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ARTICLE

Coping with Sinkholes: A Systematic Literature Review

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ABSTRACT

Sinkholes have frequently occurred around soluble rock formations, but they have been indirectly related to imprudent human practices, based on long-standing recognition. The aim of this study was to explore how to improve sinkhole hazard management to decrease the extent of related risks. The main methodology was a systematic literature review that identified and synthesized the relevant information. The proposed analytical framework served as the basis for review criteria, and the scope of literature was mainly restricted to relevant text data. Analytical categories and analytical units were both used in the text synthesis process. Sinkholes were traditionally treated as natural events; however, major stakeholders started to pay attention to them as human-induced events under climate change. These players extensively included international organizations, sinkhole-prone countries (e.g., Venezuela, China, Saudi Arabia, etc.), and sinkhole-resistant countries (e.g., United Arab Emirates, Kenya, Australia, etc.) in this study. A key theme in the literature was that these stakeholders would no longer deal with sinkholes as natural events but as human-induced events, based on potential advantages (i.e., managing manmade sinkholes and implementing emergency operation plans). Similarly, as addressing emergency prevention, public awareness, technological application, social challenges, education, and training, the key tenet of study would be further achieved in terms of managerial implications. The results of this study suggested that human activities would act as negative factors in sinkhole occurrence more directly than were indicated previously. Hence, the understanding of sinkhole hazard management would be quite deepened via social environment, while policy makers were to proactively manage the issue with the sincere cooperation of local residents.

Keywords: Limestone; Natural hazard; Human-induced events; Emergency prevention; Social challenges

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1. Introduction

Not all natural hazards are natural, unusual, sudden, or unpredictable in their main characteristics [1, 2], despite the fact that some (like Kentucky Methods) have preserved the natural features of natural hazards [3]. The occurrence of natural hazards is not a result of what the environment has done, but of the values, attitudes, behavior, decision-making, or other activities of humans over the long term. Difficulties in the field of emergency management have not been created by nature but by human society. In short, nature has not played games at all, but humans have played games by deliberately or accidentally stimulating the vulnerabilities of populations.

Sinkholes have technically been considered to be natural hazards; however, this no longer holds true, particularly in the scenario of climate change [4]. When soluble rocks underground are dissolved by groundwater, they can form cavities and lead to the occurrence of natural sinkholes. Further examination of the groundwater flow has shown the occurrence of sinkholes to be increasingly related to human activities such as air pollution, flash floods, construction, and waste disposal as well as broken underground water pipes. Despite the fact that appropriate professionals have already recognized that the occurrence of sinkholes is caused by both natural and anthropogenetic causes, sinkholes, as cascading disasters, have surprisingly become a type of manmade emergency in the 21st century again. A good case is the occurrence of sinkholes in Central Iran (i.e., Abarkooh plain) [5].

The exact number of sinkholes per year worldwide is unknown. Karst has existed on 7–12% of the global land surface, and human structures have rapidly increased in karst terrain. Slovenia, which is well-known for its karstic terrain, is where the word, karst, first appeared. Approximately 25% of the world's population relies on karst water [6, 7]. Nonetheless, the stability level near sinkholes may be misleading because of a lack of consideration regarding sinkhole formation and poor reporting [8]. Therefore, the question arises of how major stakeholders have dealt with the issue of sinkholes worldwide.

The aim of this study was to examine how sinkholes have been and can be effectively managed to achieve the ultimate purpose of emergency management, such as minimizing fatalities, financial losses, and psychological impacts. This study holds great importance, because it has the potential to rudimentarily change the way sinkholes will be managed by incorporating manmade factors into scientific risk assessment, among other things. Increasingly, international organizations, sinkhole-prone countries, and sinkhole-resistant countries have acknowledged that sinkholes are human-induced events, rather than considering them natural events. A common theme of the reviewed literature was that going forward [9], all three stakeholders will consider sinkholes as human-induced events and not as natural events. Accordingly, the phases of emergency prevention, disaster awareness, use of technologies, sustainable development, education, and training will be addressed.

