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Part 2: Spatial-Temporal Occurrences of Sinkholes as a Complex Geohazard in Florida, USA

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Abstract

Solutional sinkholes pose a serious threat in karst regions. Few studies have actually addressed the mechanisms of their formation in any great detail (for solutional and collapse sinkholes) to enable an understanding of the sinkhole hazard in a scenario of global change. A brief case study is developed for Florida, USA as a state plagued by most of the contemporary challenges of sinkhole formation. This paper addresses work that has already made a contribution to an understanding of sinkhole formation and development and makes its own contribution by detailing a case study for Seffner, Florida, where Jeffrey Bush was engulfed by a collapse sinkhole in 2014 that was subsequently reactivated in 2015. The findings from this case study reveal a high incidence of sinkhole occurrence when temperatures are low and precipitation is also 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.

Keywords: Limestone dissolution; Carbonation; Water abstraction; Irrigation; Environmental acidification; Aquifer contamination; Desalinization

Introduction

Even though limestone dissolution, which is affected by carbonation, should diminish with the temperature increases expected with climatic warming as part of anthropogenic climate change, recent research has shown that dissolution occurs at relatively high average temperatures [1]. This means that limestone will dissolve at various scales, including at the landscape scale, affecting calcareous bedrock and causing hazards that climatic warming should have curbed.

Solutional processes that occur below the ground surface are susceptible to both the dissolution of percolating naturally acidic groundwater, but this groundwater is affected by surface acidification. This acidification can result from human contamination in various ways, linked with pollution, and is contingent on temperature variations. Regardless of the type of human agency, the end-product of acidic groundwater includes ramifications for the subsurface chemical weathering of calcareous rocks.

Thornbush and Viles [1] for instance, demonstrated the potential for limestone dissolution even with an average (steady) temperature of 19°C in a climatic cabinet. Discs of Bath limestone experienced a notable weight loss, especially within the first 13 days of exposure in varying strengths of carbonic acid solutions. Test solutions that were more acidic conveyed considerable weight loss, more than weakly acidic solutions. This study revealed the importance of acid concentration in limestone dissolution occurring at a relatively high average temperature.

The implication of these findings is that limestone dissolution has the potential to occur even when surface temperatures are high on average and that acidic concentration may be a primary control over temperature-affected chemical reactions inducing limestone dissolution. Although more basic research is needed in controlled laboratory settings, the findings can be applied to a real-world problem that could worsen as surface acidification ensues. Since acids are moisture-dependent, it is also important to consider these moisture inputs (e.g. rainfall) in the chemical breakdown of calcareous materials.

The aim of this paper is to consider solutional sinkholes and collapse sinkholes, both involving limestone dissolution, as a field application of the cabinet simulation experiment already published [1]. Existing relevant literature will be relayed first before a case study is used to highlight the significance of limestone dissolution within the context of a geomorphological hazard in karst landscapes.

A complex geohazard

The formation of solutional sinkholes should be treated as a multivariate (complex) problem that is influenced by both natural as well as anthropogenic inputs. It is not as simple as just examining temperature-pressure relations, as is typical of contemporary hydrogeological approaches to dissolution [2]. There are other factors controlling dissolution that include environmental variables, such as when environmental acidity affects the strength of carbonic acid to induce the chemical reaction in calcareous materials.

Therefore, the concentration of atmospheric carbon dioxide is critical. At present, concentrations of atmospheric carbon dioxide continue to increase to the current level of 406.07 ppm measured in January 2017 at the Mauna Loa Observatory, Hawaii (Scripps-UCSD) [3]. According to this source, just this year, the Earth's atmosphere has gained 3.43 ppm in carbon dioxide from the same time in 2016; it is 5 ppm increased this year (end of February 2017) compared to February 2016.

The National Aeronautics and Space Administration (NASA) conveys that atmospheric carbon dioxide is normally around 200 ppm during glacial periods and up to 280 ppm during interglacials [4]. In 1950, the atmospheric concentration of carbon dioxide reached over 300 ppm, which has not occurred in the past 650,000 years [4]. This of course has been effectively linked to the burning of fossil fuels. Problematically, given sufficient moisture for scavenging this pollutant gas by rain, carbonic acid enters the hydrological cycle and is able to act on sediments and rocks beneath the ground surface.

