



Hazardous Karst

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The Groundwater Project

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Hazardous Karst

*The Groundwater Project
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Dedication

My involvement with karst sinkholes started in the first year after graduation and later lead to a master's degree on the South African dolomite-sinkhole problem south of Pretoria. As an academic I supervised numerous research projects on this geohazard and am still involved in writing codes and standards specific to safe development on dolomite/karst within urban areas. This book is the culmination of a lifetime's involvement with the dolomite/karst issues in South Africa and is dedicated to all working towards creating a safe living environment on karst: researchers, government institutions, and consultants, but most importantly to the Proterozoic dolomites on my doorstep.

Louis van Rooy

My passion for dolomite started with writing a book and directing a film on the springs that provide drinking water to Pretoria, South Africa's capital city, since its founding to this day. This led to greater involvement with karst culminating in a separate research report building on vadose zone research titled *The Karst Vadose Zone: Influence on Recharge, Vulnerability and Surface Stability* (Dippenaar, et al. 2019a) and after that participating in and attending more workshops and seminars on the topic. I dedicate this book to everyone who made this possible for me professionally. I specifically dedicate this book to my wife Tharina, and daughters Femke and Lexi, who all support me daily throughout everything I do and give me the will and happiness to do all of this with pleasure.

Matthys Dippenaar

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The Groundwater Project Foreword

The 2022 United Nations (UN) World Water Day theme “*Groundwater – Making the Invisible Visible*” was pivotal in raising global awareness about groundwater as an invaluable resource, and the year concluded with the UN Water Summit on Groundwater at the UNESCO headquarters. One of the key outcomes of the Summit was a call for governments and other stakeholders to scale up their efforts to better manage groundwater.

Groundwater makes up 99% of all liquid fresh water on Earth, underpinning its importance in providing drinking water to the world, sustaining food production, and maintaining healthy ecosystems. Many important global organizations have concluded that there is a freshwater crisis and given that nearly all freshwater is groundwater, the freshwater crisis is a groundwater crisis. During drought in many locales, groundwater is the only freshwater available, putting even more pressure on groundwater resources.

According to the World Health Organization and UNICEF ([WHO/UNICEF, 2025](#)), 2.1 billion people (1 in 4) live without safely managed drinking water and 3.4 billion people (4 in 10) live without safely managed sanitation. With groundwater directly supporting 8 of the 17 UN Sustainable Development Goals, groundwater is an invaluable resource. Safe and reliable access to groundwater directly supports the 2026 UN World Water Day (March 22) Theme “*Water and Gender Equality*” focusing on ensuring that women and girls have equal rights and leadership in water management.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, pioneers in advancing the understanding of groundwater by providing groundwater education to everyone. Recognizing that the world needs more highly skilled groundwater scientists to solve the water crisis, the GW-Project plays a pivotal role in creating the knowledge base for building the much-needed human capacity for the development and management of groundwater.

The GW-Project gained global recognition with publication of 64 original books, 94 translated books (in 59 languages), 7 interactive groundwater educational tools/modules, and over 50 high-quality educational videos, all made possible by a dedicated international group of over 1000 volunteer professionals from a broad range of disciplines throughout 70 countries on six continents. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, youth, undergraduate and graduate students, groundwater professionals, and the general public.

The GW-Project operates with the philosophy that high-quality groundwater education should be freely accessible for everyone, and to that end our publications are available free-of-charge on our [website](#). We thank our corporate sponsors and private donors for making this possible. Please consider sponsoring the GW-Project so we can continue to provide groundwater education free of charge.

The Groundwater Project Board of Directors, January 2026

Foreword

Terrain with the solution channeled features known as karst at, or slightly below, the land surface makes up about 15 percent of the Earth's continental land area ([Encyclopedia Britannica](#)). More than 25 percent of the world's population lives on, or obtains their water from karst aquifers according to the [Karst Waters Institute](#).

Karst is a geological process but unlike nearly all other geological processes, karst processes can change the landscape so fast that the changes can have sudden impact on the functioning of urban areas. There is an immense body of scientific literature about karst, but relatively few books on the topic. This book, *Hazardous Karst*, is the fourth to be published in a planned Groundwater Project book series on karst. Previous karst publications include: [Introduction to Karst Aquifers](#), [Karst: Environment and Management of Aquifers](#), [The Edwards Aquifer](#), and a book particularly useful for characterizing karst [Practical Groundwater Tracing with Fluorescent Dyes](#).

The scope of this book is comprehensive in that it considers the factors that govern the formation and evolution of karst including the mineralogical, hydrogeological, and hydrogeochemical processes, as well as the urban factors that result in damage to infrastructure and its repair. Louis van Rooy and Matthys Dippenaar emphasize karst as an important factor in urban settings. They present excellent examples, many from the Pretoria area of South Africa, where the authors have decades of involvement in research and practice including assessing risk caused by karst features and repair of the damage when hazardous events occur. Karst literature is rich in its diversity of perspectives given the multidisciplinary makeup of the scientific communities that study karst. The perspective of Van Rooy and Dippenaar is based on their academic roots in engineering geology.

The Groundwater Project strives to enhance understanding of groundwater by presenting high-quality diagrams and photographs. This book is exemplary in this regard with figures for visualizing the features that explain the evidence of karst conditions in both the surface and subsurface. Nearly all of the karst features and processes that occur in Pretoria are important in other karst areas around the globe.

John Cherry, The Groundwater Project Leader
Guelph, Ontario, Canada, October 2025

Preface

Large parts of Earth are underlain by soluble rock prone to dissolution such as evaporites, dolomite, and limestone. Pretoria, the capital of South Africa, is a good example of an historic concentration of humans due to reliable source of spring water from karst. Springs in karst terrain are where water daylights on the ground surface from large underground cavities connected by fractures and dissolution channels.

Karst aquifers store exceptionally large volumes of water between the ingress point of rainwater to where it exits through caves or palaeo sinkholes (springs) to form rivers. While intergranular and fractured rock aquifers are susceptible to changes in weather and climate meaning that the aquifer dewateres and has to recharge again, the same is not always true for karst where the water in some of the solution cavities has been there for millennia.

Unique landforms in karst terrains include surface manifestations like sinkholes and springs. Sudden collapse of the Earth's surface may pose a hazard to infrastructure and human life; moreover, karst aquifers are vulnerable to contamination through epikarst, grykes, and sinkholes that provide direct access from contaminant sources on the surface or in the shallow subsurface. These vulnerabilities can affect the chemical quality of spring outflow, and some immobilized contaminants may remain in the vadose zone where they can affect biotic life.

Karst and karst processes are regarded as a natural hazard in areas where it coincides with human development. It is important to understand karst where variable conditions occur spatially and temporally given the heterogeneity in the karstification and the change occurring over time through dissolution, precipitation, and sinkhole formation. It is extremely difficult to preempt future behavior which calls for very specific investigation techniques from engineering, geological, and hydrogeological perspectives.

Hydrological and geotechnical risk assessment in karst is specific to soluble rock and have specific requirements for professional competence. Performing the work and providing the correct recommendations requires a thorough and comprehensive representation of the karst conditions. The outcomes of such work need to be understandable to and usable by a broad audience, then distributed widely.

This book aims to provide a comprehensive evaluation of karst theory with specific application to investigation methodology linked to different karst environments, hazard determination, and how to mitigate and rehabilitate hazard events. The book is for all interested in, and living on, or developing infrastructure in karst environments including the general public, academia, professionals, government agents, university students, school students, and karst experts. It also provides standard international vocabulary for communication purposes.

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We deeply appreciate the thorough and useful reviews of and contributions to this book by the following individuals:

- ❖ Eve L. Kuniansky - Emeritus Scientist, United States Geological Survey, USA;
- ❖ Frederick Paillet – Emeritus Scientist, United States Geological Survey / University of Arkansas, USA;
- ❖ David J. Weary - Emeritus Scientist, United States Geological Survey, USA; and
- ❖ Dan Green – Senior Geologist & Chief of Operations, PELA Geoenvironmental, USA.

A special thank you to Eve Kuniansky, the editor, for her contribution to this book. She provided valuable recommendations that made this book as good as it is now. Thank you, Eve, for this. We also thank Amanda Sills for her valuable input as reviewer, and Rees Storm who made edits and corrections to later versions of the book. We thank Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for reviewing, editing, and producing this book.

Hazards and risk on dolomite land in South Africa have been the focus of research in the Geology Department, University of Pretoria, and this book would not have been possible without the contributions from many postgraduate students.

Financial support from the University of Pretoria, private consulting firms, the National Research Foundation in South Africa, and the Water Research Commission (WRC), specifically for funding the project that culminated in a report *The Karst Vadose Zone: Influence on Recharge, Vulnerability and Surface Stability* (Dippenaar et al. 2019a), are appreciated.

1 Welcome to the World of Karst

1.1 About this Book

There is a plateau which the Slovenes call *Kras*, Italians *Carso*, and Germans *Karst* that is well distinguished, and “limited by the Gulf of Trieste (Adriatic Sea), alluvial plain of Soča (Isonzo) river, Eocene flysch Vipava River, and flysch hills of Brkini” (Kranjc, 1997). The pre-Roman, pre-Latin, and Illiryan names of the plateau are unknown, but its Romanized form, *Carsus*, in classical Latin is known, and the base of that name was **Karus*, with the root **kar* meaning stone or rock. This is proven by the Greek version of the name that Ptolemy wrote as *Καρωνδαδιω όρει* (*Kar(u)sádios oros*) (Snoj, 1997).

The word is ultimately of Mediterranean origin, and it is likely derived from the Proto-Indo-European root *karra* meaning rock (Gams, 2003) and may be connected to the homonym—same sound but different meaning—cited by Ptolemy (*Kar(u)sádios oros*) and perhaps also to the Latin *Carasardius* (Bezljaj, 1982; Snoj, 2003).

All variations of the word in the local South Slavic languages are derived from a Romanized Illiryan base that yielded the Latin and Dalmatian *carsus*. This later metathesized from the reconstructed form **korsъ* into forms such as the Slovene *kras* and Serbo-Croatian *krš* (Pavšič, 2006). Some languages preserved the older, non-metathesized, interchange of two or more contiguous syllables, letters, or segments, resulting in forms like the Italian *Carso*, German *Karst*, and Albanian *karsti*. The lack of metathesis prevents borrowing from languages such as Slovene (Pfeiffer, 1961; Pörtner, 1986).

In Amharic, an Ethiopian language, *kers* means open, belly, large hole below the ground. Groundwater, for instance, is *kerse-mdr-wuha* meaning water in the open spaces below the ground. In Oromo, a crushitic language of Afro-asiatic origin, *kersa* loosely translates to cliff, rock, or similar terms (personal communication, Seifu Kebede, 23 August 2023).

In *The Original and evolution of the term “Karst”* the author Kranjc (2011) concludes that the term karst derived from the name Kras (Slovene), Carso (Italian) and Karst (German) of the plateau in the background of the Bay of Trieste (Adriatic Sea) lying predominantly in Slovenia and in Italy. From the accusative form of the name (*Carsum*) modern names evolved in the ninth century, but during the nineteenth century when the toponym Karst transformed in the general term, the professional literature was written in German and therefore the German form of the name Karst has been most widely adopted.

The Dolomites region of Italy is the place where the dolomite mineral was first recognized by the French geologist Déodat de Dolomieu, in the second half of the eighteenth century. These mountains represent an exceptionally exposed portion of the Southern Alps, a northern Italian mountain range produced by the deformation of the Tethyan passive continental margin. The region underwent several tectono-magmatic

events, from Permian volcanism and rifting, to opening of the Western Tethys, to the final Paleogene/Neogene compression with over thrusting and strike-slip tectonics leading to the present south-vergent thrust belt configuration. Although the sedimentation protracted from Mid Permian to Cretaceous, the Dolomites landscape is characterized by magnificent Triassic Mountain groups, which are worldwide known as one of the most spectacular examples of ancient carbonate platforms. These platforms record a set of different styles in carbonate deposition related to paleoclimatic fluctuations with frequent transitions from arid to humid conditions. UNESCO has declared the Dolomites region a World Natural Heritage site and it is one of the most studied sites in the world for the modern synthesis of the depositional evolution of carbonate platforms (Figure 1; L. Milani, personal communication, 3 March 2011).

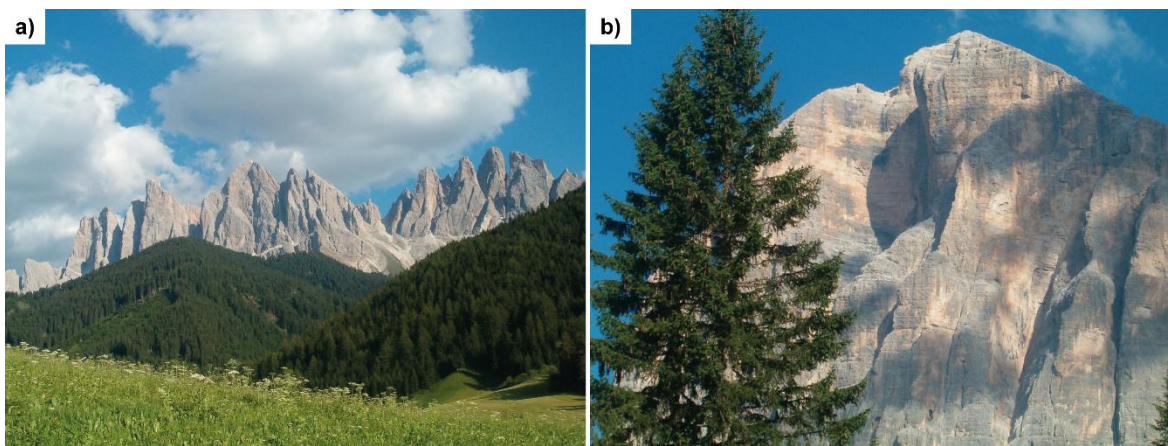


Figure 1 - The Dolomite region in Italy exhibiting a jagged appearance: a) due to dissolution on b) joints (Photographed by L. Milani, personal communication, 3 March 2011).

The landscapes evolved in soluble rock manifested as underground cavities and caves, recharged by losing streams, with surface subsidence and sinkholes. Karst refers to these landscapes that are underlain by soluble rock such as carbonates and evaporites and characterized by features such as sinkholes, caves, and springs; often lacking in perennial stream networks, ponds, wetlands, or lakes. The term karst encompasses the geology, the process, the geomorphological development, and the landforms.

The development of karst involves both biological and depositional processes to produce carbonate rocks that readily dissolve and precipitate depending on the chemistry of the water flowing through the rock. The development and physical manifestation of karst in soluble rocks are due to groundwater flow, the hydrogeological characteristics, and the geochemical evolution. The following influence the formation and characteristics of karst (Kuniansky et al., 2022):

- original depositional environment,
- lithologic and stratigraphic variability,
- diagenetic processes,
- post-depositional structural deformation,

- geomorphological evolution of the landscape,
- variability and changes in precipitation, and
- geochemical weathering occurring both over short and long geological time scales.

Karst covers a significant part of the planet (Figure 2), necessitating a proper understanding of its formation, development, current processes, and interaction with humanity and the environment.

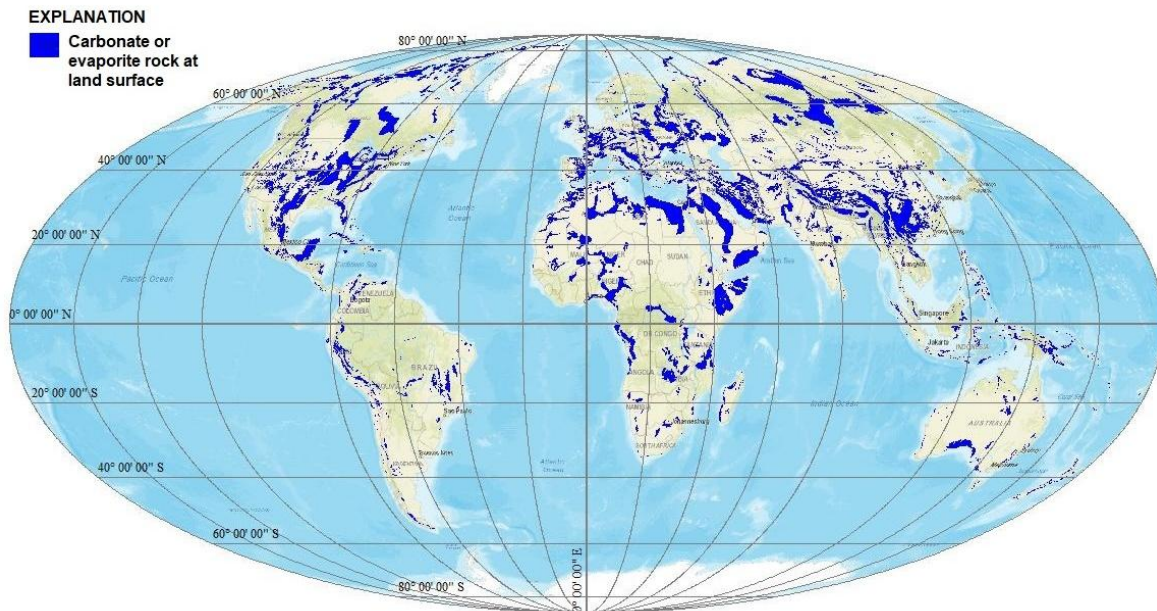


Figure 2 - Outcrop of carbonate and evaporite rocks forming karst terrains and aquifers around the world. The map indicates the unconfined parts of karst aquifers not the total extent as many of these formations dip underground (adopted from Kuniansky et al., 2022).

Karst landscapes, as opposed to those developed on terrigenous clastic sediments, are formed by complex biological and physical processes that impact the development of the permeability of the sediments. Depending on the chemistry of the water flowing through the rock, carbonate minerals readily dissolve, and/or precipitate via both marine and meteoric diagenesis. The dual porosity nature of karst aquifers poses a scientific challenge in studying groundwater flow and contaminant transport and requires cognizance of both marine and meteoric diagenesis of carbonate sediments. Join us to discover the wonderful, mysterious, but also hazardous world of karst (Figure 3 and Figure 4).

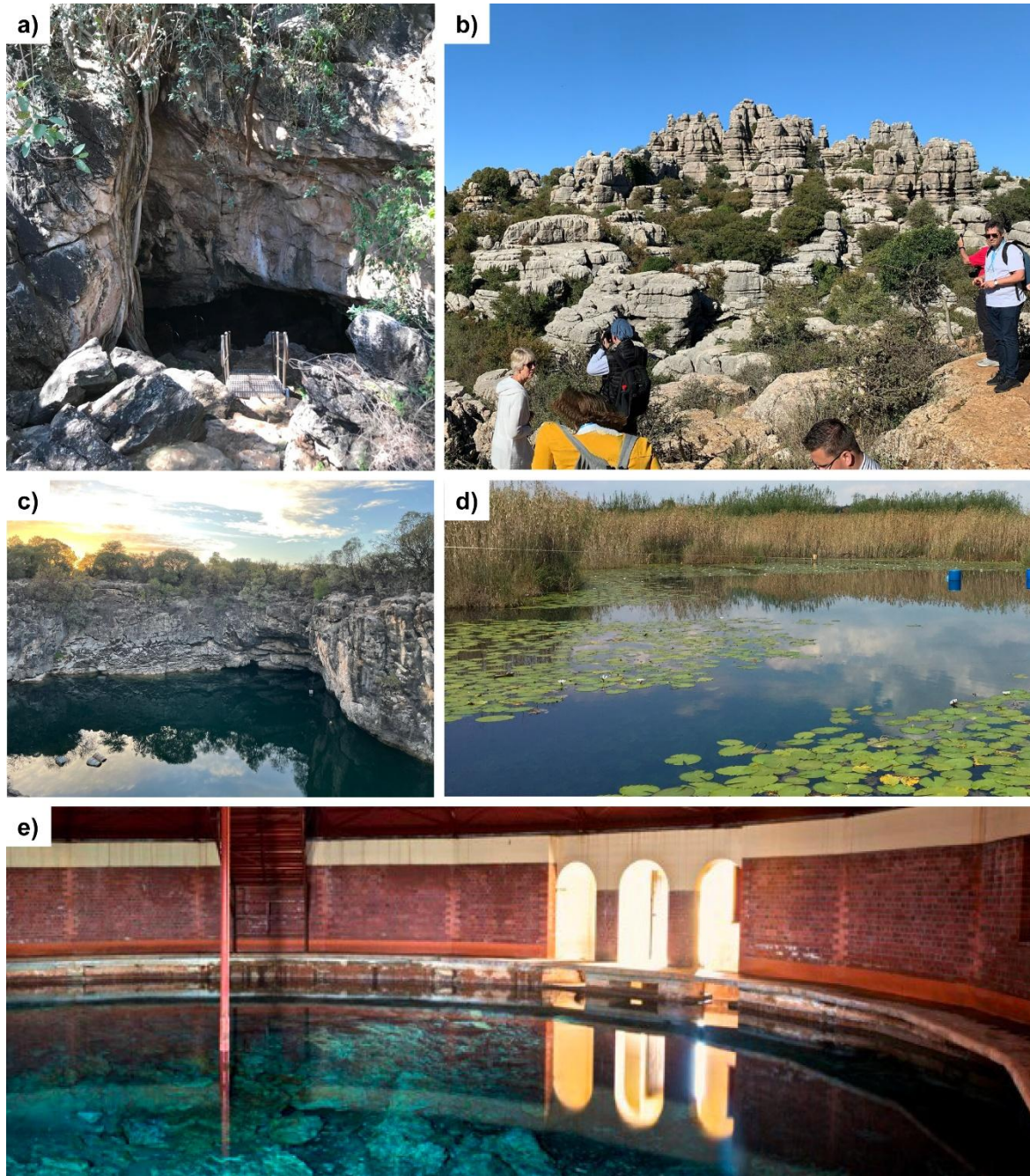


Figure 3 - The world of karst is the result of water soluble rocks forming a) rock cavities in Botswana; b) surface landforms in Spain; and c) d) e) springs in South Africa (photographs by Dippenaar, <https://commons.wikimedia.org/wiki/File:Caving2.jpg>).



