan aquifer was developed to simulate the spatial variation of water levels in the surficial sand layer and the confined limestone layer. The regional-scale model acted as a ‘reference’ model, and the output of the regional-scale model (especially the simulated water levels of each layer) provided the input data for developing the high resolution local-scale model. The local-scale high resolution model was calibrated against piezometers recorded water level data. After
calibration, the model output was exported for further analysis on risk level of sinkhole occurrence.

Another difficulty in developing the above-mentioned regional-scale and local-scale models was a lack of sufficient subsurface field-measured data including hydraulic conductivity and locations and dimensions of underground karstic cavities and voids. Therefore, typical values from the literature were obtained and reasonable assumptions were made in order to simplify the model development procedures.

6.3.2 Simulation code

The implemented regional-scale and local-scale models were simulated using the MODFLOW-2005 computer code currently released by U.S. Geological Survey (Harbaugh 2005).

MODFLOW-2005 is a three-dimensional (3D) finite-difference groundwater model that simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Groundwater flow from/to external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. It has been widely applied to many case studies and is the most frequently used groundwater model tool (Anderson et al. 2015).
6.3.3 Regional-scale model

6.3.3.1 Model domain

The study area was at the cross section of Wekiva Pkwy Bridge (SR 429) and SR 46 as shown in Figure 40. However, the boundaries of the regional-scale model domain marked in a black curve in Figure 41 was determined to extend off-site in order to: (1) minimize the boundary effect; (2) reduce simulation error caused by local scale groundwater flow simulation; (3) include more field-measured geologic, geophysical data; (4) include more hydrologic and hydrogeologic data. The boundaries of the model domain were characterized by the hydrologic boundaries normal to the flow direction or parallel to the flow direction depending on flow rate. The hydrologic boundaries were obtained from simulated water levels from the north-central Florida groundwater flow model – a developed and calibrated groundwater flow model from St. Johns River Water Management District utilized to simulate groundwater flow in the north-central Florida area (https://fl.water.usgs.gov/PDF_files/wri95_4296_davis.pdf). Note that the blue arrows in Figure 41 indicate the regional groundwater flow patterns (simulated by the north-central Florida groundwater flow model).
Figure 41 Model domain
6.3.3.2 Discretization

Model discretization is an important controlling factor of model implementation. A fine discretization can reduce simulation error and provide more accurate model output, while a coarse discretization can enlarge simulation error and provide less accurate model output. However, the model run time for a fine discretization model is much longer than a coarse discretization model. Therefore, careful selection of a proper discretization is crucial in numerical modeling for sufficient accuracy of simulation and reasonable computation time.

For the regional-scale model, the model domain was horizontally discretized into 248 rows and 218 columns with a uniform grid spacing of 30 m by 30 m. The model domain was vertically divided into three layers. Layer 1 represented the surficial aquifer primarily composed of fine to medium sand. Layer 2 represented the upper confining unit primarily composed of clay and sandy clay. Layer 3 represented the upper Floridan aquifer consisting of several sequences of limestone and dolostone. The spatial discretization of the model domain is shown in Figure 42. The top elevation of each layer were shown in Figure 43a, 43b and 43c, respectively. Noted that the top elevation of Layer 1 that represents the land surface elevation was obtained from USGS National Elevation Dataset (https://lta.cr.usgs.gov/NED) which provides basic bare earth elevation information for earth science studies and mapping applications in the United States, and the top elevations of Layers 2 and 3 were obtained from the maps showing the locations and elevations of various hydrostratigraphic units within the study area (William and Kuniansky 2016).
Surficial Layer (Surficial Aquifer)
Primarily composed of sand

