Global warming causes increased sinkhole collapse– Cases studies in Florida, USA and the Pearl River Delta, China

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Abstract

The occurrence frequency and intensity of many natural geohazards, such as landslides, debris flows and earthquakes, have increased in response to global warming. However, the effects of such on development and spread of sinkholes has been largely overlooked. Most research shows that water pumping and related drawdown is the most important factor in sinkhole development, but in this paper evidence is presented which highlights the role played by global warming in causing more sinkholes. Cases were studied in Florida, USA and the Pearl River Delta of China. The results show that the four peak “dry” and the three highly phases (i, ii, iii) of sinkholes is closely related. A prediction equation was also obtained according to the curve fitting with the correlation coefficient is 0.99, which is of significance for studying the occurrence and prediction of other sinkhole collapse events and global warming on an international scale.

Keywords

Sinkhole; Drought index; Karst; Trend prediction; Curve fitting

1. Introduction

Global warming resulting from climate change has altered the occurrence frequency and intensity of many natural geohazards, including landslides, debris flows and earthquakes (Calbó et al., 2010; Coe and Godt, 2012; Seneviratne et al., 2012; Gariano and Guzzetti, 2016; Heuvel, et al., 2016; Turkington, et al., 2016; Yongming Lin, et al., 2017). As an example of the mechanism for this, research has shown that 5%–10% of global permafrost will melt if global temperatures rise by 2°C, causing a significant increase in landslides and mudslides (Dong and Jia, 2004).

Sinkholes are a widespread type of geohazard, mainly distributed in the United States, China, Italy, Spain and Russia (Gutiérrez, et al., 2014; Lei, et al., 2015). The impact of climate change on sinkhole occurrence is expected, because rising temperatures will change natural hydrological processes (Gabriella Szépszó, et al., 2014), enhance dissolution of limestone (Mulec and Prelovšek, 2014) and promote soil failure (Zhou, et al., 2014). Recent reviews in the literature have shown that sinkhole hazards will probably intensify in the future as a result of climate change (Rogelio Linares, et al., 2017). The findings from the case (Thornbush, 2017) study reveal a high incidence of sinkhole occurrence when temperatures are low in winter months (especially January). This suggests that temperature (rather than precipitation) may be the principal driving climatic factor, along with associated human impacts. But the quantification of climatic impacts on sinkholes has been limited. This is largely because of a lack of long-term hydrological and climate data, and a lack of representative sinkhole inventories, inclusive of chronological information.

In this paper, the causal effects of global warming on sinkhole development and intensification are fully investigated using statistical analysis of sinkhole cases in the state of Florida, USA. There is a strong corresponding relationship between sinkhole increased after drought and drought indexes (Dry). A prediction equation was also obtained according to the curve fitting with the correlation coefficient is 0.99.

2. Materials and methods

2.1. Drought index in Florida

Global warming as a result of climate change is a quantifiable phenomenon (Shi et al., 2010; Gariano, et al., 2016; Turkington, et al., 2016), with a demonstrable increase in global temperatures by ~0.57°C over the last century. It has been reported that the global surface temperature is likely to rise a further 0.3 to 1.7°C in the lowest emissions scenario during the 21st century, or by 2.6 to 4.8°C in the highest emissions scenario. It is an indisputable fact that global warming has caused drought (IPCC, 2013). Drought index is a measure of drought conditions and calculated based on rainfall, air temperature, and other meteorological factors (Keetch and Byram, 1968; Alley, 1984).

There are 9 droughts in Florida from 1960 to 2006 (1963, 1967, 1977, 1981, 1987, 1988, 2000, 2002, and 2006) (Fig.1). Drought was most severe in 2000, followed by 1987 and 1963.

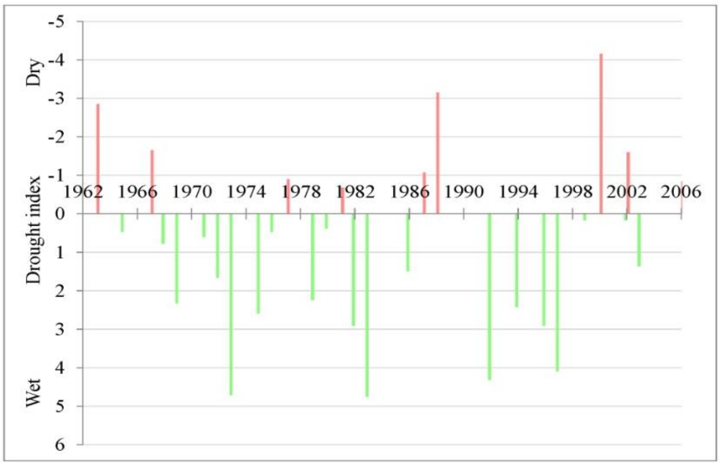

Fig. 1. Drought indexes from 1960 to 2006 in Florida. The red line is dry, and the green line is wet

2.2. Sinkhole collapse events in Florida

In Florida, sinkhole collapse events are recorded in the Florida Subsidence Incident Report, authored by the Florida Geological Survey, which provides a primary publicly available sinkhole database. More than 2800 sinkholes have been reported in Florida since the 1950s, and 2767 of them were fully recorded between 1960 and 2006. The data recorded includes occurrence time, location, shape, dimensions, soil type, side slope, land use and land cover (Han, et al., 2016). Sinkhole claims were on the rise from 2006 to 2010. Sinkhole claims jumped from 2360 to 6694 in 2010, according to a 2010 report by the Florida Office of Insurance Regulation (Fig.2).

