Karst geomorphology and related environmental problems in Southern Africa – A review

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Highlights

- Karst is a landscape that has developed on soluble rocks such as carbonates, and some partially soluble non-carbonate rocks.
- In southern Africa, karst is abundant in the interior of the region, while coastal karst is sparsely distributed.
- Human impacts such as mining, construction, agriculture, as well as climate change threaten karst in the region.

Abstract

Globally many valuable karst resources are under severe threat due to anthropogenic activities. This paper presents a review of the geomorphology of karst landforms including caves, sinkholes, etc. in southern Africa. It further presents the environmental threats and challenges faced by these karst landscapes, their genesis and controlling factors, as well as their possible mitigation and remedial measures. The karst landscapes in the region are most abundant in the interior of the sub-continent, whereas coastal karst is sparsely distributed, and is mainly found in the Eastern and Western Cape, and Kwa-Zulu Natal provinces of South Africa, as well as parts of Namibia. The karst of the interior is largely limited to the Proterozoic dolomitic limestone, while coastal karst is formed in the Tertiary coastal limestone and Quaternary calcareous sandstones. The human impacts threatening karst in southern Africa include mining and mineral extraction, construction and development, agricultural activities, climate change, and changes in the local hydrogeology. Anthropogenic impacts have particularly affected the karst landscape of the Gauteng and northern Free State Provinces of South Africa due to groundwater extraction associated with mining. Changes in land use and water management, consequential to development pressures and a variety of climate change scenarios, are the most significant threats currently facing southern African karst terrain. It is argued that sustainable engineering technologies, informed by sound geomorphological research, are necessary to ensure that future development, property, and life on karst terrain are safe from avoidable environmental problems.

Keywords: Karst; Dolomite; Environmental problems; Southern Africa; Limestone

1. Introduction

Karst terrain may be defined as landscapes that have developed on soluble rocks such as carbonates (limestone, dolomite and marble), evaporite rock (anhydrite, gypsum, and halite), and some partially soluble non-carbonates such as quartzite and siliceous sandstones (Ford and Williams, 2007; Lewin and Woodward, 2009; Goldscheider et al., 2020). These terrains are normally characterized by the existence of surface landforms such as dolines, poljies, and sinkholes. Their subsurface features include underground conduits and voids which may develop into caves, and extensive subsurface water systems (Stevanović, 2015; Parise et al., 2018; Fiorillo and Malik, 2019). Evaporite seldom forms surface karst, but is often embedded between other rock types. Apart from 'true' karst, there are karst-like or 'pseudokarst' landscapes which resemble karst topography which is however, a result of non-dissolution processes (Brink, 1985; Ford and Williams, 2007; Holler, 2019). Thermokarst, lava tubes, and soil piping are some examples of pseudokarst land features. The debate concerning karst formed on sandstone is, however, highly complex due to many sandstones being (at least to some degree) calcareous, thus raising the question of the percentage of carbonate mineral required for the development of 'true' karst as opposed to pseudokarst.

Although the global distribution of karst is not even (Fig. 1), with a dense distribution in the Middle East, Europe, North America, southern Africa, and southeast Asia, it is important to note that karst terrain is found across all continents (Ford and Williams, 2007; Chen et al., 2017; Goldscheider et al., 2020). Karst terrains form spectacular surface and subsurface landscape features due to their interaction with groundwater and surface water systems. Of the common carbonate rocks, limestone and dolomite are the most abundant (Ford and Williams, 2007), although dolomite karst systems are less common, and less exploited compared to their limestone counterparts (Narany et al., 2019). Limestone often forms along with dolomite, with dolomitization and de-dolomitization being the major process for the alteration of one limestone to dolomite, and dolomite to limestone respectively (Evamy, 1967; Mcneill and Kmschvn, 1993; Warren, 2000; Mehmood et al., 2018).

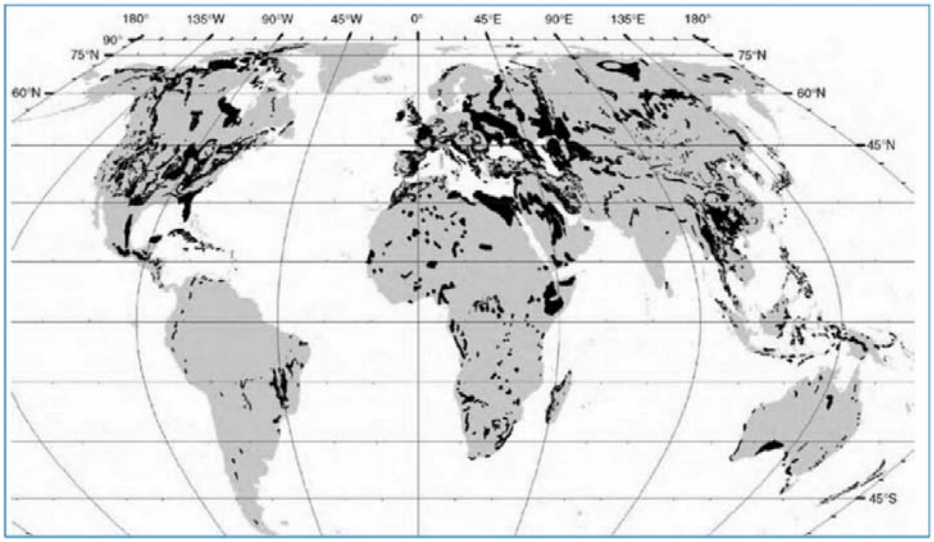

Fig. 1. The global distribution of carbonate outcrops (Ford and Williams, 2007).

