Determining Susceptibility to Sinkholes Due To Climatic Factors in Ekurhuleni: A Multi-Criteria Decision-Making Approach

Baleseng T Mokoena [1*], Walter Musakwa [2], Eric Nyembezi Makoni [3]

[1,2] Dept. of Geography, Environmental Management & Energy Studies, Faculty of Science, University of Johannesburg, Johannesburg, South Africa – balesengmokoena211@gmail.com; wmusakwa@uj.ac.za

[3] Dept. of Urban and Regional Planning Faculty of Engineering & Built Environment, University of Johannesburg, Johannesburg, South Africa - emakoni@uj.ac.za

KEYWORDS: MCDA, GIS, Planning Support Systems, Sinkhole Susceptibility, Dolomite, Land Suitability

Abstract

The occurrence frequency and intensity of many geoenvironmental hazards such as landslides and sinkholes have increased over the years, partly due to climate change. However, the effects of such occurrences and the spread of sinkholes have not been thoroughly explored by researchers in South Africa. Most research shows that water ingress caused by water pipe leakages and water table movements are the common causes that exacerbate the increase of sinkhole occurrences. The Ekurhuleni Municipality is known to have 52% dolomite coverage, affecting most low-income areas in the city. This environmental constraint has caused huge amounts of developable land loss as well as financial loss in the city. Consequently, this study aims to assess the likelihood of sinkholes occurring and their spatial susceptibility, by using the Analytic Hierarchy Process (AHP) as a multi-criteria decision-making method. Nine sinkhole factors were prepared, including dolomite, shallow undermining, proximity to mines, average annual rainfall, hydrology, MSDF (urban development), elevation, soil type, and groundwater yield. Susceptibility maps were then prepared using the GIS-MCDA methodology. The results show that 12% of the city is highly susceptible to sinkhole occurrences, with 20% moderately susceptible, 26% marginally susceptible and 42% not likely to be affected. The highly susceptible areas are mostly located in the southern and northern parts of the city.

1. Background

The current urban and settlement geography of South Africa has been shaped by centuries of inequitable control of access to land and urban spaces. Land dispossession and segregation under colonialism, enforced by policies like the Native Land Act 27 of 1913 and the Group Areas Act 41 of 1950, limited access of black South Africans to well-located land, property ownership and economic opportunity (Bundy, 1979; Feinberg, 1993; Christopher, 1989). Under apartheid planning, an uneven urban geography was created, including townships on the urban fringe, spatial segregation from jobs and poor access to infrastructure and services (Mabin, 1992; Mabin & Smit, 1997; Dewar & Uytenbogaardt, 1991).

The democracy era has seen a planning system set up to resolve these issues of inherent inequality and to create a more integrated, equitable and sustainable settlement pattern. The Constitution of the Republic of South Africa (1996), the Housing Act 107 of 1997 and the National Development Plan 2030 make policy commitments for improvements towards better access to land, housing and sustainable human settlements (Republic of South Africa, 1996; Republic of South Africa, 1997; National Planning Commission, 2012). In particular, the Spatial Planning and Land Use Management Act 16 of 2013 (SPLUMA) has stated spatial justice, spatial sustainability, efficiency and spatial resilience as the key principles of spatial planning (Republic of South Africa, 2013). But it is hard to achieve such goals because there is a difference between land availability and land suitability.

The problem is especially relevant for Ekurhuleni since a large part of its area is underlain by dolomitic formations. Kleinhans (2017) found that approximately 989 km² of the Ekurhuleni Metropolitan Municipality, representing nearly half of its total area, is classified as dolomite land. The study further documented 241 ground-movement incidents between 2005 and mid-2013, with water ingress identified as a significant trigger of dolomite-related sinkholes and subsidences, particularly through sewer lines, leaking water lines, surface water ponding and stormwater infrastructure. The geological structure of dolomitic terrain may create conditions in which there is an increased likelihood of sinkhole formation and ground instability. Risk factors associated with this problem include geological and hydrogeological features, as well as human activities such as variations in groundwater conditions, water ingress and infrastructure leakage (Buttrick et al., 2001; Buttrick et al., 2003; Kleinhans, 2017). Thus, the issue of susceptibility to sinkhole formation is not only a problem of geotechnics but also of spatial planning.

GIS-based MCDA constitutes an appropriate methodology to apply in such cases since susceptibility is a result of interactions between various spatial factors. It is possible to integrate geological, hydrological, topographical, climatic and land-use data using GIS, whereas MCDA allows for weighting and combining these criteria (Malczewski, 1999; Malczewski, 2006). At the same time, AHP provides an approach for applying expert opinion in multi-criteria analysis (Saaty, 1980).

