Journal of Geology & Geophysics

Thornbush, J Geol Geophys 2017, 6:3
DOI: 10.4172/2381-8719.1000287

Review Article Open Access

Part 1: Contemporary Challenges and Current Solutions in Sinkhole Occurrence and Mitigation

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Received date: February 27, 2017; **Accepted date:** March 30, 2017; **Published date:** April 5, 2017

Abstract

This review considers the current literature on sinkhole formation and occurrence. It incorporates several examples from around the world in order to gain a broader geographical scope on the problem. Challenges associated with sinkholes center around atmospheric acidification (pollution) and the formation of dissolution sinkholes. In addition, urbanization and its imposed changes on surface drainage as well as aquifer contamination also bear upon this geohazard. Solutions have been grasped through the deployment of geophysical techniques, in particular GPR. Engineering solutions are presented and critically discussed. Preventative planning based on early detection (through geophysical, GIS and multivariate analysis plus modeling, and possibly remote sensing techniques) are among the most effective available solutions. More research is needed to investigate the effects of increasing surface temperatures and interactions (synergies) with pollution.

Keywords: Karst regions; Climate change; Groundwater levels; Urbanization; Surface drainage; Pollution-climate synergies; Anthropogenic geomorphology

Abbreviations: DEMs: Digital Elevation Models; GIS: Geography Information Systems; GPR: Ground-Penetrating Radar; LiDAR: Light Detection and Ranging; UK: United Kingdom; US: United States; USGS: US Geological Survey

Introduction

Limestone dissolution is affected both by pollution and climate, as acidic concentration and temperature work to weather carbonate rock. This paper focuses on sinkholes from the perspective of anthropogenic atmospheric acidification and within the context of global warming. As a climate-affected hazard, sinkholes forming in karst regions pose problems for ground stability and are thereby considered to be a geological hazard (geohazard).

They are a complex issue of growing concern in Florida, for instance, and other limestone-rich regions around the world. The aim of this review paper is to identify contemporary challenges in the global appearance of sinkholes, with an American focus (brief case study, Part 2) on Florida, and presentation of modern techniques and approaches for mitigation and remedy of the problem.

According to the USGS Water Science School, "sinkholes" are commonly found in areas of carbonate rock as well as where there are salt beds or naturally dissolved rocks by groundwater [1]. Any water-soluble rock can, therefore, be naturally susceptible to sinkhole formation. These are normally visible only when the ground finally gives way and collapses due to a lack of support after much dissolution and or spaces and caverns have developed (out of sight) below the ground surface. As such, they represent a landform where chemical weathering (dissolution) of soluble rocks meets climate (intense rainfall or drought causing the water table to fluctuate) and climate change that can be affected by human impacts on natural systems.

The formation of sinkholes is easily evident in the built environment and appear in various American states, as for instance from Texas to Florida and up to Pennsylvania (the USGS recognizes occurrences in the seven states of Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania in the US alone [1].

They typically develop in areas of poor (or no) natural drainage, where water collects. Some of these can be quite large, affecting up to hundreds of thousands of square meters of land and appear more than 30 m below the surface [1].

Table 1 presents a summary of some examples of generic "sinkholes" reported [2]. It is evident, based on this information, that these landforms are geographically diverse, and affect locations outside of the US (e.g., China, Russia, Siberia, Canada, Guatemala, Germany, Brazil, New Zealand, etc.). Even the reported American incidents located were more widespread than anticipated by the USGS, with an additional at least seven states being affected (New Jersey, Washington, DC, Oklahoma, Ohio, Maryland, California, and Kansas).

As evident for the US alone, the distribution of states underlain by soluble rocks, such as karst (from evaporite as well as carbonate rock) as well as evaporites (salt and gypsum) alone, is more widespread than just seven states and most (if not all) can be affected by sinkhole formation to some degree, depending on the proportion of the state comprising this soluble material.

