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ORIGINAL ARTICLE

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

Han Xiao[1] · Yong Je Kim[1] · Boo Hyun Nam[1] · Dingbao Wang[1]

Abstract Sinkholes occur when surface soils 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. Sinkhole occurrence is related to local-scale hydrogeologic conditions (groundwater recharge rate and hydraulic head difference between water table and potentiometric level). Historical data have shown that sinkholes are more likely to occur in the beginning of wet season and the frequency of occurrence varies seasonally. In this study, the East-Central Florida region, which is vulnerable to sinkhole hazard, is selected as the study area, and the relationships between temporal and spatial distributions of observed sinkholes and hydrogeologic conditions are quantitatively investigated. The analysis results indicate that the seasonality of sinkhole occurrence is due to the seasonal variation of rainfall and groundwater level, and sinkholes are most likely to occur when the local-scale head difference stays constant at a peak value after a sharp increase over a short period of time. In space, sinkhole density increases linearly with increases in groundwater recharge rate and hydraulic head difference.

Keywords Sinkholes · Seasonality · Recharge rate · Head difference · East-Central Florida

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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 genetic framework of sinkhole formation and karst topography development was explained in details by Beck (1986) and Waltham et al. (2005) and is briefly described hereinafter. 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

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sinkhole formation and development of karst topography. The carbonate bedrock is slowly recharged by the infiltrated weakly acidic rainwater through the thick overlying clayed sediments, while is rapidly recharged through the 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 timescale, creating small cavities/voids. As time goes on, they grow larger and the overlying surficial soils move downwards 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 flowrate and cavities/voids growth rate. Eventually, sinkhole occurs when surface soils fall into the subterranean cavities/voids due to a loss of compaction. Noted that the hydraulically interconnected cavities and voids can: (1) form extensive conduit systems that convey large amounts of groundwater flow with high velocities in 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 m^2/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 while 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 is 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 over time to be 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 forming periodically corresponding to several times of 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. Afterward, karstification process recovers and becomes active again followed by a recession of sea. 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, and the seasonal variation was mentioned in many studies. 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 is 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 of water table generates a fastly increased weight

while the unchanged or slowly rising potentiometric level still 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/and 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 distributions of observed sinkholes and spatial and temporal variations of the impact factors and determining 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, where 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. Noted 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 indicated from the results 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 increases linearly with the increase in recharge rate and head difference.

Overview of the study area

The East-Central Florida (ECF) region that selected as the study area is shown in Fig. 1. 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 km^2. 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.

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 1200 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 1200 mm (Tibbals 1990).