It means that this research has implications that are more than the mere creation of geological risk maps. It may assist in determining the susceptibility of certain areas to inform land-use decisions, guide more precise geotechnical investigations and determine whether some areas are appropriate for construction, while others require mitigation measures or restrictions on development. It may allow for considering the precautionary and sustainability principles inherent in South African planning and environmental systems (Republic of South Africa, 1998; Republic of South Africa, 2013). In the case of historical inequality in urban space, one of the aspects of spatial justice may be ensuring that future human settlements are physically safe and appropriately located.

2. Introduction

2.1 Climate change and sinkholes in urban areas

A sinkhole can be defined as a subsidence structure induced by the collapse of subsurface karst activities or groundwater runoff channels, otherwise known as a near-circular ground collapse (Liu et al., 2023). Furthermore, sinkholes are formed in areas with underlying soluble bedrock, such as limestone (Liu et al., 2023). It has been found that, in recent years, the occurrence of sinkholes has become an increasing concern in areas where susceptible geological conditions intersect with human activities and changing environmental conditions (Taheri et al., 2019; Liu et al., 2023). This increase in sinkhole occurrence can be influenced by both natural and anthropogenic factors, including geological conditions, groundwater processes, rainfall, soil characteristics and human activities that alter natural ground and hydrological conditions (Taheri et al., 2019; Liu et al., 2023). Therefore, acquiring accurate geological and hydrogeological data and identifying potential sinkhole-prone areas are viewed as critical steps in assessing sinkhole susceptibility, supporting urban planning and mitigating the damage caused by ground collapse (Taheri et al., 2019; Liu et al., 2023).

Furthermore, scholars have over the years identified that climate change will have detrimental economic and physical consequences across many human activities (Bulkeley, 2013; Corfee-Morlot et al., 2009). Cities are particularly important in this regard because they are both significant contributors to climate change and highly exposed to its impacts, including extreme rainfall, heat, drought and water-related risks (Bulkeley, 2013; Corfee-Morlot et al., 2009). The Organisation for Economic Co-operation and Development (OECD) analysis has suggested that there is an urgent need to start mitigation and adaptation actions early to reduce future risks and costs (Corfee-Morlot et al., 2009). This will then decrease the impacts of climate change in cities regarding heat waves, intense rainfall, drought and water shortages (Bulkeley, 2013; Corfee-Morlot et al., 2009). These climate-related changes are particularly relevant to sinkhole susceptibility because changes in rainfall patterns, groundwater conditions and water availability can influence the hydrological processes associated with ground instability and sinkhole formation (Liu et al., 2023).

3. Methodology

In this section, we delineate the study area and outline the systematic methodology employed to construct the Sinkhole Susceptibility Index for the City of Ekurhuleni. The approach adopted integrates Geographic Information Systems (GIS) with Multi-Criteria Decision Analysis (MCDA), offering a robust framework for spatial analysis and evidence-based decision-making in urban planning (Hongoh et al., 2011; Musakwa et al., 2017).

By leveraging GIS technology, which allows for the spatial analysis and visualisation of diverse datasets, and MCDA, which facilitates the integration of multiple criteria and their relative importance, our methodology offers a comprehensive and systematic approach to sinkhole susceptibility assessment. This approach aligns with contemporary planning paradigms, emphasizing the importance of data-driven decision-making processes (Hongoh et al., 2011; Musakwa et al., 2017).

Furthermore, our methodology draws on insights from previous studies that have demonstrated the efficacy of GIS-MCDA approaches in urban planning contexts (Hongoh et al., 2011; Musakwa et al., 2017). By synthesizing these methodologies and adapting them to the specific context of the City of Ekurhuleni, our study contributes to the ongoing discourse on evidence-based planning and sustainable urban development.

In summary, the adoption of a GIS-MCDA approach underscores our commitment to employing rigorous and innovative methodologies in urban planning research, with the goal of facilitating informed decision-making processes that enhance the liveability, sustainability, and resilience of urban environments.