2. Literature review

2.1 Key concepts

Sinkholes, as slow-onset disasters, have their mechanisms, although they may collapse suddenly [10]. Sinkholes have occurred on soluble rocks (also known as *karst* terrain, including limestone, salt beds, and carbonate rock) as groundwater moves through cracks and then dissolves the bedrock under the big frame of the weather system. Sinkholes have recently been associated with various human activities, such as oilfield activities, over-extraction of underground water, water leakage via pipes, mining, and subway construction. In particular, soil creep or failure through silts and clays has been brought on by subsurface water flow from numerous broken pipes [11].

The majority of sinkholes have been classified as a type of manmade emergency [12]. Sinkholes may be depicted not only as natural hazards (i.e., physical or chemical erosion underground), but also as manmade emergencies. However, when many sinkholes (including those caused by natural hazards) are directly or indirectly affected by careless human activities, many of them (or even all sinkholes) may be re-classified as manmade emergencies.

In the United Kingdom, some researchers and practitioners have differentiated between sinkholes and crown holes [13]. Soil failures occur annually throughout the nation in the mining industry. In the UK, the natural occurrence of soil failure has been considered a sinkhole. However, when soil failure occurs owing to human-induced activities, it is classified as a crown hole. Nonetheless, the present study uses the term sinkhole to ensure consistency.

Sinkholes have both negative and positive impacts on human society[14]. Sinkholes damage the built environment and can cause economic damages and psychological impacts. In such cases, sinkholes can lead to loss of life. However, in some cases, sinkholes have a positive effect. Sinkholes have formed beautiful landscapes with intrinsic values, as in the case of the cockpit karsts in Jamaica. In addition, sinkholes have become aquifer recharge sites around St. Johns River in Florida, USA. Sinkholes have generated microhabitats that can accommodate a variety of plants, trees, animals, and other organisms, regardless of national boundaries. It is beneficial for resource management in a region, reminding that sinkholes have exposed mineral resources[15]. Similarly, because sinkholes have often brought a range of nutrients to the surface, they benefit soil fertility and agricultural productivity.

2.2 Previous studies

Although the field of emergency management has included the class of sinkholes (as geological hazards or geohazards) in its management scope, related research has not been extensive compared to that on other emergencies[16]. Many disciplines, including geomorphology, hydrogeology, applied geology, geophysics, geochemistry, and geotechnical engineering, have studied sinkholes scientifically. Nonetheless, the discipline of emergency management has not paid adequate attention to sinkholes, partially because sinkhole occurrences have not been officially reported frequently. Instead, by referring to emergency management principles and technological applications, the field of emergency management has often discussed frequently occurring hazards in a region. These hazards include earthquakes with tsunamis, hurricanes with floods, climate change, endemics, and others[17]. For instance, multiple Middle Eastern researchers (from Iran, Turkey, Syria, and other countries) have expressed interest in researching the frequency of catastrophic earthquakes.

To collect, measure, analyze, and monitor the occurrence of sinkholes and their related impacts has been challenging[18]. Overutilization of groundwater is directly or indirectly associated with sinkholes worldwide; however, little empirical data are available. Similarly, appropriate databases are lacking for sinkholes and surface water. In addition, because the data collection process has been anecdotal, the quantification of sinkhole data has also been fragmented.

Moshodi et al. (2016) studied methods to improve the poor status of stakeholder management around sinkholes in Merafong, South Africa[19]. They presumed that stakeholder management efficiency would contribute significantly to appropriate sinkhole management. At the regional level, round-trip communication between the city government and other stakeholders, trust relationships among various stakeholders, and the participation of all stakeholders in sinkhole hazard management are recommended.

Examining the issue of sinkholes in terms of mining geology as an applied science, Agnieszka et al. (2017) highlighted the importance of integrating various factors[20]. Because numerous factors are associated with the occurrence of sinkholes in a given area, these should be included in sinkhole hazard management. These factors include mining conditions, spatial distribution, risk factors, analytical hierarchy, and correct interpretations.

Salem (2019) examined the issue of anthropogenic disturbance around sinkholes within the Dead Sea basin[21]. The formation of sinkholes in the region increased considerably, particularly between 1951 and 2000, owing to decreasing water levels, seismic and tectonic activities, and human involvement. However, the occurrence of regional sinkholes was predicted to decrease as long as the protection of nature was given preference over individual monetary benefits.