Clay Layer (Upper Confining Unit)
Primarily composed of clay

Limestone Layer (Floridan aquifer)
Primarily composed of limestone and dolostone

Figure 42 Spatial discretization of regional-scale model (horizontally and vertically)
Figure 43 Boundary conditions and spatial variation of top elevation: (a) Layer 1; (b) Layer 2; (c) Layer 3
6.3.3.3 Parameters
Because of the limitations of available field-measured data due to lack of sufficient geophysical surveys, estimation of relevant hydrogeologic parameters based on field measured data was not conducted. Instead, the calibrated hydrogeologic parameters from the developed and calibrated north-central Florida groundwater model (Motz et al. 1995) shown in Table 13 was utilized. For Layer 1, the horizontal and vertical hydraulic conductivities were 30 and 3 m/d, and the porosity was 0.2. For Layer 2, the horizontal and vertical hydraulic conductivity were 1 and 0.1 m/d, and the porosity was 0.3. For Layer 3, the horizontal and vertical hydraulic conductivities were 600 and 60 m/d, and the porosity was 0.4.

6.3.3.4 Boundary conditions
For Layer 1, no-flow boundary and general-head boundary were used to represent the hydrologic boundaries as shown in Figure 43a. The no-flow boundary was assigned to the inactive areas that were located outside the model domain since the groundwater flows in the inactive areas were not simulated. The general-head boundary was assigned to the model boundary where a groundwater exchange between inside and outside of the model domain occurred. The reference water levels and values of conductance were obtained from the developed and calibrated north-central Florida model. Recharge boundary and evapotranspiration boundary were used to represent the exchange between surface water and groundwater on top of Layer 1. In order to set up the values for recharge boundary, the infiltration rate was calculated from the daily recorded measured rainfall from rain gauge SR46A operated by St. Johns River Water Management District. In order to set up the values for the evapotranspiration boundary, the potential
evapotranspiration was obtained from USGS Florida Evapotranspiration Network data collection sites, and the extinction depth was determined from the updated land use and land cover map from St. Johns River Water Management District.

For Layer 2, the no flow boundary was used to represent the hydrologic boundaries as shown in Figure 43b because Layer 2 represented the confining unit which has very small hydraulic conductivity hence the groundwater flow in and out of the model domain was considered negligible.

For Layer 3, no-flow boundary, general-head boundary and pumping well boundary were used to represent the hydrologic boundaries as shown in Figure 43c. Similarly, the no-flow boundary was assigned to the inactive areas, and the general-head boundary was assigned to the model boundary where groundwater exchange between inside and outside of the study area occurred. The reference water levels and values of conductance were obtained from the developed and calibrated north-central Florida model. The pumping well boundary was assigned to represent the groundwater production wells constructed in the limestone layer. The pumping rate and well depth were obtained from the St. Johns River Water Management District consumptive use permit (CUP database).

6.3.3.5 Initial conditions
The initial conditions of water levels of each layer were obtained from the output of the developed and calibrated north-central Florida model.
6.3.3.6 Simulation results

The simulated water level of layer 1, which represented the water table elevation, was shown in Figure 44. Based on the simulation results, contours of water level were generated. Based on the generated contours, the general groundwater flow pattern can be observed from southwest to northeast. Based on the generated contours, the boundary of the local-scale high resolution model can be generated. The model domain of the local-scale high resolution model was shown in Figure 44.

The objective of developing the regional-scale model was to understand the general pattern of groundwater flow in the study area and its vicinity in order to identify and delineate the model domain of the local-scale high resolution model.
Table 13 Hydrogeologic parameters

<table>
<thead>
<tr>
<th>Layer</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>30 [m/d]</td>
</tr>
<tr>
<td></td>
<td>Anisotropy</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>0.01 [m/d]</td>
</tr>
<tr>
<td></td>
<td>Anisotropy</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Horizontal Hydraulic Conductivity</td>
<td>600 [m/d]</td>
</tr>
<tr>
<td></td>
<td>Anisotropy</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Source: Motz et al. (1995)

Figure 44 Water table elevation simulated by the regional-scale model and the model domain of the local-scale model
6.3.4 Local-scale model