3.1 Study Area

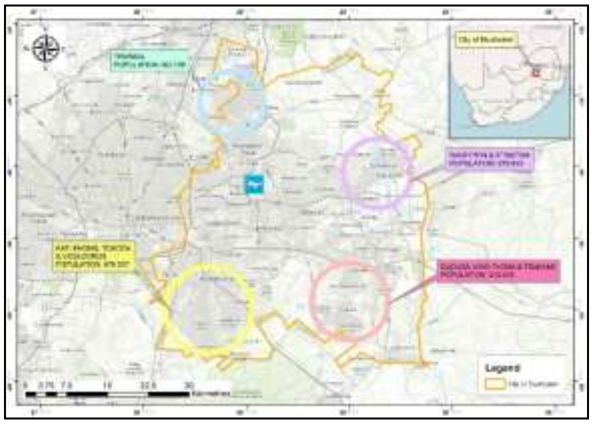

Figure 1: City of Ekurhuleni

The geographic expanse of the City of Ekurhuleni encompasses a conglomeration of nine towns, which include previously designated Black townships. Situated to the east of Gauteng Province in South Africa, Ekurhuleni shares borders with both the City of Johannesburg and the City of Tshwane (Figure 1). Within each town or Central Business District (CBD), there exists a diverse mix of suburban neighbourhoods, industrial zones, and townships. This amalgamated urban area spans approximately 1975 square kilometres and hosts a population of around 3,178,870 inhabitants (City of Ekurhuleni, 2020).

Moreover, it is crucial to acknowledge the complex socio-economic landscape and urban development challenges that characterize the City of Ekurhuleni. Research conducted by Turok and Borel-Saladin (2017) illuminates the spatial inequalities and persistent segregation prevalent in South African cities, including those within the Gauteng Province. Furthermore, studies such as those by Mthembu-Salter and Matyas (2020) underscore the imperative of implementing inclusive urban planning strategies to address the diverse needs of communities within rapidly expanding metropolitan areas like Ekurhuleni.

3.2 Evidence Based Planning

Despite the abundance of available technology, urban planning professionals frequently rely on a diverse array of information sources, including their professional expertise, past experiences, data collection efforts, interactions with community stakeholders and decision-makers, as well as formal education (Krizek, Forsyth, & Slotterback, 2009). However, these sources often lack a clearly defined role in relevant planning research and are not always practical (Krizek, Forsyth, & Slotterback, 2009). Evidence-based planning (EBP) emerges as a crucial approach, aiming to leverage scientific evidence to address urban challenges and inform decision-making (Krizek, Forsyth, & Slotterback, 2009). By shifting away from subjective judgments and towards data-driven analysis, planners can enhance the quality and efficacy of their decisions (Krizek, Forsyth, & Slotterback, 2009). Policymaking increasingly relies on EBP, fostering more informed and robust decision-making processes (Krizek, Forsyth, & Slotterback, 2009)

Moreover, the concept of Planning Support Systems (PSS) aligns closely with evidence-based planning principles, empowering planners with the tools to make informed spatial and land use decisions (Musakwa et al., 2017; Mokoena, Musakwa, & Makoni, 2023). This approach not only instils confidence among practitioners and the public but also enhances professional and political decision-making and fosters greater trust among citizens (Musakwa et al., 2017). From a political perspective, evidence-based planning offers advantages such as improved service delivery through access to accurate, reliable, and current data (Mokoena, Musakwa, & Makoni, 2023).

As cities evolve into smart, digital environments, evidence-based planning remains integral to their development. Digital cities, informed by evidence-based approaches, leverage Planning Support Systems to effectively manage vast quantities of urban data and facilitate informed decision-making. Additionally, the increasing availability of city data enhances the potential success of Planning Support Systems by ensuring that information is channelled effectively for decision-making purposes. This is particularly evident in projects such as creation of a Land Suitability Index for new housing development areas, which utilise data-driven methodologies to optimize land use planning (Mokoena, Musakwa, & Makoni, 2023).

2.2.1 Challenges in Implementing Evidence-Based Planning

While evidence-based planning offers numerous benefits, its implementation poses several challenges for urban planners. One key challenge is the availability and quality of data. Despite advancements in data collection technologies, gaps and inconsistencies in data often persist, hindering the accuracy and reliability of planning decisions (Malczewski, 2006; Musakwa et al., 2017). Furthermore, integrating diverse data sources and ensuring their compatibility can be technically challenging and resource-intensive (Malczewski, 2006; Musakwa et al., 2017).

Moreover, cultural and institutional barriers within planning organizations may impede the adoption of evidence-based approaches, as traditional decision-making processes and biases may resist data-driven methodologies (Krizek, Forsyth, & Slotterback, 2009). Resistance to change and a lack of expertise in data analysis techniques can also hinder the effective utilization of evidence in planning processes (Malczewski, 2006).