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 Fig. 2a, b and described in Table 1. Descriptions of the hydrogeologic framework and each hydrostratigraphic unit are as follows, and detailed descriptions are 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
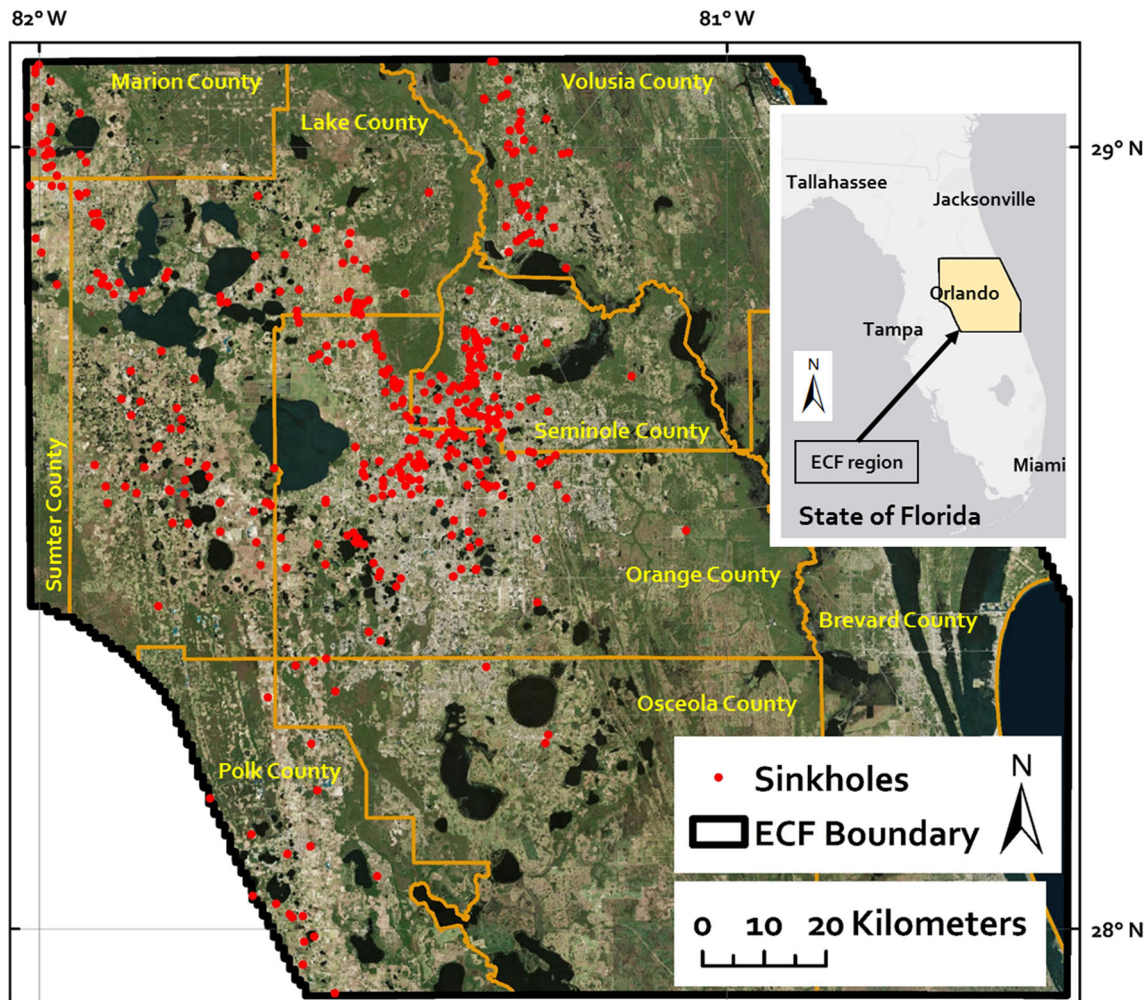
Fig. 1 Location of the study area and spatial distribution of the reported *sinkholes*

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.