Figure 4 - The world of karst is also the result of water soluble rocks providing a) an evaporate deposit in the USA; b) c) caves for exploration, speleologists and spelunkers; and d) stone for artists/monuments with this example from Spain (photographs by Dippenaar, <https://commons.wikimedia.org/wiki/File:Caving2.jpg>).

1.2 How to Use This Book

This book builds from presenting the formation of karst to its hazards, then describing techniques for investigating and assessing karst, followed by opportunities for learning through case studies and exercises (Figure 5). None of the schematics are to scale. A map of South Africa is provided in Figure 6.

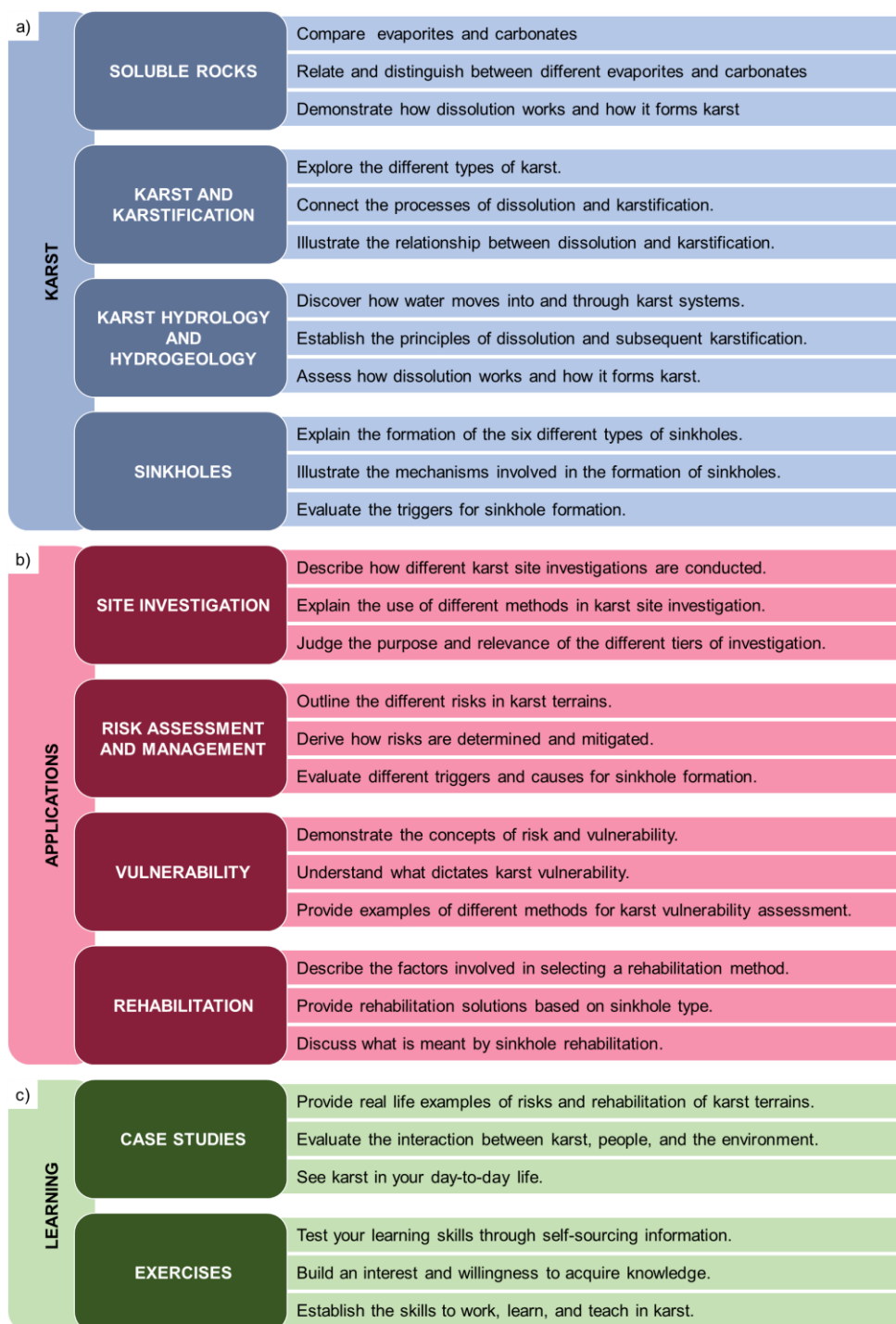


Figure 5 - The first part of the book a) provides background and basic theory on karst with specific reference to the hazards followed by b) investigation and assessment of the hazards, both surface subsidence and groundwater vulnerability, including rehabilitation; and then c) learning through case studies and exercises.



Figure 6 - Map of South Africa to help locate places referred to in this book.

2 Soluble Rocks

2.1 Evaporites and Carbonates

Many rocks form from minerals that precipitate from solution. The most common are evaporites formed of halite and gypsum, and carbonates formed of calcite, as well as its polymorphs such as dolomite. The most common minerals are shown in Figure 7. Their chemical compositions are listed here.

- Halite NaCl
- Gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
- Calcite CaCO_3
- Dolomite $\text{CaMg}(\text{CO}_3)_2$

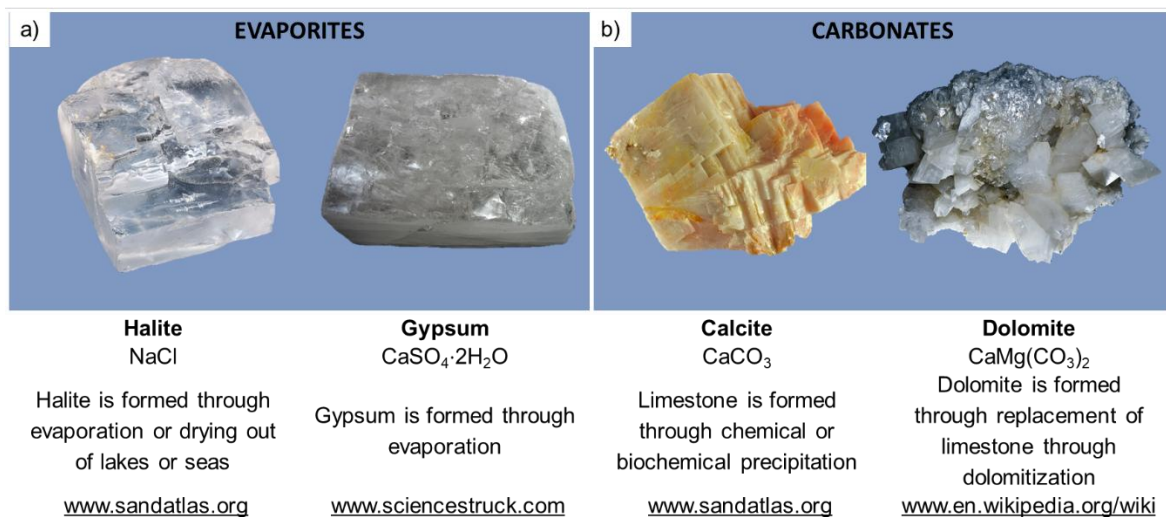


Figure 7 - The most common evaporite rocks are formed by a) halite, and gypsum or common carbonate minerals such as b) calcite and dolomite.

Evaporites form through evaporation from water and the type of salt precipitation depends on the amount of evaporation (Marshak, 2018):

- when 80% of trapped seawater in a basin evaporates, gypsum forms,
- when 90% of trapped seawater in a basin evaporates, halite forms, and
- when 100% of trapped seawater in a basin evaporates, it is composed of 80% halite, 13% gypsum, along with some other minor salts and carbonates.

Some examples of evaporite and carbonate rocks are shown in Figure 8. Evaporites are more prone to continuous dissolution followed by reprecipitation than carbonates that take longer to dissolve. Like carbonates, evaporites can form karst landscapes and vary between localized to widespread deposits that form in both marine and non-marine environments. In arid areas they are thin and shallow and often cover relatively small areas (Stewart, 1953).



Figure 8 - Some evaporites are formed in arid areas over small basins such as those shown in a) and b) from Badwater Basin with deposits of halite and minor calcite, gypsum, and borax (Death Valley, Nevada, 2018); relatively thick deposits of gypcrete shown in c) and d) are shown in the Northern Cape Province (South Africa, 2018); examples of carbonates with widespread use are e) this limestone used as f) a monument plaque at Castillo Monumente Colomares (Malaga, Spain, 2019); and examples of ancient g) chert-poor dolomite and h) dolomite interlayered with chert are shown in Dinokana, South Africa (2018). All photographs by Dippenaar.

Carbonates form through biochemical processes where they are composed of physical remains such as shells of organisms, or through chemical processes where they are formed by precipitation of minerals from aqueous solutions. Carbonates are minerals with a carbonate anionic group (CO_3^{2-}). Limestone and dolomite—sometimes called dolostone—are the main lithologies prone to karstification that can result in sinkhole formation. They are mineralogically distinct, but also different in their formation, and dolomite is different in properties such as hardness, porosity, and solubility. The composition and classification of limestone and dolomite are shown in Figure 9. Figure 9 illustrates the continuum between pure limestone (pure calcite mineral) and pure dolostone (pure dolomite mineral).

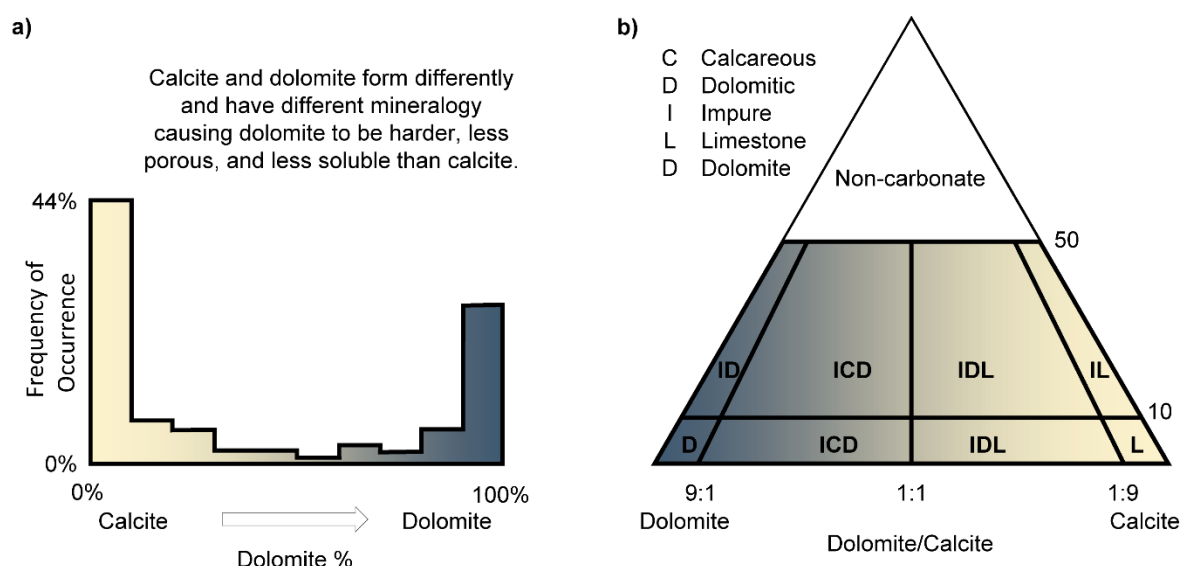


Figure 9 - A continuum exists between a) dolomite and calcite mineral content in limestone and dolomite rocks that relates to the classification b) of rock types comprising of calcite and dolomite mineral content combinations between the end points of limestone and dolomite (inspired by Leighton & Pendexter, 1962; Warren, 2000).

A good summary of the classification of carbonate rocks is provided by Kendall and Flood (2011) with the following bulleted history of the classification of limestones from 1932 to 1952.

- Early classifications circa 1932 by Twenhoffel
 - Organic origin
 - Chemical origin
 - Mechanical origin
- 1930s by workers
 - Hard rock
 - Mud or soft rock

- 1950s by workers
 - Uncemented
 - Calcilutites (mud-sized)
 - Calcarenites (sand-sized)
 - Calcilutite (gravel-sized)
 - Mixture of all three above
 - Primary hard rock (chemically or biochemically cemented)
 - Secondary hard rock (diagenetically modified)
- Division by Pettijohn (1952) into two groups
 - Autochthonous (formed in situ by biochemical processes)
 - Allochthonous (consisting of transported and redeposited material)
- Folk (1959) stated that limestones are divided into eleven types that are easily recognizable and are made up of (1) allochems that are transported or differentiated from carbonate bodies, (2) 12–micron microcrystalline calcite in an ooze matrix, and (3) coarse and clearer sparry calcite that mostly form a simple pore-filing cement in the rock. Allochems provide the structure framework for limestone. The rock types are illustrated in Figure 10a

Dunham (1962) produced a classification of carbonate rocks that is based on depositional texture, noting several textural features that are especially useful when classifying carbonate rocks. He classified carbonate rocks based on their depositional environment as shown in Figure 10b using the following features:

- the presence or absence of carbonate mud (i.e., particles passing a 20-micron sieve),
- abundance of carbonate grains retained by a 20-micron sieve,
- whether grains are mud-supported or grain-supported, and
- evidence of organic binding during deposition.

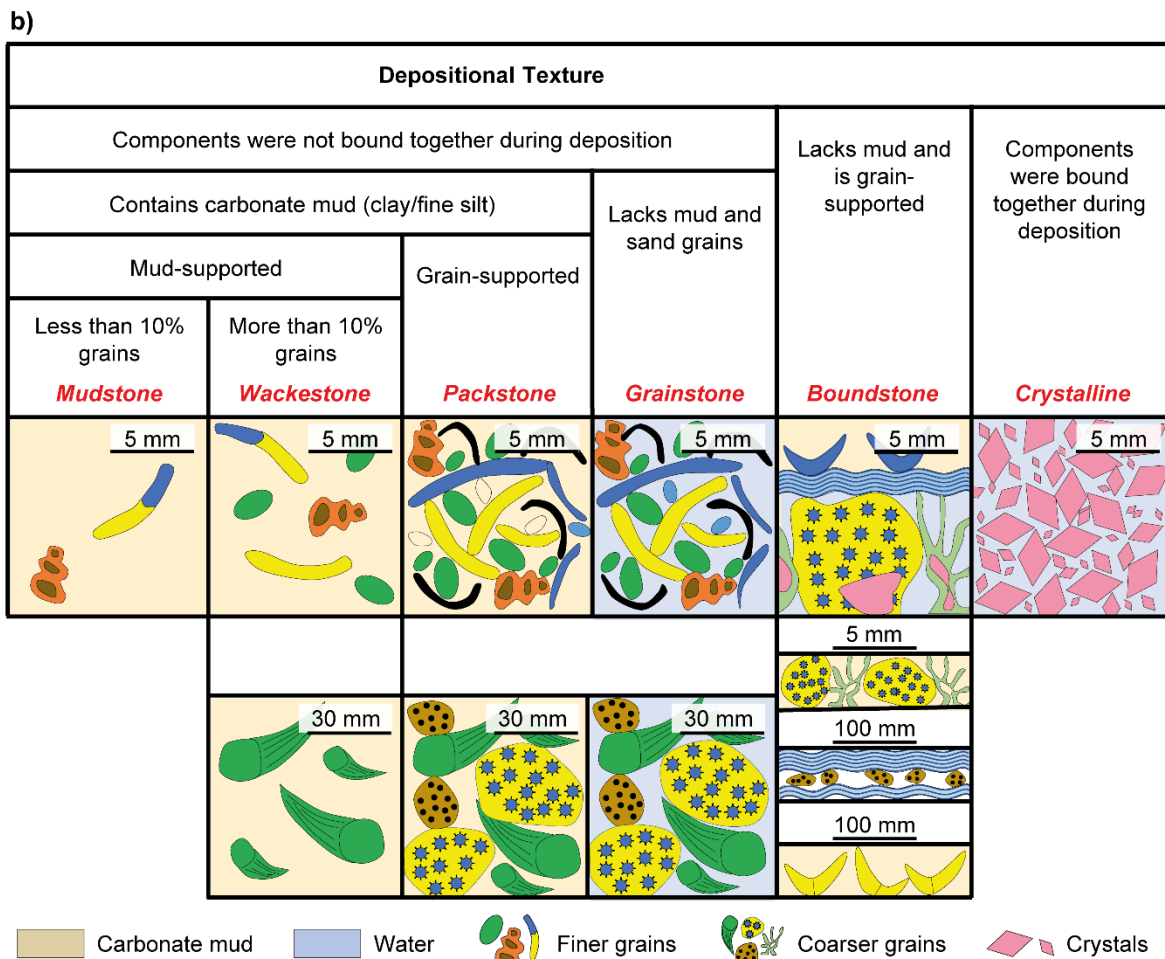
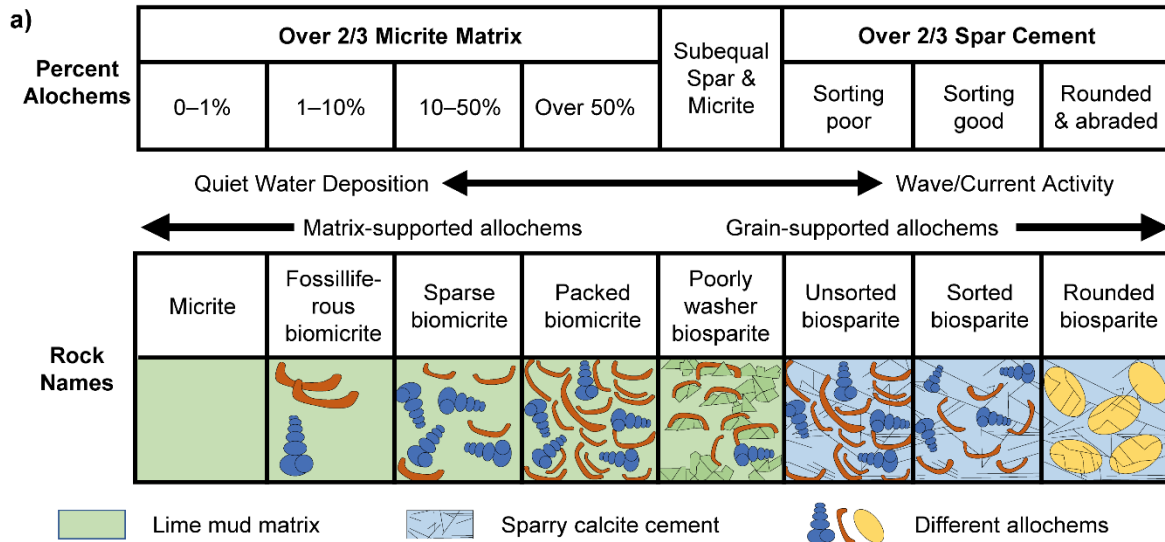


Figure 10 - Carbonate rock classification by a) Folk (1959) and b) Dunham (1962).

Mudstone contains less than 10% grains (Dunham, 1962) and generally indicates that it was formed in calm water with apparent inhibition of grain-producing organisms that are typically associated with a low-energy deposition setting (Loucks et al., 2003).