Overcoming these challenges requires concerted efforts to improve data infrastructure, foster a culture of evidence-based decision-making, and provide training and support for planners to effectively utilize data in their practices (Malczewski, 2006; Krizek, Forsyth, & Slotterback, 2009). Collaboration between planners, researchers, policymakers, and technology providers is essential to address these challenges and advance the integration of evidence-based approaches in urban planning (Mokoena, Musakwa, & Makoni, 2023). The success of integrating data-driven methodologies in projects such as the development of a Land Suitability Index for housing in Ekurhuleni underscores the importance of such collaborative efforts (Mokoena, Musakwa, & Makoni, 2023).

3.3 Criteria Selection

The process of selecting criteria was informed by a range of literature spanning human settlements, urban planning, smart cities, and national policies such as the National Development Plan (NDP), in addition to considering the specific needs of the City of Ekurhuleni (UN-Habitat, 2010; National Research Council, 2009; Malczewski, 2006). This inclusive approach ensured that the chosen criteria were comprehensive and aligned with both theoretical frameworks and practical considerations. To streamline the selection process and enhance clarity, the initial pool of criteria was condensed to nine key factors, aiming to mitigate complexity and eliminate redundancy. Furthermore, a paramount consideration throughout this process was to ensure that the chosen criteria were logically coherent and directly linked to the overarching objective of assessing sinkhole susceptibility within the City of Ekurhuleni.

The final criteria, presented in table 1, comprised dolomite, rainfall, hydrology, groundwater yield, shallow undermining, soil type, proximity to mines, MSDF development status (built-up/non-built-up), and slope/elevation. Their inclusion reflects the understanding that sinkhole susceptibility is not determined by a single factor, but by the interaction of geological conditions with groundwater, surface-water processes, climatic conditions, terrain characteristics and human interventions. The selection of these criteria was therefore aligned with the objective of developing a spatially explicit susceptibility index for Ekurhuleni.

Expanding upon this discussion, the selection of criteria should incorporate relevant expert knowledge and existing evidence to ensure that the identified criteria appropriately reflect the environmental and spatial conditions associated with the phenomenon being assessed (Malczewski, 2006; Saaty, 2008). The selected criteria were subsequently subjected to AHP pairwise comparison to determine their relative priority weights and rankings. The resulting priority weights and rankings are presented in Table 1 and were subsequently incorporated into the GIS-MCDA analysis.

Category	Priority	Rank
Dolomite	15.5%	1
Rainfall	12.4%	2
Hydrology	12.4%	2
Groundwater yield	12.4%	2
Shallow undermining	11.5%	5
Soil type	11.5%	6
Mines	11.5%	6
MSDF (Built up/none built up)	7.4%	8
Slope/Elevation	5.5%	9

Table 1: AHP Pairwise Comparison Results

3.4 Computing the Sinkhole Susceptibility Index

To derive the Sinkhole Susceptibility Index, we employed the Weighted Linear Combination (WLC) method within ArcGIS software. This approach computes the total score (Si) representing the developability of each land unit using the equation:

$$Si = \sum_{i=1}^{n} w_i \cdot x_i \quad (1)$$

where Si = total sinkhole susceptibility score,
Wi = weight of each criterion, and
Xi = value of each criterion for the land unit.

This method allows us to integrate all nine selected criteria and assign appropriate weights to each, thereby providing a comprehensive assessment of sinkhole susceptibility.

The Weighted Linear Combination approach is widely used in GIS-based multi-criteria analysis because it enables multiple weighted criteria to be integrated into a single composite spatial index (Malczewski, 2006; Musakwa et al., 2017). The incorporation of criterion weights is particularly important because it reflects the relative contribution of each of the nine selected criteria to the overall assessment of sinkhole susceptibility.

The Sinkhole Susceptibility Index was reclassified to a range of 1–10, where 1 represents the lowest level of suitability and 10 represents the highest level of suitability for development from a sinkhole susceptibility perspective. Field validation visits were also conducted to determine the accuracy of the Sinkhole Susceptibility Index.

3.5 Assigning Criteria Rule Sets and Mapping

This phase of the study involved the acquisition of spatial data about the selected criteria and the formulation of rule sets. Spatial data predominantly sourced from the Council of Geosciences and the City of Ekurhuleni constituted the primary dataset for this research endeavour.

Following data acquisition, the information was processed and stored within a geodatabase for subsequent analysis. Rule sets corresponding to each of the nine selected criteria were then identified based on existing literature, as highlighted by Musakwa et al. (2017). Utilizing these rule sets, thematic maps were generated for each criterion, with categorizations ranging from 1 to 4 on a susceptibility scale. In this scale, a rating of 4 indicates areas not likely to be affected by sinkhole occurrences, whereas a rating of 1 signifies areas highly susceptible to such events. The criteria, rule sets and corresponding susceptibility ratings are presented in Table 2. Notably, the categorization process was guided by relevant literature, with the original unverified citation replaced by (Malczewski, 2006; Musakwa et al., 2017).