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/where water table is higher than potentiometric level, and upward seepage occurs when/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

Fig. 2 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
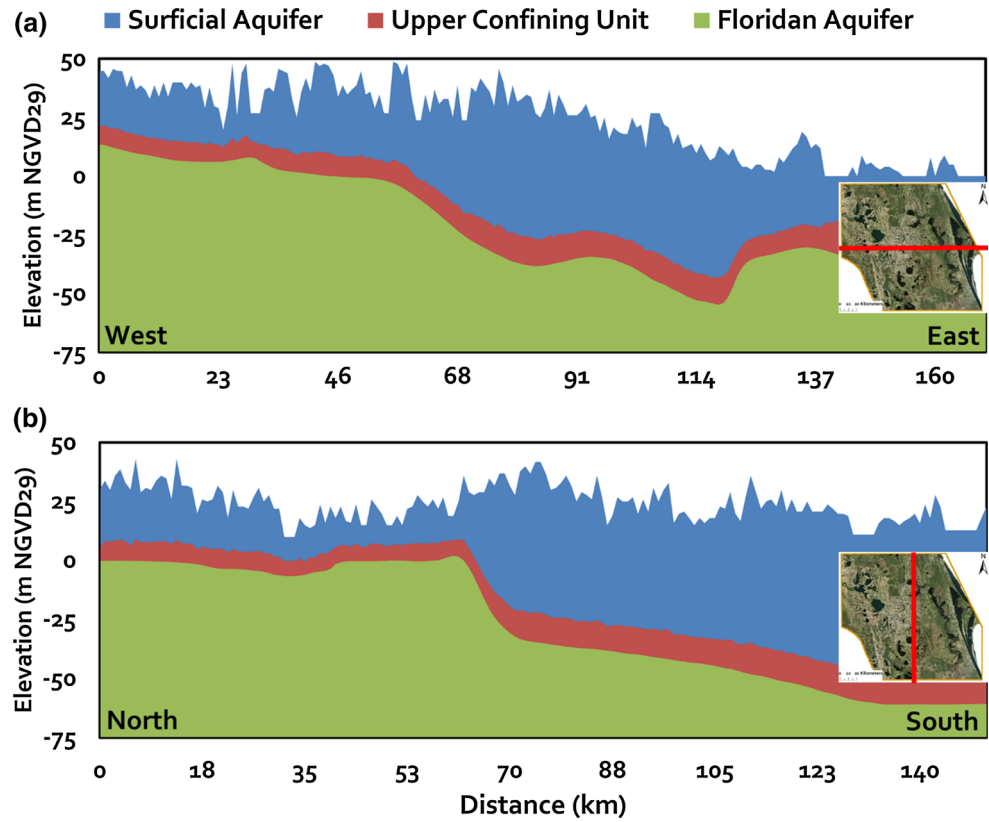
Table 1 Descriptions of the hydrostratigraphic units (adapted from Miller 1986; Williams and Kuniansky 2016)