In addition, rock weaknesses (along joints, bedding planes, and faults), along with earthquakes (as in California) and unconsolidated (sandy or clayey) deposits, in addition to altered drainage, can trigger sinkholes. Based on information contained in Table 1, for instance, the states surrounding the original seven recognized by the USGS as sinkhole-prone can also be affected, including New Jersey, Washington, DC, Oklahoma, Ohio, Maryland, California, and Kansas [1].

Location	Date
South Amboy, New Jersey	March-2015
Guilin, Guangxi Zhuang, China	January-2015
Suburban Washington, DC	January-2015
Zhenjiang, Jiangsu, China	December-2014
Quanzhou, China	December-2014
Siberia-200 m deep	November-2014
Tampa, Florida	November-2014
Crimean capital of Simferopol	September-2014
Ross Township, near Pittsburgh, Pennsylvania	August-2014
Siberia	July-2014
National Corvette Museum, Bowling Green, Kentucky	February-2014
Xi'an, Shaanxi province, China, 27 October 2013	October-2013
Antipayuta, Russia-15 m wide	September-2013
Oklahoma City, Oklahoma	September-2013
Summer Bay Resort, Clermont, Florida-15-18 m	August-2013
Montreal, Quebec-8 m long, 5 m wide	August-2013
Toledo, Ohio	July-2013
Arlington, Texas	June-2013
Russian Black Sea resort of Sochi	March-2013
Guangzhou, China-305 m^2 wide, 9 m deep	January-2013
Harbin City, northeast China	August-2012
Turkmenistan, Karakum Desert-70 m wide	July-2012
Guatemala City-81 cm, 12 m deep	July-2011
Beijing, China	April-2011
Leshan, China-20 m wide	January-2011
Chevy Chase, Maryland	December-2010
Schmalkalden, central Germany	November-2010
Shanxi Provincial People's Hospital, Taiyuan, China	August-2010
Guatemala City	May-2010
Los Angeles, California	September-2009
La Jolla, California-61 m by 73 m	October-2007
Pinheiros subway station, Sao Paulo, Brazil	January-2007
Waihi, North Island, New Zealand-50 m wide, 15 m deep	December-2001
Austin Peay State University's football field-12 m deep	-
Sharon Springs, Kansas	-

Table 1: Summary table of "sinkhole" occurrences. Dates appear in reverse chronological order. Includes undated events (-) [2].

Sinkhole occurrence

There are different types of sinkholes: 1) dissolution; 2) cover-subsidence (for sandy sediments); and 3) cover-collapse (for clayey sediments, which can occur abruptly over a period of hours) [1]. Any of these can be represented in Table 1 (affected by sediment types/size of overburden) in addition to dissolutional types (which occur where there is limestone or dolomite (carbonate rock) and or evaporites (salt, gypsum, or anhydrite [1]). Events reported in October 2015, for instance, from the UK (e.g., 20 m wide, 10 m deep sinkhole that opened up in Fontmell Close in St. Albans, Hertfordshire [4]), are likely more representative of the third type of sinkhole (cover-collapse), where water lubricates clayey layers to cause eventual collapse. The recent incident that received much media attention involved the death of Jeffrey Bush, who was then (in 2013) 36 years of age and vanished into a 6 m wide, 30 m deep sinkhole while sleeping in his home one night in February 2013. This sinkhole, that occurred in a Tampa suburb in Seffner, Florida, has since reopened [5]. So, these erosional landforms are capable of being reactivated years later.

Under natural circumstances, sinkholes form due to various environmental influences. These are summarized in Table 2. These erosional features appear alongside gullies and swallow holes in the Hungarian Karst Mountains [6]. They appear in karst regions experiencing drought and floods [7] and are affected by drastic changes in rainfall, such as torrential rains in southern China [8]. In Florida, the distribution of new sinkholes differs from existing ones; there are processes acting today that are different from in the past [9]. Climate change could accelerate the formation of large closed depressions/collapse dolines, which take 1 million years to form [10]. Drainage is key, as it affects both surface and underground waterflow routes and their development through time [11]. There are interactions, as with corrosion and geomorphic processes, including slope deformations and karst, fluvial, glacial phenomena; for example, Dead Sea sinkholes, which are forming through slow salt dissolution and form within highly conductive zones [12,13].