By integrating the nine selected criteria and their respective rule sets, the study aimed to delineate and characterize land parcels susceptible to sinkhole occurrences. Furthermore, an assessment of the pairwise matrix revealed a consistency ratio of 1.2, indicating a level of inconsistency in the pairwise comparisons. Nevertheless, the resulting weights were retained for the purpose of the Sinkhole Susceptibility Index and interpreted in conjunction with the broader GIS-MCDA framework.

The integration of literature-based rule sets, AHP weighting and GIS-based spatial analysis provides a systematic framework for assessing spatial variations in sinkhole susceptibility (Malczewski, 2006; Saaty, 2008; Musakwa et al., 2017). This approach strengthens the transparency of the Sinkhole Susceptibility Index and supports its use as a strategic spatial screening and planning support tool.

Criteria	Highly Susceptible (4)	Moderately Susceptible (3)	Marginally Susceptible (2)	Insusceptible (1)
Dolomite	Areas without dolomite	N/A	N/A	N/A
Shallow Undermining	>3km	1-3km	1-2km	<1km
Proximity to Mines	>15km	10-15km	5-9km	<5km
Average annual rainfall	>500 mm	400-500 mm	400-300 mm	<200 mm
Hydrology (rivers/wetlands	>3km	1-3km	1-2km	<1km
MSDF – Urban development (Built-up Areas-Non-Built Up)	Built-Up Areas	N/A	N/A	N/A
Elevation	1200-2000m	200-400m	401-1200m or 2001-2500m	Sea level, <200m or N2500m
Soil Type	Favourable structure	Somewhat favourable	Marginally favourable	Unsuitable
Ground Water Yield	Fractured 0.1-0.5 l/s	Fractured 0.5-2.0 l/s	Intergranular and Fractured 5.0 l/s-0.5 l/s	Karst>5.0 l/s;2.0-5.0 l/s

Table 2: Criteria Rule Sets

4. Results

Figure 2 displays the Sinkhole Susceptibility Index on a scale of 1–4, where 1 is defined as highly susceptible to sinkholes, 2 as moderately susceptible, 3 as marginally susceptible and 4 as insusceptible (not likely to be affected).

Further discussion on specific criteria reveals their relative importance in assessing sinkhole susceptibility. For instance, dolomite presence emerged as the most critical criterion, with a priority ranking of 15.5%, highlighting its substantial influence on land vulnerability. Similarly, factors such as rainfall, hydrology, and water table elevation garnered considerable importance, reflecting their significant contributions to sinkhole formation processes.

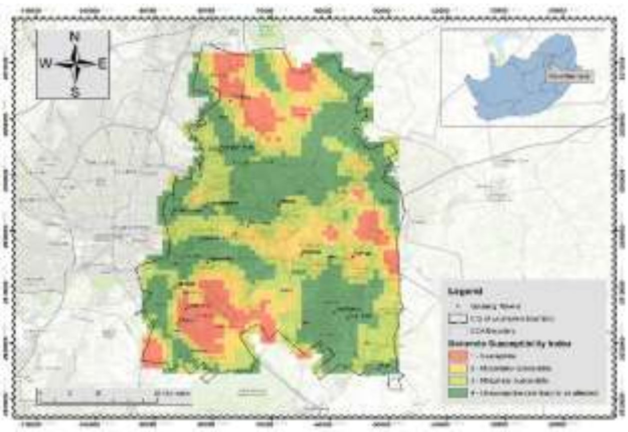

Figure 2: Sinkhole Susceptibility Index

Table 3 shows the percentage of areas that are susceptible to sinkholes in the City of Ekurhuleni. The results show that 12% of the city is highly susceptible to sinkhole occurrences, with 20% moderately susceptible, 26% marginally susceptible and 42% not likely to be affected. The highly susceptible areas are mostly located in the southern and northern parts of the city, namely Tembisa in the north and Katlehong, Thokoza and Vosloorus in the south.

Sinkhole Susceptibility Classes	Sinkhole Susceptibility Index	Hectors	Percentage
Highly Susceptible	1	22827	12%
Moderately Susceptible	2	38700	20%
Marginally Susceptible	3	50517	26%
Insusceptible (not likely to be affected)	4	82259	42%

Table 3: Sinkhole susceptibility percentage

The relationship between the spatial distribution of sinkhole vulnerability and the history of the formation of the settlement pattern in Ekurhuleni also has some significant implications. As the results show, 12% of the municipal area has high vulnerability, while some of the zones most vulnerable to sinkholes are located in the north and south of the municipality, specifically in Tembisa, Katlehong, Thokoza, and Vosloorus. These zones are characterized by large settlements which have a long history of marginalization in terms of the allocation of strategic land in urban areas (Turok & Borel-Saladin, 2018).