Areas underlain by calcareous rock, including global aquifers, are particularly subject to the action of acidic water percolating (from the surface) in the ground and capable of dissolving bedrock and any calcareous geological structures on the way. Aquifer contamination deserves consideration because aquifers provide a natural resource (up to 25% of the world's drinking water) that needs safeguarding, while being vulnerable to pollution, since they are affected by the connection between subsurface and subsurface drainage as well as the subterranean formation of conduit networks [5].

Sinkholes pose serious engineering problems as they impact the human environment. They affect a variety of landscapes around the world, and not just karst regions, including expanding urban settings. It is known, for instance, that karst impacts and hazards are rapidly increasing due to urban development in the midst of improper planning that is causing environmental and engineering problems, including sinkholes as well as floods and landslides [6].

Geohazards were considered broadly in the review presented in Part 1. The focus of this second paper (in Part 2) is the spatial-temporal occurrence of sinkholes. In particular, human-environmental interactions affecting the appearance of ground subsidence and sinkholes are considered here, with an emphasis on local geology and aquifers, drainage and water quality, fluctuations in the level of groundwater, and the concentration of pollutants, etc., which are all relevant to the case study presented. Other authors have already written about the main types of both natural and human-induced geohazards evident in karst environments, including subsidence and sinkholes; slope movements; flash floods; and pollution [7].

Causation of occurrence

The appearance of sinkholes has been tracked to various settings. These are determined by moisture availability for chemical weathering, such as coastal and humid (tropical) settings, where chemical weathering is enhanced due to high moisture availability. Even in the absence of moisture (humidity, precipitation, fog, etc.), however, arid regions experience sinkholes. The reason for this is that climatic variables are not alone in affecting their formation. Rather, properties of the local geology, including rock type and whether precipitates have formed, affecting rock resistance also impact their formation. Their incidence in arid environments, in particular, attests to the importance of the harshness of the saline environment. Other triggers of sinkhole development could be faults, but this is not chemical unless these crustal fractures bring up groundwater.

It is not enough to have moisture present. The right conditions involve other factors, such as intensity and duration of exposure, and this is affected by climate and climate change. Areas where storms will become accelerated, for instance, are more likely to experience an increase in sinkhole activity. This is influenced by the extent of limestone cover, which also affects exposure, so that both surface and subsurface geology can determine the appearance of sinkholes.

It is also important, for instance, to consider the overburden rock type affecting drainage and the entrance of contaminants into the ground subsurface. According to Kaufmann [8], for example, subsurface voids that are enlarged by the process of dissolution can destabilize overburden rock (and sediments) and lead to collapse, which can also propagate upward in the ground subsurface toward the surface, creating collapse sinkholes at ground level. In this investigation, Kaufmann used results from geophysical surveys (gravimetric, electrical, and geomagnetic) to compare with simplified theoretical models in order to derive three-dimensional structural models for different locations where solution and collapse sinkholes are evident.

Other authors have adopted an experimental approach of artificial cavities that allows for a general classification (tree typology) based on time and modality of realization [9]. These artificial cavities can then be compared to existing (real-world) situations presently occuring in different locations around the world.

Case Studies

A case study approach is presently popular in the environmental literature, and these (case studies) have often been deployed in sinkhole research to investigate this geohazard. At the Dead Sea, for instance, the sinkhole hazard was augmented at the end of the 1980s [10]. This was thought to be associated with water-level lowering, affecting sinkhole formation at the coast. Other geohazards also apparent at the coast included subsidence, landslides, and reactivated salt-karsts. All of these geohazards are considered to be human-induced [10].