6.3.4.1 Model domain
The study area was the Wekiva Parkway Bridge Construction Site located at the center of the regional-scale MODFLOW model domain as shown in Figure 44 and 45. The boundary of the model domain was marked in black in Figure 44 and zoomed-in in Figure 45. Also, the locations of in-situ installed SPT boring logs were shown in Figure 45. The soil classification data collected from the SPT tests was very useful to determine soil characteristics such as hydraulic conductivity and was detailed described later in this section. The boundary of the model domain was characterized by the hydrologic boundaries that either normal to the flow direction or parallel to the flow direction as indicated by the simulated water level from the above-mentioned regional-scale model. The criterion of defining the boundary of local-scale high-resolution model was exactly the same as the criterion of defining the boundary of the regional-scale model described earlier.

6.3.4.2 Discretization
The purpose of implementing the high resolution local-scale model was to improve the spatial resolution by finer spatial discretization horizontally and vertically in order to generate a high-resolution recharge map for analyzing the risk level of sinkhole occurrence based on hydrologic perspective.

Horizontally, the model domain was discretized into 235 rows and 211 columns with a uniform grid spacing of 3 m by 3 m; vertically, the model domain was divided into five layers. This was
different from the discretization criterion of the regional-scale model with a uniform grid spacing of 30 m horizontally and 3 layers vertically. For the local-scale high resolution model, the model domain was discretized into 5 layers based on the soil property data collected from the SPT tests. Based on the classifications of soil types identified by SPT boring logs, the soils above limestone (Layer 5) were divided into four soil layers. Layer 1 represented the fine sand layer. Layer 2 represented the silty fine sand layer. Layer 3 represented the clayed fine sand layer. Layer 4 represented the clay and clayed fined sand layer. Layer 5 represented the limestone layer. The locations of the SPT boring logs were shown in Figure 45. The soil classification output from one of the SPT boring logs (SPT Boring Log SB-2) was also shown in Figure 45. It can be obviously observed that the overburden soil above the limestone layer was classified into four layers. Layer 1 was loose gray-brown fine sand. Layer 2 was medium dense dark brown silty fine sand. Layer 3 was medium dense brown fine sand with silt. Layer 4 was soft gray sandy lean clay. Therefore, for the high resolution local-scale groundwater model, from top to bottom, Layers 1, 2, 3, and 4 represented different soil layers and Layer 5 represented the limestone layer. The spatial discretization of the model domain was shown in Figure 46.
Figure 45 Locations of the SPT boring logs
Figure 46 Spatial discretization of regional-scale model (horizontally and vertically)

- Loose gray-brown fine sand
- Medium dense dark-brown silty fine sand
- Medium dense brown fine sand with silt
- Soft gray sandy lean clay
- Limestone

235 Rows and 211 Columns

Grid Size: 3 [m]
(High Resolution)
6.3.4.3 Parameters

The hydrologic parameters such as porosity, specific storage and specific yield used in the local-scale groundwater model were the same as the regional-scale model as shown in Table 13 except for the hydraulic conductivity. The local-scale model was discretized into five layers. Layers 1, 2, 3, and 4 represented the overburden surficial soils, and Layer 5 represented the underlying limestone layer. The spatial variation of hydraulic conductivity of each layer was different because the soil characteristics were different in each layer, and the soil characteristics were spatially varied. In the regional-scale model developed previously, the spatial variation of hydraulic conductivity was not considered due to lack of in-situ field measured soil data. However, in the local-scale groundwater model, the spatial variation of hydraulic conductivity was taken into consideration, because the soil classification data were collected from the 12 SPT boring logs. The collected soil classification data from the 12 SPT tests enabled determining the spatial variation of hydraulic conductivity in high resolution. The criterion of determining the spatial variation of hydraulic conductivity was described in the following paragraph.