Wackestone contains more than 10% grains (Dunham, 1962) and is subdivided into either mud-dominated or pore spaces filled with mud. It generally indicates calm water and a restriction of grain-producing settling (Loucks et al., 2003).

Packstone is a grain-supported carbonate rock that is divided into mud-dominated with pore spaces filled with mud representing low-energy processes and grain-dominated with some inter-grain pore spaces free of mud representing high-energy processes. They may form from compacted wackestones with early or late mud infiltration of deposited mud-free sediments (Dunham, 1962).

Grainstone is a grain-supported mud-free carbonate rock deposited in moderate-energy to high-energy, grain-producing environments with variable hydraulic significance (Loucks et al., 2003). Grainstones may be formed in high-energy grain-productive environments without mud, deposited by currents dropping out the grains and bypassing mud to elsewhere, or winnowing deposited muddy sediments (Dunham, 1962).

Boundstone shows signs of binding during deposition and generally is deposited in higher energy environments where currents can provide nutrients to the organisms that form the boundstone and carry away waste products (Dunham, 1962). Embry and Klovan (1971) further expanded the boundstone classification based on the fabric of the boundstone, providing three subdivisions.

- Framestone has a rigid framework that is built by organisms.
- Bindstone is when the organisms encrust and bind loose sediment together.
- Bafflestone is where the organisms do not form a framework or bind the sediments together but provide protected areas for the sediment to accumulate by baffling the flow.

Crystalline carbonates lack evidence of depositional texture for classification, and dolomitization obliterates the original limestone texture (Loucks et al., 2003).

Calcite is a mineral composed of CaCO_3 and occurs in rocks such as limestone, travertine, micrite, chalk, and tufa. When metamorphosed, it becomes marble with similar mineralogy.

Dolomite is a mineral composed of $\text{CaMg}(\text{CO}_3)_2$. To distinguish between the mineral dolomite and the rock dolomite, a rock made up of more than 50% of the mineral dolomite is dolostone but is often referred to as dolomite. Whereas limestone precipitates directly from solution, dolomite mostly forms through chemical alteration of limestones by infiltration of magnesium-rich waters (dolomitization). As such, dolomites tend to have irregular boundaries in the rock and to lack bedding (Bednar, 2008; Selley, 2000).

Dolomite is less prone to chemical weathering (dissolution) than limestone and is resistant to physical weathering. Dolomite can be interlayered with chert depending on the depositional environment, and present-day karst in dolomite is due to dissolution over long periods of time.

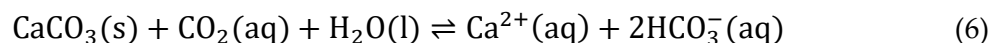
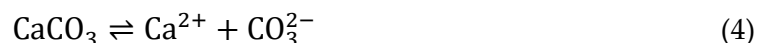
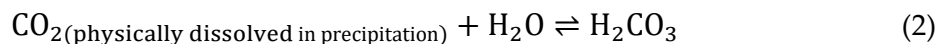
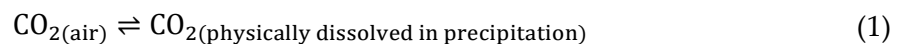
2.2 Carbonate Dissolution

Decomposition is the weathering process resulting in the change of a rock's composition (chemistry, mineralogy) and structure. For carbonate rocks in water-surplus environments this happens through carbonate dissolution. The process of dissolution is slow and occurs at outcrops, underground rockhead (soil covered bedrock surface), and in fissures.

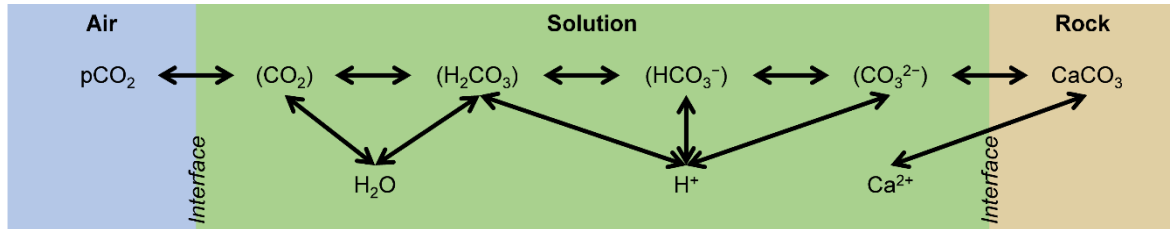
Atmospheric carbon dioxide (CO₂) slightly acidifies water (H₂O), and this weak carbonic acid cause carbonate rocks to dissolve over time.

Carbonate dissolution occurs in the following steps.

- Atmospheric CO₂ dissolves into atmospheric water (i.e., precipitation), Equation (1).
- Carbonic acid forms when the physically dissolved CO₂ is hydrated, Equation (2).
- H₂CO₃ dissociates, Equation (3).
- Carbonate rock in contact with water releases some ions from the crystal lattice, Equation (4).
- CO₃²⁻ associates with H⁺, to form bicarbonate Equation (5).
- The combination of Equations (1), (2), (3), (4), and (5) yields the dissolution equation for limestone, Equation (6),.



The partial pressure of carbon dioxide is $p\text{CO}_2$. Carbon dioxide dissolves in rainwater as (CO_2) to form weak carbonic acid (H_2CO_3) , and then further dissolves to break into bicarbonate (HCO_3^-) and later to carbonate (CO_3^{2-}) . If excess hydrogen (H^{1+}) is removed from the water (i.e., pH increases), then calcium (Ca^{2+}) ions dissolved in the water can combine with carbonic acid (H_2CO_3) to precipitate calcite (CaCO_3) . The opposite happens with dissolution where solid calcite dissolves to form aqueous carbonate (CO_3^{2-}) , then aqueous bicarbonate (HCO_3^-) , and eventually gas carbon dioxide $(\text{CO}_{2(\text{gas})})$ as shown in Figure 11.



Dissolution and precipitation process for calcite at the water-rock interface:

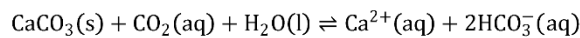
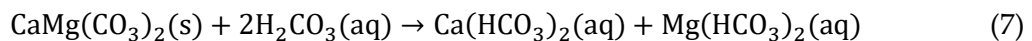


Figure 11 - Dissolution and precipitation of calcite for weak carbonic acid (reproduced from Bögli, 1980).

In dolomite, the ions released move as an aqueous solution with the groundwater, and practically no solid residue remains, Equation (7).



In open systems, carbonate is replenished continuously from the atmosphere and combines with water to form carbonic acid, while carbon from organic material in soil further promotes acidity (Figure 12). Bacterial respiration is a vital source of organic carbon that occurs within soils where organic material and ample oxygen are present. The production of acid is common in the shallow portion of organic-rich environments such as lakes, marine environments, wetlands, ponds, and septic tank systems where the carbonate dissolution rate is higher than in deeper zones. By shallow, we mean the upper few 100's of centimeters where acidity is maintained and corresponds with high $p\text{CO}_2$. In closed weathering systems, fluids do not have access to organic material in soil nor to atmospheric carbon. This means that CO_2 and other constituents are only replenished upon recharge. As the CO_2 is consumed, the partial pressure of atmospheric carbon dioxide $p\text{CO}_2$ decreases while the pH and Ca^{2+} increase, thereby reducing dissolution rates (Blatt et al., 1972).

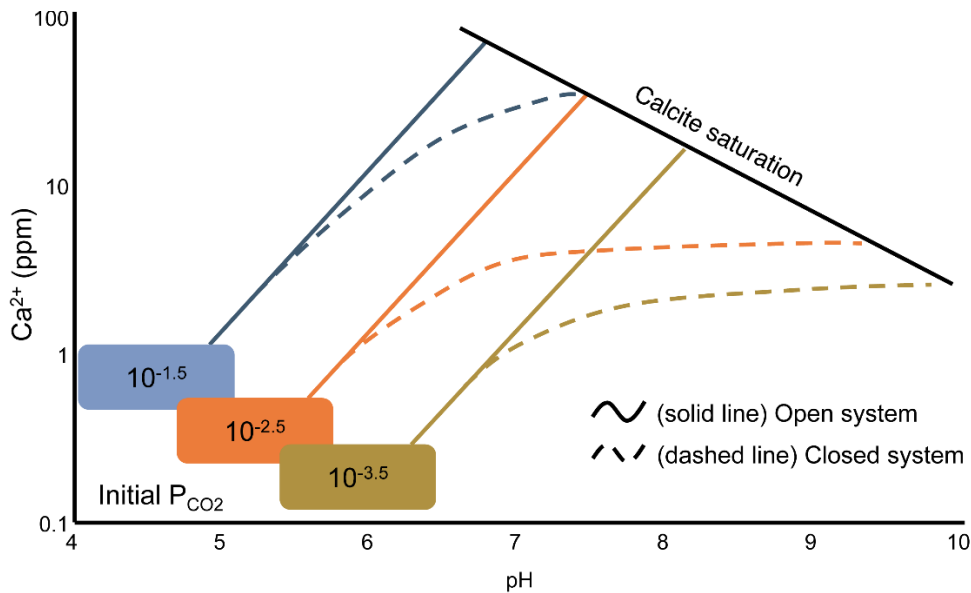


Figure 12 - Open and closed system showing calcite solubility is controlled by the acidity of the water and concentrations of carbon dioxide, calcium, and carbonate ions. These parameters are also influenced by the availability of carbonate from the atmosphere and increased acidity due to organic matter in open, as opposed to closed, systems (Blatt et al., 1972; Dippenaar, van Rooy, et al., 2019).

Less availability of carbon from CO₂ reduces the dissolution rates, and subsequently carbonate outcrops exist due to the lack of chemical weathering. Early stages of dolomite dissolution from fresh, unreacted surfaces are non-stoichiometric, implying that the CaCO₃ component is released faster than the MgCO₃ component. The large atomic radius of Ca²⁺ compared to that of Mg²⁺ is possibly the reason for this because it results in the Mg-O bond having stronger covalency. Thus, at similar pH conditions, the calcite is more soluble (Figure 13).

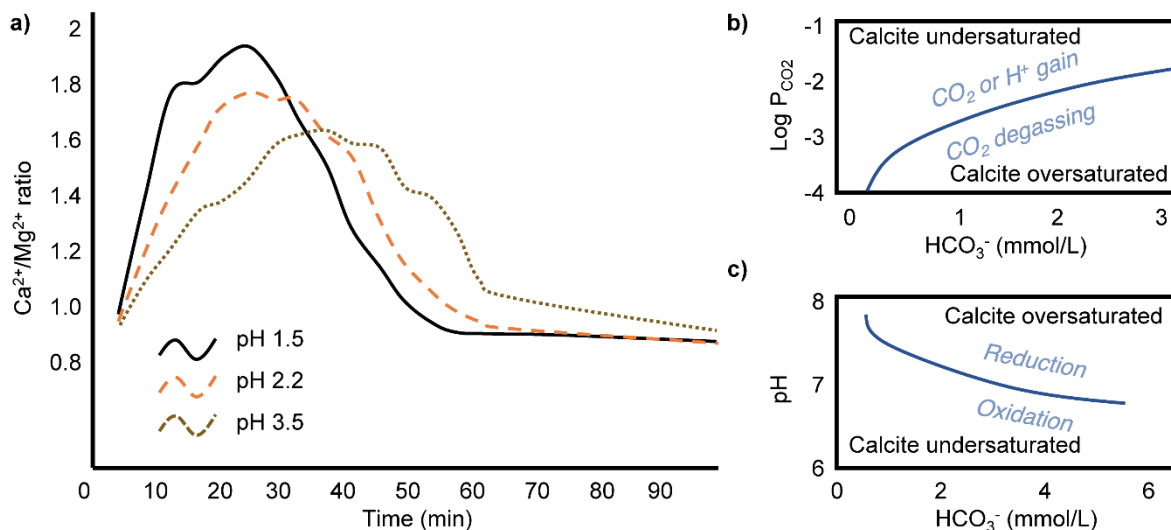


Figure 13 – a) Early stages of dolomite dissolution from fresh, unreacted surfaces are non-stoichiometric so the CaCO₃ is released faster than the MgCO₃ due to the large atomic radius of Ca²⁺ compared to that of Mg²⁺ resulting in stronger covalency of Mg-O making it less soluble. b) Conditions for CO₂ gain or degassing as a function of partial pressure of carbon dioxide and bicarbonate concentration. c) Conditions for reduction or oxidation as a function of pH and bicarbonate concentration. Based on Busenberg & Plummer (1982); Herman & White (1985); Lund and others (1973); and Singurindy and Berkowitz (2003).

Therefore, it is possible for carbonate systems to exist with dolomite or limestone rock outcrops that lack obvious chemical dissolution despite its propensity to chemical weathering.

Calcite (CaCO_3) and dolomite (MgCO_3) solubility are dependent on pH and saturation and reducing conditions. During the early stages of dolomite dissolution, the ratio of $\text{Ca}^{2+}/\text{Mg}^{2+}$ is complex as shown in Figure 13 . Calcite is released faster than dolomite due to the large atomic radius of Ca^{2+} compared to that of Mg^{2+} resulting in stronger covalency in Mg-O making calcite more soluble in early time.

2.3 Evaluating Understanding of Evaporites and Carbonates

Opportunities to assess your knowledge of evaporites and carbonates are provided by [Exercise 1](#), [Exercise 2](#), and [Exercise 3](#). Opportunities to assess your knowledge of carbonate dissolution are provided by [Exercise 4](#) and [Exercise 5](#).

3 Karst and Karstification

3.1 Karst

Karst refers to terrains with complex geological features and specific hydrogeological characteristics. According to Kuniansky and others (2022), the term is often used interchangeably for karst landscape (karst terrain), geological or hydrogeological setting (karst terrane) and the groundwater system (karst aquifer). These terrains comprise soluble rocks such as limestone, dolomite, and various evaporites such as gypsum and halite. Some definitions of karst are supplied in Table 1.

Table 1 - Definitions of karst.

Definition	Reference
Karst is a distinctive terrain developed on soluble rock with landforms related to efficient underground drainage.	Waltham & Fookes, 2003
Karst is a landscape, normally on limestone, that is characterized by underground drainage, caves, sinkholes, dry valleys, thin soils, and bare rock outcrops.	Waltham & Fookes, 2003
Karst refers to an ensemble of morphological and hydrological features and the dominant process responsible for them: dissolution of soluble rocks (mostly carbonates and evaporites),	Gutiérrez et al., 2014
The term karst is used to refer to the landscape (karst terrain), geologic or hydrogeologic setting (karst terrane), or groundwater system (karst aquifer) in areas underlain by soluble bedrocks	Kuniansky et al., 2022

To have a single universal definition, we define it as follows: The term karst is used to refer to the landscape (karst terrain), geologic or hydrogeologic setting (karst terrane), or groundwater system (karst aquifer) in areas underlain by soluble bedrock (Kuniansky et al., 2022).

Due to dissolution of these soluble rocks during the geological past, characteristic landforms develop that are collectively referred to as karst (Karimi, 2012) including: karrens, sinkholes, shafts, poljes, caves, swallow holes, caverns, estavelles, intermittent springs, submarine springs, lost rivers, dry river valleys, intermittently inundated poljes, underground river systems, denuded rocky hills, karst plains, and collapses. Karst topography does not only apply to soluble rocks but can be found in quartzites, granite and basalt despite their low solubility (Ford & Williams, 2007). This is referred to as pseudokarst (Figure 14).



Figure 14 - Examples of karst features in non-soluble rocks: a) pseudokarst suffusion in Namaqua-Natal Province Granitoids of Bizana South Africa (photograph by Dippenaar, 2002), b) pseudokarst piping daylight in Nebo Granite of Lebowakgomo, South Africa (photograph by van Rooy, 1992), c) pseudokarst sinkhole Mpuluzi Granitoid Batholith of Hlatikulu, Eswatini (photograph by Brink, 1979) and d) pseudokarst in Black Reef Quartzite of Kaapschehoop, South Africa (photograph by Dippenaar, 2016).

Karst systems comprise surface, rockhead, and underground features that form different landscapes (Table 2); it can be classified into five types: Juvenile Karst kI, Youthful Karst kII, Mature Karst kIII, Complex Karst kIV, and Extreme Karst kV (Waltham & Fookes, 2003) as shown in Figure 15.

Table 2 - Karst features and landforms (Waltham & Fookes, 2003).

Type	Process and Products	Extent
Surface micro-features	Dissolution fretting of bare rock; karren runnels (e.g., gryke, cutters, pinnacles)	Meter scale
Surface macro-features	Dry valleys, dolines, poljes, cones, towers	Kilometer scale
Subsoil features	Dissolution in soil water; various complex morphologies	Tens of meters
Sinkholes	Surface depressions related to underground cavities	1–1,000 m across
Caves	Cavities formed by dissolution and empty or filled with sediment	Meters to tens of meters

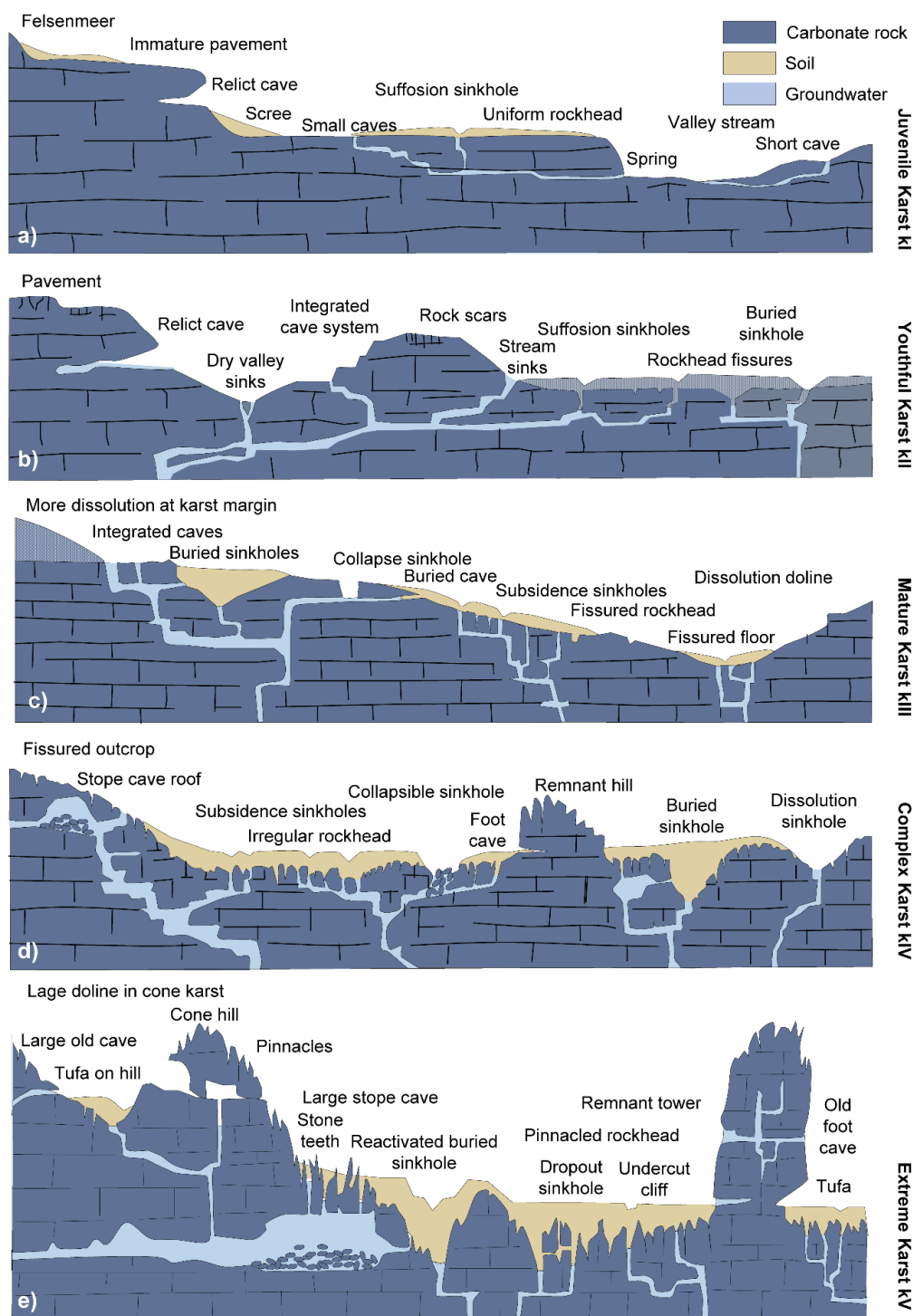


Figure 15 - An engineering classification of karst (Waltham & Fookes, 2003) comprises five classes. a) Juvenile Karst only occurs in deserts and periglacial zones on impure carbonates. b) Youthful Karst has many small fissures and only small sinkholes form. c) Mature Karst is common in temperate regions with extensive fissuring, large dissolution sinkholes, and small collapse sinkholes. d) Complex Karst is localized in temperate regions and normal in tropical regions with pinnacled rockhead and many large dissolution sinkholes. e) Extreme Karst only occurs in wet tropics with abundant and complex dissolution cavities.