In many areas of sedimentary rock, groundwater is in contact, and interacts with, carbonate minerals, of which more than half of these carbonates are dolomite. Over 20% of the world's population depends largely on the groundwater found in karst substrates (Singurindy and Berkowitz, 2003; Ford and Williams, 2007; Stevanović, 2018; Olarinoye et al., 2020). This is especially true for Europe, where for some countries, more than 50% of their potable water supply is received from karst areas (Hartmann et al., 2014; Olarinoye et al., 2020). A number of areas in southern Africa, such as Botswana, northern Namibia, Gauteng and the North West Provinces of South Africa also rely heavily on groundwater contained in karstic aquifers (Holland and Witthüser, 2009; Haarhoff et al., 2012; Cobbing and De Wit, 2018; McGill et al., 2019). The groundwater quality is, however, affected by the water-carbonate rock interactions with dissolution (including impurities due to trace elements), and precipitation being the two major processes affecting water chemistry (Singurindy and Berkowitz, 2003; Stevanović, 2015). These processes affect the water pH, redox potential, electrical conductivity and total dissolved solids, which are all important parameters of water quality. While dolomite is dominated by $CaMg(CO_3)_2$, it contains many impurities, including manganese (Mn), iron oxide (FeO), silicate (SiO_2), pyrite (FeS), and zinc (Zn), which further affect the water quality and the local geomorphology (Marker, 1970; Button, 1973, 1975; Martini and Kavalieris, 1976; Eriksson et al., 1995; Franchi, 2018).

The already mentioned de-dolomization is an important process in carbonate rock. It is described as a process whereby dolomite dissolution is coupled with calcite precipitation and the liberation of magnesium into solution (Evamy, 1967; Warren, 2000; Mehmood et al., 2018). In simple terms, dolomite in water, decomposes into its constituents; which are $CaCO_3$ and Mg^{2+} in the aqueous phase. $CaCO_3$ is then re-precipitated as calcite replacing the parent dolomite, and Mg^{2+} remains in solution, in the magnesium-rich aqueous phase (Equation (1)). In impure dolomites however, the chemistry of Mn, Fe, and SiO_2 has to be taken into consideration, especially in the southern African dolomites where the Mn content is considerable (and is the source for some of the region's Mn ores). Due to the volume and flow rate of water, the dissolution of dolomite and precipitation of calcite may vary in both rate and location, thus forming voids (e.g. caves, and ultimately sinkholes (Palmer, 2007; Parise, 2019);) in areas of dissolution, and deposits (speleothems) in areas of precipitation (Ford and Williams, 2007). Consequently, karst landscapes also host the largest proportion of cave systems in the world, which are important as habitat for some plant and animal species (Ford and Williams, 2007; Holland and Witthüser, 2009; Hobbs and de Meillon, 2017).

$$CaMg(CO_3)_2 + 2H^+ \leftrightarrow Ca^{2+} + Mg^{2+} + 2HCO_3^- \leftrightarrow Ca(CO_3) + Mg^{2+} + 2H^+ \quad (1)$$

$$CaMg(CO_3)_2 + Ca^{2+} \leftrightarrow 2Ca(CO_3) + Mg^{2+} \quad (2)$$

In addition to de-dolomization being caused by the interaction of dolomite with groundwater systems, de-dolomization may also be caused by the infiltration of calcium-rich surface water into dolomitic rock. Since Ca^{2+} has a higher affinity to the CO_3^{2-} ion compared to Mg^{2+}, the Mg^{2+} ion is displaced from the dolomite complex (Equation (2)), thus resulting in the formation of two $CaCO_3$ molecules and the liberalization of the Mg^{2+} ion into solution (Evamy, 1967). De-dolomization through this process does not involve the classic dissolution and precipitation reactions previously outlined, but rather a displacement reaction. As a result of these processes, carbonate rock often exists as a mixture of the two minerals, dolomite and calcite (Fig. 2) in different proportions (Warren, 2000; Singurindy and Berkowitz, 2003). A classification scheme based on the bulk composition of the carbonate rock may be used to classify the resulting rock type (Ford and Williams, 2007) (Fig. 2). According to the proportion of dolomite to calcite in this classification, dolomite may range from being pure dolomite to calcareous dolomite, dolomitic limestone, and ultimately pure calcite, where all or more than 90% has transformed to calcite.

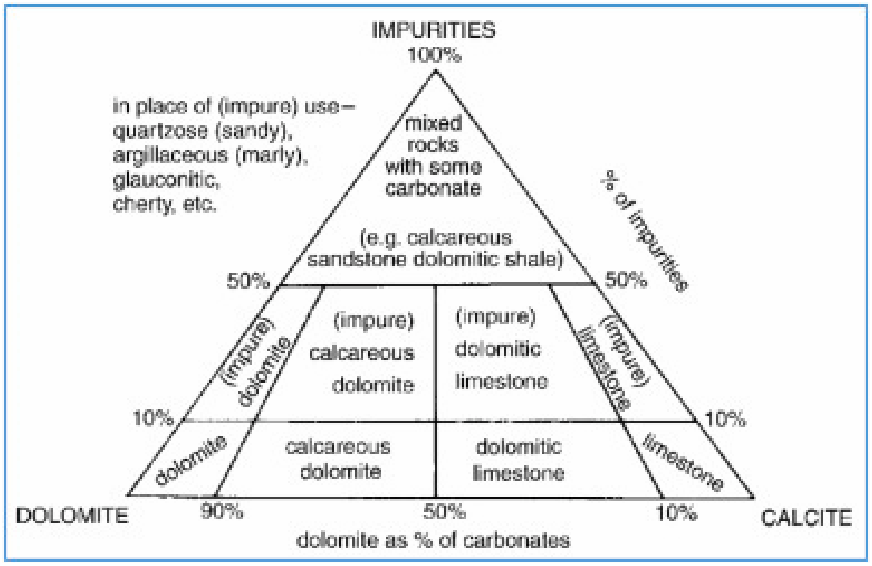

Fig. 2. The bulk compositional classification of carbonate rock (Ford and Williams, 2007).