In total, there are 12 SPT boring logs installed within the model domain of the local-scale groundwater model. Take the boring log named ‘SB-2’ for example (Figure 45). From Figure 45, it can be seen that there were four layers above the limestone layer situated at the bottom of the soil column, including loose gray-brown fine sand, medium dense dark brown silty fine sand, medium dense brown fine sand with silt, and soft gray sandy lean clay. Each type of soil has its own characteristics. For fine sand, the typical range of hydraulic conductivity is varied from 0.02 – 20 m/d (Domenico and Schwartz 1990). Thus, the hydraulic conductivity value selected to
represent Layer 1 was chosen as 10 m/d (the average value of 0.02 m/d and 20 m/d). For silty
fine sand, the typical range of hydraulic conductivity is varied from 0.001 – 0.5 m/d (Domenico
and Schwartz 1990). Thus, the hydraulic conductivity value selected to represent Layer 2 was
chosen as 0.25 m/d (the average value of 0.001 m/d and 0.5 m/d). For fine sand with silt, the
typical range of hydraulic conductivity is varied from 0.0005 – 0.1 m/d (Domenico and Schwartz
1990). Thus, the hydraulic conductivity value selected to represent Layer 3 was chosen as 0.05
m/d (the average value of 0.0005 m/d and 0.1 m/d). For sandy clay, the typical range of
hydraulic conductivity is varied from 0.001 – 0.01 m/d (Domenico and Schwartz 1990). Thus,
the hydraulic conductivity value selected to represent Layer 4 was chosen as 0.005 m/d (the
average value of 0.001 m/d and 0.01 m/d). For limestone, the typical range of hydraulic
conductivity is varied from 0.1 – 2000 m/d (Domenico and Schwartz 1990). The hydraulic
conductivity of limestone is highly dependent on the RQD ratio (Qureshi et al. 2014). Qureshi et
al. (2014) conducted a study on the relationship between limestone permeability and RQD ratio,
and developed an empirical equation to calculate the value of limestone hydraulic conductivity
based on RQD ratio. Based on the RQD ratio and the empirical equation, the hydraulic
conductivity value selected to represent Layer 4 was calculated to be 3.024 m/d.

Noted that there were 12 SPT boring logs that were capable of identifying soil classifications.
The soil characteristics collected from the other 11 SPT boring logs were analyzed in the same
manner and the hydraulic conductivity values were obtained in the same way. Once the hydraulic
conductivity values at the 12 SPT boring logs sites were obtained, kriging interpolation method
was applied to generate the spatial variation of hydraulic conductivity from Layers 1 to 4 as shown in Figure 47, 47b, 47c, and 47d, respectively.

The spatial variation of hydraulic conductivity in Layers 1, 2, 3 and 4 were imported into the high resolution model. It should be noted that these values were estimated values in that the exact values of hydraulic conductivity were still unknown in that these values were estimated based on soil type rather than aquifer pumping test which could provide accurate localized hydraulic conductivity values. However, these values act as an effective initial estimate and can be adjusted if necessary later in the calibration procedures.
Figure 47 Estimated hydraulic conductivity: (a) Layer 1; (b) Layer 2; (c) Layer 3; (d) Layer 4
6.3.4.4 Boundary conditions

The no-flow boundary, general-head boundary, recharge boundary and evapotranspiration boundary were used to implement the high resolution local-scale model. For Layer 1, no-flow boundary and general-head boundary were used to represent the hydrologic boundaries that have zero flux exchange and non-zero flux exchange. The no-flow boundary was assigned to the inactive areas that were located outside the model domain since the groundwater flows in the inactive areas were not simulated. The general-head boundary was assigned to the model boundary where a groundwater exchange between inside and outside of the model domain occurred. The reference water levels and conductance values were obtained from the output of the regional-scale groundwater model. Recharge boundary and evapotranspiration boundary were used to represent the exchange between surface water and groundwater on top of Layer 1. In order to set up the values for recharge boundary, the infiltration rate was calculated from the daily recorded measured rainfall from rain gauge SR46A operated by St. Johns River Water Management District. In order to set up the values for the evapotranspiration boundary, the potential evapotranspiration was obtained from USGS Florida Evapotranspiration Network data collection sites, and the extinction depth was determined from the updated land use and land cover map from St. Johns River Water Management District. The boundary conditions applied to Layer 1 were shown in Figure 48. For Layers 2, 3, and 4, the boundary conditions were implemented in the same manner under same criterion that no-flow boundary was assigned to the inactive areas that were located outside the model domain since the groundwater flows in the inactive areas were not simulated and general-head boundary was assigned to the model boundary where a groundwater exchange between inside and outside of the model domain.
occurred. For Layer 5, general-head boundary was assigned to the entire model boundary since limestone is highly permeable and groundwater exchange between model boundaries was always existing.