Mostafiz et al. (2021) assessed the risk of sinkholes in the state of Louisiana, USA[22]. Considering that the occurrence of sinkholes includes slow, overlooked, or insidious characteristics, the risk of these sinkholes is likely smaller than that of other hazards. Despite the small loss in human life, the economic damage owing to sinkholes was substantial in this region. In addition, the economic risk has increased owing to mineral extraction, population increase, climate change, and regional development.

Mathiesen (2023) investigated whether the occurrence of sinkholes in Great Britain was a natural hazard or a man-made emergency[23]. The initial opinion was that sinkholes in the nation should be considered natural hazards, assuming that the formation of sinkholes started much before the beginning of human activities. However, whether the current frequent occurrence of sinkholes is aggravated by climate change continues to be examined. In addition, stopping the occurrence of sinkholes is almost impossible because of the related expenses.

2.3 Premise of this focus

A basic assumption in the present study is that humans have negatively fused their life patterns into the natural environment in various ways, including contamination of water, abuse of water, and degradation of land [24, 25]. Compared with the status of nature approximately a century ago, further negative interaction has occurred, even below the surface, including environmental degradation and soil erosion (e.g., soluble rock formations). The hypothesis of this study is that in terms of emergency management, the interaction of humans with the physical environment has not been positive but has had a rather negative impact.

Two approaches to the occurrence of sinkholes are proposed in the present study. The two are unique depending on the cause of sinkhole occurrence. The proponents of sinkholes as natural events consider that a key attribute of sinkhole occurrence is the saturation of the Earth's surface with water during the karst formation processes [26]. In other words, sinkholes occur primarily because soluble rocks underground dissolve in water. From a broad perspective, this approach classifies sinkholes as typical natural hazard cases.

However, proponents of sinkholes as human-induced events consider anthropogenic activities as the root cause. Although a few sinkholes are natural phenomena, further investigation supports the idea that human-induced activities have substantially facilitated the impacts of these sinkholes [27]. For sure, the extent of heavy rain, waste release, broken underground water pipes, and groundwater have greatly deteriorated due to human-induced climate change. This approach considers sinkholes as a type of manmade emergency.

3. Methodology

3.1 Review protocol

To systematically explore appropriate literature on the topic of sinkhole hazards, the methodology of a systematic literature review was adopted [28]. An analytical framework was constructed as described in **Figure 1**. Briefly, three detailed steps were followed: review protocol design, literature screening, and text extraction and synthesis. Each step is expected to contribute equally to the systematic arrangement of the various text data in this study.

The review protocol elaborates on multiple components of the analytical framework [29]. The review protocol consists of a research question, variables, approaches, and direction of interaction, and occupies a major portion of the analytical framework. The review protocol, as a research plan, is frequently improved immediately after any flaw is detected during the process of continuous research. In turn, these efforts facilitate the research remaining focused on the original goal (or limit the scope of the research), particularly without major deviations.

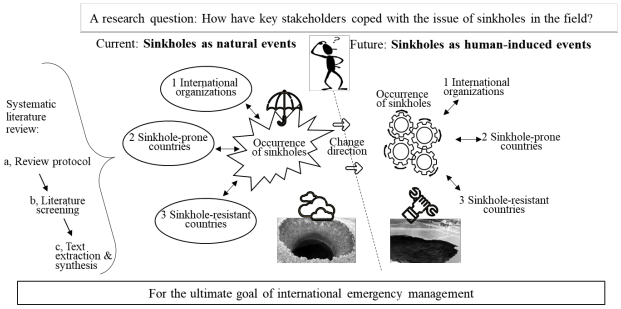

Figure 1. Analytical framework.

3.2 Literature screening

To identify relevant literature, reliable research databases such as Google Scholar, Scopus, Web of Science, ScienceDirect, Academic Search Complete, EBSCO, JSTOR, Oxford University Press, and IEEE Xplore were utilized extensively. Examples of used keywords included "sinkholes," "sinkholes and natural hazards," "sinkholes and manmade emergencies," "sinkhole hazard management," "sinkholes and implications," and "sinkholes and the human society.".

An effort should be made to limit the scope of the literature review to pertinent text data [30]. Accordingly, inclusion and exclusion criteria were established. In terms of textual content, the primary criterion was related to whether a given text discusses sinkhole hazard management, man-made sinkhole emergencies, sinkholes, and human activities. Other criteria for inclusion or exclusion included recent publication (i.e., for the last five years, when necessary), full-text studies, and accredited sources (or peer-reviewed journals).