Land subsidence and sinkholes affect an increasing population along coasts, and have implications for pipelines and infrastructure in addition to buildings. Various exemplar case studies exist, as for instance in the town of Casalabate in the Apulia region of southern Italy, where a combination of stratigraphic, hydrogeological, and geophysical techniques have been employed for susceptibility mapping of sinkholes [11]. Another case study from the Apulia region of southern Italy, examined sinkhole hazards cross-temporally as relict or old and more recent landforms that have been evolving through time [12]. Sinkholes in this region were found to have developed through karst processes and can be possibly reactivated, so that they pose a risk to the built environment; as for instance in the town of Salento nearby Lecce, where the recent evolution of sinkholes has been tracked using aerial photos cross-temporally. Such a cross-temporal consideration allows for deciphering any time-related associations in sinkhole development and distribution.

Also in the interior Apulia region of southern Italy, in the town of Altamura in the Murge plateau, several sinkholes formed since 2006 above subterranean calcarenite quarries [13]. The calcarenite is covered by up to 15 m of clay, and rock weathering has caused failures and instability that have propagated upward, forming surface sinkholes in urban areas and on land planned for construction. Detailed maps of the subsurface cavities have helped to identify sinkhole-prone areas that may affect future development.

A set of cases was presented by del Prete et al. [14] for the plain areas of Campania, Apulia, and Calabria in southern Italy. Collapse sinkholes, in particular, threaten human safety, since they occur suddenly without any premonitory signs and are considered to be catastrophic, causing severe economic loss and casualties. They are produced by a variety of environmental conditions, as for instance at

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the Tyrrhenian margin along the carbonate massifs and intramontane (Apennine) basins; on calcarenites overlying limestone along the coast in Apulia; and due to earthquake-induced liquefaction in Calabria. These case studies point to the importance of site-specific causation based on an environmental interpretation.

Elsewhere in the world, Saudi Arabia experiences both natural and human-induced sinkhole hazards because of its soluble sediments, which have been derived from carbonate and evaporite rocks as well as salt diapirs and sabkha deposits [15]. Even in such a hyperarid climate, human activities (particularly groundwater extraction) have destabilized existing cavities, so that climate alone does not account for their occurrence. The condition can be worsened by human activities, such as groundwater abstraction and ground destabilization. Remote sensing has been used alongside trenching and geophysics to locate the distribution of sinkhole-prone areas.

A Case Study: Seffner, Florida, USA

Due to urban expansion in Florida, development is increasing the risk of sinkholes. The death of Jeffrey Bush, for instance, represents only one of 15,000 confirmed sinkholes in the State, with the west coast town of Springhill having the greatest number of verified sinkholes [16]. Indeed, the counties of Hernando, Pasco, Hillsborough, and Pinellas are cumulatively known as "sinkhole alley," with nearly one verified sinkhole for every 31 residents [17]. Sinkholes are a predominant landform in Florida because the State is fully underlain by soluble (carbonate) rock, and here limestone dissolution and water movement greatly affect the landscape [17,18]. According to this source, between 2006 and 2010, sinkhole claims tripled in Florida.

In west-central Florida, the formation of sinkholes is accelerated by human activities, such as groundwater pumping as well as construction and development [17]. More specifically, rapid water extraction can reduce groundwater fluid pressure around aquifers like the Floridan aquifer system. Construction activities that can trigger sinkhole formation include weight loading through the building of structures, well drilling, mining, etc. Cover-collapse sinkholes generally occur abruptly, and their rates have increased in the past several decades in west-central Florida because of declining groundwater levels, especially during periods of low annual rainfall and drought [17]. A summary of possible sinkhole triggers occurring in Florida is provided in Table 1.

Cause	**Trigger**	**Details**
Natural	Soluble rocks	Carbonates (limestone, dolomite and marble) and evaporites (gypsum and salt) that are susceptible to dissolution in wet or humid conditions resulting in solutional sinkholes
	Structural weaknesses	In limestone: joints, bedding planes, fractures/fault zones
	Water movement	Ponded water, wetting, rivers, coasts, changes in the water table, etc.
	Earthquakes	Settling of sand and clay, resulting in cover-subsidence and cover-collapse sinkholes
	Regional declines of groundwater levels	Due to low annual rainfall and drought
Human	Modified drainage and diverted surface water	Due to construction activity, causing focused infiltration of surface runoff, flooding, erosion; broken water and/or sewer pipes; irrigation wells
	Groundwater pumping	Reduced groundwater fluid pressure, e.g. above aquifers; well drilling; urban water supply; crop freeze protection
	Mining	For any buried natural resource, e.g. coal
	Weight loading	Building of structures, e.g. impoundments to treat or store water, sewerage, or runoff; heavy equipment

Table 1: Sinkhole triggers in Florida, USA [5].