6.3.4.5 Initial conditions
The initial conditions refer to the initial water table elevation and potentiometric elevation before simulation. The initial water table elevation and potentiometric elevation were obtained from the output of the regional-scale model described previously.

6.3.5 Calibration
The water table elevation simulated by the local-scale model was calibrated against the observed water table elevation measured by the in-situ installed piezometers. Model calibration was achieved through a trial-and-error method by modifying the values of hydraulic conductivity of each layer until the simulated water levels match the observed water levels to a satisfactory degree. However, the values of hydraulic conductivity of Layers 1, 2, 3, 4 and 5 were adjusted within a reasonable range (not allowed to exceed the maximum typical value while not allowed to be lower than the minimum typical value).
Figure 48 Boundary conditions applied to Layer 1

Figure 49 Locations of the installed piezometers and the seasonal variation of water level measured from Piezometer 1-2
In total, there were 20 piezometers installed to measure water table status from Aug. 17th, 2016 to Jul. 30th, 2017, as shown in Figure 49. The water table elevation is varied seasonally dependent on the seasonal rainfall. The seasonal variation of rainfall measured from Piezometer 1-2 was visualized in Figure 49, and the annual-averaged rainfall measured from the 20 piezometers were tabulated in Table 14. The simulated water level from Layer 1 was used for calibration, since it represents the simulated site water table.

After calibration, the simulated water levels and the observed water levels matched satisfactorily. The $R^2$ was 0.45 as shown in Figure 50, indicating a good measurement between simulated water levels from the calibrated groundwater model and the observed water levels from the field-measured hydrologic data from the in-situ installed piezometers. The adjusted hydraulic conductivity of each layer were shown in Figure 51a, 51b, 51c, 51d, 51e, 51f, 51g, and 51h, and the spatial variation of the calibrated water table elevation was shown in Figure 52.
Table 14 Annual-averaged rainfall measured from 20 piezometers

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Figure 50 Comparison between the simulated heads and the observed heads

Simulated Vs. Observed Heads

$R^2 = 0.45$
Figure 51 Calibrated hydraulic conductivity: (a) Layer 1 (horizontal); (b) Layer 1 (vertical); (c) Layer 2 (horizontal); (d) Layer 2 (vertical); (e) Layer 3 (horizontal); (f) Layer 3 (vertical); (g) Layer 4 (horizontal); (h) Layer 4 (vertical)
Figure 52 Calibrated water table elevation
6.4 Results and discussions

6.4.1 Groundwater recharge

The high resolution recharge map for the Wekiva Parkway Bridge Site was developed and visualized based on the output of the local-scale model as shown in Figure 53. The recharge rate is the downward seepage rate of groundwater from the surficial layer (Layer 1) to the limestone layer (Layer 5). Positive values of recharge rate indicate downward seepage and negative values indicate upward seepage. The unit of recharge rate is millimeter per year.