3.2 Karstification

Karstification is the process of chemical decomposition, dissolution and solutional erosion of soluble rocks to form characteristic landforms and systems of underground

water movement. Karstification depends on numerous factors, including pH of precipitation, pCO_2 , the hydraulic gradient, the climate, and the properties of the karst such as its extent and fracturing. Dissolution and hydrodynamic erosion can cause total removal and ghost-rock karstification that include large, weathered features and corridors, ghost-endokarst and weathered galleries (e.g., Dubois et al., 2014; Ford & Williams, 2007, Kuniansky et al., 2022).

Traditional karstification involves total removal of soluble rock, whereas ghost rock karstification occurs through stages of dissolution and erosion. Karstification by total removal requires both considerable chemical energy for the dissolution of the carbonates and hydrodynamic energy for the removal of the undissolved particles, and it is therefore characterized by three processes: (1) chemical dissolution of soluble rock, (2) simultaneous mechanical removal of dissolved species and mechanical erosion of particles, and (3) the formation of open voids. Decomposition of carbonates happens through an acid-base reaction when acidified water interacts with the rocks. For the dissolution to continue, the source of acid must be renewed, and this happens through the introduction of slightly acidic recharge water that is undersaturated in calcium carbonate. Dissolution occurs first through the micritic content and continues to larger particles over time (Dubois et al., 2014).

Ghost-rock karstification, on the other hand, requires considerable chemical energy for the dissolution of the carbonates, but only limited hydrodynamic energy to remove the dissolved species without removing the undissolved particles, thereby causing the undissolved particles to remain in the cavities (Dubois et al., 2014). Alterite and some unconsolidated materials are removed in the process of ghost-rock karstification. This forms cave-type spaces and occurs in various environments by dissolution resulting from hypogene conditions (i.e., processes that originate deep within the Earth, driven by internal heat and pressure) due to changing temperature pressure and/or fluid composition. The Alterite and unconsolidated particles are then removed by erosion caused by increasing flow rate (Klimchouk, 2018). Traditional and ghost-rock karstification are shown in Figure 16.

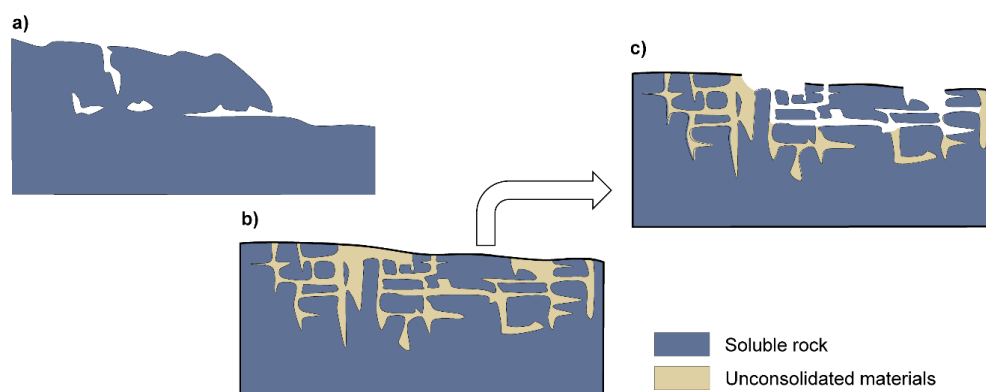


Figure 16 - Traditional karstification is where a) total removal occurs due to significant dissolution and hydrodynamic erosion. In ghost-rock karstification, b) dissolution zones are filled with residue either without any removal or with c) partial erosion. Ghost-rock karstification typically happens due to significant dissolution but low hydrodynamic erosion (Dubois et al., 2014).

The comprehensive karst system is shown in Figure 17. The landforms and groundwater flow are complex and intricate, distinguishing karst from other landscapes. Dissolution at the soil/rock interface creates an abrupt transition as opposed to a gradual transition of weathering processes. The rockhead profiles in karstic rocks can be extremely irregular. Vertical or inclined joints provide flow paths for infiltration of rainwater and soil-water and are enlarged into fissures that are more pronounced near the rockhead where corrosive soil-water first interacts with the carbonate bedrock. With time, the fissures are enlarged to develop a pinnacled rockhead in the upper part of the rock mass (Waltham & Fookes, 2003). When the rate of dissolution exceeds the rate of erosion, cavities form in the phreatic zone as mineralized water is removed and replaced by fresher water, and grykes form in the vadose zone. The grykes are often filled with insoluble impurities that remain to form residual dolomite – sometimes referred to as wad.

Where karst occurs at the land-ocean interface *sabkhas* run parallel to coastlines (with the possible facies including evaporates, pebble-conglomerates, algae mats, and dolomitization, all in the absence of fossils) that are flooded during times of strong onshore winds and spring tides. Steep-sided and enclosed landforms with flat floors that occur in karst regions, may have orientation controlled by structural features such as faults and folds, guide and enhance erosion to form *poljes*. *Tufa* is sedimentary rock composed of calcium carbonate that precipitated through evaporation while occurring commonly as an incrustation around the mounts of springs along streams (the more compact and dense variety is referred to as travertine) (Lapidus, 1990).

Allogenic rocks comprise minerals and rocks that are derived from pre-existing rocks transported from their original location, and *authigenic* rocks are composed of mineral constituents the formed where the rock was found (Lapidus, 1990). Weathering and erosion (via water such as rivers, gravity, wind, and other agents) therefore transports sediment to other places for the deposition of allogenic rocks, whereas deposition in the immediate settings of sediment or precipitation of dissolved constituents will form authigenic rocks.

Karren refers to the occurrences of caves, sinkholes, losing streams, and distinctive erosional features, developing on the exposed soluble bedrock surfaces (Kuniansky et al., 2023).

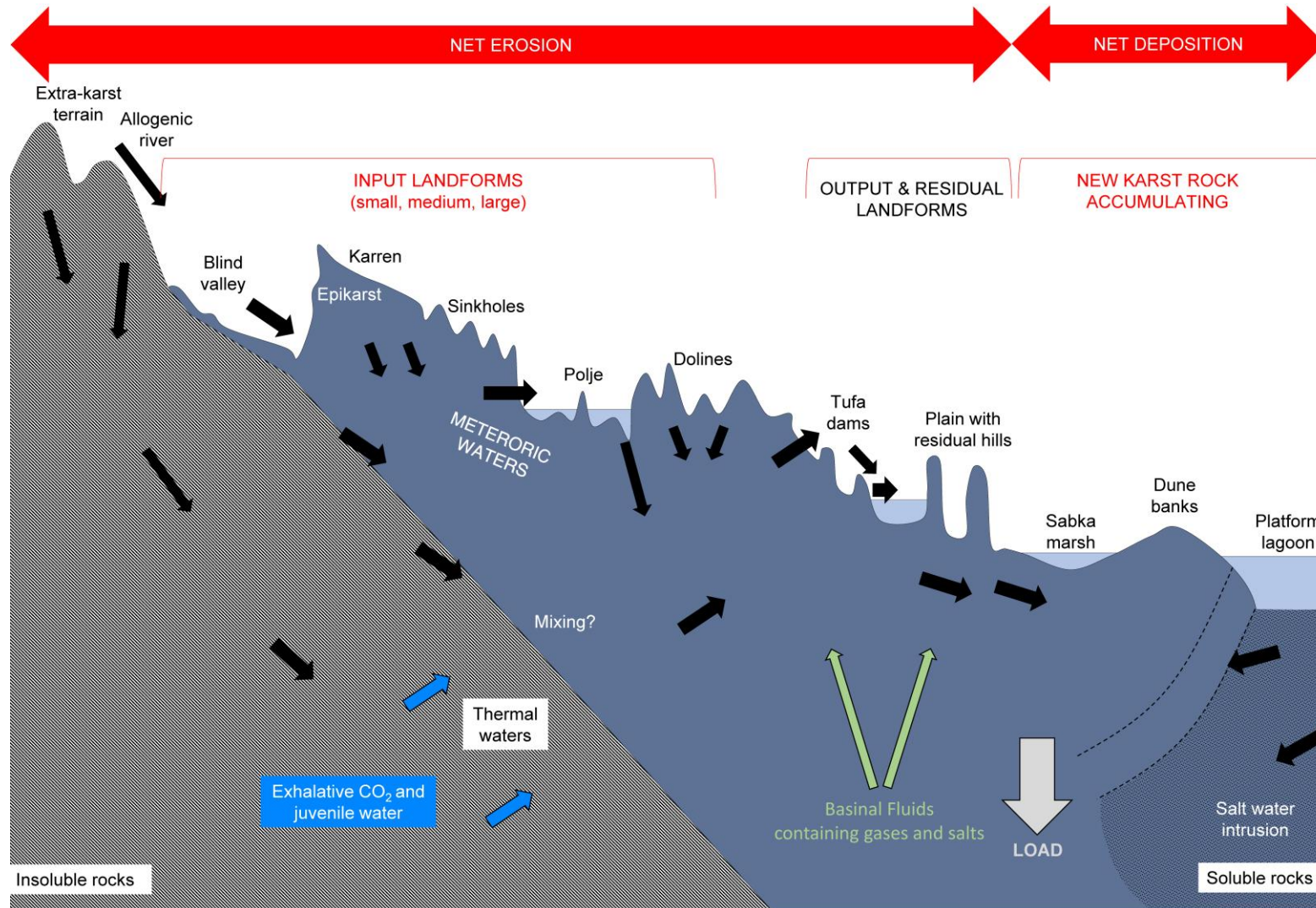


Figure 17 - The comprehensive karst system (modified from Ford & Williams, 2007).

The rate of speleogenic (i.e., the process of cave formation) wall retreat or karst development is greatly affected by acid solution, hydraulic-shear forces, and erosion by corrosion, implying that many mechanisms of weathering all have a significant influence on karst landscape development. Subsurface karst where sub-horizontal and sub-vertical conduits along faults, fractures and bedding planes intersect are termed caves with examples shown in Figure 18. There are two types of caves (Radulović, 2013).

- Fluvial caves are predominantly formed by erosion of turbulent streams and form erosion features such as potholes, subsurface canyons, and natural bridges.
- Corrosion/solution caves are most widespread and are predominantly formed by chemical erosion and have smaller diameters and lengths.



Figure 18 - Air filled caves: a) and b) Gcwihaba caves, Botswana (2018); c) and d) Grand Canyon Caverns, Arizona, USA (2019); e) and f) Makapan's Caves, Mokopane, South Africa (2021) (photographs by Dippenaar).

Epikarst is the well-drained, high storage, coarse-grained horizon overlying fractured karst that overlies the fresh rock containing fractures and cavities. Epikarst allows for slow percolation of water into the bedrock resulting in groundwater recharge. It is associated with juvenile karst or karst subjected to disintegration.

Some conceptual models of karst and associated recharge are shown in Figure 19.

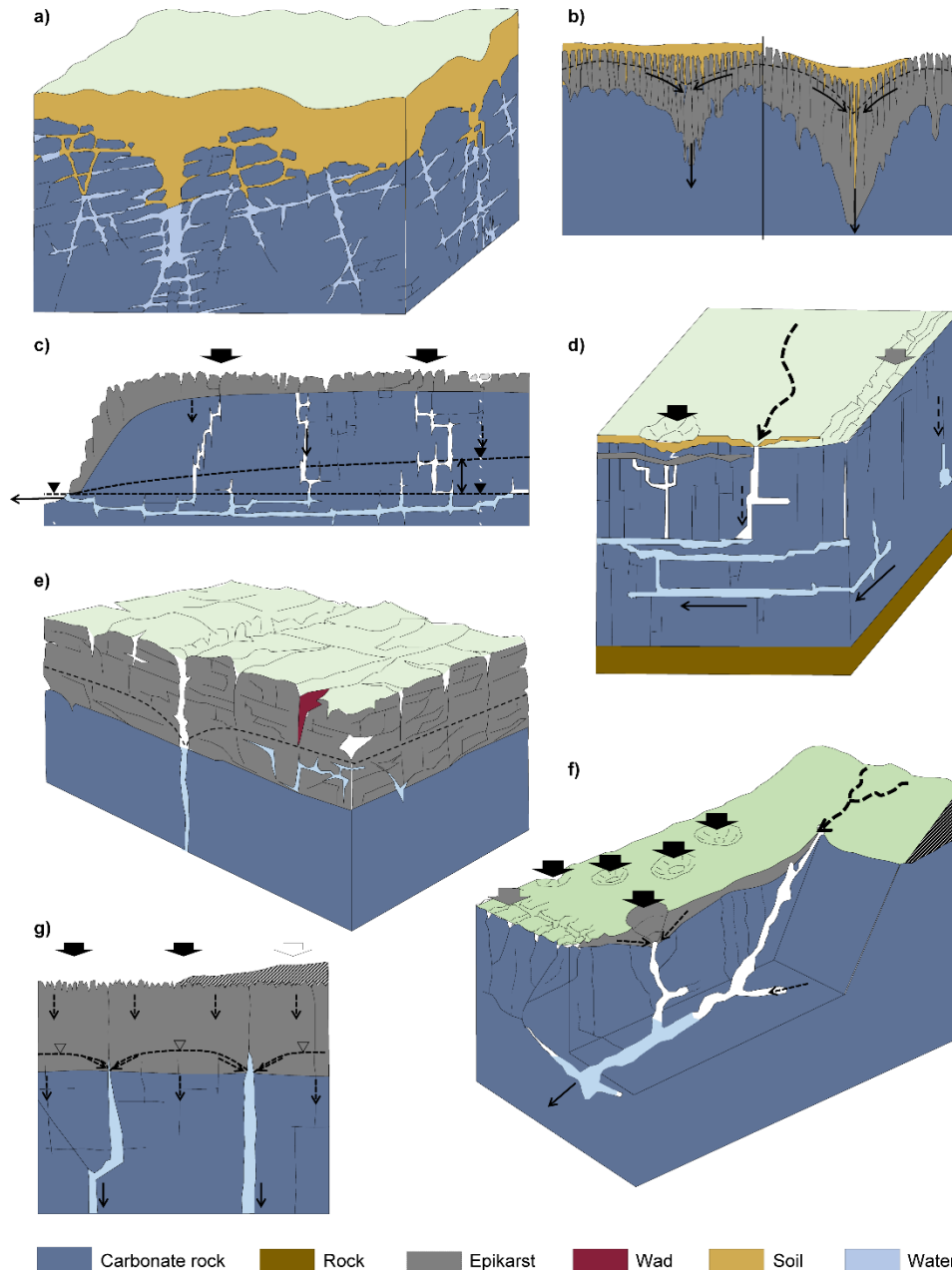


Figure 19 - Conceptual models of karst (adapted from Dippenaar, van Rooy, et al., 2019). These models can be related to groundwater recharge depending on the vertical sequence of materials covering the bedrock. Diffuse recharge may occur a) where thick soil covers dissolution cavities (Lattman & Parizek, 1964) and b) where an epikarst zone occurs between soil and bedrock (Williams, 1983). Where c) no or thin soil cover is present, concentrated recharge in high relief areas may discharge directly from springs at lower elevations (Therond, 1973), d) may flow through cave systems (Doerfliger & Zwahlen, 1995), or e) accumulate as perched water (Mangin, 1975). Concentrated recharge may enter the aquifer directly through f) swallow holes (Gunn, 1986) or from g) groundwater perched in discrete fractures of the epikarst zone (Klimchouk, 2004).

3.3 Evaluating Understanding of Karst

Opportunities to assess your knowledge of karst are provided by [Exercise 6](#), [Exercise 7](#), and [Exercise 8](#). Opportunities to assess your knowledge of karstification are provided by [Exercise 9](#), [Exercise 10](#), [Exercise 11](#), and [Exercise 12](#).

4 Karst Hydrology and Hydrogeology

4.1 Flow Zones in Karst

Karst aquifers are unique in terms of geology, and they consist of soluble carbonate rocks like limestone and dolomite that exhibit complex fracture networks with conduits and sinkholes. These aquifers consist of soluble features that cause rapid and preferential flow paths that result in dynamic groundwater systems with intricate vadose zone conditions providing natural connections for the interplay between groundwater and surface water (van Wyk et al., 2025).

The epikarst or the subcutaneous zone, is the upper portion of the weathered bedrock or the soil-rock interface in karst landscapes. It forms part of the vadose zone with overlying materials and an underlying transmission zone that connects to the phreatic zone by means of recharge. Epikarst develops as a function of bedrock structure, lithology, climate, time since last glaciation, rock solubility, vegetation cover, and groundwater depth. Three types of epikarstic zones are distinguished in unconfined carbonate aquifers, namely rapidly draining, seasonally saturated, and perennially saturated epikarst (Alley, 1997; Williams, 2008).

Infiltration occurs at the surface, and the flow becomes slower and more lateral with depth. The top portion of the epikarst is dominated by vertical infiltration of water from the karst surface. With depth, the vertical movement of water decreases as openings in the rock get narrow and become less abundant. The water begins to move laterally, then becomes increasingly concentrated to form shafts (Klimchouk et al., 1996). The soil-rock interface governs water storage and movement. Where present, the epikarst horizon governs this, causing gradual percolation and providing storage.

For epikarstic systems, the weathered soluble rock forms a very well-drained, coarse-grained horizon. Its behavior is essentially inverse to normal residual horizons. Here a gravelly horizon develops above fresher bedrock forming a high-storage, gravelly layer from which slow release of diffuse flow can result in deeper percolation into the bedrock.

In some instances, the properties of the overburden do not meet those described above for epikarst. In dolomitic and more mature karst landscapes the systems are generally not unconfined, and the residual and weathered materials comprise high storage, low permeability soils filling deep grykes between pinnacles. The fractured rock is absent on this bedrock surface, and the storage is in fine sands and silts formed through extremely long periods of decomposition of the dolomite.

Pinnacled dolomite develops as a function of climate and geological history. These rockheads typically form in the wet tropics where they have time and the necessary environment to mature fully (Waltham & Fookes, 2003). Limestone that was covered by

Pleistocene ice was eroded to expose the hard rock surface with only minimal fissuring during post-glacial dissolution processes.

In pinnacled karstic systems highly variable bedrock topography develops that comprises deeply weathered grykes and solid rock pinnacles. Grykes are filled with residual material such as wad, chert rubble from the dissolution of soluble rock leaving the silica to collapse, transported soils, or younger caprock. The wad usually has high specific retention, often coupled with very high porosity and low density despite its low hydraulic conductivity. Water can be stored in these residual horizons for very long periods.

Both the calcite and magnesite in dolomite are highly soluble and are therefore entirely removed during the leaching of dolomite. Chert (SiO_2) and other impurities such as Mn^{2+} and Fe^{2+} remain that can form residual dolomite—in some instances referred to as wad—through enrichment. Mn-oxides such as birnessite coat other minerals and form reactive surfaces on fine chert and quartz grains. Birnessite's surface area can reach $300 \text{ m}^2/\text{g}$, resulting in it being able to carry 15–25% of its weight in water. The soil is porous and sponge-like with an increase in porosity and permeability compared to the original dolomite rock. This material represents the residual dolomite—dolomite as decomposed in-situ—or wad and can co-exist with residual chert breccia—chert horizons disintegrated in-situ. Examples of wad are shown in Figure 20 (Dippenaar, Swart, et al., 2019). Additional examples of wad as well as dolomite-chert interlaying are shown in Figure 21.