Influence	Details
Natural	Substrate/rock properties and dynamics, e.g. solubility and strength [14]
	Landscape evolution along coasts, e.g. inlets and bays [15]
	Known to occur more in evaporite than carbonate karsts due to higher solubility and lower strength [6]
	Seismic events/earthquakes [16]
	Groundwater flow-affected by rainfall (recharge) [17]
Human	Climatic change [6]
	Changes to drainage patterns-sinkhole frequency increases near drainages, fault, etc. [18]
	Subsurface drainage also needs consideration-e.g. karst aquifers vulnerable to pollution (acidification) [19]
	Overburden/sedimentary cover burying carbonatic bedrock outcrops (where there are pressurized aquifers, seismogenetic faults, and springs-lakes/ponds enriched with CO_2 and H_2S); upward erosion through vertical conduits (deep faults) from piping where there are acidic fluids [20]
	The Dead Sea-its rapid fall in the last 30 years due to water abstraction (water quantity) [21]

	Groundwater contamination (water quality), e.g. Apulia, SE Italy [22]

Table 2: Influences on sinkhole formation.

Beside natural forces, there are also human activities that are affecting the formation of sinkholes. Human impacts in the Caribbean, for instance, include destruction of natural vegetation; contamination of water supplies; urbanization; quarrying; and so on [7]. So that biotic and abiotic elements are involved [6]. Changes to natural drainage patterns, including water diversions, can also cause sinkholes to form. New sinkholes can also develop due to groundwater pumping and can be linked to development practices and construction. For example, standing water (in swimming pools, ponds, etc.) can trigger them, as can the addition of weight on the ground surface (as with reservoirs, dams, coolant tanks, etc.). They have the capacity to drain entire lakes, as was seen in St. Louis, Missouri [23]. Sometimes they are already apparent, but only below the ground surface, so that they are buried and invisible before development, as for instance where aquifers are present.

Sinkholes are not a new phenomenon, but their occurrence is more noticed as the world becomes increasingly urbanized and more structures are susceptible to failing under their appearance. In Missouri alone, over 160 catastrophic collapse sinkholes (which are rarer than bowl-shaped (cover-subsidence) types), were reported by the public between 1970 and 2007, with the majority being small-sized (<3 m across, 3 m deep) [23]. Toward the eastern US, carbonate rock aquifers (consisting of limestone, also dolomite and even marble) are affected because of the water-yielding properties of carbonate rocks, which lead to wells and springs (as in the submarine springs of coastal Florida) that affect subsurface water drainage [24]. A new irrigation well, for example, that developed in west-central Florida led to hundreds of sinkholes ranging in size from <0.3 m to over 45 m across and spanning over 80,000 m^2 [25].

In addition to the impacts of groundwater pumping, which lead to over 80% of identified subsidences in the US, there are also the human impacts associated with the drainage of organic soils, where organic carbon drains from agricultural lands and makes for acidic (and in some cases some very acidic, pH 3.4-4) groundwater [25]. Acidic soils affect groundwater quality and the dissolution of soluble rocks. Evaporites alone make up 35-40% of the US, even if buried at depths, and can cause sinkholes to develop over the course of days to years (for salt and gypsum) and at a slower rate (from centuries to millennia) for carbonate bedrock [25,26]. However, this natural process can be expedited by human influences.

Atmospheric pollution, particularly in wet environments, can lead to the development of acids and environmental acidification. Carbonic acid, for example, has been shown to cause limestone dissolution; the chemical reaction is known to occur early (as soon as within 13 days) in the dissolution process and even at relatively high temperatures (19°C) [27]. According to this, it seems that previously weathered surfaces are less affected by carbonic acid dissolution [27]. However, it can affect new-build, including limestone-containing materials, such as concrete, which are widely used in modern urban construction. Surface acidification is affected by atmospheric quality, but can also be influenced by vegetation (organic acid) as well as climatic regime (precipitation, humidity), and so requires a systems approach. Vegetation, for example lichens, has been associated, for instance, with solution basin formation in the Burren, Co. Clare of Ireland [28].