3.3 Text extraction and synthesis

Three analytical units were used for text extraction. These units are intended to include all key stakeholders in sinkhole hazard management worldwide, such as international organizations, sinkhole-prone countries, and sinkhole-

resistant countries. To further explain, international organizations have demonstrated their leadership in the management of natural hazards on a global scale. Sinkholes have undoubtedly posed a threat to sinkhole-prone countries (such as Mexico, which has over 2000 sinkholes)[31], but sinkhole-resistant countries (like South Korea) have generally been unaffected by sinkholes[32]. The above-extracted data was then synthesized for comparison between two analytical categories: sinkholes as natural events and as human-induced events. This synthesis clearly answers the original research question.

4. Results: Sinkholes as natural events

4.1 International organizations

As a major disaster management institution within the United Nations (UN) system, the UN Office for Disaster Risk Reduction (UNDRR) has acknowledged that human activities have repeatedly hastened the occurrence of sinkholes; however, they continue to classify sinkholes as natural events[33]. The UNDRR maintains that the best way to deal with sinkholes is to avoid their impact. Because sinkholes occur naturally, people cannot stop their occurrence but only eschew related risks via emergency planning.

The UN Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER) has provided information on sinkholes since 2006 through its portal website[34]. Although UN-SPIDER has considered sinkholes as both natural hazards and man-made emergencies, the focus is on the former. As satellite technology has been applied to monitor the occurrence of sinkholes on Earth, the UN Office for Outer Space Affairs (UNOOSA) manages the UN-SPIDER portal.

A few international non-governmental organizations (INGOs) have intensified their specialization in sinkholes[35]. A select number of INGOs have worked for a single category of natural hazards (including sinkholes) in multiple regions owing to proactive hazard management, monetary pressure on public organizations, and humanitarian aid. EcoPeace is one of the few INGOs that has asked the industry to pay for economic damage caused by the continuous occurrence of manmade sinkholes around the Dead Sea[36].

4.2 Sinkhole-prone countries

Governments in Venezuela have considered natural hazards as the primary cause of a number of sinkholes in their regions, while also considering potential economic benefits[37]. At least four sinkholes are located at the top of the Jaua-Sarisariñama National Park. Information about naturally formed sinkholes has been distributed worldwide to attract diverse tourists and explorers. Even helicopter tours are being provided for tourists, despite temporary restrictions on exploration[38].

In China, the focus has been on sinkholes as potential natural hazards, despite the nation being threatened by several manmade sinkholes around construction sites[39]. In particular, southern China has a karst topography; thus, many regional sinkholes have been the focus of discussion. This is probably because the occurrence of manmade sinkholes is not considered as something new or of great interest; news reporters and scientists often consider these events as natural sinkholes.

Acknowledging that approximately 60% of the nation's territory consists of soluble sediments, Saudi Arabia has given considerable importance to the need to improve structural stability by taking into account other influencing factors in addition to natural hazards[40]. Geological settings have been a direct cause of sinkhole occurrences throughout the nation. Two sinkholes in Riyadh, Al-Kharj, have been focal points because of their huge magnitude. However, Saudi Arabia has not been confronted with only impacts linked to natural hazards.

4.3 Sinkhole-resistant countries

Although the United Arab Emirates (UAE) has generally been evaluated as a sinkhole-resistant nation, the city of Al-Ain in Abu Dhabi has experienced several shallow sinkholes[41]. The city government of Al-Ain has currently classified sinkholes in its administrative zone as geo-hazards among the eight hazard categories (including natural and man-made hazards, based on the UNDRR classification)[42]. This means that the city of Al-Ain certainly considers sinkholes to be a natural hazard, indicating the need for geophysical research.

The East African Great Rift Valley in Kenya has been influenced by the occurrence of sinkholes, mainly because of

the large amount of water generated during floods or heavy rains[43]. Some believe that this is a result of the African continent being split into two different plates, reflecting a remarkable natural phenomenon. However, the fact that this area belongs to an active tectonic zone is also a major cause of sinkhole occurrence, particularly owing to the impact of hydrological change.