6.4.2 Risk level of sinkhole occurrence

A correlation analysis between relic sinkholes and recharge rate was conducted. The generated high resolution recharge map was overlaid with the map showing the locations of the relic sinkholes as shown in Figure 54 and the recharge rates associated with the relic sinkholes were extracted. The number of sinkholes within each recharge category was counted and the sinkhole density within each recharge category was calculated. Then, a relationship between sinkhole density and recharge rate was developed as shown in Figure 55.
Figure 53 Spatial variation of high resolution groundwater recharge

Figure 54 Locations of relic sinkholes
Figure 55 Relationship between sinkhole density and recharge rate

Figure 56 Risk level of sinkhole occurrence
The risk level of sinkhole occurrence is higher in areas that have higher recharge rate, and lower in those areas that have lower recharge rate. From Figure 55, sinkhole density was low in those areas that have recharge rate lower than 600 mm/yr, and sinkhole density was moderate in those areas that have recharge rate varied from 600 mm/yr to 650 mm/yr, while sinkhole density was high in those areas that have recharge rate higher than 650 mm/yr. The risk level of sinkhole occurrence is highly related to sinkhole density. In this study, the risk level is recognized as high if sinkhole density is greater than 650 mm/yr, and is recognized as moderate if sinkhole density is varied from 600 mm/yr to 650 mm/yr, and is recognized as low if sinkhole density is lower than 600 mm/yr. Based on this criteria, the spatial variation of risk level of sinkhole occurrence at the Wekiva Parkway Bridge Site was shown in Figure 56.

6.4.3 Regression analysis

Due to limitations of available field-measured geophysical data, as well as the time required to develop and calibrated a groundwater model, it is not always efficient to use groundwater model to simulate the recharge rate. In short, it is necessary to develop a method to estimate recharge rate instead of using groundwater model. Thus, a regression analysis was conducted to explore the relationship between recharge rate and its key controlling factors based on the recharge rate simulated by the local-scale model. The objective of development of this regression model was to simplify the procedures for reasonably estimating recharge rate.

From Darcy’s Law, the key controlling factors of recharge rate include vertical hydraulic conductivity, water level of surficial sand layer, water level of limestone layer, and thickness of...
confining layer. These controlling factors should be taken into consideration for the regression analysis. The mathematical expression to estimate recharge rate based on Darcy’s Law is shown as Equation 1.

\[ Re = K_z \times \frac{H_S - H_L}{L} \]  \hspace{1cm} (1)

where

- \( Re \) – Recharge rate (m/d)
- \( K_z \) – Vertical hydraulic conductivity (m/d)
- \( H_S \) – Water level of surficial sand layer (m)
- \( H_L \) – Water level of limestone layer (m)
- \( L \) – Thickness of confining layer (m)

From Equation 1, recharge rate is directly proportional to the water level difference between the surficial sand layer and the limestone layer, that is, recharge rate increases if the water level difference increases and decreases if the water level difference decreases. In general, water level difference is affected by rainfall and evapotranspiration. Therefore, recharge rate is influenced by rainfall, evapotranspiration, vertical hydraulic conductivity, and thickness of confining layer, and these controlling factors were included in the regression analysis. The mathematical expression of the regression analysis is shown as Equation 2.

\[ Re = a \times (K_z \times \frac{P - ET}{L}) + b \]  \hspace{1cm} (2)

where
Re – Recharge rate (mm/yr)
Kz – Effective hydraulic conductivity (mm/yr)
P – Mean daily rainfall (m)
ET – Mean daily evapotranspiration (m)
L – Thickness of confining layer (m)
a, b – Regression coefficients (-)

Mean daily rainfall was calculated from the measured rainfall data recorded by rain gauge SR 46A operated by St. Johns River Water Management District. Mean daily evapotranspiration was calculated from the potential evapotranspiration data collected by Florida Evapotranspiration Network data collection sites. Effective vertical hydraulic conductivity was computed from the calibrated vertical hydraulic conductivity and thickness of confining layer. Thickness of confining layer was the difference between the top elevation of confining unit and the top elevation of limestone layer. Recharge rate was obtained from the developed and calibrated local-scale model.