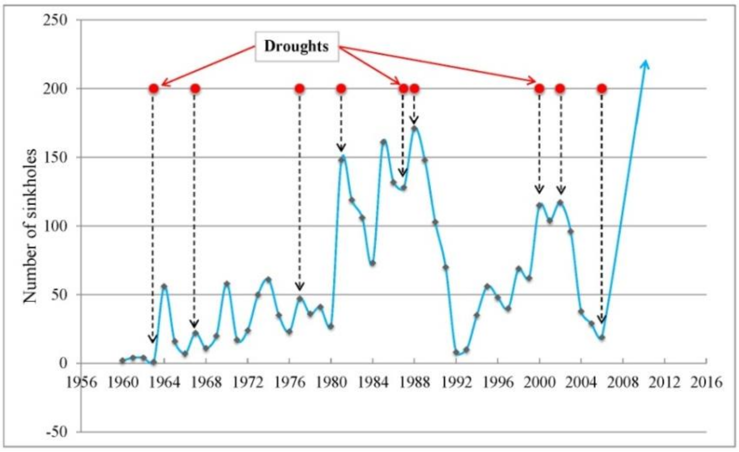

Fig. 2. Number of sinkholes from 1960 to 2006 in Florida

2.3. Correlation analysis

Sinkhole collapses in the USA from 2006 to 2010 can also be divided into three basic consistent peak periods: Phase i between 1963 and 1980, Phase ii between 1980 and 1992 and Phase iii between 1992 and 2006. From Fig. 3 it is evident that the peak time and trend of sinkhole collapse events and drought periods are quite consistent. To further investigate the relationship, the association can be quantified using curve fitting analysis.

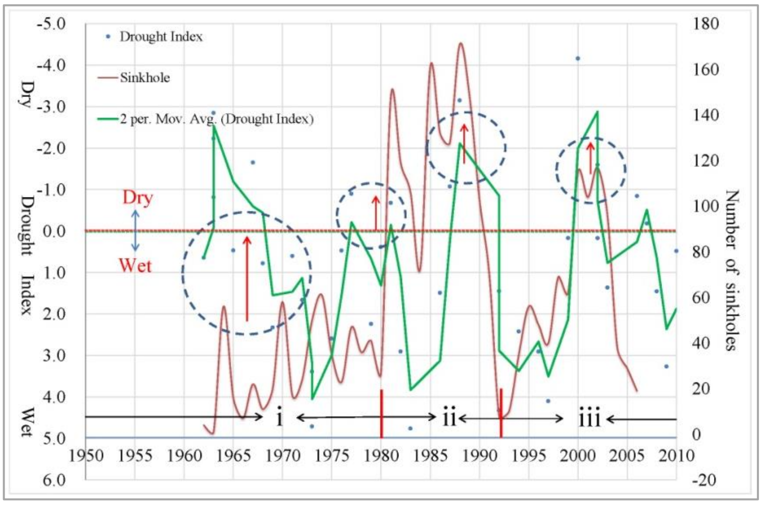

Fig.3. Graphical illustration of the relationship between sinkhole quantity and drought in Florida, USA. Note the four peak "dry" and the three highly phases (i, ii, iii) of sinkholes is closely related.

It is very interesting that the relationship between sinkhole and global change in the Pearl River Delta of China is very similar to that of the Florida of USA. There is a strong corresponding relationship between sinkhole quantity and drought index, and they are consistent in the peak trend (Fig. 4).

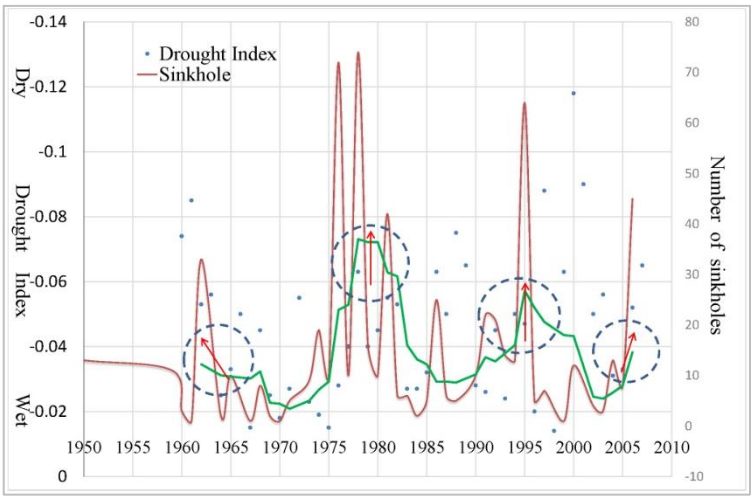

Fig.4. Graphical illustration of the relationship between sinkhole quantity and drought indexes in the Pearl River Delta of China. The green line is drought index average. Note the four “dry” and “sinkhole” peaks are highly consistent trends.