Sinkholes as geohazards

Sinkholes pose a serious hazard to humans. Among these are: land subsidence; infrastructure and building damage; danger to human safety; etc. This can be considered an environmental quality problem, as involving pollution and acidification, when acid-sensitive (calcareous) rocks are affected. Moreover, they are can form in salty (arid/coastal) regions, where there are evaporites, and many examples of this exist from around the world (Table 3).

Condition	Example
Salty (arid/ coastal) regions	Eastern part of Saudi Arabia-land subsidence problems [29]
	Eastern Dead Sea shoreline in Jordan-old water channels and water table effects, plus active tectonism [30]
	Apulia in southern Italy-coastal plains [15,31]
	Plains in carbonatic ridges of bedrock outcrops in the Apennines [20]
Rock type: evaporites	Britain-evaporite karst causing subsidence and building damage [32]
	Hamburg, Germany-salt diaper; seismically affected [16,33]
Rock type: calcareous	Co. Durham, UK-gypsum dissolution below town of Darlington [34]
	NE Spain-evaporite dissolution (gypsum, halite, Na-sulphates) under alluvial deposits; groundwater flow accelerates dissolution [17]

Table 3: Some examples of locations of sinkhole hazards.

In turn, sinkholes affect human structures. For example, the Madrid-Barcelona high-speed railway is affected by human-induced sinkholes; land usage in Hamburg, Germany; and causing damage to the built environment, as with mining geohazards in Reading [35-37].

Sinkhole challenges and solutions

There are implications of sinkhole occurrence for planners, developers/construction, engineers, and the insurance industry [31]. Planned development, for instance “safe development” using subsidence-proof designs and the role of “preventive planning” have been deployed as longer term responses to the challenges [14,38]. Long-term sustainability has also been advocated, as for instance [7,19]. Finally, there is a role of geomorphological methods, such as sinkhole susceptibility mapping; cross-temporal geomorphological mapping; spatial-temporal predictions; GIS; DEMs; air photo interpretation and borehole drilling; archival research, etc. Table 4 presents the methods currently available to address challenges and head toward solutions. These appear with consideration of their advantages and disadvantages in an assessment of methodological contributions.

Citation: Thornbush MJ (2017) Part 1: Contemporary Challenges and Current Solutions in Sinkhole Occurrence and Mitigation. J Geol Geophys 6: 287. doi:10.4172/2381-8719.1000287

Method	Advantages	Disadvantages
GIS (including digital map data)	Allows for spatial analysis; can assess specific problems; multicriteria approach	Scale dependent; need georeferencing and software (e.g. ArcGIS) expertise
Remote sensing	Can be integrated with geological information (geothematic data); can integrat geophysical information	Surface-based assessment; restricted by resolution
Geophysical surveys (e.g., seismic, geoelectrics/ electrical resistivity tomography, georadar/GPR, resistivity imaging, and magnetic, conductivity, microgravimetric)	Subsurface detection and mapping	Equipment (some expensive/specialist) and expertise required
DEMs and modeling	Allow for topographic assessments, e.g. of flooding; predictive modeling possible	Scale dependent; informed by datasets; need to be field-verified for "ground-truthing"
LiDAR	High resolution	Surface detection
Geological information and geothematic data; geomorphological mapping	Support other methods, e.g. remote sensing, GIS; linked cartography; cost-effective; hazard mapping possible to inform planning	Data availability; scale dependent
Aerial photo interpretation	Cross-temporal analysis possible	Surface analysis only; limited to availability

Table 4: Current solutions possible through a variety of methods.

Recent academic attention has been directed at sinkholes. For example, a review paper published in the journal Geomorphology in 2011 as part of karst geomorphology focused on the natural hazards occurring in karst areas, including subterranean karst [39].

Additionally, a special issue by the journal Environmental Geology was concerned with environmental impacts as well as natural and anthropogenic hazards [40]. Because sinkholes can be human-induced, it is important (and timely) to consider sinkholes from the perspective of an "anthropogenic geomorphology," whereby human activities (in mining, agriculture, and construction) are considered as shaping the hazard [41].