Thus, the obtained results show that the interaction between geotechnical risks and an already existing unequal urban area takes place. In the metropolitan area with a long-standing history of discrimination and unequal access of the historically marginalized populations to strategically located land and urban opportunities, the presence of land prone to sinkholes can create additional obstacles for development. However, these findings do not imply that historically marginalized zones were deliberately located in the zones of high vulnerability.

As far as planning is concerned, this highlights the need for sinkhole susceptibility data to be incorporated into decision-making regarding future land development and investment. Sites with a high susceptibility will require extensive investigation and/or mitigation measures for specific types of development, while sites with moderate susceptibility will need further assessment prior to development. On the other hand, sites with low susceptibility can present greater opportunities for development based on other considerations (Musakwa et al., 2017; Mokoena, Musakwa & Makoni, 2023).

In summary, the results are not limited to the delineation of physical hazard zones. They offer spatial data that can help municipalities make more rational decisions regarding future development and environmental factors that could affect them. In the case of South Africa's ongoing effort to build more integrated and equitable settlements, the early identification of geotechnical risks is especially relevant because it can help prevent the establishment of development projects that may expose communities to future risks and costs. In this sense, the Sinkhole Susceptibility Index generated from this study can become an important planning tool that will allow environmental risk to be considered at an early stage in the identification and planning process (Musakwa et al., 2017; Mokoena, Musakwa & Makoni, 2023).

5. Discussion

The findings of this study demonstrate the benefit of integrating GIS, MCDA and AHP to evaluate the spatial susceptibility to sinkholes in the City of Ekurhuleni. The results confirm that sinkhole susceptibility varies across the municipality and is influenced by the interaction between geological, hydrological, climatic, topographical, soil and land-use characteristics. Among the criteria assessed, dolomite rock emerged as the most important criterion, with a priority weight of 15.5%, followed by rainfall, hydrology and water table. The application of the Sinkhole Susceptibility Index therefore provides a systematic and spatially explicit approach to understanding how these multiple environmental conditions interact to influence development risk.

The results reveal clear spatial differences in susceptibility across Ekurhuleni. Approximately 12% of the municipal territory was classified as highly susceptible, 20% as moderately susceptible, 26% as marginally susceptible and 42% as not likely to be affected. These findings are particularly important for spatial planning because they indicate that nearly one third of the municipal area, representing 32%, has high or moderate susceptibility to sinkhole occurrence and therefore requires particular attention in land-use planning and development decision-making. At the same time, the 42% of the municipality that is not likely to be affected represents an important spatial opportunity. However, the absence of sinkhole susceptibility does not automatically guarantee land suitability for development, as such areas must still be assessed in relation to infrastructure, environmental conditions, accessibility, land use and socio-economic factors.

The spatial distribution of susceptibility also raises important considerations regarding the relationship between environmental risk and inherited urban patterns. Highly susceptible areas are predominantly located in the north and south of Ekurhuleni, including areas such as Tembisa, Katlehong, Thokoza and Vosloorus. These are large and well-developed areas with a history of spatial marginalisation. The findings should not be interpreted as evidence that historically disadvantaged communities were deliberately located in areas with sinkhole risk. Rather, they demonstrate an important intersection between the inherited urban fabric and the environmental limitations of the municipality. Communities that were historically disadvantaged in terms of access to strategically located urban land may face additional development constraints where geotechnical hazards overlap with existing patterns of urban marginalisation.

This reinforces the distinction between land availability and land suitability. Land in Ekurhuleni cannot be regarded as suitable for human settlement simply because it is vacant, accessible or identified for development. The 12% of land classified as highly susceptible and the 20% classified as moderately susceptible require more detailed geotechnical and hydrogeological investigations before development decisions are made. Depending on site-specific conditions, development may require appropriate engineering solutions or, in some instances, restrictions on development. Similarly, the 26% classified as marginally susceptible should not be regarded as automatically suitable, but rather as land requiring further assessment. The 42% not likely to be affected presents better opportunities for development investigation, subject to the

https://doi.org/10.5194/isprs-archives-L-4-W3-2026-99-2026

assessment of other suitability conditions. In this regard, the index serves as a strategic screening tool for identifying areas that require further investigation as well as areas that may present relatively better development opportunities.