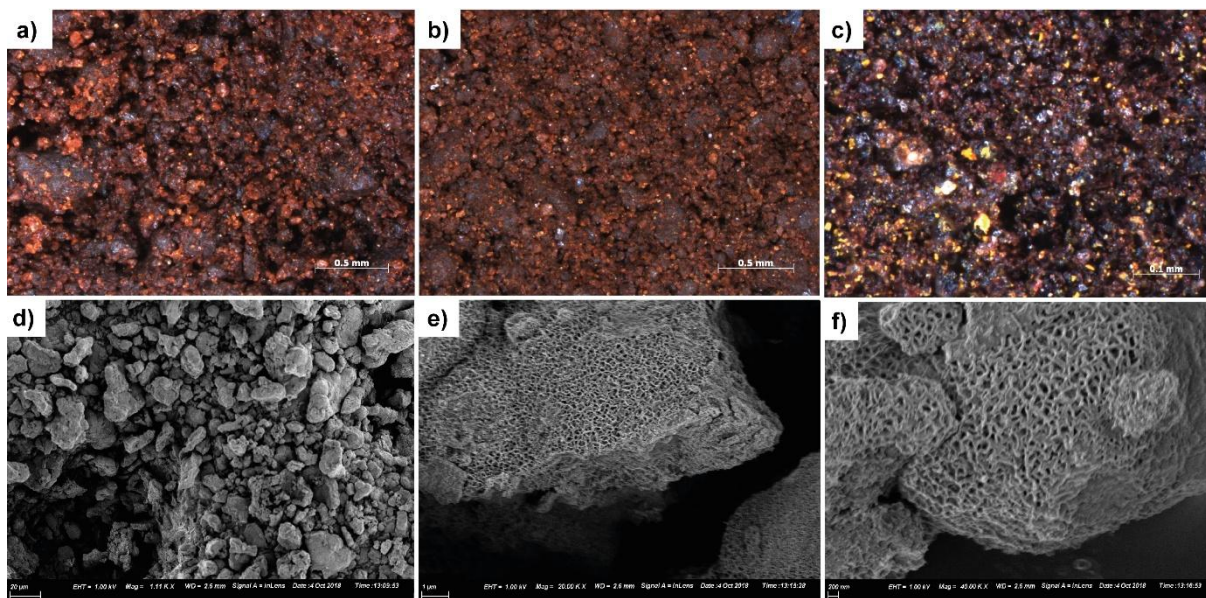


Figure 20 - Stereomicroscope images of wad from undisturbed samples at a) x20 magnification, b) x94 magnification, c) x94 magnification after tri-axial test and d) SEM images of wad at x1000 magnification, e) x20000 magnification and f) x40000 magnification showing voids in the mineral birnessite (Dippenaar, Swart, et al., 2019).

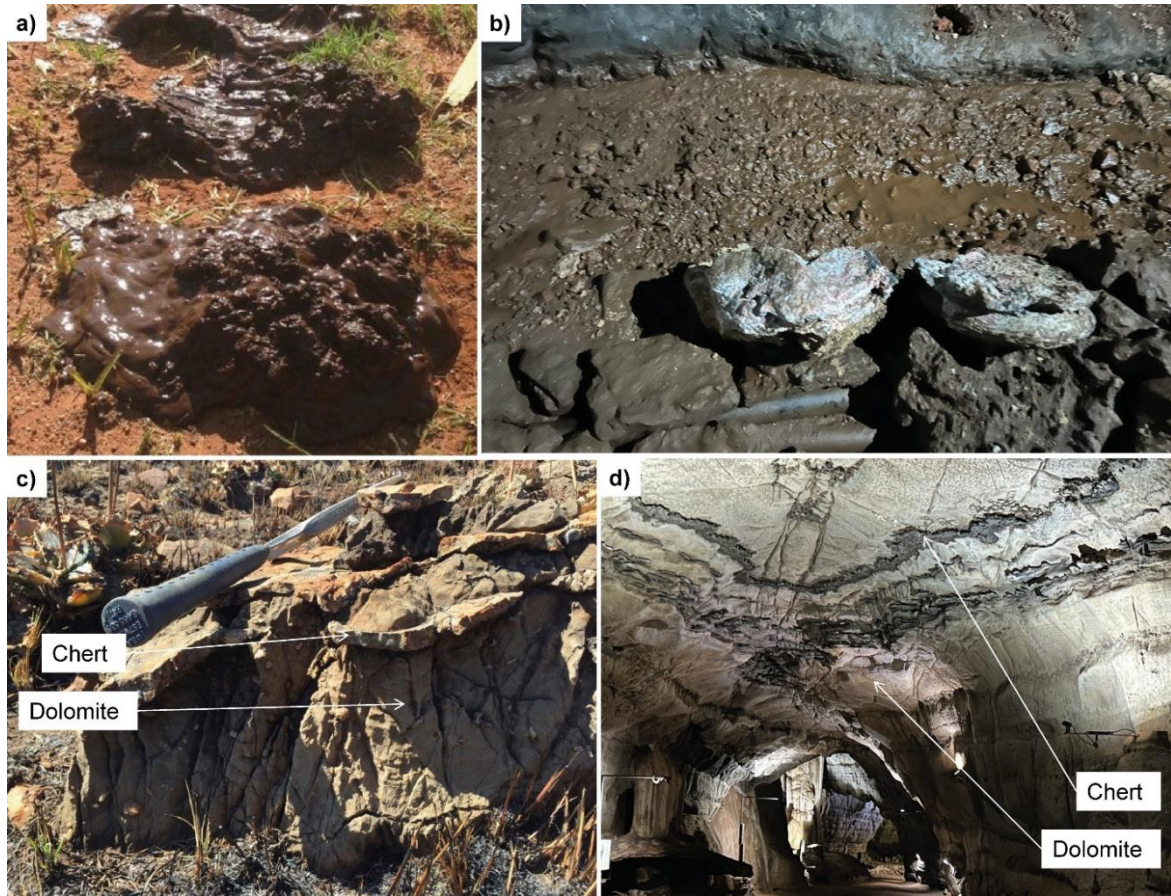


Figure 21 - Examples of wad a) from percussion drilling in Soweto, South Africa (2016); b) in situ in Sudwala Caves in South Africa (2023). Interlayering of dolomite and chert c) in outcrop showing elephant skin weathering, and d) exposed in a dissolution cave of Sudwala Caves in South Africa (2023) (photographs by Dippenaar).

Different types of porosity exist in different soils and rocks, as dictated by their geological origins and geomorphological development. These different types of porosity result in different hydrogeologic behavior in terms of hydraulic conductivity and storage, and all three types of porosity can occur individually or combined (Figure 22).

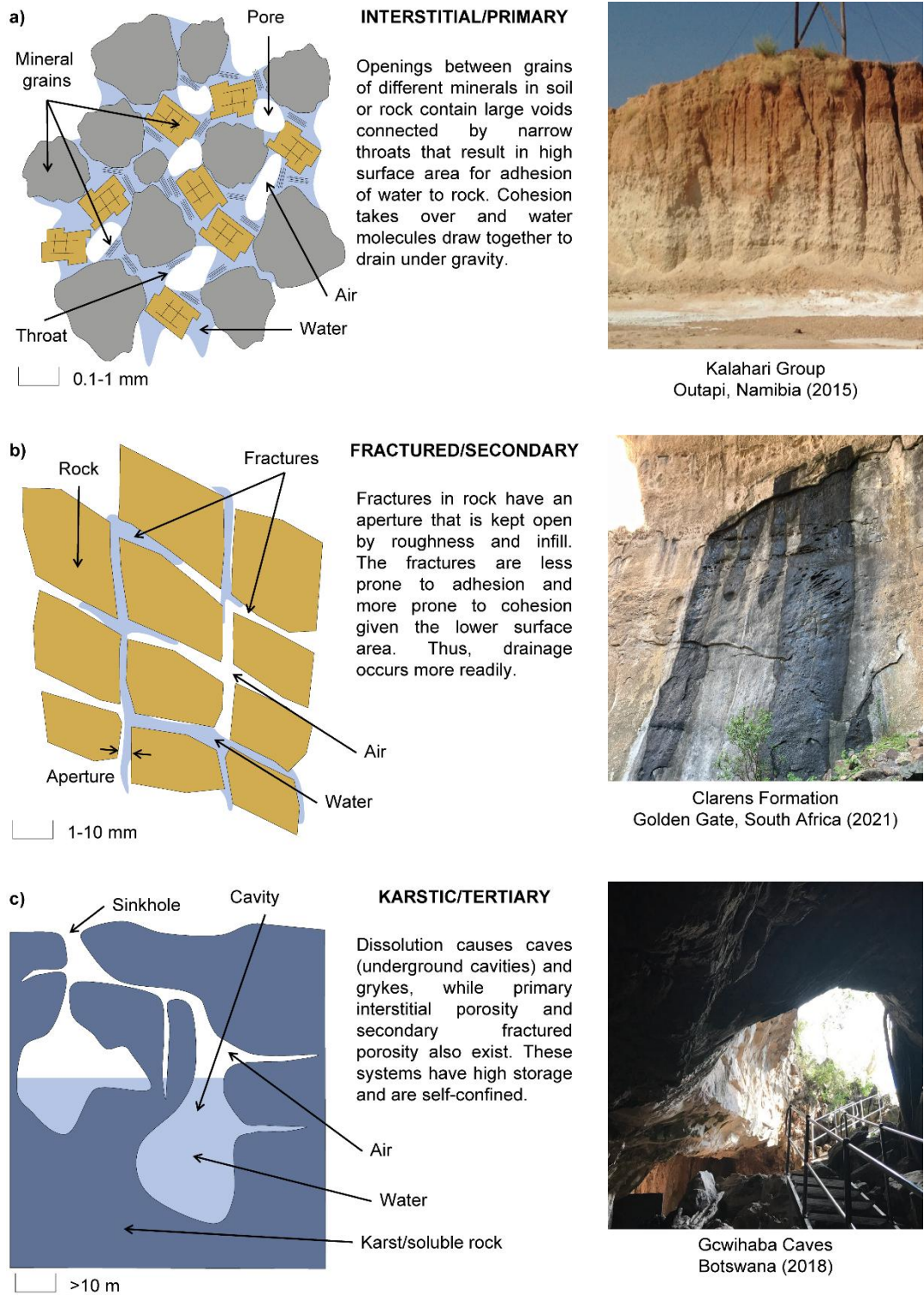


Figure 22 - Significant differences are shown between traditional primary porosity as in a) sandy soils of the Kalahari Group in Outapi, Namibia (2015); secondary porosity as in b) fractured rock of the Clarens Formation Sandstone in Golden Gate, South Africa (2021); and the tertiary porosity of large dissolution caves/cavities as in c) karst of the Gcwihaba Caves of Botswana (2018) (photographs by Dippenaar).

Porosity of carbonate rocks changes over time and subsequently hydraulic properties change. These temporal changes in porosity, are used to classify karst aquifers as follows (Choquette & Pray, 1970).

- 1) Eogenetic karst aquifers generally comprise younger, near-surface carbonates and form due to changes occurring at deposition and early exposure.
- 2) Mesogenetic karst aquifers form due to changes occurring during deep burial.
- 3) Telogenetic karst aquifers generally comprise uplifted old carbonate rocks and change following post-burial exposure and erosion.

The matrix porosity and permeability are substantially lower in telogenetic compared to eogenetic karst aquifers due to its increased diagenetic alteration associated with its age and depth of burial (Kuniansky et al., 2022; Choquette & Pray, 1970).

The conduit network or cave pattern depends on local scale drivers such as the type of porosity and the type of recharge, as well as regional or system scale drivers such as the hydraulic gradient and the relationship between direction of the hydraulic gradients and orientation of the drainage or fracture planes. Recharge occurs through epikarst, or through breaks in the epikarst such as sinkholes and vertical fractures or fissures (Palmer, 2000). Recharge in karst occurs as allogenic, autogenic, diffuse, or concentrated (Figure 23).

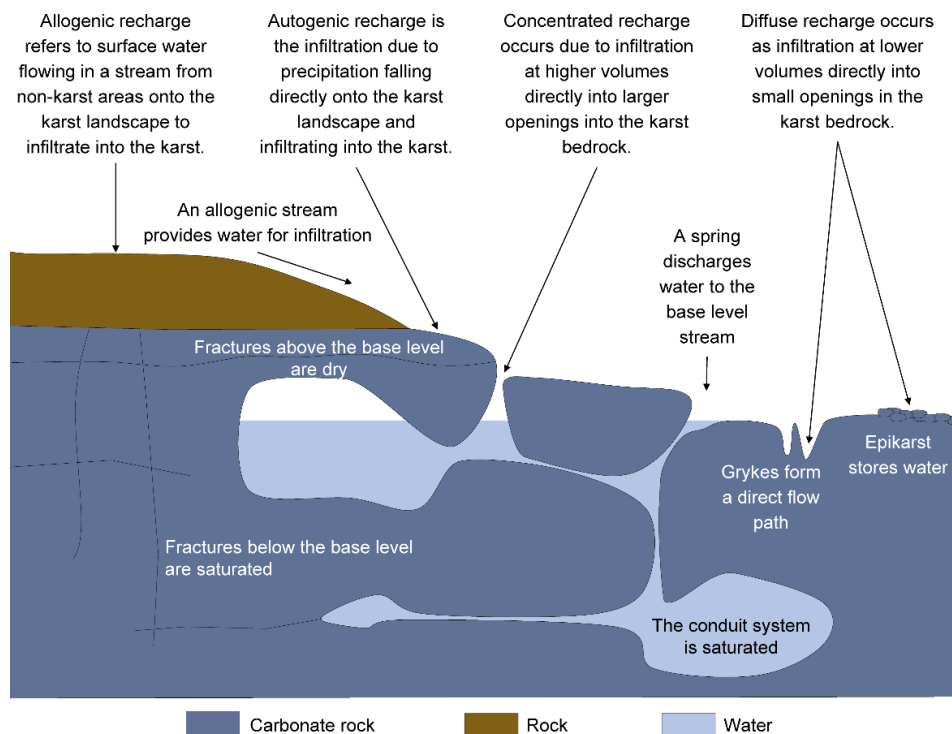
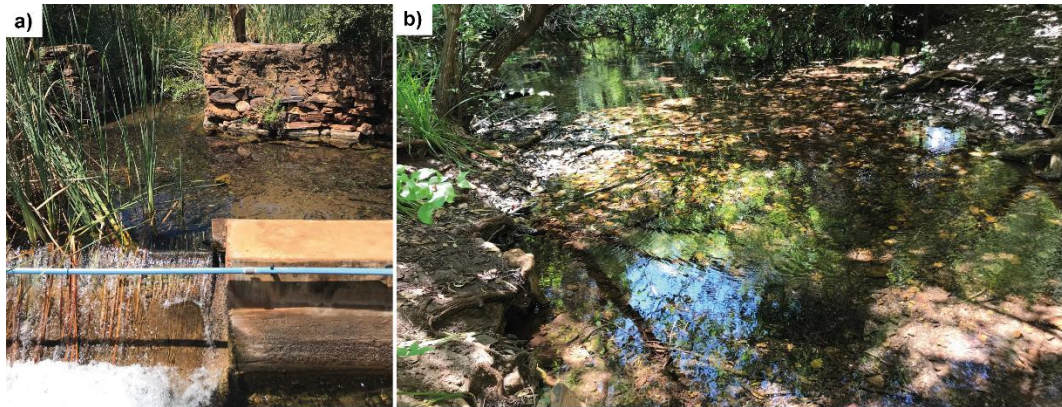


Figure 23 - Allogenic, autogenic, diffuse, and concentrated recharge.

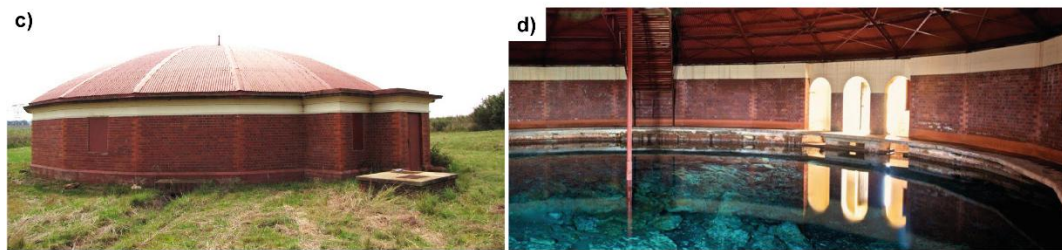
Groundwater discharge to the surface occurs through springs. Some examples of karst springs are shown in Figure 24. In karst systems, springs vary significantly based on physical form and discharge rates, and can be subdivided as listed here (White, 1988).

- Open conduit gravity springs that form where water emerges at cave mouths.
- Alluviated conduits that form where water emerges at raised pools created by glacial or alluvial action.
- Rise pools that form at shallow flooded conduits.

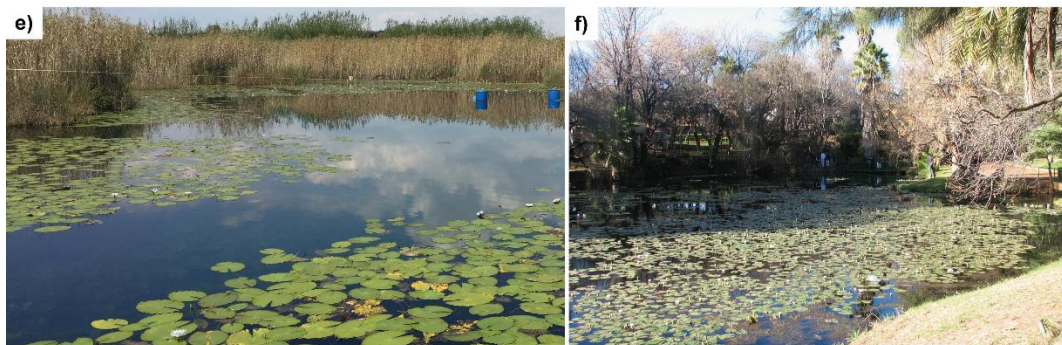
- Artesian springs that form when groundwater head is higher than the ground surface elevation with water rising from considerable depth.
- Springs that discharge from fracture swarms widened by dissolution.



Dinokana Eye, partial water supply to Dinokana (North-West Province, South Africa, 2018)

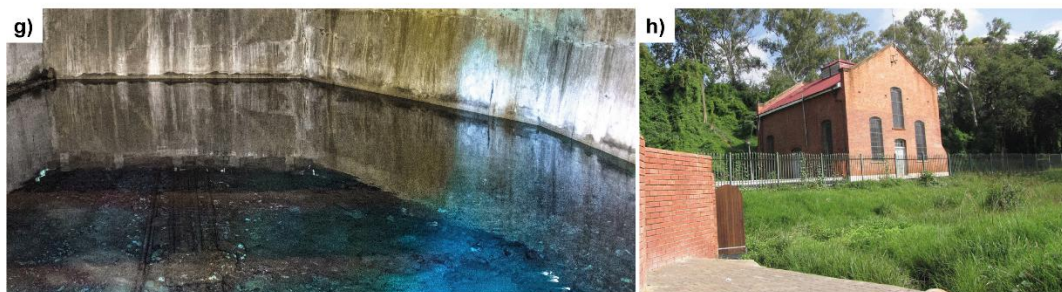


Grootfontein spring, partial water supply to Pretoria (Pretoria, South Africa, 2017)



Marico Eye (North-West Province, South Africa, 2017)

Kuruman Eye (Northern Cape, South Africa, 2005)



Lower Fountain (Pretoria, South Africa, 2015)

Figure 24 - Photographs of artesian karst springs from which water is supplied to communities in South Africa. a) and b) Dinokana Eye supplying water to Dinokana settlements in the North-West Province (2018); c) and d) Grootfontein spring augmenting water supply to Pretoria in Gauteng (2017); e) Marico eye in the Northwest (2017); f) Kuruman eye augmenting water supply to Kuruman and surrounds; g) and h) Fountains springs augmenting water supply to Pretoria in Gauteng (2017) (photographs by Dippenaar).

Challenges faced in modeling flow in karst aquifers accentuate the importance of studying these systems. Modeling of rapid flow velocities, heterogeneity, and preferential pathways in karst systems is notoriously difficult (Goldscheider et al., 2000; Simaubi et al., 2023). Insights from studies of karst systems can be extrapolated and applied to improve understanding and modeling techniques in other hydrogeological systems (van Wyk et al., 2025).

4.2 Flow Through Karst

Karst aquifers have unique geological characteristics and complex hydrological processes that provide valuable insight into flow through the vadose zone to the natural connection locations where interplay between surface water and groundwater flow processes occurs. The karst vadose zone thickness is crucial in modulating residence times and groundwater dynamics that have implications for contaminant transport and recharge processes (van Wyk et al., 2025).

Epikarst is the uppermost top of weathered carbonates just below the soil zone if present and both form the unsaturated or vadose zone. Water circulation in karst occurs in the vadose zone through vertical and horizontal joints, the latter often associated with bedding planes, in the epiphreatic zone (intermittently saturated), and the phreatic zone. Flow paths form through dissolution and become larger and more heterogeneous over time. Infiltration occurs vertically downwards through soil and epikarst or grykes in pinnacled rock with slower rates in grykes, depending on the infill properties, or moving rapidly through larger dissolution features.