Geologic series		Age	Hydrogeologic unit		Thickness	Composition
Surficial sediments		Pliocene to Holocene	Surficial Aquifer		5–50 [m]	Sand, Silt, Clay, Gravel
Hawthorn group		Miocene	Upper Confining Unit		0–70 [m]	Sand, Silt, Clay
Permeable Zone	Uppermost Ocala Ocala-Avon Park	Eocene to Miocene	Floridan Aquifer System (FAS)	Upper Floridan Aquifer	60–150 [m]	Carbonate Limestone and Dolostone
	Avon Park	Middle Eocene		Lisbon-Avon Park composite unit	100–350 [m]	
				Middle Avon Park composite unit		
	Lower Avon Park Oldsmar	Early Eocene		Lower Floridan Aquifer	200–350 [m]	
Cedar Keys formation		Paleocene	Lower Confining Unit		–	Dolomite and Anhydrite

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 m^2/day depending upon localized hydrogeologic conditions. The inflow is downward groundwater seepage from the overlying SAS when/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/where the water table is lower than the potentiometric level.

Karst features of the FAS

Karst features including sinkholes, sinking streams and springs are present over most of the extent of the FAS, resulting in 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 move downward and dissolve the carbonate bedrock (Kuniansky et al. 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 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/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 that 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).

Data sources

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 Fig. 1.

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).

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/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 Fig. 3a, b, respectively. It can be observed that 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 and 1.8 m, and 90 % no greater than 10.7 and 9.2 m, respectively. The length and depth distribution of reported elongated-shaped sinkholes are plotted in Fig. 3c, d, respectively. It is estimated that 50 % elongated-shaped sinkholes have their

diameters and depths no greater than 2.9 and 1.4 m, and 90 % no greater than 7.6 and 6.1 m, respectively. In general, circular-shaped sinkholes are larger in diameter/length and deeper in depth in comparison with elongated-shaped sinkholes.

Temporal distribution of observed sinkholes and temporal variation of rainfall and groundwater level

The frequency of monthly occurrence of the 414 reported sinkholes is plotted in Fig. 4. 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.

Fig. 3 Size distribution of *reported sinkholes*: **a** *Diameter*; **b** *Depth*; **c** *Length*; **d** *Depth*
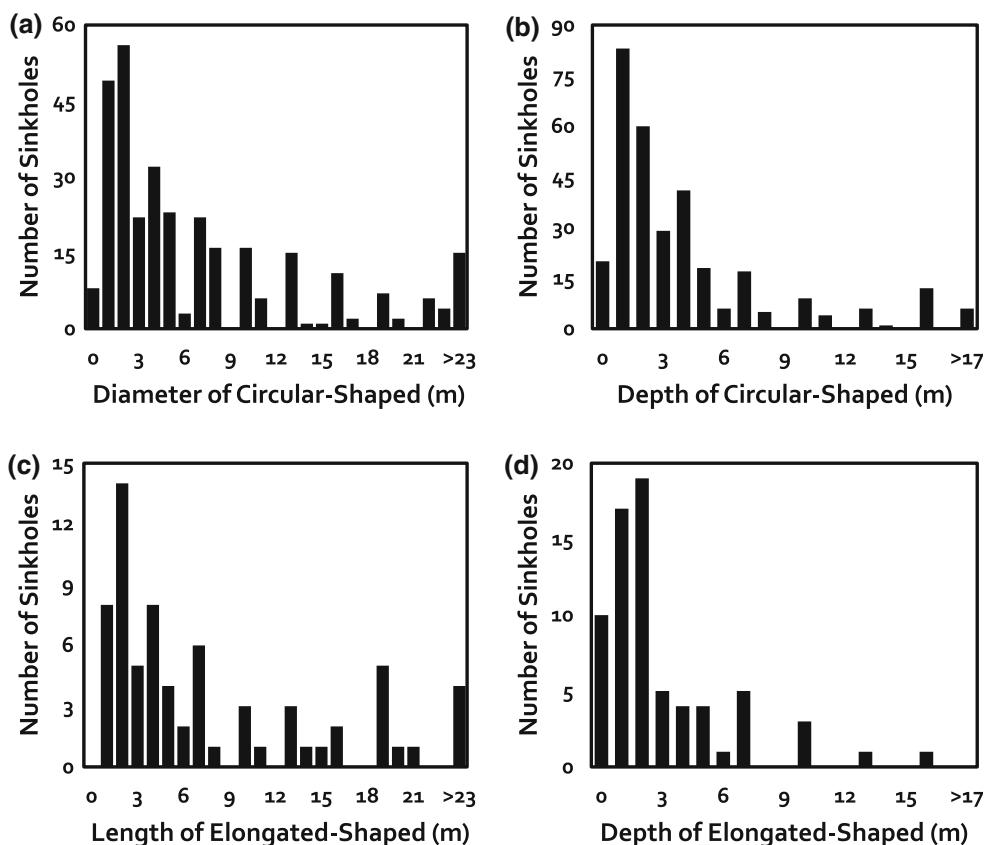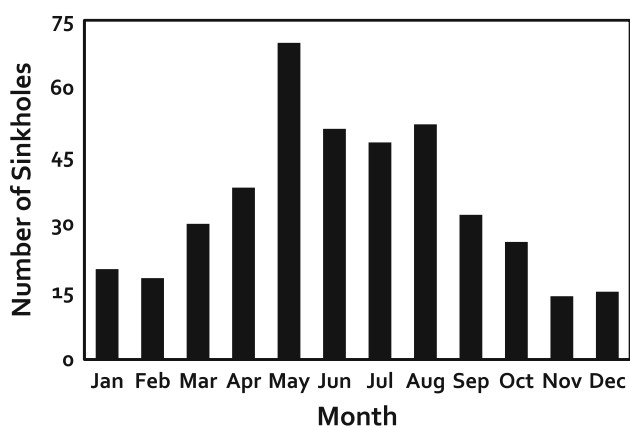
Fig. 4 Frequency of *monthly* occurrence of the 414 *reported sinkholes*