The findings also have practical implications for evidence-based spatial planning and human settlement development. The susceptibility index can function as a Planning Support System by providing municipalities with spatial evidence during the early stages of land identification, spatial planning and infrastructure investment. Rather than responding to sinkhole risks only after development has taken place, the index supports preventive decision-making by identifying higher-risk areas that require further investigation and directing attention towards safer development options. This is particularly relevant to the principles of spatial justice, spatial sustainability and spatial resilience established by SPLUMA (Republic of South Africa, 2013).

Importantly, the findings emphasise that environmental safety should be considered as an integral component of spatial transformation. Spatial justice should not be limited to improving access to housing and urban land, but should also include access to safe, environmentally appropriate and sustainable land. The identification of 32% of Ekurhuleni as highly or moderately susceptible is therefore not only a technical finding but represents a significant constraint for future human settlement development, infrastructure investment and urbanisation. Conversely, the 42% of the municipal area that is not likely to be affected provides an evidence base for investigating alternative development opportunities where other land suitability conditions are favourable.

The study nevertheless acknowledges that the Sinkhole Susceptibility Index is a strategic-scale analysis and does not substitute for site-specific geotechnical investigations. The accuracy of the index remains dependent on the availability, spatial resolution and temporal accuracy of the datasets, as well as the validity of the assumptions underlying the classification and weighting of the criteria. Future studies should incorporate more detailed geological and hydrogeological data, recent climate data, complete sinkhole inventories, infrastructure leakage information, remote sensing and additional field validation. The inclusion of sensitivity and uncertainty analysis would further strengthen the robustness of the index classifications.

6. Conclusion

This study reveals the benefit of the use of GIS, MCDA and AHP to evaluate sinkhole susceptibility in the City of Ekurhuleni. The Sinkhole Susceptibility Index demonstrates clear spatial differences, with 12% of the municipality classified as highly susceptible, 20% moderately susceptible, 26% marginally susceptible and 42% not likely to be affected. The findings provide important evidence for distinguishing between land availability and land suitability and for integrating geological and environmental risk into land-use planning, infrastructure development and human settlement decision-making.

Overall, the study demonstrates that sinkhole susceptibility should be considered during the spatial planning process as a criterion for land development planning rather than as a technical issue addressed only once development has been completed. Through considering geological and climatic risks in planning for land, infrastructure and human settlements, GIS-MCDA can enable spatial planning to move from reactive hazard management to preventive and science-based spatial transformation.

The scientific significance of this study therefore lies not only in quantifying where sinkhole susceptibility occurs, but in revealing how geospatial evidence can expose the intersection of environmental risk and inherited spatial inequality, enabling future development to move beyond reproducing patterns of constrained opportunity towards safer, more resilient and more equitable urban territories.

Acknowledgements

We would like to acknowledge the South African National Research Foundation (NRF) for funding this study, Grant No. 138145 and No. CHN22111671544, and No. BRIC231109162268.

References

Bulkeley, H. (2013) *Cities and Climate Change. Abingdon: Routledge*. doi: 10.4324/9780203077207.

Buttrick, D.B., Trollip, N.Y.G., Watkeys, M.K., Hobbs, P.J., van Schalkwyk, A. and Pieterse, N. (2001) '*A geological and geotechnical assessment of the stability of dolomite land in South Africa', Environmental Geology*, 40, pp. 547–553.

Buttrick, D.B., van Schalkwyk, A., *Theron, E. and de Jager, E. (2003) A Guide to Practical Applications of the National Standard for Dolomite Land*. Pretoria: Council for Geoscience.

Christopher, A.J. (1989) *Land Reform and the South African City*. Johannesburg: Witwatersrand University Press.

City of Ekurhuleni (2020) *Integrated Development Plan 2020/21.* Germiston: City of Ekurhuleni Metropolitan Municipality.

Corfee-Morlot, J., Kamal-Chaoui, L., Donovan, M.G., Cochran, I., Robert, A. and Teasdale, P.-J. (2009) *Cities, Climate Change and Multilevel Governance*. OECD Environment Working Papers, No. 14. Paris: OECD Publishing. doi: 10.1787/220062444715.

Dewar, D. and Uytenbogaardt, R.S. (1991) *South African Cities: A Manifesto for Change*. Cape Town: University of Cape Town Press.

Feinberg, H. (1993) *The African Land Question: A Historical Perspective.* Johannesburg: Wits University Press.

Hongoh, V., Hoen, A.G., Aenishaenslin, C., Waaub, J.-P., Bélanger, D., Michel, P. and the Lyme-MCDA Consortium (2011) *'Spatially explicit multi-criteria decision analysis for managing vector-borne diseases', International Journal of Health Geographics*, 10, p. 70. doi: 10.1186/1476-072X-10-70.