Florida is part of the "Sun Belt," which includes middle and eastern Tennessee, northern Alabama, central and southern Kentucky, and central and northern Gulf Coast Florida, where population from the upper Midwest and metropolitan Northeast is migrating [19]. As population continues to grow, there is increased urbanization and contiguous development, especially residential and infrastructural that indirectly causes sinkholes to form [18]. Planners can control development at an early (development approval) stage, and so have options available to avoid (or at least minimize) the risks associated with sinkhole hazards [20]. This is especially important to consider because early intervention reduces remediation costs and the number of alternative options decline after development [20].

Remediation in west-central Florida, for instance, has involved the use of compaction grouting [21]. This requires injection under high pressure to displace and fill voids and compact soil, and is considered to be a method of soil improvement. Commonly, compaction grout is applied from the rock surface upward as "upstage grouting," with one segment resting on another until a stable depth (e.g. sound rock) is reached. Compaction is supposed to strengthen the soil between successions of applications. In this way, soil densification is achieved, effectively sealing seepage paths. Complications that may result from this approach to sinkhole remediation include added weight as well as damage to buildings and structures from the intrusion of grout. A fast rate of injection can also lead to lateral displacement, which can further add to weight and cost and contribute to settlement of the underlying soil and building foundation that the soil supports. Compaction can result, which ultimately strengthens the soil. In regions of highly soluble rock, however, weathering can compromise the integrity of rock to support a load.

Methodological approach

Recent attention was drawn to the sinkhole hazard with the death of Jeffrey Bush in Seffner, Florida, USA. He was engulfed while he slept in his home by a 30-m deep collapse sinkhole that opened in February 2013, and since reopened in August 2015 [22]. The collapse sinkhole appeared where limestone underlies the Floridan aquifer. The hydrogeology of the area is affected by temperature and pressure, but acidification also factors into sinkhole formation [2].

Climatic information gleaned from the Florida Climate Center for Tampa International Airport (012842) was examined for temperature and precipitation normals between 1981 and 2010 for Hillsborough County [23]. This summary conveys the lowest minimum temperatures in January and the highest maximum temperatures in August (Figure 1a). Precipitation is lowest in November and highest in August (Figure 1b). Overall trends during this period (1981-2010) show high mean temperatures in summer months (June-September), when precipitation is also high, and low temperatures in winter months (December-February), also when precipitation is low.

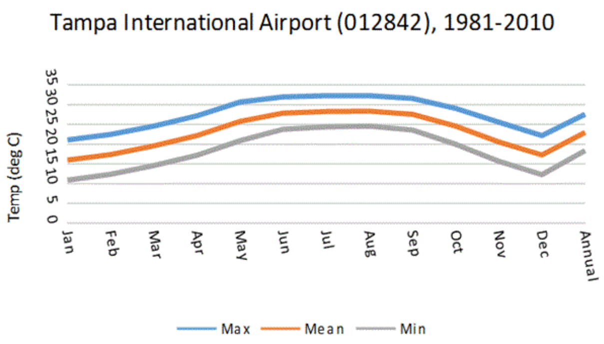

Figure 1(a): Monthly temperatures at the Tampa International Airport [23].

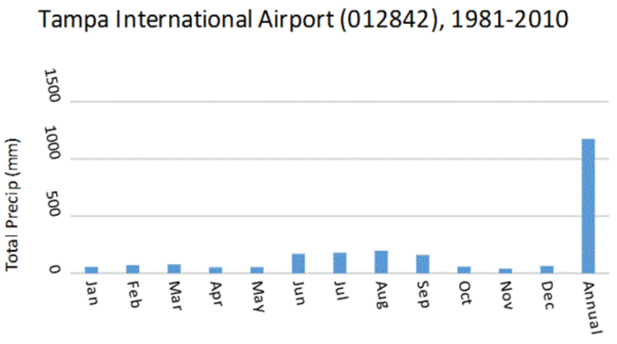

Figure 1(b): Monthly precipitation at the Tampa International Airport [23].