One of the most wide-scoping human impacts on the landscape is that of anthropogenic climate change. More work is needed to investigate the consequences of humans (through climatic change) on landscape change and hazards, such as sinkholes.

Urbanization is one of the areas that need particular continued address, especially because of the implications for karst hydrology. Some of the current challenges and some potential solutions are presented in this section, with climate change indicated as the first challenge.

Contemporary Challenges

Climate change

The relationship between temperature and the rate of dissolution of calcareous rocks needs to be revisited. As aforementioned, dissolution continues to occur even at high temperatures, with most weight loss evident early following exposure to carbonic acid [27].

Sinkholes have also been observed appearing in thermal springs, as in Turkey, where at the Kozakli geothermal field a sinkhole some 30 m across and 15 m deep developed in January 2007 [42]. This means that dissolution can occur even at high temperatures, which has implications in a warming planet.

Urbanization and drainage

Analysis of Turkish sinkholes in the Karapinar region, investigating 30 factors affecting their occurrence (of existing and new sinkholes), found that more sinkholes formed where there was greater drainage, well, and fault density and where there was a lowering of groundwater [43]. Similarly, water pumping was one of the reasons for paleosinkhole reactivation in the Ventanielles area of Oviedo in NW Spain in addition to alterations to drainage due to the construction of an underground parking lot in combination with gypsum dissolution [44]. In Tangshan, China, groundwater management for multi-aquifer systems could restore groundwater levels to confined states in lands that are at risk of collapse so that remediation is possible [45].

Water quality is another major issue affecting many aquifers around the world, even though many have not be tested, as for instance the aquifer providing water to the city of Merida in southeastern Mexico [46], where the Ring of Cenotes is known to represent sinkholes [47]. Elsewhere, in Bexar County, Texas, contaminated spills as well as leakage of hazardous substances and polluted urban runoff from developing urban areas on karst limestone outcrops in the recharge zone of the Edwards aquifer is a major concern, especially in the more porous subdivisions of outcrop [48].

Sinkholes can appear in flat terrain, where wetlands are present due to poor drainage, as is the case with the Dougherty plain in southwestern Georgia, USA [49]. Similarly, on the Hamadan plain situated northwest of Iran, there are 39 sinkholes of various sizes and another nine located in the Lar valley north of Iran [50]. They are known to form on carbonate bedrock here, but have also been found where there is dolomite (and not just limestone) in South Africa, where sinkholes as well as compaction subsidence and potentially polluted dolomite aquifers occur [51-54]. Here, dolomite extends around Johannesburg and Pretoria, and sinkholes develop due to fluctuations in the water table (e.g., produced by dewatering for gold mining, etc.), and poses an increased risk where there is urban development due to changes in runoff and surface drainage as well as water leaks [55]. This problem is worse where low-cost housing (and informal settlements) appears, as sinkholes with a large diameter form on dolomite located within 15 m of the ground surface. In the Cheria area of NE Algeria, imposed loading affecting the stability of karst terrain depends on geomechanical properties (strength, etc.) as well as gallery depth and dimensions [56,57]. Stability is particularly compromised with increased cavity width and a roof thickness:gallery width ratio of at least 0.30 is required to ensure stable conditions.

Sinkholes are known to develop in former stream channels, where these (streams) can pose a risk to buildings and highways, as is evident in the Burlington limestone found in Springfield, Missouri [58]. The appearance of aquifers can also trigger sinkholes, as for instance in Turkey, where Egirdir lake is connected to a karst aquifer via sinkholes located on its western border [59]. This affects drainage patterns as well as anything entering the water cycle at ground level and contaminants can spread a great distance in this system. A similar problem is evident in Kermin city in southeastern Iran, where a drawdown of the water table has occurred (80 cm per year) that accelerates land subsidence (6 cm per year) [60]. In Tuzla, Bosnia Herzegovina, subsidence up to 12 m between 1956 and 2003 was effectively counteracted, particularly in urban areas (where uplift displacements are actually taking place) since it was affected by brine withdrawals impacting the level of the water table [61]. One of the most recognized variables affecting sinkhole development is that of hydrology in karst areas, where improper design and location of storm drainage discharge can lead to increased erosion as well as sinkhole development [62].