Kleinhans, I. (2017) *Rehabilitation of sinkholes and subsidences on Dolomitic Land Ekurhuleni Metropolitan Municipal Area of Jurisdiction Gauteng South Africa.* PhD thesis. Pretoria: University of Pretoria. Available at: http://hdl.handle.net/2263/63306.

Krizek, K.J., Forsyth, A. and Slotterback, C.S. (2009) *'Is there a role for evidence-based practice in urban planning and* *policy?', Planning Theory & Practice,* 10(4), pp. 459–478. doi: 10.1080/14649350903417241.

Liu, R., Sun, H., Qin, J. and Zheng, Z. (2023) *'A multi-geophysical approach to assess potential sinkholes in an urban area',* Engineering Geology, 318, 107100. doi: 10.1016/j.enggeo.2023.107100.

Mabin, A. (1992) *'Comprehensive segregation: The origins of the Group Areas Act and its planning implications',* Journal of Southern African Studies, 18(2), pp. 405–429.

Mabin, A. and Smit, D. (1997) *'Reconstructing South Africa's cities? The making of urban planning 1900–2000'*, Planning Perspectives, 12(2), pp. 193–223.

Malczewski, J. (1999) *GIS and Multicriteria Decision Analysis*. New York: John Wiley & Sons.

Malczewski, J. (2006) *'GIS-based multicriteria decision analysis: A survey of the literature'*, International Journal of Geographical Information Science, 20(7), pp. 703–726. doi: 10.1080/13658810600661508.

Mokoena, B.T., Musakwa, W. and Makoni, E.N. (2023) '*Creating a land suitability index for the new priority human settlements & housing development areas: A focus on Ekurhuleni, South Africa', The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-1/W2-2023, pp. 553–558.* doi: 10.5194/isprs-archives-XLVIII-1-W2-2023-553-2023.

Musakwa, W. (2017) *'Data on strategically located land and spatially integrated urban human settlements in South Africa',* Data in Brief, 15, pp. 805–808. doi: 10.1016/j.dib.2017.10.044.

Musakwa, W., Tshesane, R.M. and Kangethe, M. (2017*) 'The strategically located land index support system for human settlements land reform in South Africa'*, Cities, 60, pp. 91–101. doi: 10.1016/j.cities.2016.08.007.

National Planning Commission (2012) *National Development Plan 2030: Our Future – Make It Work*. Pretoria: National Planning Commission.

National Research Council (2009) *Informing Decisions in a Changing Climate.* Washington, DC: The National Academies Press. doi: 10.17226/12626.

Republic of South Africa (1996) *Constitution of the Republic of South Africa, 1996.* Pretoria: Government Printer.

Republic of South Africa (1997) *Housing Act 107 of 1997.* Pretoria: Government Printer.

Republic of South Africa (1998) *National Environmental Management Act 107 of 1998*. Pretoria: Government Printer.

Republic of South Africa (2013*) Spatial Planning and Land Use Management Act 16 of 2013.* Government Gazette, 36730. Pretoria: Government Printer.

Richardson, S. (2013) *Sinkhole and subsidence record in the Chuniespoort Group dolomite, Gauteng, South Africa.* MSc dissertation. Pretoria: University of Pretoria.

Saaty, T.L. (1980) *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation.* New York: McGraw-Hill.

Saaty, T.L. (2008) *'Decision making with the analytic hierarchy process',* International Journal of Services Sciences, 1(1), pp. 83–98. doi: 10.1504/IJSSCI.2008.017590.

Taheri, K., Shahabi, H., Chapi, K., Shirzadi, A., Gutiérrez, F. and Khosravi, K. (2019) *'Sinkhole susceptibility mapping: A comparison between Bayes-based machine learning algorithms', Land Degradation & Development, 30(7), pp. 730–745.* doi: 10.1002/ldr.3255.

Turok, I. and Borel-Saladin, J. (2017) *'The spatial dynamics of inequality in South Africa: The case of Gauteng',* Urban Studies, 54(3), pp. 585–602.

Turok, I. and Borel-Saladin, J. (2018) *'The theory and reality of urban slums: Pathways-out-of-poverty or cul-de-sacs?',* Urban Studies, 55(4), pp. 767–789. doi: 10.1177/0042098016671109.

UN-Habitat (2010) *The State of African Cities 2010: Governance, Inequality and Urban Land Markets.* Nairobi: United Nations Human Settlements Programme.