Chert restricts downward flow, forming seeps and small springs. In certain instances, karst systems are compartmentalized by intrusive dikes and sills. This is common in the dolomitic areas of South Africa, for example in the Far West Rand of Gauteng, which houses the capital city Pretoria and roughly a quarter of the country's population. Dikes are shown with an example of skarn—metamorphosed carbonate rocks—in Figure 25.

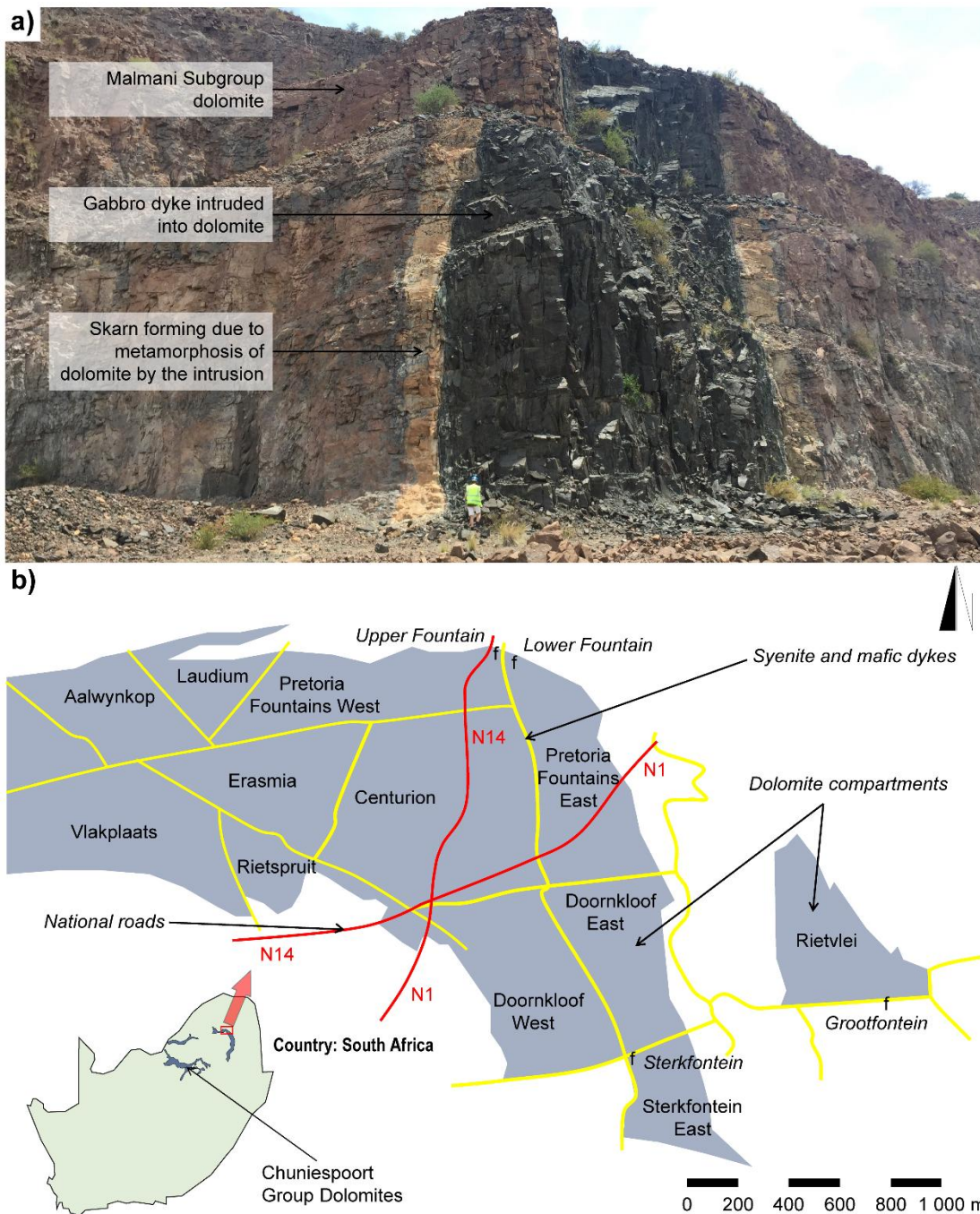


Figure 25 - a) Mafic dike dividing the Eccles Formation into the Aalwynkop and Laudium compartments and forming skarn on the contact (photograph by Dippenaar). b) A plan view map of dikes intruded into the Malmani Subgroup dolomites and chert in and around Pretoria, South Africa.

Hydraulic properties vary between normal fractured rock, shallower more juvenile and epikarstic rock, and deeper more mature and pinnaced karst (Figure 26). Epikarst generally has fractures with high storage capacity, and high permeability. Some examples of epikarst are shown in Figure 27. Pinnaced karst generally has deep grykes between pinnacles, filled with high storage, low permeability residual dolomite derived from weathering and in-situ consolidation, or chert rubble that may have higher storage.

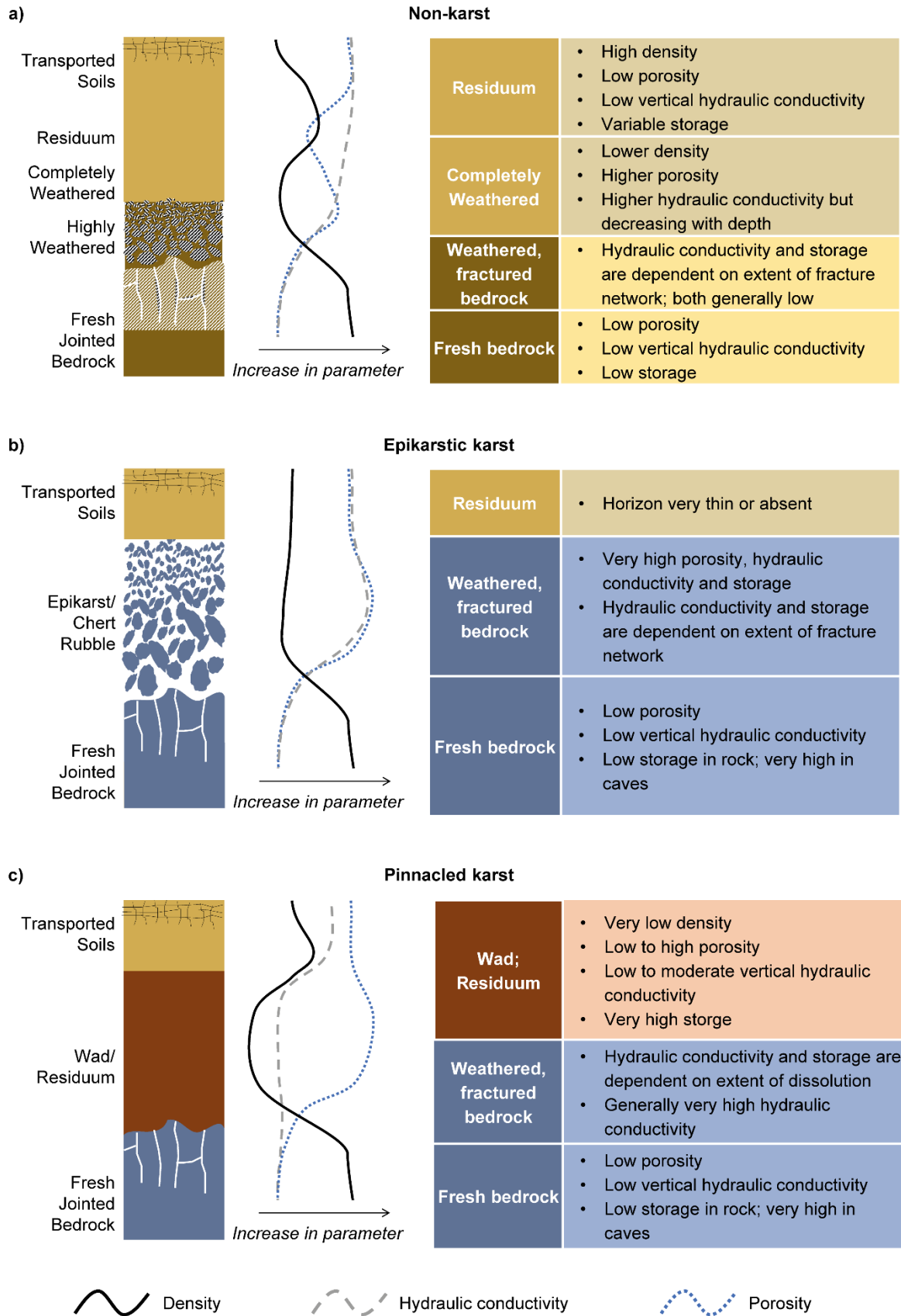


Figure 26 - Hydromechanical properties of a) non-karstic, b) epikarstic, and c) pinnacled karstic systems, including relative values of density, hydraulic conductivity, and porosity (modified from Dippenaar, van Rooy et al., 2019).

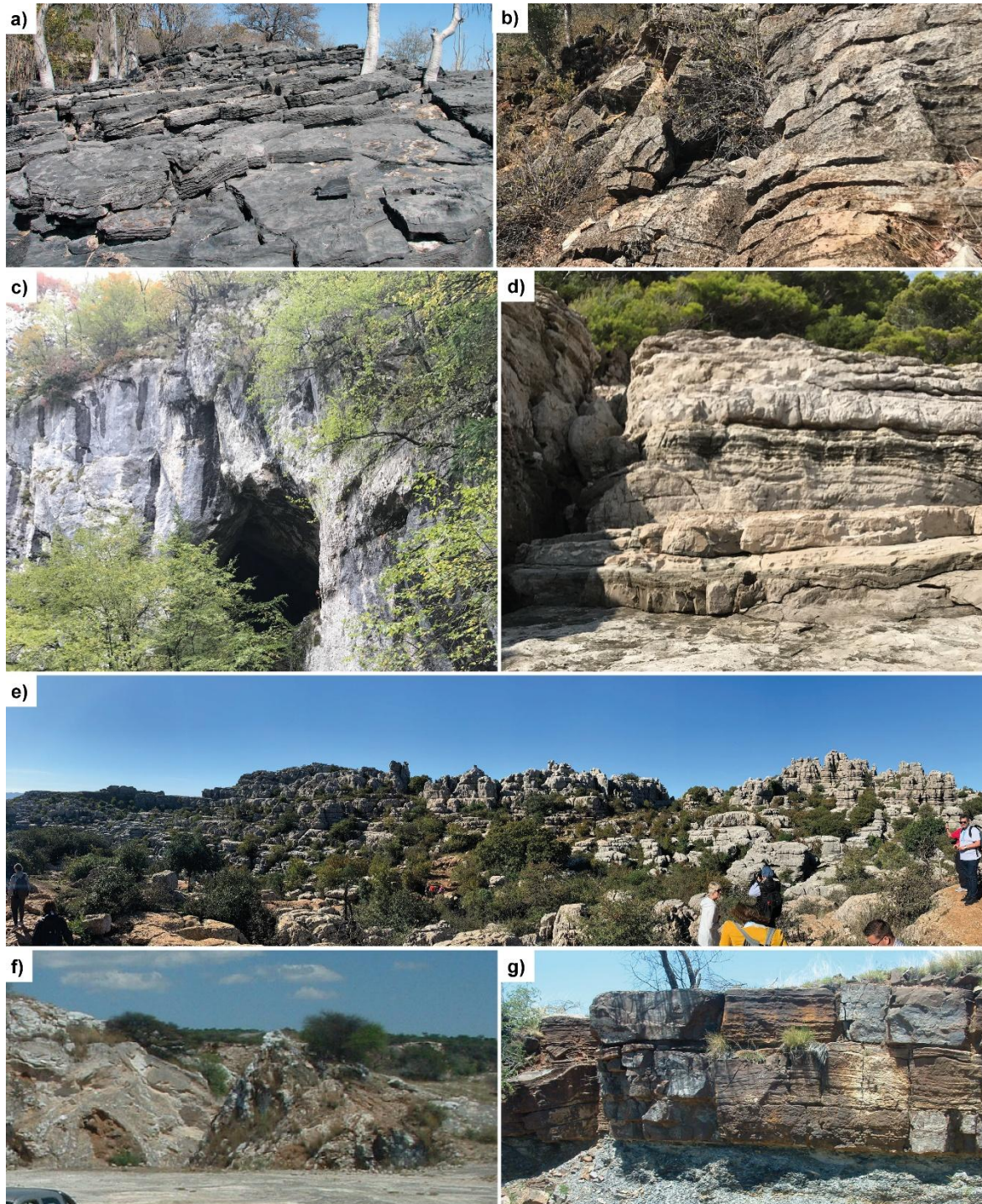


Figure 27 - Photographs of epikarst and dolomite outcrops a) Etosha National Park in Namibia (2010); b) Aha Hills in Botswana (2018); c) Plitvice in Croatia (2017); d) Dubrovnik om Croatia (2017); e) El Torcal de Antequera in Spain (2019); f) dolomite and calcrete in Taung, North-West Province, South Africa (2008); g) dolomite overlying mudrock in Tung, North-West Province South Africa (2008) (photographs by Dippenaar).

Pinnacled karst is mature and due to decomposition, forms pinnacles with grykes in between. A residual sandy silt soil termed wad forms in the grykes and has high storage with low hydraulic conductivity. If the formation contains chert, a gravelly cherty soil with higher likelihood of percolation will develop. Some conceptual models and examples of pinnacled karst are shown in Figure 28 and Figure 29.

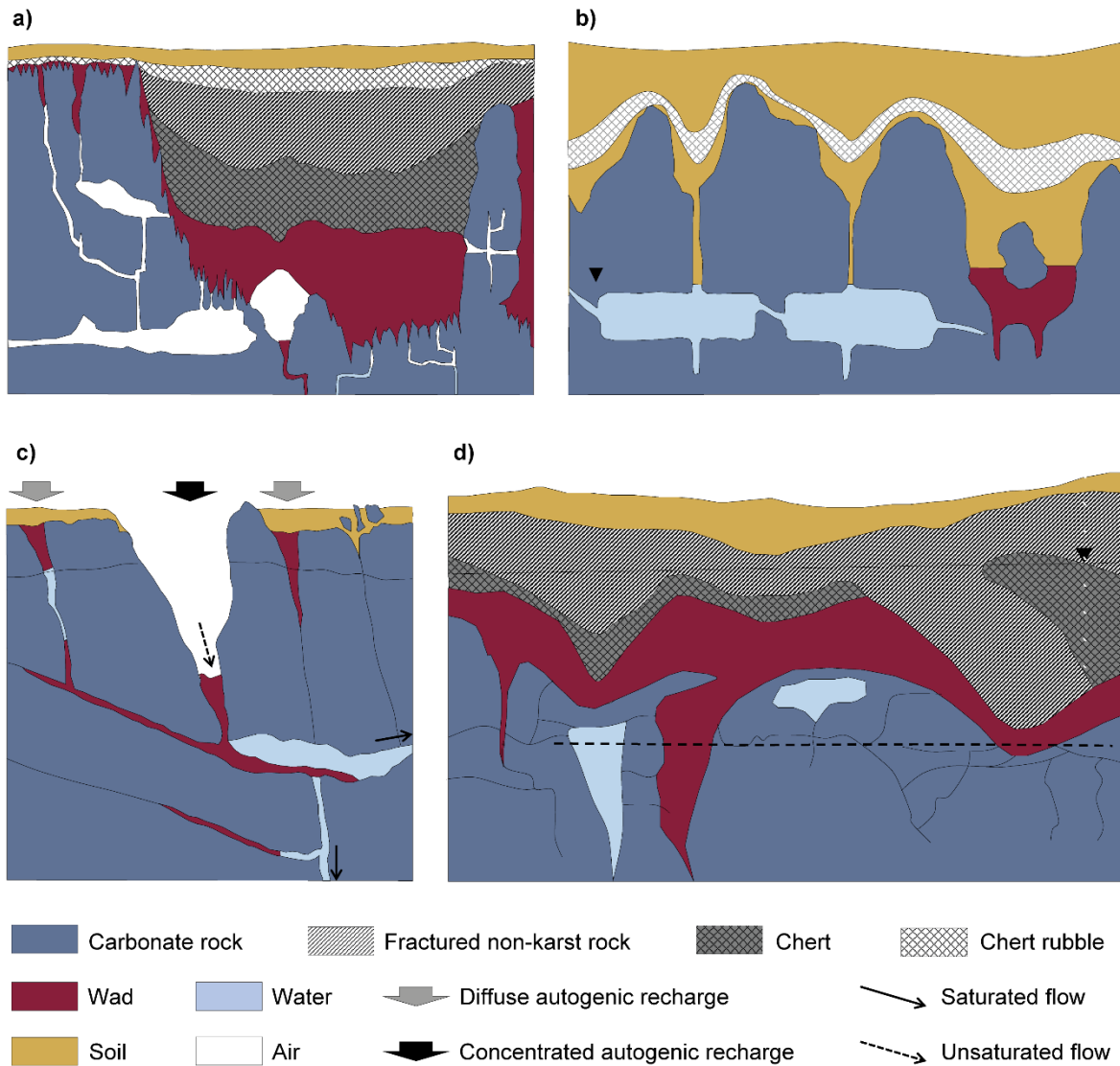


Figure 28 - Some conceptual models of pinnaced karst. a) A sinkhole infilled with younger sedimentary rocks (Trollip, 2008, Waltham & Fookes, 2003). b) A cave system below groundwater level (Brink, 1979). c) A swallow hole providing access to groundwater (Trollip, 2008); d) Residuum covering infilled grykes and isolated cavities in bedrock (Vegter, 1995) (modified and annotated from Dippenaar, van Rooy et al., 2019).

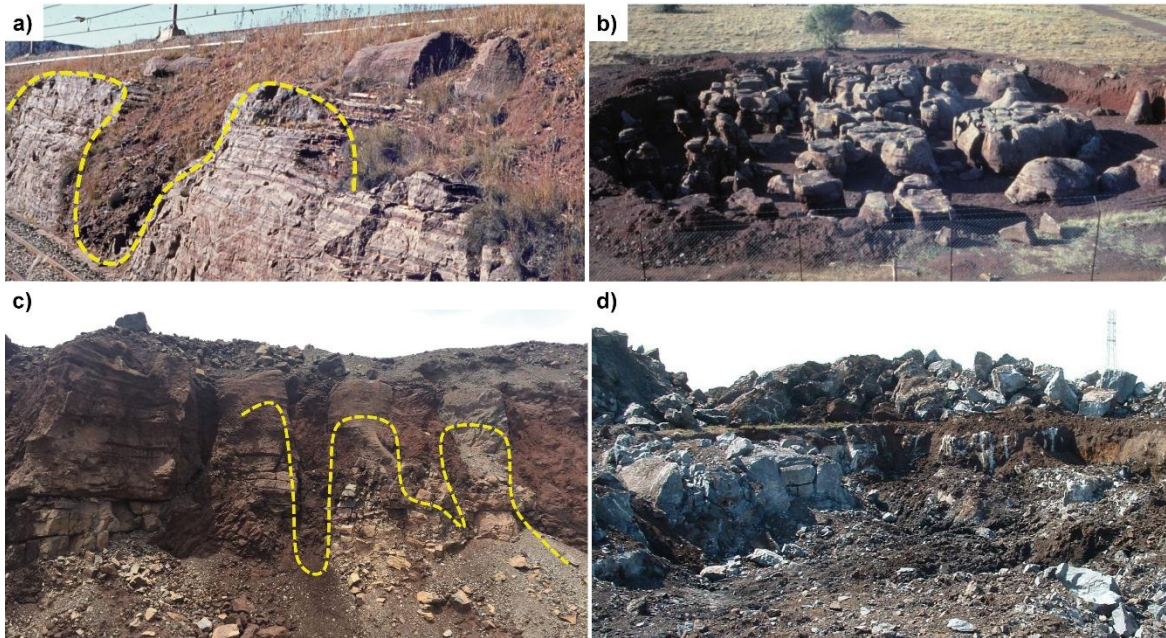


Figure 29 - Examples of a) shallow rockhead pinnaced karst; b) exposed pinnacles after removal of gryke infill; c) irregular pinnacles with deep gryke infills; and d) removal of pinnacles prior to construction (photographs, (a) and (b) van Schalkwyk (1973); (c) and (d) Dippenaar (2004).

4.3 Evaluating Understanding of Karst Hydrogeology

Opportunities to assess your knowledge of flow zones in karst are provided by [Exercise 13](#), [Exercise 14](#), [Exercise 15](#), [Exercise 16](#), and [Exercise 17](#). Opportunities to assess your knowledge of flow through karst are provided by [Exercise 18](#) and [Exercise 19](#).