Through data fitting as shown in Figure 57, the values of regression coefficients ‘a’ and ‘b’ were equal to 448.17 and 377.77, respectively. The mathematical expression of the regression model was also shown in Figure 57. The R² value reaches 0.40, indicating that the performance of the developed regression model is good.
Figure 57 Regression analysis
The developed simple regression model and the derived expression could be applied to other similar sites to estimate recharge rate as well as determine the risk level of sinkhole occurrence without the necessity to develop and calibrate a groundwater model.

6.5 Conclusion

Sinkholes are widely distributed in Florida karst terrains and have been recognized as the primary geologic hazard threatening human life and property in Florida, USA. Previous studies indicated that groundwater recharge is the governing factor affecting sinkhole occurrence. However, due to limitations of available data because of lack of regular geophysical survey, calculating recharge rate in the karstic sinkhole-prone areas in central Florida has not been achieved. In this study, a regional-scale and a local-scale groundwater models were developed and calibrated based on limited field-measured data and empirical data from the literature to quantify the recharge rate in a sinkhole-prone area in central Florida. Based on the output of the developed and calibrated local-scale model, a high resolution recharge map was generated. Then, sinkhole density under each recharge level was computed, and the risk level of sinkhole occurrence under each recharge category was determined. Finally, a regression analysis between recharge rate and its controlling factors was conducted. Based on the developed simple regression model, recharge rate can be estimated without needing to develop and calibrate a groundwater model. The outcome of this study is expected to provide a scientific understanding of how recharge rate can affect the risk level of sinkhole occurrence and provide an efficient and effective tool to estimate recharge rate and risk level of sinkhole occurrence in other similar sinkhole-prone areas.
6.6 References


Kuniansky EL (2014) Taking the mystery out of mathematical model applications to karst aquifers—a primer. In Kuniansky EL and Spangler LE (eds), U.S. Geological Survey karst interest group proceedings, Carlsbad, New Mexico, April 29–May 2, 2014


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http://dx.doi.org/10.3133/pp1807
CHAPTER 7
SUMMARY AND CONCLUSION

In general, the objectives of this dissertation research include: (1) assessing the impacts of sea-level rise on saltwater intrusion into the saturated surficial aquifer; (2) assessing the impacts of storm surge on saltwater intrusion into the saturated surficial aquifer; (3) assessing the impacts of sea-level rise on saltwater intrusion into the unsaturated zone above the saturated surficial aquifer to evaluate the variation of salinity level in the vegetation root zone; (4) assessing the impacts of groundwater recharge and head difference on sinkhole occurrence; (5) assessing the risk level of sinkhole occurrence based on the relationship between groundwater recharge and sinkhole occurrence based on a case study conducted in a highly karst sinkhole prone area.

Among them, the first, second, and third objectives are developed to assess the impacts of natural hazards such as sea-level rise and intensified storm surge in the coastal areas in east-central Florida, and the fourth and fifth objectives are developed to assess the impacts of natural hazards such as land subsidence and sinkholes in the inland areas in east-central Florida.

Saltwater intrusion into the coastal aquifer is a very complex process. The most effective indicator of saltwater intrusion into coastal aquifer is the landward migration of saltwater/freshwater transition zone. Within the transition zone, groundwater density and salinity is higher than that of freshwater but lower than that of seawater due to mixing. However, the dimension of the transition zone is very difficult to measure since density and salinity is highly spatially varied, and the locations and movements of the transition zone is very difficult to track since density and salinity is highly temporally varied. Besides, groundwater recharge in highly
karst areas is very complex situation and the recharge rate is very difficult to quantity. Due to lack of sufficient hydrogeologic data, the understanding of localized subsurface karst development is highly limited. Also, the subsurface flow system is comprised of both matrix flow of which Darcy’s Law applies and conduit flow of which Darcy’s Law cannot be applied. Therefore, analytical solutions are unable to be derived for quantifying salinity distribution in coastal surficial aquifer and recharge rate in inland karst aquifer, and numerical methods are used by developing and calibrating three-dimensional regional- and local-scale groundwater flow and contaminant transport models to simulate the extent of saltwater intrusion into coastal aquifer and recharge rate in inland karst aquifer.