The appearance of sinkholes in Florida is, therefore, a complicated issue that involves more than subsurface solution. There is a mixture of factors influencing the area and not all of them are directly associated with urban expansion in this Tampa suburb. Reported sinkholes in the area were considered in order to ascertain any patterning that could help to elucidate the sinkhole hazard in Hillsborough County.

An existing database compiled by Earth Tech "Florida's Most Experienced Residential Sinkhole Repair Company" was used to acquire data for the analysis of this case study [24]. A total of 3,503 sinkhole occurrences were reported for Seffner, Florida; 277 were within an 8-mile radius of "Seffner, FL, United States" (Figure 2). The information included is spatially referenced a red dots in the database and includes the following variables: occurrence date (month/day/year); owner; dimensions (length, width, and depth) in feet; slope in degrees; soil type; and database comments, which sometimes include dimensional information. Those reports with dates (N=153) were sampled and are included in this case study, representing over 40 years of record between 1970 and 2013.

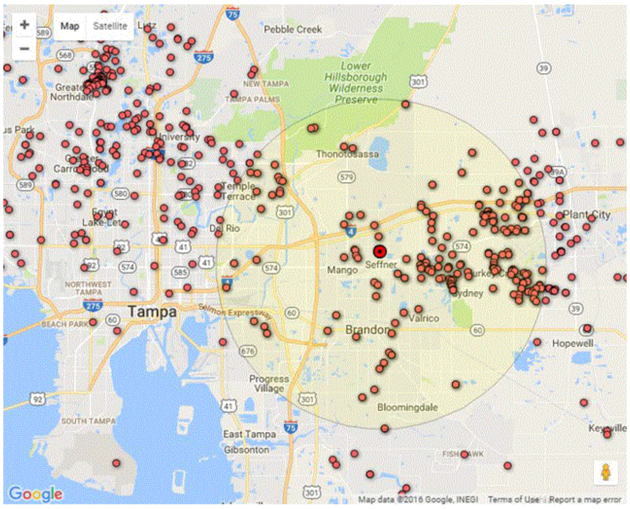

Figure 2: Study sample of sinkhole occurrences within 8 miles of "Seffner, FL, United States," N=277, including 153 with dates [24].

Those points within the 8 mile radius that had dates (at least month and year) were examined in detail and frequency data established month and year of occurrence in particular. In this way, it was possible to decipher a seasonal trend in the distribution of sinkholes contained in the database.

Findings with Discussion

A temporal analysis revealed that most sinkholes formed in winter months (especially January), particularly when freezing temperatures were recorded (typically December-February). For example, it is known that 80 sinkholes appeared in January 2010 just east of the study area near Plant City [25]. The database used in this study by comparison reports 70 sinkholes for January 2010 (Figure 3a). Other cold spells, as for example in 1985 when 20 sinkholes were reported, also led to their formation (see Figure 3a). As illustrated in Figure 3b, most sinkholes (96 out of 153, or 63%) occurred in winter months. However, it is not just temperature (e.g. seasonality) that directly spurred these sinkholes to form.

Water extracted in Florida for the protection of its winter strawberries is part of the cause in the formation of sinkholes in the area. Specifically, before a winter frost or cold spell, farmers extract irrigation water from the Floridan aquifer to spray on their crops, relying on the heat released during the conversion of water to its solid state. This heat released allows strawberries to remain viable even when temperatures are severely reduced with the occurrence of sporadic frosts in winter months, as for example occurred in January 2010 and led to the formation of various sinkholes due to water lowering as a consequence of due to extraction.