5 Sinkhole Hazards

5.1 Types of Sinkholes

Gambolati and Teatini (2021) define land subsidence as "... a sudden or gradual settling of the land surface caused by changes in the stress regime of the structure or subsurface." It is driven by the extraction of groundwater and lowering of groundwater levels. Many external factors, such as overburden mechanics, age, and time of exposure to weathering, and anthropogenic influences, affect the development of subsidence. Sinkholes are a form of subsidence that often occur more rapidly than the slow compaction of clastic sediments. A sinkhole is a "... surficial landform, found in karst areas and consists of an internally drained topographic depression that is generally circular, or elliptical in plan view, with typically bowl, funnel, or cylindrical shape" (Wilson, 1995).

In karst terrain, sudden land subsidence due to the collapsing of carbonate or evaporite rocks into large voids or bedding plane conduits is a specific hazard for land use development. Drought and groundwater development lower the groundwater levels, increase the effective stress on the supporting rock, and drainage of the water-filled cavities can result in the formation of sinkholes. This is exacerbated by precipitation and floods following a drought period that can increase karst sinkhole formation. Urban expansion often leads to the discovery of sinkholes and other karst features, and construction and borehole drilling can affect groundwater levels and recharge patterns that can induce sinkholes (Kuniansky et al., 2022).

Sinkholes develop through bedrock dissolution, rock collapse, down-washing, and/or soil collapse (Bednar, 2008). Beck (1984) distinguishes between solution sinkholes where a surface depression forms from bedrock solution, and cavities that form through cave roof collapse creating steep-sided holes. Based on these processes, one can distinguish between six different types of sinkholes that form in karst as shown in Figure 30 and Figure 31, with photographic examples shown in Figure 32.

SINKHOLES FORMING IN ROCK

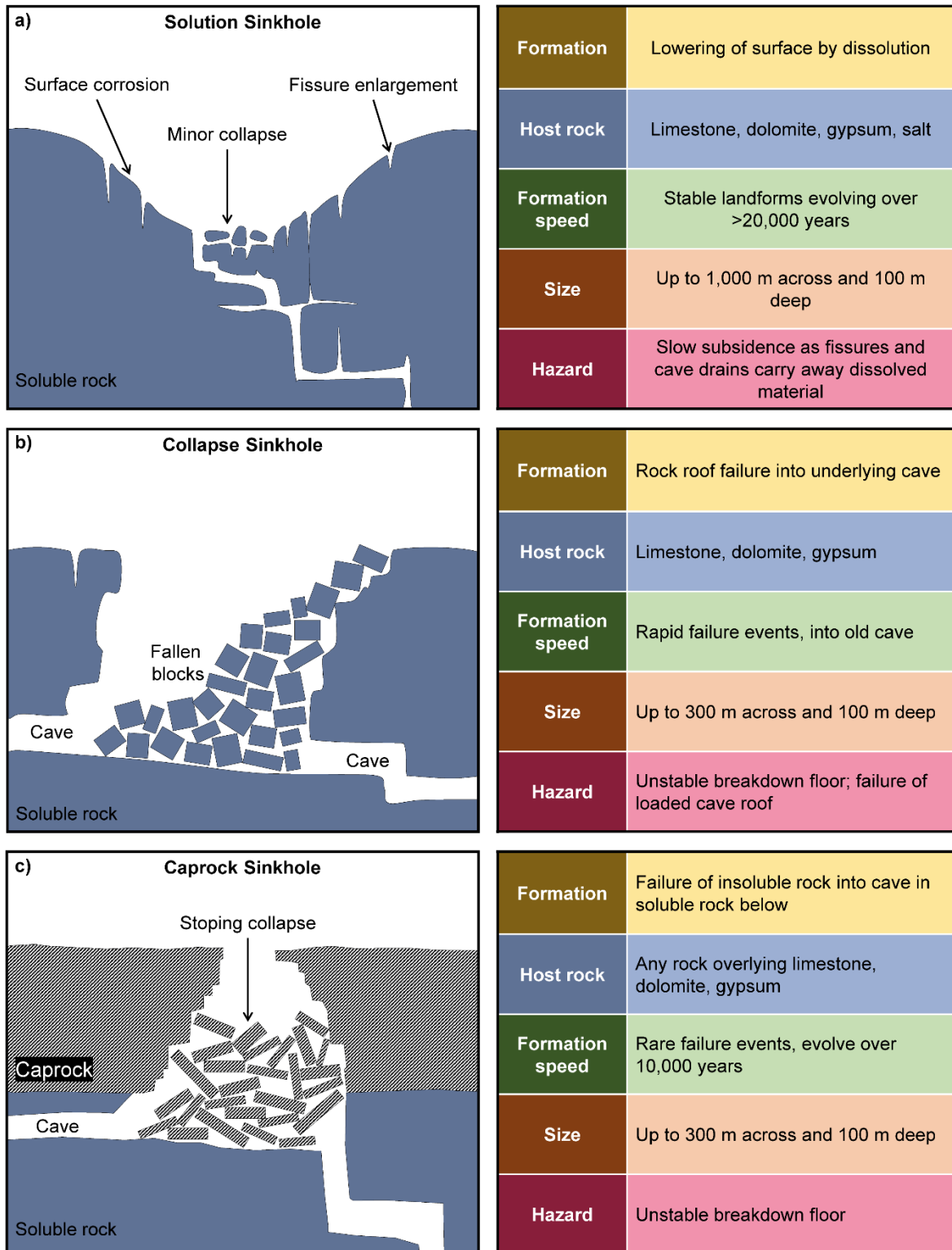


Figure 30 - Classification of sinkholes forming in rock environments, listing typical parameters for each of the following sinkhole types: a) solution sinkhole, b) collapse sinkhole, and c) caprock sinkhole (modified from Waltham & Fookes, 2003).

SINKHOLES FORMING IN ROCK OVERLAIN BY SOIL

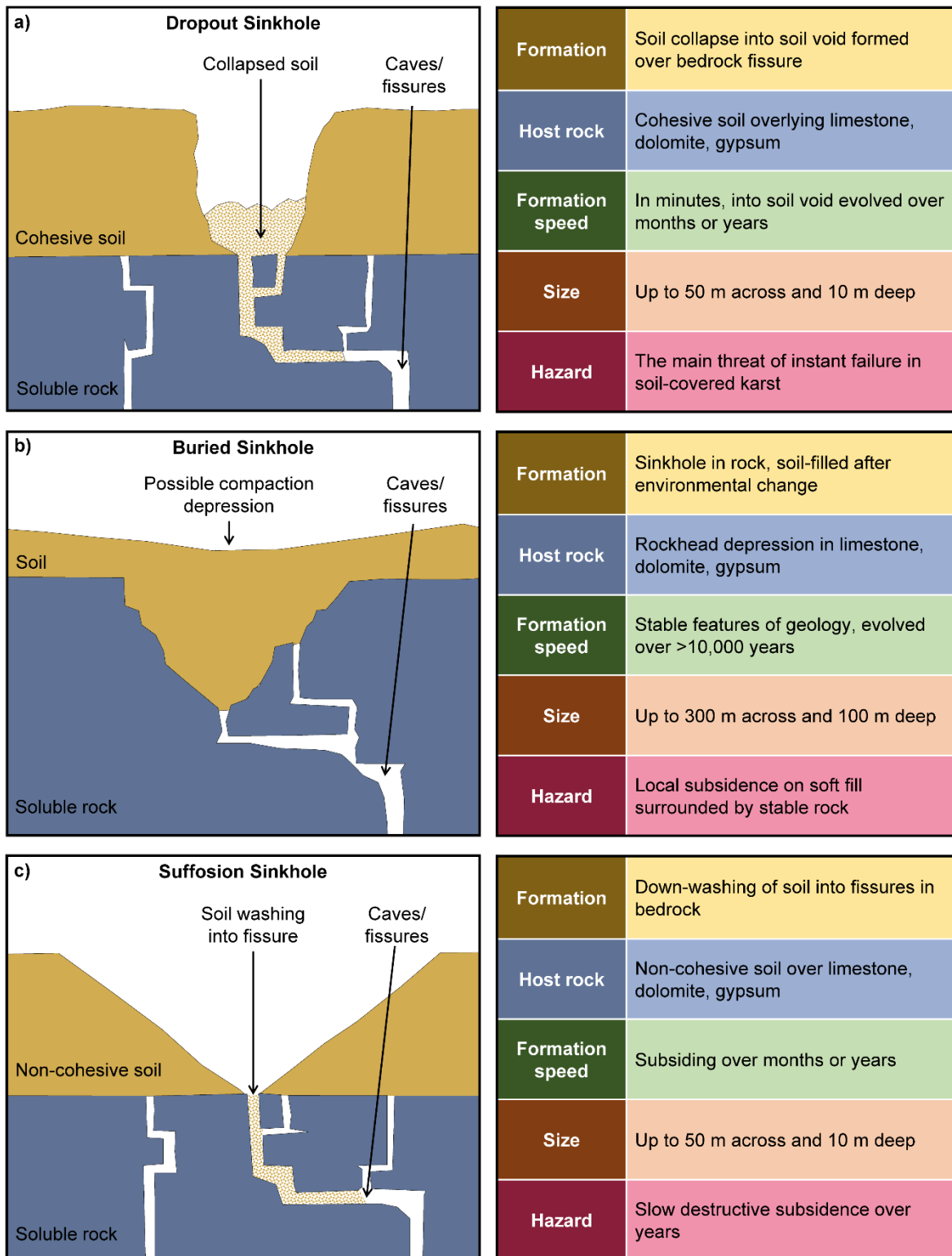


Figure 31 - Classification of sinkholes forming where soil overlays rock, listing parameters for each of the following sinkhole types: a) dropout sinkhole, b) buried sinkhole, and c) suffusion sinkhole (modified from Waltham & Fookes, 2003).

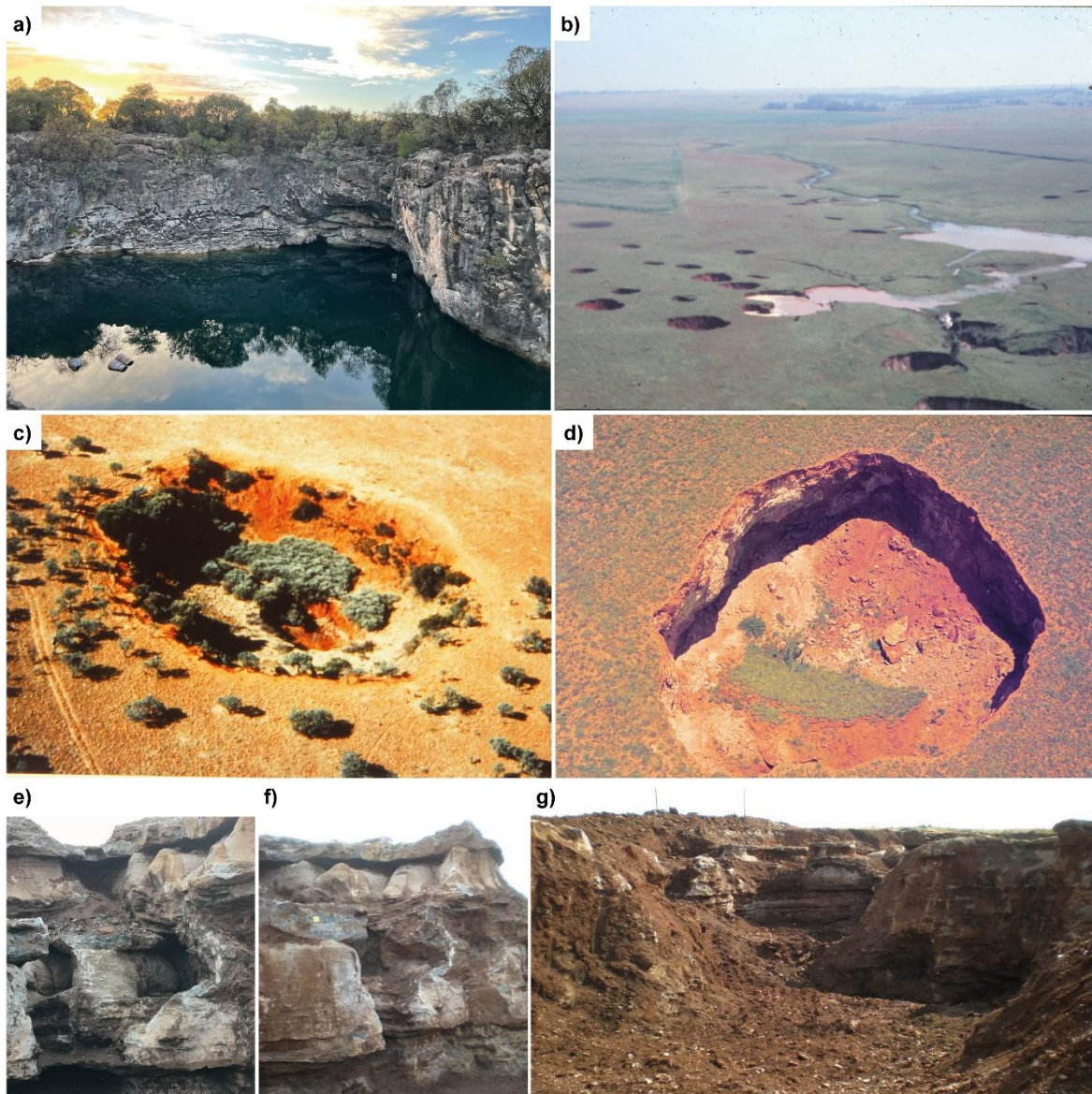


Figure 32 - Photographs of sinkholes in South Africa. a) Wondergat, South Africa's largest natural sinkhole; b) sinkhole development after flooding from the Wonderfontein spruit (Far West Rand); c) mobilization of Kalahari sand infill in a paleosinkhole (Doornfontein Mine); d) final roof collapse of over a cavity (Far West Rand); e) shallow dissolution features (Khutsong); f) shallow dissolution features interlayered with chert (Khutsong); and g) excavated sinkhole with chert interlayering visible in background (Khutsong) (photographs labeled a, e, f and g by Dippenaar, 2021; photographs labeled b, c, and d by Wolmarans, 1984).

5.2 Development of Sinkholes

For sinkholes to develop, parts of the blanketing (overburden) layer need to mobilize into a cavity serving as a receptacle (Figure 33). Residual dolomite and limestone will mobilize rapidly, whereas thick blanketing layers of rock have a low mobilization potential. On removal of the blanketing layer, a void may develop above the throat of the receptacle. This void may grow upwards and possibly reach a stronger, shallower horizon. At this stage the roof is temporarily stable, and the upward evolution of the void may stay open due to a soil arch forming between rock pinnacles, but it will fail under a triggering

mechanism (e.g., a leaking pipe). Without arch formation during mobilization of the blanketing layer, a surface subsidence may occur (Buttrick & van Schalkwyk, 1998).

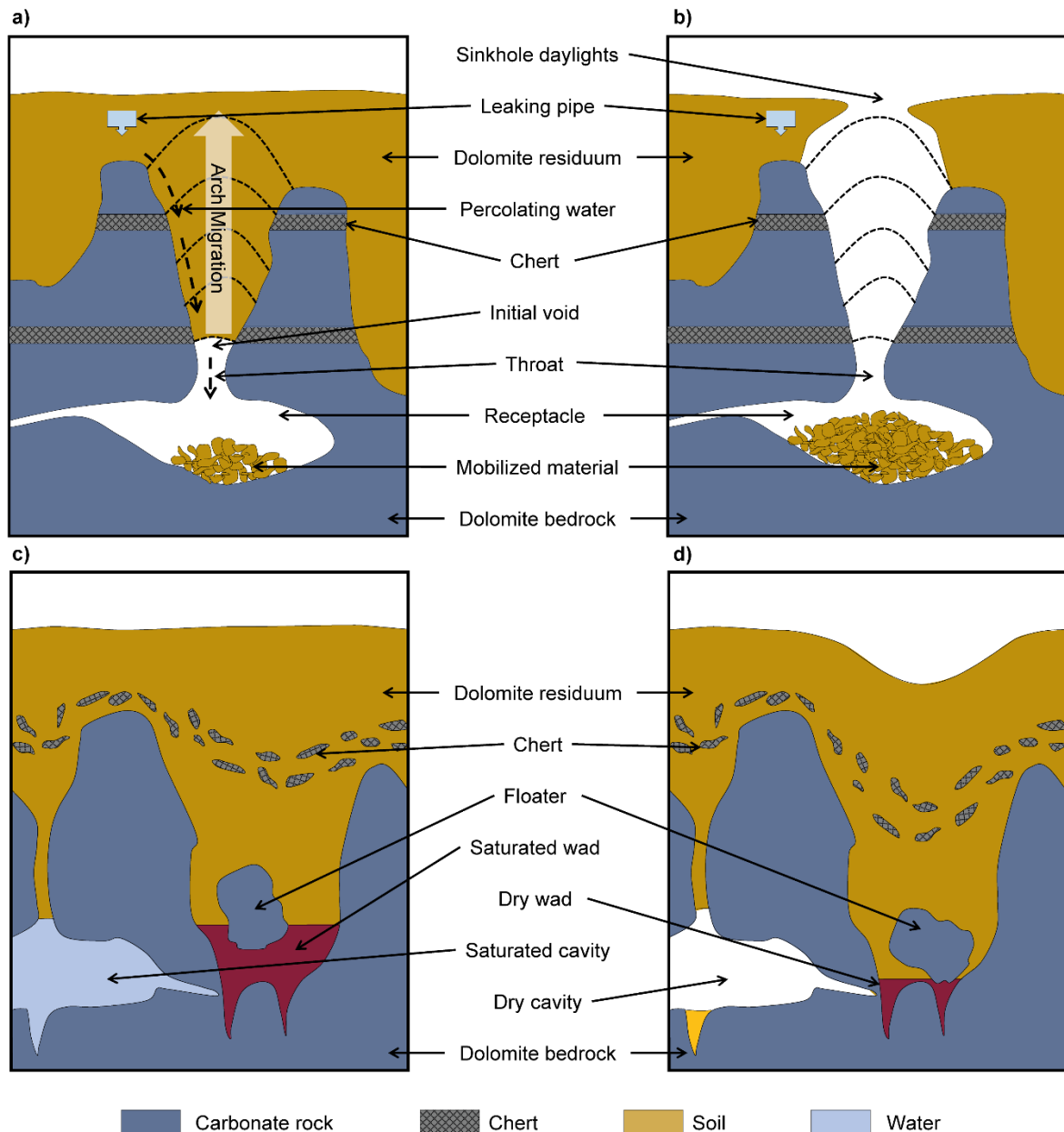


Figure 33 - Overburden soils fall through the throat into the receptacle creating an arch that migrates a) upward until the cavity b) daylight and is referred to as a dropout sinkhole as opposed to a c) buried suffusion sinkhole manifesting as d) surface subsidence without cavity daylighting (adapted and modified after Brink, 1979; Buttrick and van Schalkwyk, 1998; redrawn from Buttrick and van Schalkwyk, 1998).

There are significant differences in the shape and size of sinkholes forming in areas where the voided bedrock is overlain by either cohesive soils (dropout sinkhole) or non-cohesive soils (suffusion sinkhole). Cohesive soils (e.g., clays) can support a soil roof (arch) above a void developed by removal/erosion of soil into bedrock fissures with sudden collapse of the thin soil roof into the void. Non-cohesive soils usually cause gradual slumping of the sandy material eroded into the bedrock fissures and caves. There is a continuum between dropout and suffusion sinkholes due to variable clay and/or sand

content occurring in natural soils. These sinkholes are collectively described as subsidence sinkholes and are generally the main hazard to civil engineering (Waltham & Fookes, 2003).

In order to become a receptacle for downward erosion of the roof material, a cavity must be dewatered, either naturally from drought or by extraction of groundwater, to the extent that the cavity is partially or totally air-filled. Erosion can occur downwards with ingress water, or as a roof collapse, both resulting in the development of a sinkhole on the surface. Sinkholes forming through dewatering and ingress are shown diagrammatically in Figure 34 and by examples in Figure 35.