Drainage is an important consideration, particularly in areas underlain by soluble rock, such as gypsum between Rapid City and Spearfish in South Dakota, where gypsum is becoming unstable due to urbanization and suburbanization in the area due to (mainly new housing) increasing development pressure [63]. It has been suggested by these authors that mapping of engineering hazards be carried out for the entire Interstate-90 development corridor in the Black Hills. The karst Madison aquifer is the main reservoir in western South Dakota, with the Rapid City and communities in the eastern Black Hills as the main water sources [64]. The (Madison) aquifer is very sensitive to contamination due to its high water velocities and limited filtering capacity. Where it is most vulnerable, there are sinkholes (as well as disappearing streams, etc.) evident along highways and where there are wastewater systems in place (in residential areas and where there is urban development). The failure of a wastewater storage lagoon in the Lehigh River valley in Allentown, Pennsylvania, for example, polluted an aquifer through cracks, fissures, and solution channels in the Allentown Formation [65]. The Black Hills of South Dakota and Wyoming are made from Jurassic gypsum and anhydrite that have led to karst collapse and subsidence, causing damage to houses and sewage retention sites [66]. Steep-sided sinkholes over 18 m deep have developed in the area, in some cases resulting in sediment disruption that has also contaminated local water wells and springs. These sinkholes have developed since 26,000 years ago and include the Vore Buffalo Jump (near Sundance, Wyoming) and the Mammoth Site (in Hot Springs, South Dakota).

Current Solutions

Detection and monitoring

Cavities and or sinkholes appearing on roads in the karst terrain of the Apulia region in South Italy are either air or sediment-filled [67]. These underground voids (holes and tunnels either air- or water-filled) occur due to rainwater infiltration into calcarenite sedimentary rocks. It is possible to detect these beneath road surfaces using geophysical methods (seismic, geoelectrics, and georadar), which have revealed that these roads are affected by surface cracks leading to structural instability. In Apulia, caves with the potential to propagate upward as well as underground quarries (tunnels), which may now be abandoned and forgotten in the midst of urban expansion, represent a significant risk [68]. The karst geohazard is being monitoring in the UK, for instance, using digital map data (bedrock and superficial deposits) in conjunction with digital elevation slope models, etc., by the British Geological Survey to derive a database used to assess subsidence in karst regions (of limestone, dolomite, chalk, gypsum, and salt) [69]. This database can be accessed using GIS to address specific problems, for example sustainable drainage systems. Soak-aways and open loop ground source (heating and cooling) pump systems, in particular, can cause ground instability in karst areas [69]. Changing groundwater levels in Dzershinsk, Russia led to the formation of suffosion sinkholes, which were likewise assessed using GIS in an aggregated dataset [70]. The use of GIS also assisted a multicriteria approach to ground deformation in Bosnia [61] and was likewise employed (with remote sensing) for land subsidence susceptibility mapping in the Kinta valley of Perak, Malaysia [71]. Similarly, a multicriteria approach was adopted for subsidence hazard mapping in the Val d'Orléans located south of Paris, France [72].

High-resolution detection methods are now available for sinkhole monitoring, as for instance LiDAR technology sinkhole mapping is particularly effective for tracking sinkholes in Kentucky that have been either filled or covered for urban development and agriculture and that are missed by low-resolution topographic maps [73]. Also in Rome, Italy, remote sensing has been integrated with geological information and geothematic data to detect potential instabilities, although it is difficult to discern sinkholes (subsurface features) based on satellite data [74]. However, subsidence zones tend to mainly overlap with alluvial areas, as of the Tiber river system [74]. In Saudi Arabia, however, it has been possible to successfully integrate remote sensing of surface features with geophysical studies deploying electrical resistivity surveys to identify circular features or rings and unconsolidated subsurface material indicating karst [75]. These authors were able to detect below surface sinkholes using the dipole-dipole method with electrode spacing of 1 m [76]. Furthermore, it was possible to obtain three-dimensional volumetric profiles using closely spaced profiling.