Several rain gauges have continuous records of daily rainfall, and rainfall data measured from one of them are used to represent the temporal variation because data measured from other gauges are quite similar. The location of the 'representative' rain gauge is shown in Fig. 5, and the temporal variation of rainfall (monthly average) is plotted in Fig. 6a (data collected from 1950 to 1997). From Fig. 6a, annual average rainfall is 1296 mm, and rainfall in wet season (from June to October) is 796 mm (61.4 %). In general, the seasonality of sinkhole occurrence (refer to Fig. 4) 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 6 months before to 1 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 Fig. 5, and the detailed information is described in Table 2. 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

Fig. 5). 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 September 23, 2012, when observed data are available, whereas three other sinkholes occurred before 2008 when observed data are 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′ were 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′ were 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 Fig. 6b–f, 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 Fig. 6d, 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 and then increased at a significant rate to 1.8 m in a very short period of time (about half a month). Afterward, head difference stayed almost unchanged from late September to late November and then increased another 0.1 m in December and reached its highest annual level in 2012. Sinkhole 3 occurred on September 23 when head difference reached the peak value after a sharp increase. From Fig. 6e, f, the situations of Sinkholes 4 and 5 are quite similar. From Fig. 6c, 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 1 week), although the increase was not as significant as the times when Sinkholes 3, 4 and 5 occurred. From Fig. 6b, 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 Fig. 6c–f, 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 Fig. 6b, the most significant increase of head difference was found in late August, while Sinkhole 1 occurred almost 1 month later on September 26th. It is assumed that head difference was not the primary cause of
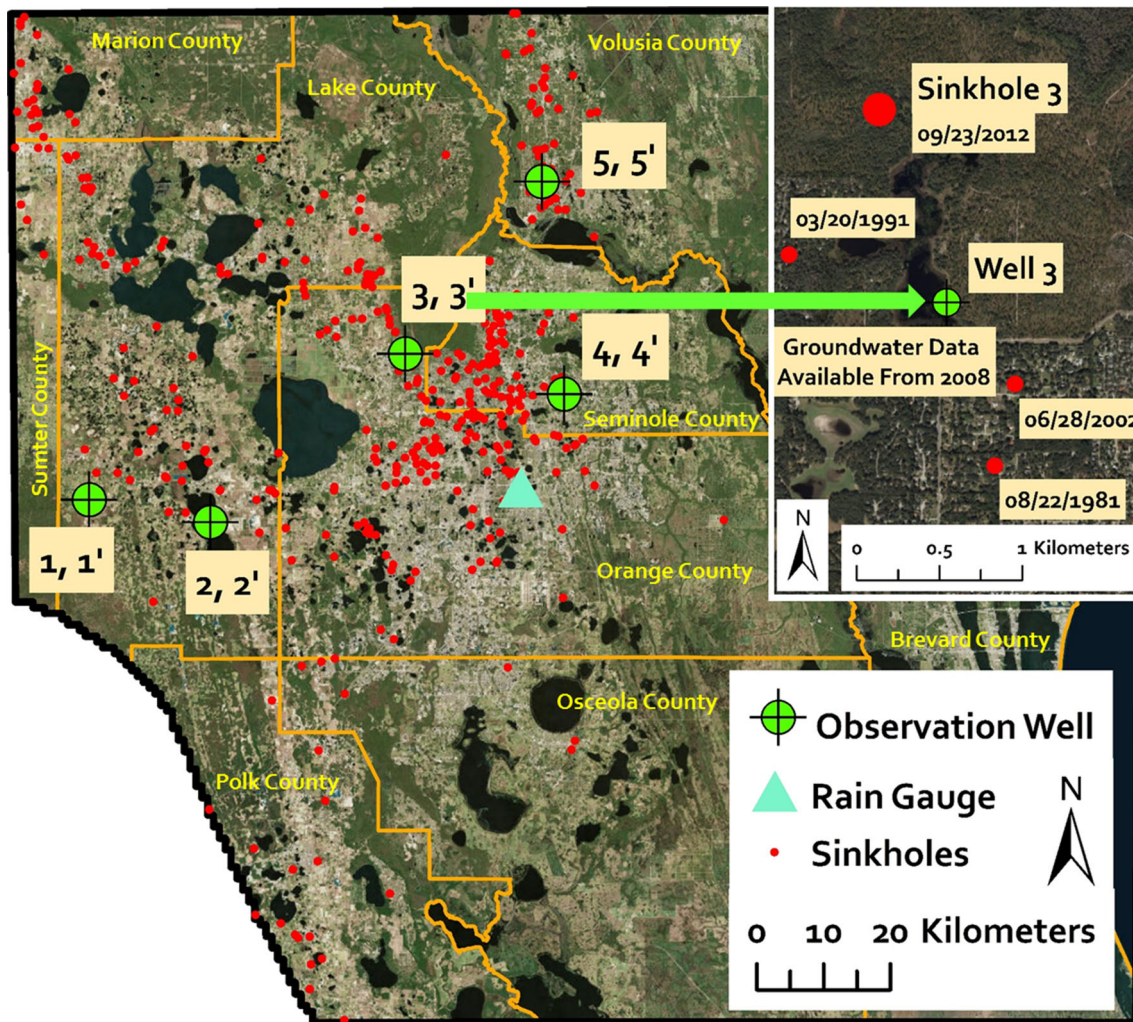
Fig. 5 Location of *rain gauge* and *observation wells*

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.

Spatial distribution of observed sinkholes and spatial variation of groundwater recharge and head difference

In the previous decades, the bottleneck of quantifying groundwater recharge and head difference was 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 part 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.