In southern Africa, karst terrain on carbonate rock covers an area of approximately 50 000 km^2 (Marker and Gamble, 1987). The karst in this region is found to be very distinct from the typical karst found in Europe and America because of largely the composition of the carbonate rock found in this region, which is rich in siliceous iron and manganese (Truswell and Eriksson, 1975; Martini and Kavalieris, 1976). The climatic history of the region is also thought to have been a factor contributing to the distinct nature of these dolomites, resulting in their characteristic 'elephant hide' weathering (Almond, 2012). This unique nature of southern African karst evokes interest in the karst landscapes of the region, including its origin and geomorphological dynamics.

The aim of this paper is to present a review of the karst landforms in southern Africa, the environmental problems facing these landscapes in the region, as well as some karst management approaches that are used in some parts of southern Africa. The southern African region referred to in this paper includes; South Africa, Botswana, Namibia, Lesotho and Eswatini (formerly known as Swaziland). Most of the work on karst in southern Africa was published before the Republic of South Africa re-classified its provinces. For that reason, reference is often made to the Transvaal Province, although the Transvaal Province now contributes to four provinces, namely Mpumalanga, Gauteng, North West and Limpopo Province.

2. Karst landforms and their geographic distribution in Southern Africa

2.1. Geographic distribution of surface and subsurface karst features

In southern Africa, karst topography may be divided into two classes: the Proterozoic dolomitic limestones found in the interior plateaux, and the Cenozoic coastal limestones found on the region's coastal areas (Marker and Gamble, 1987) (Fig. 3). The karst areas found in the interior plateaux include the karst on the Transvaal Supergroup dolostone, karst on the Cango Cave Supergroup limestone, and karst in other areas such as Namibia. Besides the active karst area, paleokarst features are known to be present in some provinces of South Africa which include; Gauteng, Mpumalanga, Northern Cape, and the North West (Martini, 2006). The Cenonoic coastal karst is found along the southern coast and covers karst found in the Eastern, and Western Cape, as well as the Kwa-Zulu Natal Provinces of South Africa (Fig. 3).

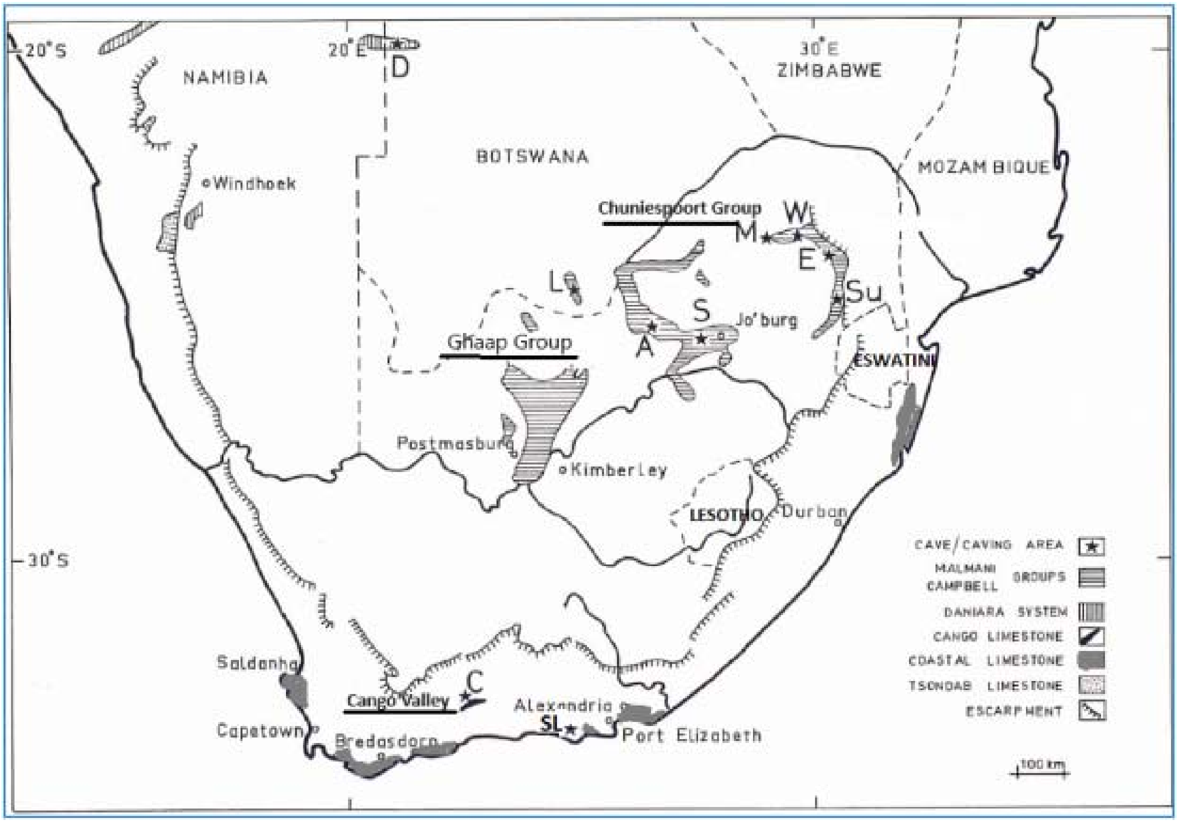

Fig. 3. The distribution of Karst landforms in southern Africa (modified after Marker and Gamble, 1987).