Geophysical surveys, including GPR, resistivity imaging, magnetic, conductivity, and natural potential, were executed in Austin, Texas as geotechnical studies of the subsurface in areas of residential buildings, shopping malls, tunnels, pavements, etc. in order to develop integrated geophysical surveys of near-surface karst features [77]. Both GPR and microgravimetric geophysical methods were employed in the coastal (Marina di Capilungo) area of Lecce, Italy, with the former (GPR) being able to detect smaller shallow voids that can be deployed with modeling data to estimate depth and shape of anomalies representing underground voids [78]. In the city of Casalabate in this region of Lecce, Italy, a combination of methods (geological analysis, aerial photo interpretation, electrical resistivity tomography, and GPR) allowed for the location of karst conduits and an identification of the zone of high sinkhole geohazard [79].

As a geophysical technique, GPR is capable of characterizing karst hazards, including cavities and paleocollapses [80]. It has been deployed in the central Ebro basin (in Zaragoza city located in NE Spain), for instance, as part of an integrated analysis that comprised historical geomorphological analysis based on maps and aerial photographs, geophysical surveying (GPR, magnetometry, gravimetry, etc.), and subsoil characterization by way of trenches, boreholes, etc [81]. Through field inspection as part of this integrated approach, it was possible to determine an external subsidence ring (twice the size of its inner zone) detected using geometrical changes in GPR profiles [82]. Moreover, GPR made three-dimensional subsurface characterization possible with the integration of three boreholes and other available information [83]. Also in Zaragoza (Spain), trenching and geophysics (GPR) were executed across two buried active sinkholes of different genetic types (suffosion, collapse, and sagging) using different antenna frequencies (50 and 100 MHz unshielded and 180 MHz shielded) in order to characterize sinkholes in covered karst [84]. Identifying different types of karst (typology) is important in the assessment of subsidence hazards [85]. Geoelectric resistivity tomography and GPR were both used for shallow subsurface cavity imaging in Al-Amal Town in Cairo, Egypt, and led to the detection of a (known) cave system plus an extension, which was inferred and also revealed (vertical) linear fractures affecting the stability of the area [86].

There are limitations associated with methods deployed in urban settings, however, as for instance of noise affecting magnetic and electromagnetic techniques; GPR itself is also limited, as in agricultural areas, where clayey soils and conductive layers disturb the signal [87]. Indeed, GPR was excluded from an investigation in the Cheria area of NE Algeria because clay layers from a Mio-Plio-Quaternary deposit on top of Eocene limestone prevented its application and instead a resistivity survey (along with geological surveying, discontinuity analysis, and borehole drilling) was deployed [56]. Modeling of sinkhole susceptibility have also been applied to the evaporite karst of the Ebro valley [88], testing for clustering based on nearest neighbor distance as well as sinkhole density, etc. In addition, a hazard assessment was conducted for the periphery of the city of Zaragoza (in the Ebro River valley of NE Spain) and, based on trenching and dating techniques it was possible to determine that sinkholes with diameter of 10-15 m may occur in this area [89].

Other alluvial settings have caused problems associated with drainage (from urban areas, such as the city of Calatayud, Spain), where flooding is dissolving the evaporite bedrock and causing subsidence and rockfalls [90]. Buildings are especially affected by dissolution and subsidence aggravated by water leaks and sewage pipes. Geomorphological mapping has been recognized as a cost-effective approach to locating subsidence and avoiding development in these hazardous zones [90]. A vulnerability assessment also from Spain (performed in the Sierra de Líbar in Andalusia) produced a hazard map conveying the risk of groundwater contamination [91]. A composite hazard map was generated for Miocene calcarenites and Pleistocene sands east of Portimao in the Algarve, Portugal that was intended for use by planners and developers [92]. Before drilling a tunnel in Switzerland, for instance, it was necessary to use a predictive model to determine whether to expect high-flow events into the tunnel (due to high water head and discharge) affecting the construction [93]. Infrastructural development (tunnel construction) elsewhere, as within the urban Doha area of Qatar, has required geophysical surveys, including electromagnetic, multichannel analysis of surface waves, and electrical resistivity tomography, which have been found to produce good quality maps of weathered limestone [94]. Borehole (or drill hole) data on its own was found to be insufficient due to the irregular shape of sinkholes. Instead, electrical resistivity has been considered a viable tool to delineate shallow solution networks in the karst area of southeastern Johnson County, Kansas [95].

