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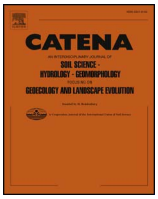

Sinkhole formation mechanisms and geostatistical-based prediction analysis in a mantled karst terrain

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ABSTRACT

Efforts to evaluate sinkhole formation and quantify the controlling factors are hindered by the lack of historical observations or coarse resolution datasets in many areas. We applied recent advances in GIS-based sinkhole mapping and spatial statistics to comprehensively investigate the factors controlling sinkhole formation in the mantled karst setting of Dougherty County, Georgia. Sinkholes form at varying spatial and temporal scales within the test site. A three-stage methodology was conducted. Firstly, 275 sinkholes that formed or were enlarged between 1999 and 2011 were detected by comparing the results of sinkhole inventories derived from two DEMs acquired in 1999 and 2011. Additionally, a LiDAR DEM (1 m resolution) was used to gather a spatially detailed sinkhole inventory of 3412 sinkholes. The sinkhole inventory data was converted into sinkhole density maps for subsequent analyses. Ordinary least squares (OLS) and geographically weighted regression (GWR) spatial statistical models were applied to quantify the impact of controlling factors on sinkhole density. Controlling factors included geologic, hydrologic, anthropogenic, hydrogeologic, and geomorphologic variables. For the two sinkhole inventory datasets analyzed, overburden thickness, aquifer fluctuations, and proximity to fractures, streams, and wetlands were the most influential controlling factors on sinkhole formation (GWR *p*-values < 0.05). Lastly, the spatial statistics results were used to 1) produce interpolated prediction sinkhole maps and 2) evaluate the accuracy of the spatial statistics' sinkhole density predictions. Results provide assessments of controlling factors on sinkhole formation and demonstrate the potential for similar applications in other karst areas with a time series of DEMs and similar ancillary datasets. The adapted GIS-based approach does not replace procedures that depend on comprehensive field surveys for both sinkhole inventory and controlling factor data acquisition, though it offers estimates for understanding sinkhole development over large areas to help select proper mitigation strategies.

1. Introduction

Karst topography can be found at any latitude and elevation around the world, with rock units potentially containing karst features covering approximately 20% of the Earth's land surface (Stokes et al., 2010; Ford and Williams, 1989). Karst landscapes are characterized by three primary morphological features: input landforms that direct surface water underground (i.e., sinkholes), subsurface conduit systems (i.e., fractures and caves enlarged by solution), and discharge areas (i.e., springs) (Ford et al., 1988). Karst features, specifically sinkholes, present hazards and engineering challenges to residential, commercial, industrial, and agricultural infrastructure, serve as entry points for groundwater contaminants, and cause vertical deformation (i.e., subsidence) by transporting sediment underground (Hyatt and Jacobs, 1996; Waltham et al., 2005; Galve et al., 2009a; Newton, 1987).

Sinkholes develop where the rock below the ground surface undergoes chemical weathering, or dissolution, via groundwater movement and infiltration from surface water or precipitation. These rock types are typically evaporates (e.g., salt beds, gypsum and anhydrite), carbonates (e.g., limestones and dolomite) and sandstones. Underground voids are created through chemical weathering processes. Soils are transported into the voids over varying time intervals via gravity, liquefaction, and other geologic processes, subsequently lowering the ground surface and forming a sinkhole. The processes of dissolution and sediment transportation where cavities form create different types of sinkholes. Dissolution sinkholes, cover-subsidence sinkholes and cover-collapse sinkholes are common sinkholes that occur in karst environments.

Sinkholes are relatively common in karst environments. In the United States (US), approximately 20% of US territory is prone to sinkholes. Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania are the area's most susceptible to sinkholes where the rock

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type is primarily carbonates (limestone) and/or evaporate rocks (salt and gypsum). We will be able to further our knowledge of the physical mechanisms driving sinkhole formation by quantifying the sinkhole formation mechanisms using geostatistical-based prediction analysis. Additionally, our approach may be used to understand sinkhole formation processes in other karst environments.

Sinkhole formation is the result of complex interactions between hydrologic (e.g., flooding), geologic (e.g., overburden thickness), geomorphologic (e.g., elevation), anthropogenic (e.g., land use), climatic (e.g., precipitation), hydrogeologic (e.g., aquifer fluctuations), and other factors (e.g., geotechnical soil strength) acting with fluctuating magnitudes over varying spatial and temporal scales. It is difficult to directly observe and quantify the influence of each factor responsible for sinkhole formation because the majority of the factors operate in the subsurface and over generally long time scales. Additionally, two or more of these processes often operate in conjunction to form or enlarge an existing sinkhole (Ford et al., 1988). However, inferences about the controls on sinkhole formation can be made by measuring the relationships between sinkhole density and the spatial distribution of the factors that control sinkhole occurrence (Doctor and Doctor, 2012).