There are three major dolomite deposit basins that are found in the interior (the Proterozoic dolomitic limestones). These deposits are all found on the Kaapvaal craton, and were formed during the Late Archaean to Early Proterozoic (Altermann and Wotherspoon, 1995). These basins include the Transvaal Basin (Chuniespoort Group dolomites) Griqualand West Basin (Ghaap Group dolomites), and the Kanye Basin, with the Transvaal Basin being the largest of the three basins (Franchi and Mapeo, 2019). The Malmani and Campbell dolomite groups of the Transvaal Supergroup cover the largest karst area of the southern African region (Fig. 3).

These dolomite formations cover an area of approximately 31 000 km^2 and account for some 63 % of the total karst area in southern Africa.

2.2. The karst of the Chuniespoort Group

One of the major karst terrains in southern Africa is that of the Chuniespoort Group (Transvaal Supergroup) found in the old Transvaal Province, now found across the provinces of Mpumalanga, Gauteng, Limpopo, and the northern Free State (Marker, 1970; Martini and Kavalieris, 1976; Marker and Gamble, 1987; Eriksson et al., 1995; Martini, 2006) (see Fig. 3, Fig. 4). This is ascribed to the Malmani Subgroup, which is a Precambrian dolomite covering approximately 14 000 km^2 (Martini and Kavalieris, 1976). It is rich in chert layers, manganese and iron (Martini, 2006). Limestone is only found in some areas, near the top of the formation. This dolomite has gone through four geological periods of formation over its more than 2.2 billion year history (Martini and Kavalieris, 1976). These periods include the Pre-Pretoria Group period, the Pre-Waterberg Group period, and the Pre-Karoo and Cenozoic or Recent periods. While most of the ancient karst has eroded over time, there are still remnants of a fossil karst landscape, dating from arguably the oldest karst forms in the world (Martini and Kavalieris, 1976; Partridge and Maud, 1987; Partridge and Watt, 1991; Edwards et al., 2020). The karst landscapes found here include karst caves such as the Sudwala Caves.

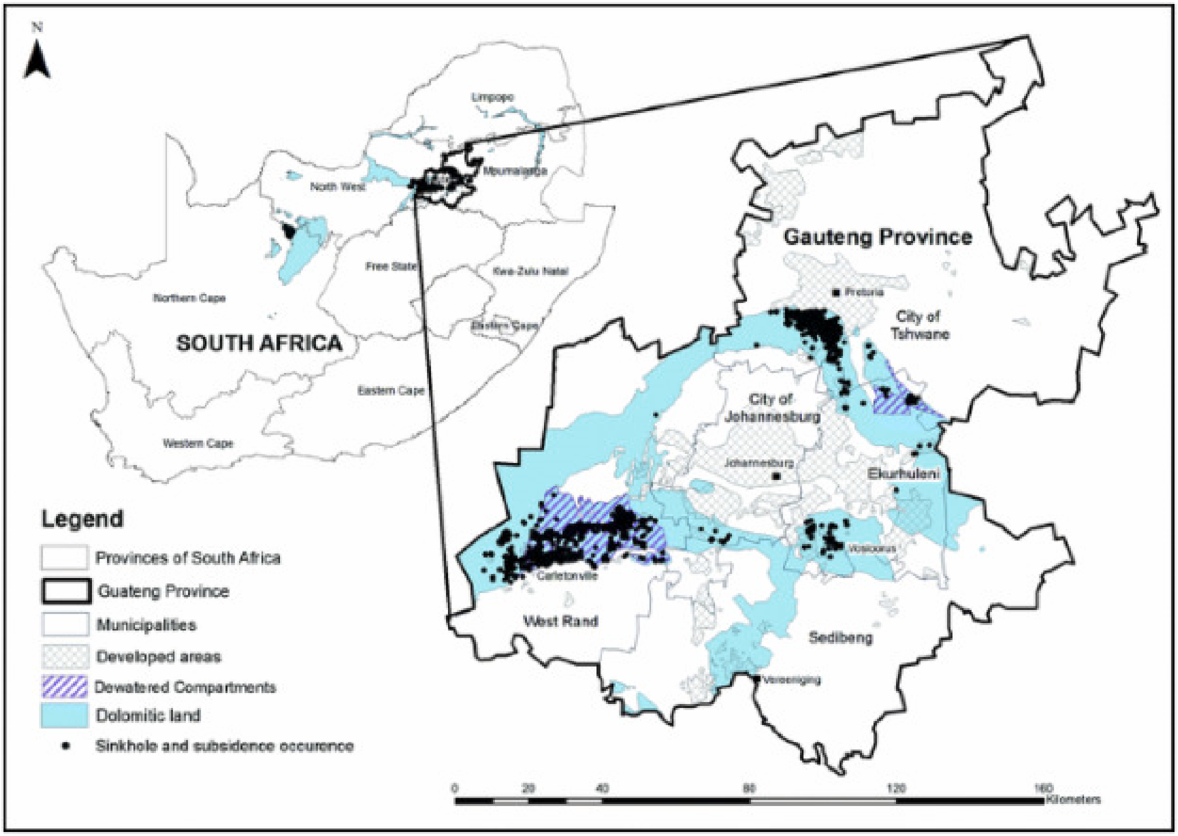

Fig. 4. The distribution of dolomitic land and instability events in Gauteng (Constantinou and Van Rooy, 2018).

2.3. The karst of the Ghaap Group

The Ghaap Plateau refers to the Griqualand West basin found on the south western part of the Kaapvaal carton. The karst of the Ghaap Plateau in Griqualand West represents the largest continuous karst terrain in the southern African region (Altermann and Wotherspoon, 1995). The dolomites of the Ghaap Plateau are rich in lead, zinc and fluorite, which are important minerals for industry. The dolomites in this area are very important as the largest source of raw material to the lime industry in South Africa. The groundwater from this karst is also very important for irrigation-agriculture, as the area is relatively arid. Karst in the region, however, is under threat due to anthropogenic activities such as mining, agriculture, and urban development.