This geophysical monitoring is crucial, as detection should always precede development, particularly in built-up areas where a concentrated population can augment karst hazards. In the city of Zaragoza, Spain, alluvial karst has been mitigated by water-proofing and filling sinkholes [96]. However, this practice (of filling sinkholes with concrete injection) has actually been increasing karst activity in urban settings. In such (urban) settings, according to these authors, the methodology that appears to work best is that of mapping using GPR surveys, borehole data, and microgravimetry surveying. Elsewhere, as in Tung Chung new town, carbonate dissolution has produced sediment-filled collapse basins [97]. These have been surveyed with drilling and seismic profiling, but gravity surveying has been most effective for identifying low-density materials. In Orléans, France, the application of microgravimetry combined with spectral analysis of surface waves, GPR, and borehole information made it possible to identify karst conduits and a zone of mechanical weakness where one sinkhole had already occurred [98]. This research showed that the occurrence of buried networks does not necessarily lead to significant gravity anomalies.

Engineered approaches

It is important to deploy sustainable methods to counteract the sinkhole geohazard. Karst terrain represents a high-risk situation for urban centers with an extensive road network, as for instance in the Campania region of southern Italy [99]. Here, collapse sinkholes can be located on carbonate slopes, particularly where there are fault lines and aquifers (and their springs). A student paper has provided a geological engineering perspective on how to stabilize sinkholes using a granular filter, concrete slab (with a filtered drain), and a rock drain to establish a bridge across bedrock fissures [100]. However, it is recognized that this method may not work because all sinkholes are unique and must be dealt with individually.

This complicates engineering solutions to sinkhole stabilization and further investigations are required. For instance, by testing the infiltration rates of karst in Texas, it was discovered that a clay loam soil consisting of 30-40% clay retains infiltration [101]. Simply infilling sinkholes is not a sustainable solution, as it would take much concrete and in some cases entire networks need to be filled due to hole connectivity. Instead of cement infilling, another (more viable) option may be infilling with garbage (in areas away from aquifers and other groundwater resources at risk to contamination), which is a plentiful material and waste disposal sites for landfill are in demand, as in the Permian carbonate outcrop east of Leeds in the UK [102].

Conclusions

The main contemporary challenges for the occurrence of sinkholes in the current environment revolve around increased surface temperature (climatic warming) and its impact on dissolution sinkholes, in particular, as well as urbanization and its effects on drainage. Solutions to these contemporary challenges are presently limited to the ability to inform planning in advance through proper detection and monitoring. The first identified challenge has been largely overlooked in the current literature and more work (especially simulations) is needed, particularly since dissolution is the primary weathering process affecting karst systems in the formation of caves and conduit systems. Second, urban expansion is occurring everywhere around the world and a global perspective is necessary (as in this review) in order to gain a spatial understanding of the occurrence. A temporal dimension is also necessary, as this would permit for a determination of rates, which may affect planning and development decisions and management. Possible solutions can be informed by detection and monitoring using a diversity of techniques, including geophysical, in an integrated methodological approach. Technology is constantly developing and solutions are being devised to resolve problems that could go a long way to promote early detection, in particular and inform decisions that could reduce the risk and hazard.

Acknowledgments

I am grateful to those people who attended my talk (on which this paper is based) at the annual meeting of the Canadian Association of Geographers-Ontario in Ottawa, 2015 and provided useful commentary and feedback.

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