Although sinkhole formation is site-specific, relationships between sinkhole density and controlling factors can be determined in areas with historical data on sinkhole development and an abundance of ancillary datasets to accurately represent sinkhole formation controlling factors and mechanisms (Wilson and Beck, 1992). Panno et al. (2013) related sinkhole location and evolution to hydrogeologic (e.g., water table depth and storage coefficients), hydrologic (e.g., recharge rates), and geologic (e.g., bedrock topography) factors in the sinkhole plain of Illinois, USA. Hubbard (2001) analyzed sinkhole distribution in the Valley and Ridge Province, Virginia, USA, and correlated the highest sinkhole densities with lithology (e.g., bedding planes), geologic structures (e.g., fold and fault axes), and hydraulic gradients related to proximity to incised segments of rivers. Al-Kouri et al. (2013) found that sinkhole occurrence was most influenced by urban land use, fault distribution, and proximity to surface water features. In the Ebro Valley (Spain) evaporite karst setting, sinkhole susceptibility and hazard have been determined by quantifying the relationships between sinkhole type and distribution and different geomorphologic units, elevation, alluvium thickness, piezometric surface, land use, and electrical conductivity of the surficial aquifer (Galve et al., 2009a, 2009b; Gutiérrez et al., 2007; Gutiérrez, 2013; Lamelas et al., 2008; Galve et al., 2008). Doctor and Doctor (2012) and Doctor et al. (2008a, 2008b) measured the influence of geologic (e.g., distance to fractures and fold axes) and hydrologic features (e.g., distance to streams and ponds) to sinkhole locations in Virginia, West Virginia, and Maryland, USA, karst regions. Yizhaq et al. (2017) constructed a stochastic cellular automata model to understand and observe the sinkholes along the Dead Sea in Israel. This model studies the scale-free behavior and growth of the sinkhole area in time due to the formation of the dissolution of subsurface salt layers as a result of the replacement of hypersaline groundwater by fresh brackish groundwater. Gao and Alexander Jr (2008) input bedrock type and overburden thickness to construct sinkhole probability maps in southeastern Minnesota and northwestern Iowa. Ozdemir (2015) related groundwater level declines and seasonal fluctuations, drainage line and fault density, and cover thickness decreases to an increase in sinkhole occurrence in the Karapinar Region of Turkey.

This study focused on the mantled karst terrain of Dougherty County, Georgia, USA (Fig. 1), an area with well-documented sinkhole development (Brook and Allison, 1986; Hyatt and Jacobs, 1996; Gordon et al., 2012; Hyatt et al., 2001). Brook and Allison (1986) used topographic maps and 1:24,000 scale, color infrared images to identify sinkholes based on the presence of surface water features, vegetation and soil moisture patterns, and topographic expression. The mapped sinkhole distribution and color infrared images were used to map fractures, joints, and lineaments. Hyatt and Jacobs (1996) found that flooding of the Flint River in 1994 triggered the formation of at least 312 sinkholes in and around the Albany area of northern Dougherty County; 88% of which formed within flooding limits. Liquefaction mechanisms were involved in the formation of the 312 sinkholes as unconsolidated overburden was transported into bedrock cavities and buoyant support was reduced as flood waters receded. Hyatt and Jacobs (1996) and Xu et al. (2016) noted that the sinkholes followed a linear pattern, which suggests that joints and fractures influence sinkhole distribution. Following Tihansky (1999), Gordon et al. (2012) suggested that rapid fluctuations of the Upper Floridan aquifer and overburden removal (2.5–4.5 m) for construction caused localized sinkhole formation in a municipal groundwater well field (Fig. 2). In the covered karst region of Lowndes County, Georgia, Hyatt et al. (2001) suggested that several factors had an influence on sinkhole locations, including elevation, soil type, overburden thickness, and potentiometric head levels.

Of the many approaches used to understand and/or predict sinkhole formation, Galve et al. (2009b) found that nearest neighbor and sinkhole density methods perform better than other techniques when identifying areas of sinkhole susceptibility, but those methods do not include sinkhole formation explanatory variables. Thus, their ability to measure the influence of various factors on sinkhole development was limited (Doctor and Doctor, 2012). Geographically weighted regression (GWR) is a technique used to measure spatially varying relationships (ESRI, 2012), such as the influence of controlling factors on sinkhole formation. GWR models a dependent variable by building a unique regression equation for individual points (e.g., sinkholes) and weighting the influence of each independent variable based on distance from the position of the dependent variable. GWR analysis results can be used to measure the overall fit of a model and quantify the degree of influence of each independent variable on a given dependent variable value.

Previous studies (Brook and Allison, 1986; Gordon et al., 2012; Hyatt and Jacobs, 1996) have not statistically quantified the relationships between sinkhole occurrence and sinkhole formation factors in the study area. The goal of this research was to evaluate the influence of controlling factors on sinkhole distribution in the mantled karst environment of southern Dougherty County, Georgia and compare it to other karst terrains. The first objective was to produce sinkhole inventory maps for 10 m resolution Digital Elevation Models (DEMs) from 1999 and 2011. Sinkholes that formed or enlarged between 1999 and 2011 were identified, hereafter referred to as temporal-difference (TD) sinkholes, for a spatiotemporal analysis of sinkhole formation. The second objective was to create a high-resolution sinkhole inventory map from a 1 m resolution LiDAR (Light Detection and Ranging) DEM. Spatial statistical techniques were utilized on these two sinkhole inventory datasets (TD and LiDAR) to fulfill the third objective of measuring the influence of controlling factors on sinkhole formation. Finally, sinkhole prediction maps were produced from spatial statistics results.

2. Study area

The study area, covering 183 km^2, is located in southern Dougherty County, Georgia, and is part of the Dougherty Plain region of the Coastal Plains Physiographic Province in southwest Georgia (Fig. 1). Precipitation averages 1270 mm/year but has shown high annual variability (Stewart et al., 1999). Long-term precipitation patterns determined from a 12-month Standardized Precipitation Index (SPI) show drought conditions occurred three separate times during the study period: 1998–2002, 2006–2008, and 2011–2013, which could intensify the formation of sinkholes.

In the occurrence of a drought the water table drops losing its stability. The heterogeneous hydraulic response during this period can cause some depressurization of the upper aquifer, which in turn can affect the stress and stability of the system (Linares et al., 2017). During this event the water table drops, due to stability and gravitational mass movements occurring in the subsurface. Moreover, in karst