2.4. Karst in other areas of the interior of southern Africa

There are a few smaller karst landscapes of dolomitic origin other than the Transvaal Basin and the Ghaap Plateau karst. These are mainly the dolomites of the Kanye Basin in southern Botswana, which is an important dolomite karst outside South Africa. The dolomites of this basin have a similar lithostatigraphy to those of the old Transvaal province, as they belong to the Transvaal Supergroup (Altermann and Wotherspoon, 1995; Eriksson et al., 1995). The dolomites of the Kanye Basin are also of shallow marine origin, rich in iron and manganese, as is characteristic of the Transvaal Supergroup dolomites (Franchi, 2018). The Kanye area south west of Gaborone is one of the main manganese mining areas in Africa, with the manganese ore (manganese oxide nodules) found in the dolomites of the Kanye Basin (Ekosse and Vink, 1998).

Apart from the Kanye Basin, karst is also found in the Cango Valley in the Western Cape Province of South Africa (Martini, 2006). The karst here is of late Precambrian age, and slightly metamorphosed limestone and shale origin, and is relatively small, with an extent of approximately 40 km^2. Surface karst features are not well developed in the Cango Valley because of the rugged terrain, but a significant number of karst caves are said to be found here such as the Cango Cave (Marker and Gamble, 1987; Martini, 2006).

2.5. Cenozoic karst of the coastal regions

The karst landscape found in the coastal areas (Fig. 3) principally consists of Cenozoic limestones that have developed from lithified calcite from marine origin (Marker and Gamble, 1987). In addition, calcareous sandstones are prominent, especially along some parts of the coasts of the Eastern Cape (Mountain, 1966; Johnson, 1989). The calcareous and gypsipherous sandstones of the Clarens Formation (formerly known as the Cave Sandstone Formation of the Karoo Supergroup) portray pseudokarst characteristics, which are of interest as they have a close relationship to true karst, but are not discussed here as their composition contains too little carbonate material to be classed as a true karst. The coastal platform of the Western and Eastern Cape Provinces has acted as a sediment sink from the Cretaceous period, and this resulted in the formation of the Bredasdorp limestones (Marker and Holmes, 2010). The coast of KwaZulu-Natal also has sandy limestone deposits, with active limestone mining operations (for example near Port Shepstone).

3. Caves in southern Africa

Caves are part of the most important morphological landscapes associated with karst environments. Historically, humans have used caves as places of shelter, refuge, burial and other spiritual needs, and as places where they could mine certain minerals (principally lime and guano) not accessible to them from the surface (Cigna and Forti, 2013). In contemporary life, caves remain valued mainly as attractive sites for tourism, as well as education. This is because the natural environment in caves is in a 'preserved' state compared to the surface, where natural and anthropogenic processes alter the natural environment more rapidly (Cigna and Forti, 2013; Parise et al., 2018). The major caves found in southern Africa are shown in Fig. 3.

3.1. The Sudwala and Echo Caves

The Sudwala Cave system contains some of the largest caverns found in the southern African karst region. The system is located in the Malmani Group dolomite karst system of the Mpumalanga Province of South Africa, which is part of the old Transvaal Province (25.37° S and 20.70° E, Fig. 3). The Sudwala Cave system is located at an elevation of 975 m above sea level, in the northern escarpment of the Drakensburg (Green et al., 2015). The Echo Caves are also found in the Malmani dolomites of Mpumalanga (the old eastern Transvaal) in the Mogaba District (24.561° S and 30.601° E, Fig. 3). The cave system is found at an elevation of 1 036 m above sea level, at the head of the Malapong valley, and is one of the most extensive cave systems found in the Malmani dolomite (Marker and Brook, 1970). Echo Caves are phreatic caves located beneath a dolomite spur that is the result of two headwaters of the Malapong River, a tributary of the Ohrigstad River (Brook, 1982). Geologically, the Mogaba area consists of Pretoria shales and quartzites, which overlie the dolomite series (Marker and Brook, 1970). The overlying landscape generally consists of plateaux and alluvial valleys with flat floors. The system itself formed on dolomitic limestones with shale and chert bands interbedded within it. It is typical of the Malmani dolomites, although there are also quartzite bands in some areas of the Mogaba region. The dissolution of dolomite is described as slow in this area, with the weak carbonic acid-rain water reacting with the dolomitic limestone, and weathering out the insoluble thin sheets of quartz (chert) found between bedding planes which is occasionally recrystallized within joints.

Paleo environmental evidence suggests that, a fluctuating water table due to climatic variation led to the development of the northern part of the Echo Cave system. This is as a result of travertine and other sediments, which are observed in this part (Brook, 1982). Alternating periods of speleothem growth and clastic infill of chambers are also observed as in Sudwala. These alternating periods were separated by periods of high and low water table levels. ^{14}C dating on the travertine of the Echo Caves suggests that the caves started developing at approximately 35000 yr B.P., and that there have been four climatic phases in the evolution of the cave system. These phases and their characteristic climatic conditions are described in Table 1. Of note is the fluctuation in the water table from 1 018 m in phase one to 1 029 m in phase two, and to 1 000 m in phase four. The development of the cave system is attributed to these fluctuations.

Table 1. Phases in the evolution of Echo Caves 35 000 yr B.P. to the present (Brook, 1982).