Australia has a unique situation of sinkhole occurrence as a natural hazard[44]. Humid climates have caused more serious sinkhole occurrences in tropical regions than dry climates. The Nullarbor Plain in Australia is rich in limestone; however, these areas are desert regions with low humidity. Only wildlife remains in this desert region; hence, the occurrence of infrequent sinkholes in the Nullarbor Plain does not critically affect the majority of the Australian population[45].

5. Implications: Sinkholes as human-induced events

Considering sinkholes as human-induced events has potential advantages over dealing with them as natural events[46]. Many stakeholders generally believe that humans cannot prevent the occurrence of sinkholes because natural hazards are beyond human control. Therefore, stakeholders have only attempted to contain (or maintain) natural sinkhole hazards. However, when addressing these as human-induced events, stakeholders will endeavor to prevent manmade sinkholes.

To elaborate, the risk of manmade sinkholes may ultimately be stopped or avoided as long as all individuals and institutions do their best to deal with the related hazards[47]. The occurrence of sinkholes as an unforeseen event preempts the possibility of planning. However, consideration of sinkholes as manmade events can encourage stakeholders to set up and implement emergency operation plans by utilizing all appropriate means and methods. As a result, even an emergency prevention phase is feasible for potential sinkholes.

These findings suggest that all three stakeholders (i.e., international organizations, sinkhole-prone countries, and sinkhole-resistant countries) should no longer consider sinkholes as natural events, but as human-induced events. In doing so, the entire picture of sinkhole hazard management will be very different from that adopted currently, such as leadership, mindset, risk perception, and supplementary aid. **Table 1** lists concrete strategies that could be implemented to manage sinkholes as human-induced events.

The suggested transition in approach is a unique contribution of the present study to the existing literature. In particular, considering that all aspects of natural sinkholes must be newly or exhaustively reviewed with respect to human-induced activities, the theoretical framework of sinkhole hazard management will be much more robust than before[48]. A clear gap (or even a mixed viewpoint) is present between natural hazards and manmade emergencies in the category of sinkholes worldwide. This gap can be bridged by viewing these events through the lens of various human activities.

The suggested transition is closely related to the issue of public awareness in emergency management when acknowledging that the shift is deeply influenced by the change in common thinking among the public[49]. Public awareness refers to the individual or collective extent of popular knowledge about sinkholes, such as the risk factors and appropriate actions. Raising awareness as a crosscutting component empowers people to participate in emergency management.

This transition will require the extensive use of cutting-edge technologies[50, 51]. Machine learning may help further evaluate manmade sinkhole susceptibility in multiple areas via the measurement of ground motion rates, provision of sinkhole risk maps, and supply of environmental information. Thus, machine learning allows stakeholders to quantitatively assess various control factors. Additionally, machine learning facilitates regional planning by monitoring of sinkholes[52].

Scientists and engineers have known approximately which areas will be affected by the occurrence of manmade sinkholes but have not been able to predict their exact locations [53]. In these circumstances, the necessity for early warning systems or Earth observations has frequently been demanded in the field. Scientists and engineers can better locate the occurrence of sinkholes by further developing technologies such as fiber-optic sensing[53], ground-penetrating radar[54], and space-based radar[55].

Because natural sinkholes must be dealt with as unnatural disasters (or human-induced events) via this transition in thinking, the issue of social challenges will be extraordinarily supported[56]. The term unnatural disaster has outlined a rift

Table 1. Strategic alternatives toward management of sinkholes as human-induced events.

Units	Appropriate strategies
International organizations	- As a transformational leader, UNDRR will address sinkholes as a manmade emergency rather than a natural hazard, while offering an inclusive (or non-exclusive) vision. - UNOOSA needs to further add information and knowledge on sinkholes as a manmade emergency to the UN-SPIDER portal, based on long-term knowledge management (i.e., arranging the right knowledge). - INGOs, including EcoPeace, will expand their specialization in human-induced sinkholes via information sharing, coordination efforts, and education and training.
Sinkhole-prone countries	- Similar to the function of exploration restriction, governments in Venezuela should extensively consider the impacts of climate change and urbanization on sinkholes in the country via both legitimate conservation policy and emergency management. - News reporters and scientists in China will fairly discuss the subject of human-induced activities around sinkholes in southern China by generating breaking news and allocating research funds. - In addition to acknowledging that groundwater has been extracted primarily for agricultural purposes in the region, Saudi Arabia will consider multiple contributing factors of sinkholes (e.g., agricultural, geological, and natural).
Sinkhole-resistant countries	- The city government of Al-Ain in UAE will investigate their sinkholes not only by conducting geophysical studies but also by developing manmade emergency management plans. - Kenya will cooperate with other nations to address climate change, such as its commitment to the Paris Agreement and climate finance, while dealing with sinkholes around the East African Great Rift Valley. - With sinkholes around the Nullarbor Plains, Australia will highlight the unique characteristics of each sinkhole case. In particular, each Australian case will be further addressed within the context of manmade emergencies by referring to specific articulations (e.g., limestone, humidity, and residential areas) of significance.