The curve of sinkhole collapse quantity and drought indexes can be fitted, as shown in Fig. 4, by Eq. (1).

$$\sqrt{((X-B)^2+(Y-A)^2)}-R=0 \quad (1)$$

The algorithm is derived using the Quasi-Newton (Broyden Fletcher Goldfard Shanno (BFGS) and Universal Global(UG)) methods, where X is the drought index, Y is the number of sinkhole collapses and A, B and R are constant parameters. The correlation coefficient is 0.99. The other parameters are shown in Table 1.

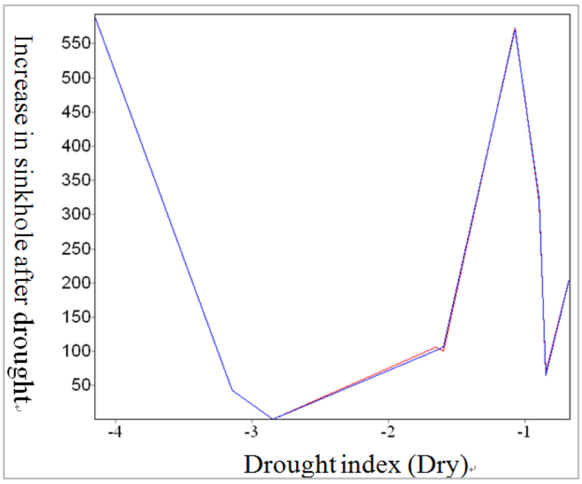

Fig. 4. Fitted curves of increase in sinkhole after drought and drought index (Dry). The blue line is target, the red line is calculated, the correlation coefficient is 0.99.

Table 1 Algorithm and parameters of the drought time curve.

Equation			Sqrt((X-B)^2 + (Y-A)^2) - R=0
Algorithm and parameters	A	173.499	Optimization: Quasi-Newton Method(BFGS) + Universal Global
	B	8100.396	Calculation End: Meet convergence criteria
	R	8100.217	Mean square error(RMSE): 2.17562755356349
			Residual sum of squares (SSE): 127.800591799266
			Correlation coefficient(R): 0.999689237322014
			The square of Correlation coefficient (R^2): 0.99937857121747
			Determine the coefficient(DC): 0.999378190981562
			Chi-Square coefficient: 0.958830651014433
			F-Statistic: 40204.8713912301

3. Results

Macroscopically, the number and frequency of sinkholes increased with global warming from 1960 to 2006 in the Pearl River Delta of China and Florida, USA.

There is a strong corresponding relationship between sinkhole quantity and drought index shown in Fig.3 and Fig.4, which demonstrates the link between global warming and increased development of sinkhole collapse events. The four peak “dry” and the three highly phases (i, ii, iii) of sinkholes is closely related.

To clearly define the quantitative relationship between sinkhole increased after drought and drought index (Dry), a curve fitting method was applied based on the optimization of Quasi-Newton (BFGS) and Universal Global methods. A prediction equation (Eq. 1) was also obtained according to the curve fitting with the correlation coefficient is 0.99.

4. Discussion

Most research has shown that pumping of water and associated drawdown is the leading cause of sinkhole formation and collapse (Anikeev and Leonenko, 2014; Youssef, et al., 2016; Rogelio Linares, et al., 2017). However, the impact of global warming should not be more ignored than human impacts. For example, altered global rainfall patterns and increasing evaporation because of higher temperatures leads to a decrease in groundwater flow, resulting in sinkhole formation, or such decreased flow may lead to intensification of water pumping and related drawdown in urban and industrial areas that in itself leads to groundwater level reduction and related sinkhole development.

Also, the addition of greenhouse gases to the atmosphere and global warming increase the dissolution of bedrock, thus increasing the intensity and frequency of sinkhole collapse (Yuan, 1997). This is especially true for areas underlain by limestone or dolomite, in which the basic carbonate dissolution formula $CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2O + CO_2$ shows the breakdown of solid carbonates in acidic conditions. The carbonate dissolution formula is reversible, but will proceed in the positive direction as temperatures increase. In susceptible areas, some closed or previously blocked karst pipes or cracks will open up under conditions of dissolution, and form new soil erosion channels. Dehydration of the soil will occur as the temperature increases, and once runoff occurs or water levels rise, the dry soil will be removed, leading to erosion and disintegration as the sinkhole forms and collapses.

The timing of sinkhole formation lags behind the drought by hours or years along with human activities, which is geologically sensible, given that water pumping and drawdown, along with soil runoff caused by rainstorm, will take some time after the onset of drought before the sinkhole opens.

This is significant for use by government disaster reduction departments, or insurers, who may require forward-modeling of likely future events, such as sinkhole collapses following periods of drought. This will allow for controls of sinkhole collapse to be established and to develop monitoring networks.

It can be concluded that, if a drought period is forecast, the sinkhole quantity may also be forecast using the equation, and similarly, areas in which quantities of sinkholes are increasing may be considered clear subjects of the impacts of global warming.

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