PHASE	CONDITIONS IN ECHO CAVE WATER	INFERRED CLIMATE AND APPROXIMATE DATES
I	Water table at 1018 m. Widespread deposition of speleothems in northern section of the cave Water	35 000 yr B.P. COLD AND WET
II	Water table at 1029 m. Burial and re-solution of some speleothems deposited in Phase I	30 000 yr B.P. - COLD AND VERY WET
III	Water table at 1018 m. Erosion of fill deposited in Phase II and deposition of stalagmites on the eroded fill surface	17 000 yr B.P. COLD AND WET
IV	Water table below 1000 m. Speleothem deposition only during short, slightly wetter phases of climate one of which occurred ca. 2675 yr B.P.	12 000 yr B.P. WARM AND DRY WITH SHORT WET INTERVALS Present

3.2. Sterkfontein Caves

The Sterkfontein Caves found within the Cradle of Humankind are also located in Gauteng Province, approximately 35 km north-west of Johannesburg. The main entrance to the Sterkfontein Caves was initially discovered by Mr. Martignalia during a blasting operation in the mining of the Sterkfontein calcite in 1896 (Martini et al., 2003). Geologically, the cave formed on the Malmani subgroup of the Transvaal Group dolomites. During the Neoarchean period, slightly acidic groundwater dissolved the phreatic Sterkfontein dolomitic rock, creating subsurface voids which later became caves with the lowering of the water table. Weakly acidic rain water which seeps into and percolates through the cracks of dolomitic rock dissolves and later precipitates calcite, leading to the enlargement of voids and the development of cave stalagmites and stalactites. Similar to the other formations of the Transvaal Group, the dolomites of the Sterkfontein cave are rich in Fe and Mn, with some chert. The Sterkfontein Cave system is a network of phreatic channels, with the 25 entrances to the system found near the top of a hill, some 1 490 m above ground. The caves in the Cradle of Humankind are significant worldwide for their prolific series of hominid fossils, and are part of the UNESCO World Heritage Site (Holland and Witthüser, 2009; Durand et al., 2010; Long et al., 2018).

4. Karst land use and environmental problems in southern Africa

4.1. Karst vulnerability and disturbance

Karst environments are highly susceptible to pollution and degradation, often as a result of anthropogenic activities taking place in these environments at a global scale (Calò and Parise, 2006; Ford and Williams, 2007; Parise et al., 2018). Such threat has become more severe with increasing human population. Consequently, there has been a growing need to locate and protect karst landscapes and sub-surface systems from degradation (Van-Beynen and Townsend, 2005). In order to avert some of these adverse environmental impacts, and to sustainably manage karst environments, a number of tools or methods have been developed to assess the vulnerability and disturbances on karst environments. The Karst Disturbance Index (KDI) is one comprehensive instrument used to assess the extent of such disturbance (Van-Beynen and Townsend, 2005; North et al., 2009; Porter et al., 2016). This tool has been used successfully to comprehensively evaluate the level of disturbance in some karst environments and identify areas that require protection or management (Calò and Parise, 2006; De-Waele, 2009; North et al., 2009; Porter et al., 2016). Table 2 is an abridged index of the elements which are used to measure karst disturbance as adapted from Van Beynen and Townsend (2005). In this index, each of the indicators is scored between zero and three, with zero indicating the least and three the most severe level of disturbance. After site-specific individual indicators have been scored according to severity, the scores are summed and divided by the highest possible score so as to attain a rating of between zero and one (Table 3).

Table 2. Disturbance index for karst environments indicators (after Van-Beynen and Townsend, 2005).

Category	Attribute	Indicator
Geomorphology	Surface landforms Soils Subsurface karst	Quarrying/mining Flooding Storm water drainage Infilling Dumping. Erosion Compaction Decoration removal or vandalism
Atmosphere	Air quality	Desiccation Human-induced condensation corrosion
Hydrology	Water quality Surface practices	Pesticides and Herbicides Industrial and petroleum spills or dumping Occurrence of algal blooms. Water quantity Changes in water table Changes in cave drip waters
Biota	Vegetation Subsurface biota in caves Subsurface biota in Groundwater	Vegetation removal Species richness. Population density Cave environment Groundwater
Cultural	Human artefacts Stewardship of karst region Building infrastructure	Destruction/removal of historical artefacts

Table 3. Classification of disturbance using the Karst Disturbance Index (KDI) (after Van-Beynen and Townsend, 2005 and subsequently modified by North et al., 2009).

Score	Degree of disturbance
0.81–1.0	Irreversible disturbance
0.71–0.8	Critical disturbance
0.61–0.7	Severe disturbance
0.51–0.6	Significant disturbance
0.4–0.5	Moderate disturbance
0.2–0.39	Minor disturbance
0.0–0.19	Pristine

The only area in which the KDI has been applied in southern Africa and in Africa as a whole, is in the Kobokwe Cave and Kobokwe Gorge, in south eastern Botswana, where the evaluation recorded a 'minor disturbance' with an overall score of 0.29, despite some indicators such as cultural indicators recorded scores of high disturbance (Tlhapiso and Stephens, 2020). Due to the significant differences between the European and South African karst, the more applicable and used method for vulnerability assessments in karst areas in southern Africa, is the VUKA method – a vulnerability mapping method for karst terrains in South Africa (Leyland et al., 2008; Leyland and Witthüser, 2009). This method is a South African based adaptation of the original European COP method for groundwater vulnerability mapping. In contrast to the KDI, which considers different impacts on karst, the VUKA method focuses particularly on the vulnerability of karst aquafers and groundwater to pollution. This is very important for South Africa, and especially the dolomites of the Far West Rand, which are the major source of water for rural and urban areas of the Gauteng and North West Provinces of South Africa (Ngcobo, 2006; Leyland et al., 2008; Leyland and Witthüser, 2009; Haarhoff et al., 2012; Schrader et al., 2014).