Fig. 6 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*
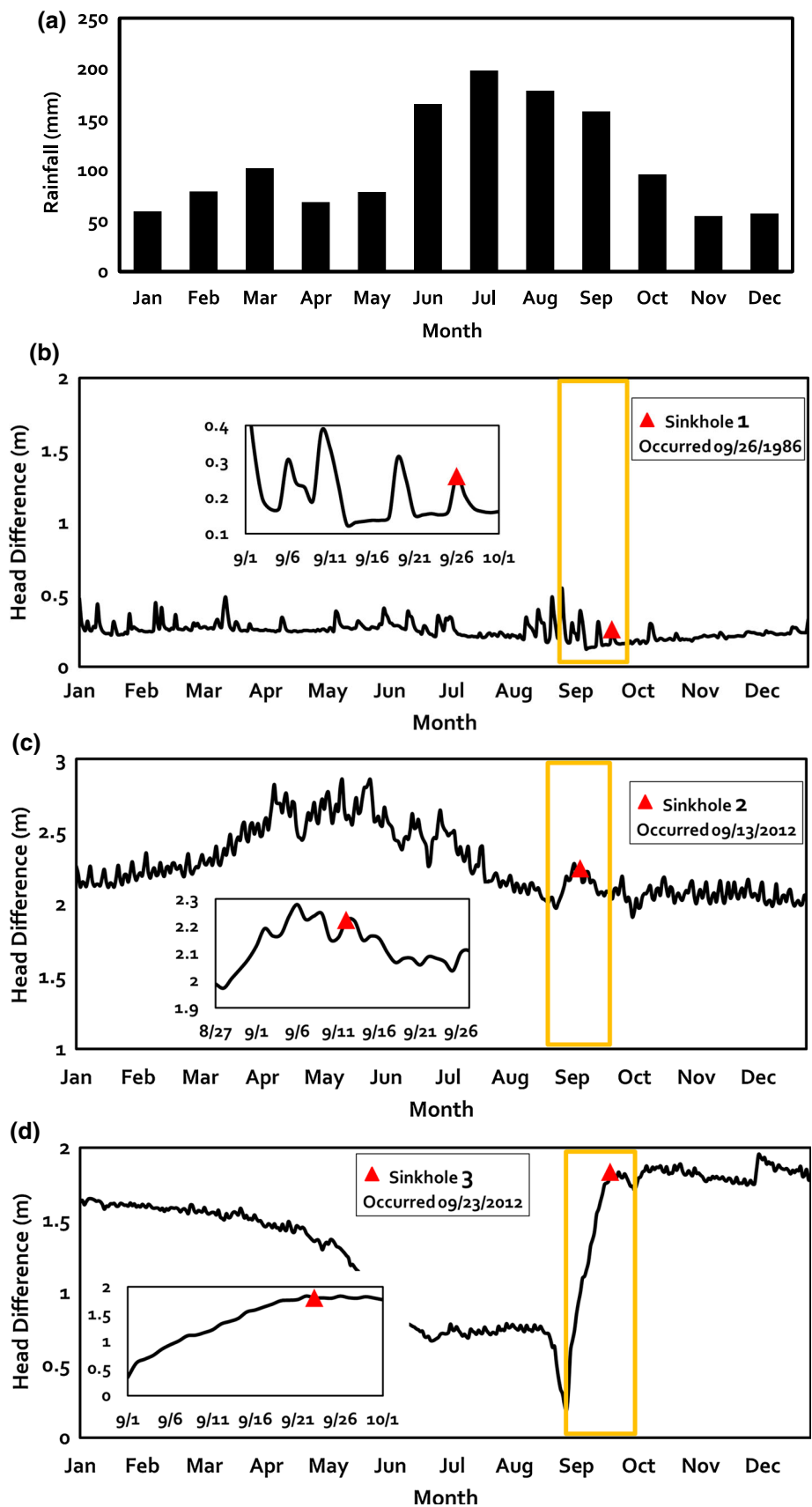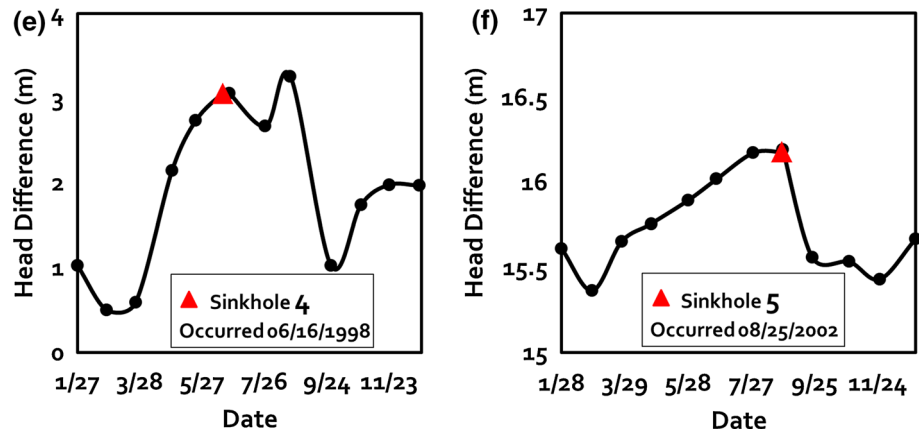between Well 5 and 5′

Fig. 6 continued

(e) Sinkhole 4 Occurred 06/16/1998

(f) Sinkhole 5 Occurred 08/25/2002

Table 2 Descriptions of the observation wells

ID	Number	Name	Latitude	Longitude	Observed value
1	09252091	L-0041	28.535	−81.913	W.T.E.[a]
	09252090	L-0062			P.S.E.[b]
2	30442915	L-1018	28.508	−81.750	W.T.E.
	30442913	L-1024			P.S.E.
3	15474993	OR-0894	28.708	−81.488	W.T.E.
	15474992	OR-0893			P.S.E.
4	09992686	S-1337	28.660	−81.274	W.T.E.
	09991414	S-1257			P.S.E.
5	05601059	V-0197	28.911	−81.304	W.T.E.
	05601057	V-0196			P.S.E.