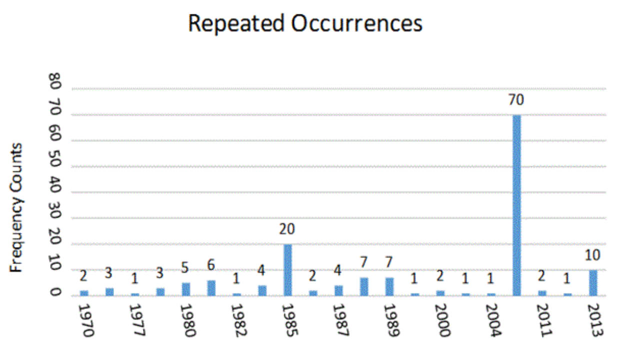

Figure 3(a): Frequency of sinkhole occurrence in the area of Seffner, Florida, 1970-2013.

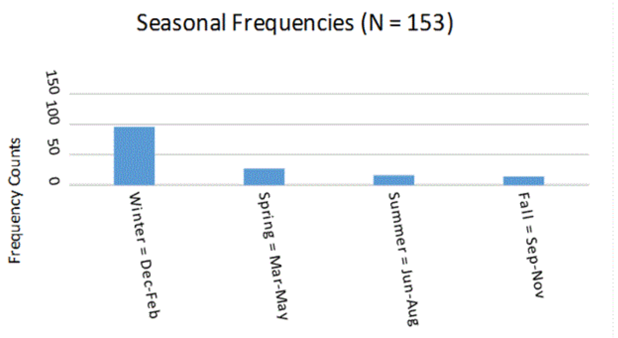

Figure 3(b): Seasonal frequency of sinkhole occurrence in the area of Seffner, Florida (1970-2013).

There are, however, other factors at work in the formation of sinkholes near Tampa, beside rapid water extracted to prevent the freezing of its winter strawberries. In fact, Florida is known for its sinkholes, and many appear as filled lakes in the contemporary landscape. An investigation of the sandhill lakes in Bay and Washington Counties, Florida, for instance, has conveyed the formation of (circular) lakes from the coalescence of sinkholes [26]. Using geophysical imaging, it was possible to discern newly formed recent sinkholes located along the lake shore in a "string of pearls" formation. At least six discrete sinkholes, with a common depth and steep-sided, were responsible for the lateral growth of these lakes (rather than suffusion or the slumping of perimeter sand).

The nature of these sinkholes has changed, however, so that current sinkholes differ in their formation from previous ones that formed in the order of a million years [27,28]. The anthropogenically altered landscape has increased the formation of these (meso- to megascale) erosional limestone landforms. Desalinization has enabled more of the brackish water contained in its aquifer to be used. This similarly affects aquifer levels and fluctuations. Any rapid change associated with water abstraction (for irrigation and other uses) will cause sinkholes to form.

It is possible that rapid fluctuations of groundwater level, as resulting from abstraction for irrigation, can lead to subsidence [29]. Furthermore, acidity could complicate the situation, as has been found for gypsum dissolution, causing subsidence and sinkholes to form in eastern England [29]. In this case, groundwater abstraction locally aggravated subsidence due to dissolution and drawdown. Groundwater flow and gypsum karsification has resulted in sinkholes 20 m across and 20 m in depth [29]. These waters are high in dissolved calcium sulfate as well as concentrated magnesium and calcium carbonates, possibly in association with acidification and the weathering of water flowing from peat mounds and bogs. This water passing, also from the rivers Tees, Ure, Nidd, Wharfe, and Aire, results in gypsum dissolution and the formation of numerous sinkholes. Redeposited calcium carbonate (as tufa and tufa cements) also cause ground subsidence due to a weak calcitic mesh laden with pipes and voids, where breccia is insufficient to bulk up and fill gypsum concavities.

Finally, the current study corroborates work by Brinkmann and Parise on the timing of sinkhole formation in Tampa, Florida [30]. Based on the Florida Geological Society database and the LexisNexis database of newspaper articles, the authors were able to piece together a temporal analysis of sinkhole occurrence over the past 20 years (between 1985 and 2004). Their work was similarly constrained as the present study, which deployed an online database that depended on individual reports of sinkholes, as there is no obligation to report sinkholes in Florida, and such reports are completed on a voluntary basis. Because of the potential for sinkholes to diminish property value, it is likely that the numbers in this study, under-represent actual occurrence [30]. Moreover, since insurance companies are not obligated to report, or in any way inform state agencies regarding sinkhole occurrence and location, these results are based on incomplete data. These authors focused on larger sinkholes; however, there was no size-based restriction on the sinkholes examined in the current case study.