between the category of natural hazards and the reality of human society. Accordingly, almost all sinkhole occurrences are caused by human activities. The transition required is an emphasis on the necessity of addressing tough social challenges around manmade sinkholes.

Sustainable development is equally important in coping with social challenges around manmade sinkholes. Conditions surrounding human behaviors or social barriers (e.g., cultural behavior and life patterns) may not be satisfactorily improved within a short time [57]. Instead, stakeholders must monitor and evaluate data throughout the year. Appropriate strategies and resources, such as sustainable development, must be flexibly provided for the transition.

To promote this transition, emergency management educators should provide knowledge on how engineering (e.g., civil engineering) and science (e.g., geology, natural resources, etc.) work around the occurrence of human-induced sinkholes [58]. Students can learn how hazards previously considered natural are transformed into manmade emergencies in local communities when assessed scientifically. By understanding the mechanism of sinkhole occurrence, students can determine strategies to decrease the impact of anthropogenic activities.

Emergency management trainers should train peer trainers in this transition [59]. These trainers can play a role in leading the manmade sinkhole preparedness phase. If emergency management trainers do not accept this new recognition of sinkholes as human-induced events, multiple trainees will continue to follow the old practices of sinkhole management. These trainers will continue to conduct exercises (or repeat) on how to monitor and assess sinkholes in hypothetical situations around household and workplace areas 61.

6. Conclusions

The occurrence of sinkholes worldwide is intermingled with irresponsible and complex human activities. Albeit sinkholes are a naturally occurring geological phenomenon, human activities have greatly increased their frequency and

severity. Effective hazard management including systematic emergency planning is essential to lessening the effects of human activities on sinkhole formation. The aim of this study was to examine how to enhance sinkhole hazard management in the international field. Based on a review of previous studies, three analytical units (international organizations, sinkhole-prone countries, and sinkhole-resistant countries) and two analytical categories (sinkholes as either natural or human-induced events) were examined to determine key implications and the way forward.

The most important finding of this study is that the above three stakeholders should approach the challenge of sinkhole hazards as human-induced events rather than as natural events. Each stakeholder should implement the proposed alternatives appropriately, such as with an inclusive vision, multi-purpose interventions, and availing climate finance. Based on the clear benefits of considering sinkholes to be human-induced activities, these stakeholders will continue to address sinkhole prevention through raising public awareness, use of cutting-edge technologies, tackling social challenges, and implementing disaster education and training.

By raising concerns about man-made emergencies around sinkholes, the present study has dealt with the issue of human-induced activities more directly than in multiple previous studies. Various scholars have fully or partially studied the issue of sinkhole occurrence from the perspective of natural hazards, which is not the main focus of this research. In short, by accounting for the human dimension, the present study has addressed the societal response or vulnerability to sinkholes to a greater extent than in previous studies.

However, a limitation of this research may arise from the individual criteria applied for evaluating the boundary between natural hazards and manmade emergencies. As such, some critics may judge the transition from the former to the latter with reference to sinkholes as an oversimplification. Despite the fact that associated complications are prevalent around sinkholes (as long-standing recognition), this research decisively asserted the transition between the two opposing categories. This study is based on an aggressive approach.

Future research should further investigate sinkholes through the lens of human-induced activities. Considering that the topic has not yet been as extensively studied as natural events, this new trend will boost the goal of sinkhole hazard management. Simultaneously, while overcoming the limitations of this research, further study can help demonstrate how human-induced factors have exacerbated the impact of sinkholes on each facet. These new findings will facilitate the transition between the two approaches in the near future.

Conflict of Interest

The author declares that he has no financial or non-financial conflicts of interest with this manuscript.

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