[a] *WTE* water table elevation, [b] *PSE* potentiometric surface elevation

The ECF model simulates annual average, steady-state water tables and potentiometric levels, recharge rate, groundwater velocity, spring discharges, and seepage from/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 is simplified into a conceptual model, consisting of three aquifers separated by several confining units (refer to Table 1). 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 are 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.

Sinkholes and recharge rate

The spatial variation of groundwater recharge rate rooted in the ECF model output is visualized utilizing ArcGIS and plotted in Fig. 7a. 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.

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 3. 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 km^2 with 59 reported sinkholes, and then sinkhole density of Category 2 is 3.88 per 100 km^2 accordingly. The analyzed result is described in Table 3 and plotted in Fig. 7b. 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 R^2 of 0.98 is indicated from the analyzed result (Category 9 not included in the regression analysis).
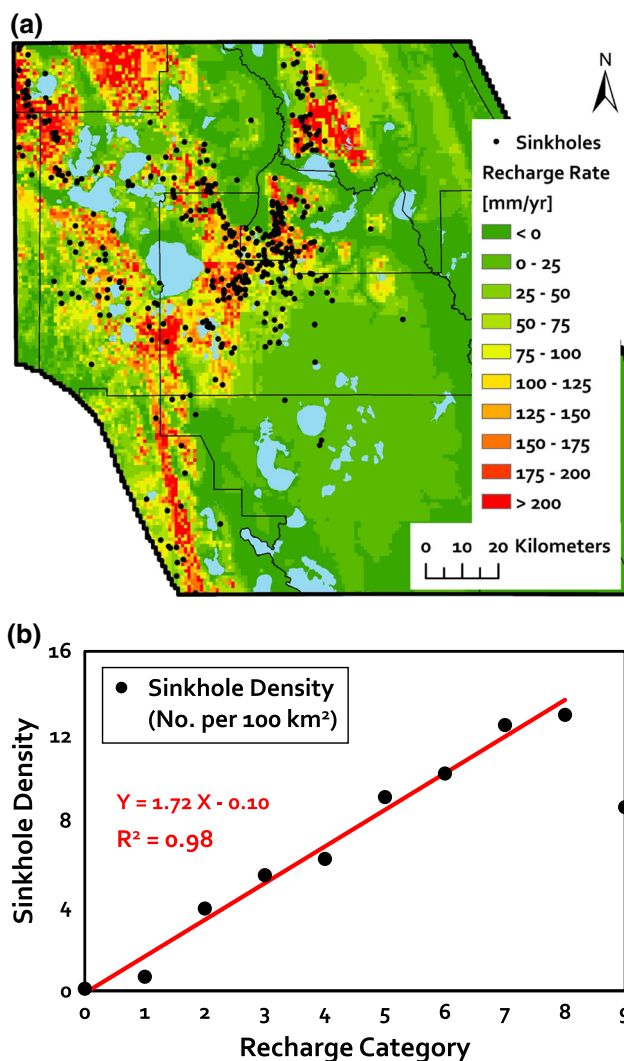
Sinkholes and head difference

The spatial variation of head difference originated from the ECF model output is visualized using ArcGIS and plotted in Fig. 8a. 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 4 and plotted in Fig. 8b. 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).

Discussion

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. In local scale,

Fig. 7 **a** Spatial variation of *recharge rate*; **b** *Sinkhole density and recharge*

Table 3 *Sinkhole density* and *recharge rate*

Category	Covering area (km^2)	Recharge rate (mm/year)	No. of Sinkholes (−)	Sinkhole density (No. per 100 km^2)
0	5836	<0	6	0.1
1	5398	0–25	36	0.67
2	1521	25–50	59	3.88
3	954	50–75	52	5.45
4	724	75–100	45	6.22
5	624	100–125	57	9.13
6	381	125–150	39	10.24
7	351	150–175	44	12.53
8	223	175–200	29	13.01
9	543	>200	47	8.66
Total	16,554	–	414	–

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 result 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 interconnected 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 has 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.

Summary and 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 aiming at determining 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 and 4 m, respectively.