The database used for analysis in this case study included information on relief (m); however, as noted by other authors, the Florida peninsula is flat and has a limited local relief of <2 m [30]. According to the authors, its low elevation causes flooding in caves. Thousands of topographic sinkholes exist, including older ones called "paleosinkholes" that formed thousands of years ago in comparison to the more recently formed types that are only aged a few decades [30]. They observed paleosinkholes in this region to be complex forms appearing at higher elevations, whereas less complex (circular) forms found at lower elevations are relatively younger and their formation dates back to the last sea-level drop.

Of the three types of sinkhole found in Florida (solutional sinkholes, cover-subsidence, and cover-collapse types, solutional sinkholes are common where bedrock appears at the surface [17]. This author mentioned springs (e.g., Sulphur Springs) in the Tampa area as well as underground conduit systems. In addition to the local geology, it is also important to consider surface conditions and weather (and climate) in particular. For example, Brinkmann and Parise [30] examined rainfall data from the National Weather Service likewise based at Tampa International Airport. They similarly discovered that most rainfall occurred in summer months (June-September), producing 55-60% of annual rainfall. Their cross-temporal analysis revealed that this "wet season" is actually getting wetter (and that Tampa has a constant "dry season" between October and May). Their results convey sinkhole occurrence commonly during prolonged drought periods (when there are lowered water tables) and immediately following the dry season due to weight added from summer rainfall. Furthermore, withdrawals from the Floridan aquifer have increased with a growing population, augmenting the impact of the dry season on the Floridan aquifer [29].

These published results make it possible to extend backward the record of sinkhole occurrence to years of substantial occurrence (e.g. >10 in 1998 (12 cases) and 2003 (11 cases)) and no major formation in 1992; 1997 was the wettest year in Tampa, and only a couple of sinkholes were reported [30]. Over time, it appears that the frequency of sinkhole formation is increasing in the Tampa area. Here, there is a good relationship between annual rainfall and sinkhole formation $r^2=0.104$ Figure 7, [30]. Most sinkholes formed in summer months (June-September; sinkhole formation desisted after September, but increased again from January to May, when aquifers dropped during dry months; their Figure 8 associated with extreme rainfall events, some brought on by tropical storms and hurricanes [30]. Some of the reported sinkholes damaged homes in the Tampa area [20].

Both this and the past study [30] convey a seasonality effect associated with rainfall and the level of the Floridan aquifer. With oscillation experienced when the Floridan aquifer either lowered due to dry-out (in the dry season) or when it was replenished in the wet season and its level was restored, so that it could once again stabilize the subsurface once it filled. Late-winter months into the early spring is when decline in the Floridan aquifer created landscape destabilization and triggered sinkhole formation. Nevertheless, over time, as rainfall increases in Tampa, more sinkholes are formed. This will lead to a future augmentation of insurance costs due to a growing risk associated with development as well as a worsening geohazard for people in addition to property.

Conclusions

This study confers with previous research (e.g., by Brinkmann and Parise) that shows a seasonality to sinkhole formation in Tampa, Florida. By adopting a case-study approach, it was possible to examine specific climatic influences on sinkhole occurrence. In this case, rainfall affecting the level of the Floridan aquifer is impacting ground stability and sinkhole formation. The case study also portrays the effect of temperature and impact of cold weather, in particular, on groundwater abstraction in the study area. This agricultural freezing technique, deployed before frosts to protect winter strawberries, is a human impact that is contributing to the occurrence of sinkholes. Additionally, acidification (both natural of sulfur springs and human-induced acidification or contamination) is another environmental factor that could trigger ground destabilization in an area that is underlain by acid-soluble rock. Therefore, a combination of natural-human impacts is responsible for the appearance of sinkholes in this area, and their development is thought to be augmented by climate change and ensuing urban expansion.

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