4.2. Environmental impacts on karst landforms

4.2.1. The impact of mining and mineral extraction

In southern Africa, most of the direct environmental impacts on karst are associated with the mining of dolomite for the cement industry in the Griqualand West sub-basin (Altermann and Wotherspoon, 1995). More widespread, however, are the significant secondary impacts on karst landforms due to the mining of gold and other mineral deposits lying beneath the dolomites in the Gauteng, Free State and North West Provinces (Oosthuizen and Richardson, 2011; Constantinou and Van Rooy, 2018). Limestone and dolomite products are used by three main industries in South Africa (Mineral Economics Directorate, 2003). These are the cement, metallurgical and agricultural industries, although some smaller industries are also potentially important stakeholders (These include construction, waste water treatment and purification sectors, and flue gas desulphurization). In 2015, 23 Mt of limestone and dolomite products were produced in South Africa, 75% of which served the cement manufacturing sector (Mineral Economics Directorate, 2016). This underscores the high demand for limestone and dolomite products. With the future projected expansion in the cement industry, these figures are expected to increase, underscoring the earlier comments concerning the use of the KDI and VUKA methods in monitoring and conducting EIAs. Limestone and dolomite mining have both direct and indirect impacts on karst landscapes. Some of the direct impacts include the alteration of the land cover and that of the karst hydrogeology. The Sterkfontein Cave was first subjected to mining activities when the Sterkfontein Hill calcite flowstone was blasted during a mining operation in 1896 (Martini et al., 2003). Although the cave system has been protected since the 1930's, it was blasted between 1918 and 1920 by a mining company allied to the calcite industry. These operations permanently destroyed spectacular flowstones which, according to photographic evidence, existed there.

Apart from dolomite mining, gold mining in areas with a dolomitic geology such as the Far West Rand, is normally associated with de-watering of groundwater compartments (Martini and Kavalieris, 1976), during which water-logged karst aquifers are drained to lower the water table (Ford and Williams, 2007). This process drastically changes the karst hydrogeology and has been associated with accelerated rates of ground subsidence and sinkholes (Oosthuizen and Richardson, 2011; Constantinou and Van Rooy, 2018). While there are different mechanisms for sinkhole development, excessive water infiltration, seismic events, and de-watering of groundwater compartments are regarded as the main drivers of these (Ngcobo, 2006; Ezersky et al., 2009; Gutiérrez et al., 2014; Han and Hwang, 2017; Dong et al., 2020).

The de-watering of groundwater compartments in the dolomites of the Far West Rand has, however, been found to be the major driver of sinkholes and surface instability events in the area. (Oosthuizen and Richardson, 2011; Schrader and Winde, 2015; Constantinou and Van Rooy, 2018).

Of note is that, approximately 98 % of the reported sinkhole and subsidence events occurred in the Gauteng Province, with the main areas being the Far West Rand and the East Rand (Fig. 4). Sinkhole development associated with mine de-watering is mainly found in the Far West Rand, with the Venterspost, Oberholzer, Bank, and Gemsbokfontein-West groundwater compartments being de-watered. In this area alone, more than 1 200 sinkhole and ground subsidence events associated with mine de-watering had been recorded by the year 2010, compared to the total of 2 500 events for the country as a whole (Oosthuizen and Richardson, 2011). Catastrophic events of sinkholes in this area include the West-Driefontein mine subsidence in 1962, which claimed the lives of 29 people (Ngcobo, 2006). The sinkhole was 55 m in diameter and 30 m deep. Other events include the Venterspost Town sinkhole of 1957 (Heath et al., 2008), and the Carletonville sinkhole in the mining village at Blyvooruitzig Mine in 1964 (Fig. 5) which claimed the lives of six people (Geocaching, 2008; Berend, 2012).

Fig. 5. The Blyvooruitzig Mine sinkhole that claimed six lives when mine employees houses were engulfed by subsidence in Carletonville, South Africa, in 1964 (Greyling, 2019).

With the closure of several mines in the Gauteng Province, post-mining environmental challenges emerge, as underground pumping activity ceases and the groundwater table rises. This influences the hydrogeology and stability of the karst landscapes. The Cradle of Humankind site is, for example, under serious threat from acid mine drainage (Durand et al., 2010). Acid mine drainage from the West Rand (due to the formation of H_2SO_4 associated with the oxidation of FeS by oxygenated water) is highly acidic (pH < 3.5) and metalliferous (Long et al., 2018). This acid leachate has been flowing into the environment for over 16 years since mine closure, and has recently reached the Cradle of Humankind heritage site. With its physico-chemical properties, the drainage is likely to have unfavourable effects on the karst and the speleothems of the heritage site in the future.

4.2.2. The impacts of construction and human settlements

Karst landscapes cover more than 12 % of the world's landscape (Lewin and Woodward, 2009; Chen et al., 2017; Stevanović, 2018), with an estimated 1.5 billion people worldwide living on karst landscapes (Avutia and Kalumba, 2014). As a result, land use and development has continued to increase on karst terrain. Development, and especially urban development, on karst terrain often leads to the hazard of human induced sinkholes and ground subsidence as natural waterways are disturbed, and run-off and service-pipe water leaks are increased (Parise and Gunn, 2007; Schrader and Winde, 2015). De-watering, and ground surcharging in other areas are again some of the main drivers of human induced sinkholes (Martini and Kavalieris, 1976; Ford and Williams, 2007; Constantinou and Van Rooy, 2018), and are a serious concern for numerous urban areas in South (and southern) Africa. Incidents of karst sinkholes and ground subsidence are regularly reported in urban areas underlain by dolomite in South Africa (Constantinou and Van Rooy, 2018).