Fig. 8 a Spatial variation of *head difference*; **b** *Sinkhole density* and *head difference*
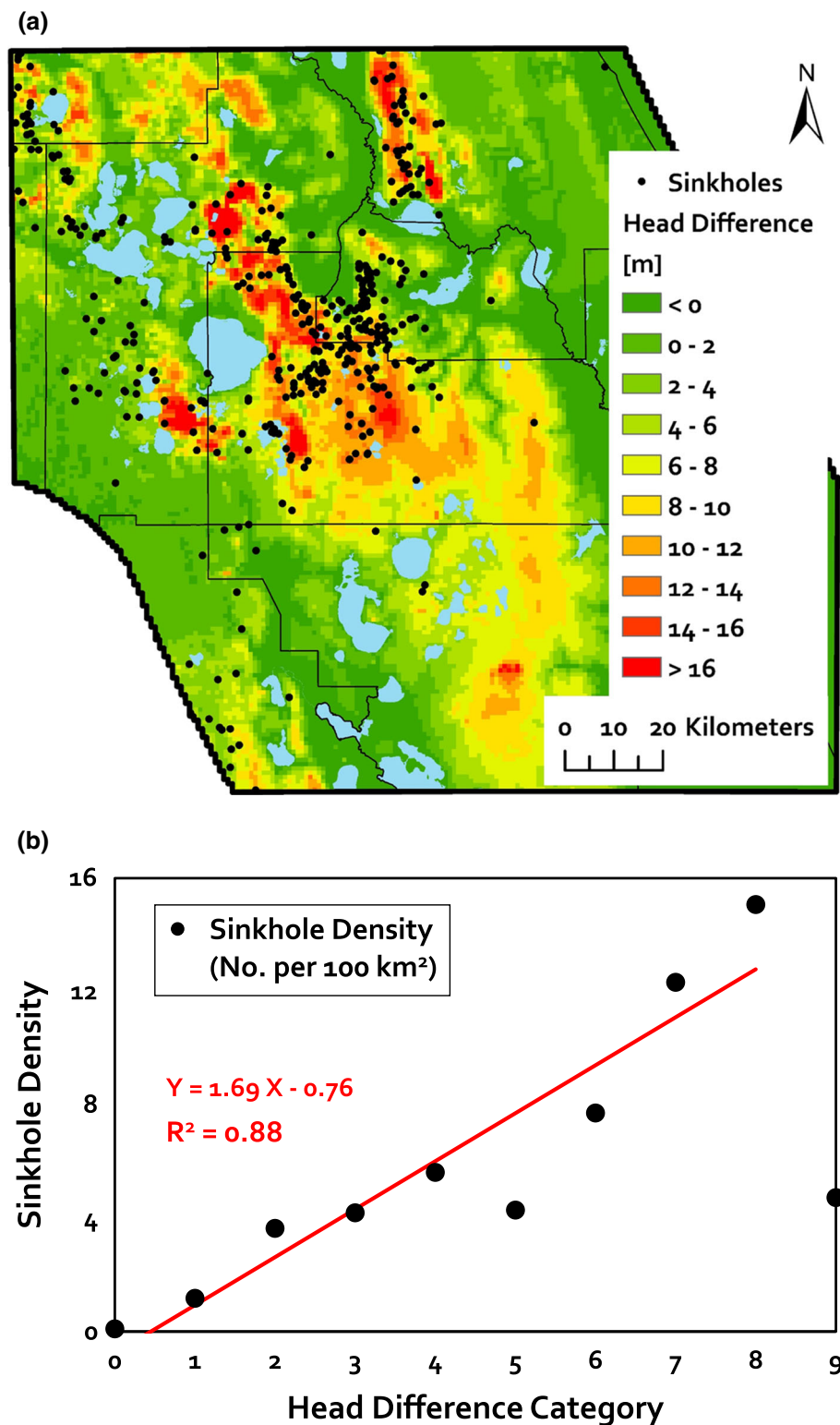
Sinkhole formation is part of a broader karstification process that has been happening in Florida for thousands of years, indicating that one sinkhole formation is a small event in a broader landscape evolution. The study of sinkholes occurred in Florida is in its early stage. The temporal scale of future 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

Table 4 *Sinkhole density* and *head difference*

Category	Covering area (km^2)	Head difference (m)	No. of Sinkholes (–)	Sinkhole density (No. per 100 km^2)
0	6196	<0	6	0.1
1	3320	0–2	39	1.17
2	1867	2–4	68	3.64
3	1456	4–6	61	4.19
4	1335	6–8	75	5.62
5	1119	8–10	48	4.29
6	674	10–12	52	7.71
7	300	12–14	37	12.33
8	139	14–16	21	15.07
9	148	>16	7	4.73
Total	16,554	–	414	–

entire state of Florida (if data are 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.

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