From the model simulation results of Chapters 1, 2, and 3, the impacts of sea-level rise and storm surge are significant in inducing saltwater intrusion into both the saturated and unsaturated zones in the coastal aquifer in east-central Florida coastal low-lying areas due to low elevation, flat topography and low freshwater recharge from infiltrated rainwater. Besides, the extent of saltwater intrusion can be even worse with a continuous rising sea level and an intensified storm surge. Although infiltrated rainwater can act as an effective hydraulic barrier to support freshwater discharge to coastal saltwater zone and impede the landward migration of saltwater to some extent, the natural remediation process requires a very long time to recover the water quality. During the recovery process, if prolonged drought due to climate change happens, the amount of infiltrated rainwater reduces and requires longer time for recovery. During the recovery process, if another storm surge occurs and cause overtopping of saltwater on coastal lowland because the rising seawater overpasses the crest of the coastal defense structures, the
salinity level in soil increases significantly and requires longer time for recovery. The developed groundwater flow and contaminant transport models are calibrated against the hydraulic heads and a good agreement between the modeled heads and observed heads is reached after calibration, indicating that the simulation results are reasonable and representative. However, due to limited available data of salinity level, the developed models are not calibrated against salinity concentrations. Further calibration is required for future model updates when sufficient field-measured TDS concentrations become available. In addition, future model updates should consider astronomic tides as well as storm surges and changes in geomorphology through erosion or accretion since they are known to dynamically interact with SLR causing non-linear effects.

The simulation results from Chapters 1, 2, and 3 provide a useful reference for climate change adaptation planning and decision-making in coastal east-central Florida area and other low-lying coastal alluvial plains and barrier island systems, especially with respect to coastal groundwater resource management, land use planning, and ecosystem protection and restoration in a changing climate. The simulated extent of saltwater intrusion contribute to ongoing attempts at forecasting vegetation community responses to sea-level rise, storm surge and climate change with a goal of maximizing endangered species habitat management activities and the discussion of impact minimization strategies. Moreover, the developed and calibrated groundwater flow and contaminant transport models can be utilized as effective tools for coastal water resources management, land use planning, and adaptation decision making in a changing climate.
From the simulation results of Chapters 4 and 5, the relationship between sinkhole occurrence and recharge rate is linear that sinkhole density increases linearly with an increase in recharge rate, and sinkholes are more likely to occur in higher recharge areas. The risk level of sinkhole occurrence in highly karst sinkhole-prone area is highly related to recharge rate, and higher recharge rate generally indicates a higher risk of sinkhole occurrence. However, it should be noted that the risk level analysis is based on recharge rate, while the effects of other controlling factors are not analyzed. Therefore, the risk level analysis is from hydrologic perspective. A comprehensive analysis of risk level of sinkhole occurrence is required for future study when sufficient hydrogeologic data become available and the other geologic controlling factors such as raveling index can be taken into consideration. In addition, sinkhole formation is part of a broader karstification process that has been happening in Florida for thousands of years, indicating that one sinkhole formation is a small event in a broader landscape evolution. The study of sinkholes occurrence in Florida is in its early stage. The temporal scale of future research will be switched from short time period (a few months or years before sinkhole occurrence) to long time period (hundreds/thousands of years) in order to expand the understanding of sinkhole formation, and the spatial scale will be enlarged to the entire state of Florida (if data is available) to improve the knowledge of the complicated karstification evolution.

The simulation results from Chapters 4 and 5 can provide water resources managers and land use planners with scientific understandings of sinkhole development and the related local-scale hydrogeologic conditions. The outcome of this study provides a basis for sinkhole risk
assessment and is expected to provide a scientific understanding of how recharge rate can affect
the risk level of sinkhole occurrence and provide an efficient and effective tool to estimate
recharge rate and risk level of sinkhole occurrence in other similar sinkhole-prone areas.
APPENDIX A
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