The South African Council for Geosciences lists fifty municipalities in South Africa that are either partially or fully underlain by dolomite (Oosthuizen and Richardson, 2011) (Oosthuizen and Richardson, 2011) (Oosthuizen and Richardson, 2011) (Oosthuizen and Richardson, 2011) (Oosthuizen and Richardson, 2011) (Oosthuizen and Richardson, 2011). Although there are legislation and guidelines, and approved construction methods for development on karst such as the South African National Standard, SANS-1936:1 of 2012 (South African Bureau of Standards, 2012), the large number of municipalities on areas underlain by dolomite show that the country needs advanced geomorphological and geotechnical methods to deal with, and hopefully minimize, karst environmental problems. The irregular and complex weathering processes of dolomite, and the formation of deep gangue infill within joints (Brink, 1985) poses increased challenges to development on karstic areas.

Surface saturation-type subsidence is the most common type of ground subsidence associated with construction and development. Ingress of water leaking from pipes, and poor management of surface water (Fig. 6) are the leading drivers of ground subsidence in this case (Oosthuizen and Richardson, 2011). The area around Centurion in Gauteng, South Africa, is highly susceptible to this type of ground subsidence (Avutia and Kalumba, 2014; Schrader and Winde, 2015), and over 200 sinkholes have been recorded in this area, related to urban development (Fig. 7). An inventory of ground subsidence and their dimensions is presented by Constantinou and Van Rooy (2018).

Fig. 6. A sinkhole that occurred in Jean Avenue in Centurion, South Africa, in 2012, removing part of a road. (Oosthuizen and Van Rooy, 2015).

Fig. 7. A sinkhole in Benoni, Gauteng, RSA that led to a road closure in 2019 (City of Ekurhuleni, 2019).

4.2.3. The impact of water discharges and agriculture

Land cover change, de-watering for irrigation purposes, and chemical contamination, are some of the impacts that are associated with agriculture, along with the use of limestone based fertilizers (Ford and Williams, 2007). In the dolomites of the West Rand, the observed impacts of agriculture include the high nitrate levels determined in water samples in the area (Holland and Witthüser, 2009; Hobbs and de Meillon, 2017). The diffuse impacts from agricultural irrigation, on the other hand, affect the salt load on karst hydrology, which would be reflected by measures such as the VUKA Index, had it been applied. De-watering of karst for irrigation agricultural purposes, and consequently the artificial lowering of the karst groundwater by approximately 120 m has also been observed in the East Rand in recent years, especially in the Bapsfontein area (Heath and Oosthuizen, 2008). By the year 2011, there had been 27 ground subsidence events that were recorded in the area due to de-watering mainly for irrigation in the East Rand area (Heath and Oosthuizen, 2008; Oosthuizen and Richardson, 2011). At the other end of the spectrum, increased infiltration of irrigation water increases the rate of weathering and solution, again impacting the meso- and micro-features of karst landscapes.

4.3. Climate change and potential mitigation and remedial measures

Climate change is predicted to have serious impacts on the hydrogeology of many regions due to changes in both temperature and precipitation patterns (Jia et al., 2017). More erratic precipitation events are predicted (Trenberth, 2011; Olsson et al., 2015; Mar et al., 2018), and groundwater recharge rates are expected to decrease. This will be accompanied by an increased demand for groundwater, especially in semi-arid areas (Viles, 2003; Hartmann et al., 2014), leading to projected increased groundwater extraction and associated karstic environmental challenges, with the increased likelihood of further instability, differential settling and ground subsidence.

4.4. Environmental management of karst landscapes

Due to the environmental challenges associated with karst, a number of environmental management measures have been taken. Land use on karst terrain cannot be prohibited as the need for land continues to increase. Instead, sustainable engineering technologies are necessary to ensure that the developments, properties and life on karst landscapes are managed to minimize risk. Geomorphic knowledge is central to this assertion (Beckedahl et al., 2002). The knowledge and understanding taken from geological studies in the southern African region are essential for efficient management of the karst environmental problems here. The involvement of geomorphic and geophysical studies may also be of key importance as the theoretical understanding of both geological and geomorphic processes is a cornerstone of karst environmental management. While some management measures may be available (Zhou and Beck, 2011; Parise et al., 2015; Stevanović and Milanović, 2015), the costs of these measures may be very high. Consequently, a cost benefit analysis of karst management approaches or strategies becomes necessary in order to prioritise areas which require most urgent attention.

5. Conclusions

Although there have been a considerable number of studies on karst, there is still an urgent need for further research in the field, especially with a focus on addressing some of the environmental challenges associated with karst in southern Africa. A considerable proportion of the southern African landscape is karstic in nature. The karst in southern Africa is distinct from that in other regions of the world because of its age and geomorphic history. The dolomites are among the oldest in the world, and are rich in chert, siliceous iron and manganese, giving them a distinct colour from 'normal' dolomites, yet also posing threats and opportunities through their unique mineral assemblages. Southern African karst contains some very important paleontological and archaeological records, which are a source of important scientific and educational information to archaeology, geology and geomorphology. The karst in the region is important for the regional water supply, especially in the semi-arid and arid parts of the region.

The southern African karst is, however, under threat from human activities such as mining, de-watering of groundwater, construction, and agriculture. Direct extraction of limestone and dolomite is one of the major threats to karst, as important karst landforms are destroyed. De-watering of groundwater, and acid mine drainage, especially in the Gauteng, North West and Free State Provinces, pose serious threats to karst terrains in these area. Some of these activities lead to karst landforms becoming an environmental hazard as it becomes unstable and prone to ground subsidence and sinkholes, as well as contributing to contamination of the groundwater. With the above, land use on karst terrain will need to be informed by sound geological and geomorphological research which may also recommend improvements to existing regulatory frameworks such as South African Bureau of Standards (2012).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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