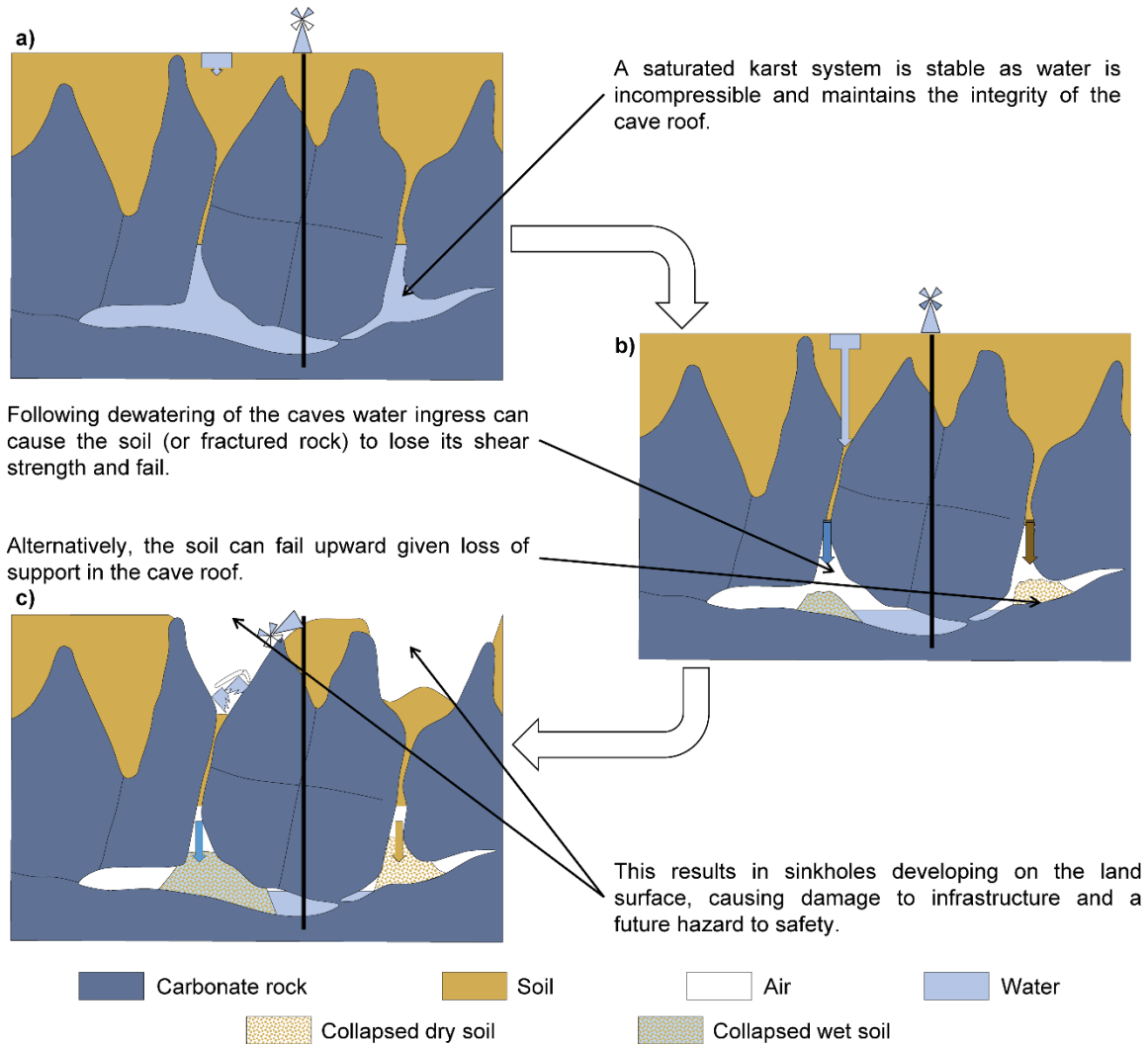


Figure 34 - Sinkholes formed through ingress and dewatering: a) stable, saturated karst system becomes unstable following b) dewatering and c) downward erosion causing sinkholes when cavities daylight (redrawn from Dippenaar, van Rooy, et al., 2019).



Figure 35 - Photographs of water ingress sinkholes. a) An initial 10 m diameter sinkhole increasing to b) 30 m diameter due to raveling and further erosion affecting two houses (Centurion, Pretoria, South Africa). c) and d) A sinkhole in a cemetery resulting in damage to graves (Pretoria, South Africa, 2010). e) and f) A sinkhole due to groundwater dewatering 20 m diameter in 2007 and tension cracks indicating development towards maximum size in 2017 (Bapsfontein, Gauteng, South Africa). g) A sinkhole due to deep mine dewatering in Far West Rand, South Africa (2019). h) A flooded sinkhole in Bapsfontein, Gauteng, South Africa (2019) (photographs by Dippenaar).

There are five interdependent conditions for a sinkhole to form. These are explained in Figure 36. Mobilization forming sinkholes due to deeper solution features are defined as the movement of the blanketing layer by subsurface erosion, slumping, or raveling due to an external agency. These external agencies may include ingress of water, ground vibrations, water-level drawdown or other activities and processes that move material downward under gravity. The water level acts as a base level for subsurface erosion and, where present, and static, acts as a positive mitigating factor limiting vertical movement of material. Potential triggers causing sinkholes are listed in Table 3.

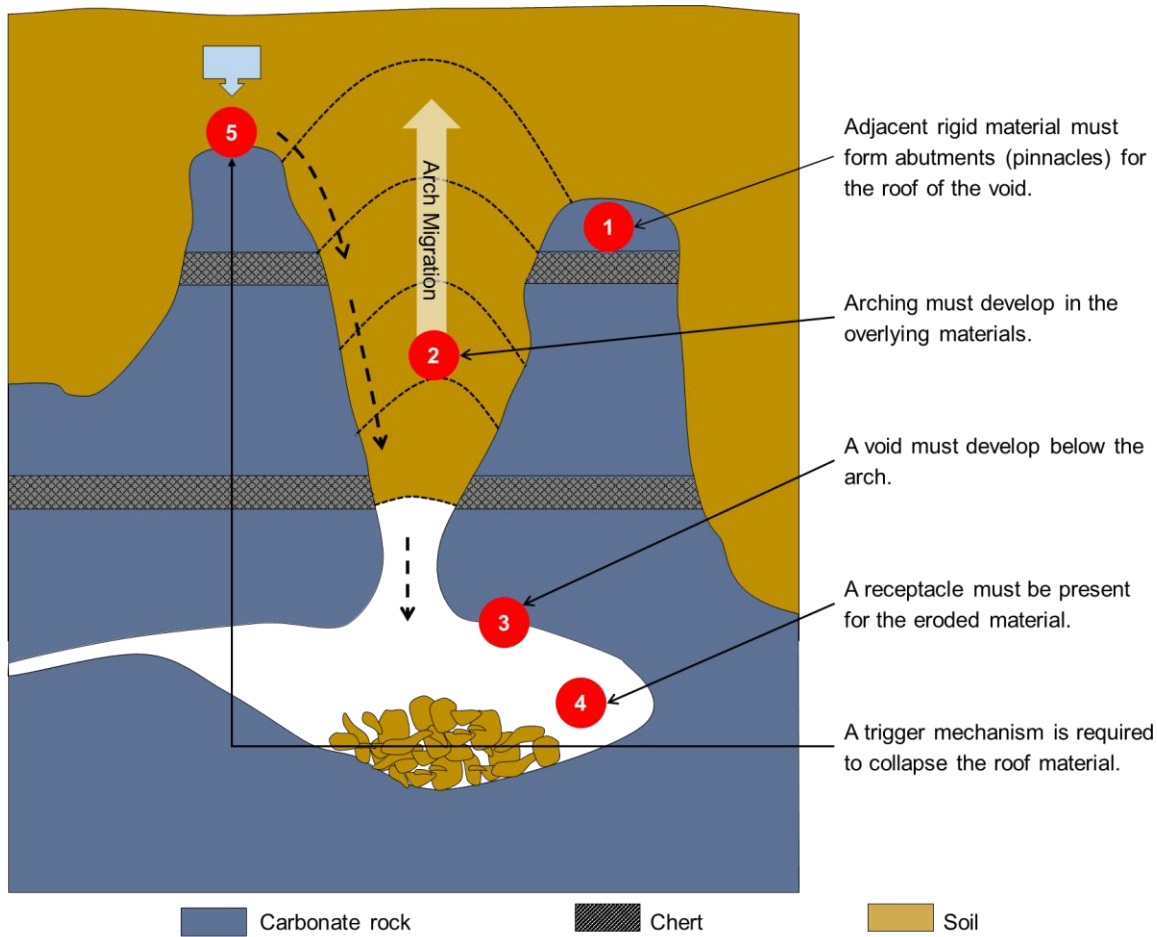


Figure 36 - Five interdependent conditions for a sinkhole to form (redrawn, modified, and annotated from Buttrick & van Schalkwyk, 1998; Jennings et al., 1965).

Table 3 - Potential triggers of sinkhole development (Gutiérrez et al., 2014).

Type of Change	Effects
Increased water into ground	<ul style="list-style-type: none"> Increases percolation, accelerating suffusion. Favors dissolution. Increases the weight of sediments. May reduce the mechanical strength and bearing capacity of sediments.
Water table decline	<ul style="list-style-type: none"> Increases the effective weight of the sediments (loss of buoyant support). Slow phreatic flow is replaced by more rapid downward percolation favoring suffusion, especially when the water table is lowered below the rockhead. Accelerates groundwater flow in areas affected by cones of depression. May reduce mechanical strength by desiccation and crystallization of salts. Hydrofracturing of poorly drained deposits surrounding cavities. Suction effect. Loose fine-grained deposits may be dragged with the pumped water causing internal erosion.
Impoundment of water	<ul style="list-style-type: none"> May create extremely high hydraulic gradients leading to rapid turbulent flows favoring internal erosion and dissolution. The base level rise may change groundwater flow paths and location of discharge zones. Major and continuous changes in the water table causing repeated flooding and drainage of karst conduits. Imposes a load.
Surficial erosion or shallow excavation	<ul style="list-style-type: none"> Reduces the thickness and mechanical strength of cavity roofs. May concentrate runoff. May create a new base level changing the path and rate of groundwater flow.
Underground excavation	<ul style="list-style-type: none"> Disturbs groundwater flow. May intercept phreatic conduits and distort groundwater flow paths. May cause sudden inrushes of water and flooding in underground openings involving accelerated internal erosion and karstification. May weaken sediments overlying voids.
Static load	<ul style="list-style-type: none"> Favors the failure of cavity roofs and compaction process.
Dynamic load	<ul style="list-style-type: none"> Favors the failure of cavity roofs and may cause liquefaction-fluidization processes involving a sharp reduction in the strength of soils.
Vegetation removal	<ul style="list-style-type: none"> Reduces mechanical strength of cover deposits (root cohesion). Increases infiltration.
Thawing of frozen ground	<ul style="list-style-type: none"> Favors dissolution. Significant reduction in the strength of the sediments.

5.3 Sinkhole Flooding

Many sinkholes occur in karst valleys and lowlands which, at the larger scale, are not recognized as closed depressions. Surface drainage from these depressions is usually via sinkholes, also referred to as swallow holes (Crawford, 1984). Historically, these sinkholes and subsurface karstic caves and fracture systems controlled the runoff and drainage from these basins (Zhou, 2007). According to Rose (2022), sinkhole flooding may be attributed to extreme precipitation events that are occurring more often recently due to climate change.

Three types of flooding sinkholes due to extreme precipitation include the following (Crawford, 1984; Rose, 2022).

- 1) The rate of stormwater flow exceeds capacity of an individual sinkhole.
- 2) The underground karst system is unable to drain the total stormwater flow.
- 3) The groundwater level rises rapidly due to diffuse infiltration.

The Kentucky Geological Survey (2023) proposes two general causes of sinkhole flooding. The first cause is when the rate of inflow of runoff or snowmelt exceeds the rate of water flow via the swallow hole, dissolution cavities, and fracture systems. The second is when water flow is reversed due to flooding in other parts of the basin and the water backs up into the sinkhole.

Crawford (1984) relates this phenomenon to the natural geological processes active during sinkhole development. The bottoms of sinkholes often collapse creating a swallow hole and may over time become plugged and collapse again during later floods. The hazard associated with sinkhole flooding is that infrastructure and urban development within shallow karst depressions can be inundated during excessive precipitation, increased runoff due to urbanization or clogging of the sinkhole throat. Roof collapse in the cave system between the sinkhole and spring may also reduce the diameter of the conduit or even block the entire conduit temporarily and drainage may be impaired, causing a backup of runoff and surface flooding around the sinkhole. Flow reversal may occur due to high water levels covering the spring eye during river flooding. Photographs of a sinkhole before and during flooding are shown in Figure 37.

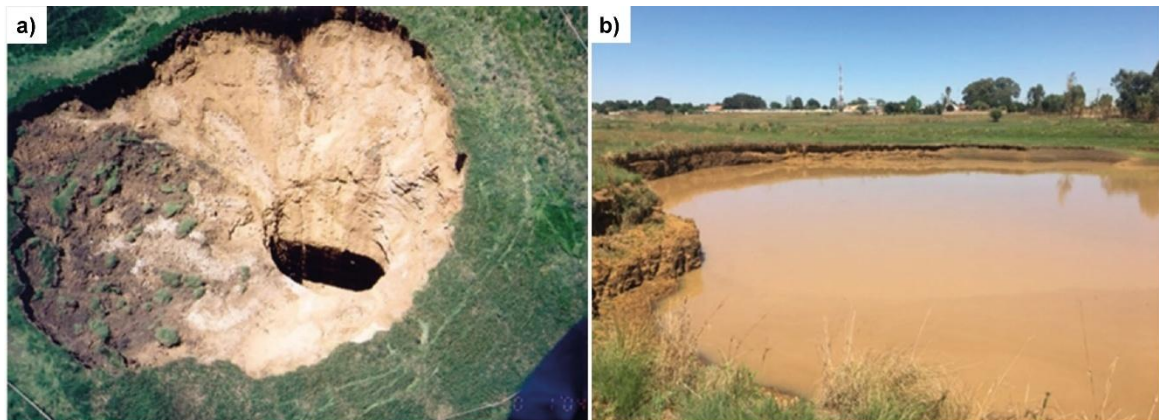


Figure 37 - Sinkhole near Bapsfontein, South Africa in a) a stream floodplain before stream flooding (photograph by Wagener) and b) after flooding (photograph by van Rooy).

An additional concern related to sinkhole flooding is groundwater contamination by runoff from urban areas (Crawford, 1984).

5.4 Evaluating Understanding of Sinkhole Hazards

Opportunities to assess your understanding of the types of sinkholes and their formation are provided by [Exercise 20](#), [Exercise 21](#), [Exercise 22](#), and [Exercise 23](#). An opportunity to assess your understanding of sinkhole triggers is provided by [Exercise 24](#). Opportunities to assess your understanding of sinkhole flooding are provided by [Exercise 25](#) and [Exercise 26](#).

6 Site Investigation

6.1 Risk-based Approaches

Site investigation is an essential part of any land development project and generally focusses on investigating the extent and spatial distribution of geological materials—e.g., rock, soil, and water—to determine the characteristics of these materials and predict behavior of the system under changed conditions.

Anticipating and modeling the response of the in-situ materials to a new development such as construction or deep excavation ensures the safety of the structure and humans. Geological processes that may influence investigated sites need to be assessed due to their potential to negatively impact development. These include geological hazards such as slope failures, flooding, and subsidence. The final aim of an engineering geological site investigation is to construct a ground model including material properties, geological processes, and site response to changed stress or hydrogeological conditions.

Hydrogeological and hydrological investigations address the relevant water cycle components that may affect the human environment. The unique karst conditions with sinkholes (swallow holes) and springs providing direct pathways between surface water (including precipitation) and groundwater, need specific investigation methods and coupled surface-groundwater modeling.

Engineering geological site investigation in karst environments needs to specifically address the issue of subsidence in the form of sinkholes as well as the influence of existing and progressive karstification. Investigating the geohazard (i.e., subsidence) in a karst environment may be deemed more important than determining the properties of materials underlying a site. Looking for subsidence-prone areas without any indication of possible sinkholes, at the time of investigation, involves both geotechnical and hydrogeological site investigations.

Knowing where the next sinkhole will form requires knowledge of the type of karst terrain and the mechanism(s) through which sinkholes form at a specific locality. Site investigation requires the acquisition and assessment of data to identify the relevant properties and hazards. This process is usually phased where different investigation methods are used at different stages. Typically, investigation progresses from simple to sophisticated techniques but is more expensive where sophisticated techniques are used. The stages of investigation can be linked to tiers from Reconnaissance Investigation (Tier 1), Feasibility Investigation (Tier 2), Design Investigation (Tier 3), to Specialist Investigation (Tier 4) as shown in Figure 38.

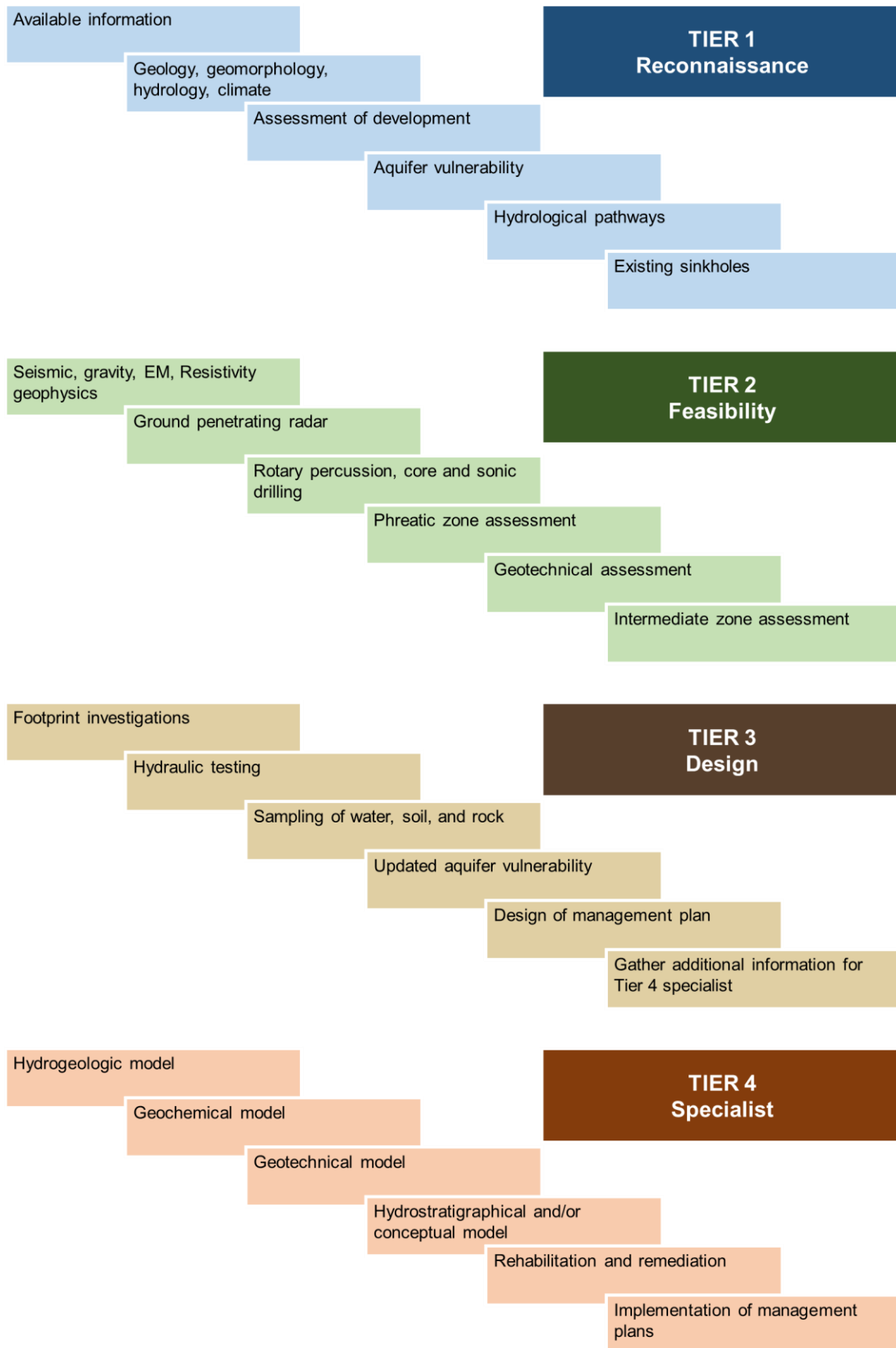


Figure 38 - Tiers of site investigation following general sequence from available data collection to feasibility stage investigations, followed by more advanced design investigations, and finally specialist level investigations where data interpretation and final modeling is executed.

6.2 Methods

Conventional methods such as gathering existing data, compiling sinkhole distribution maps, along with review of hydrogeology reports, water well records, and existing drilling information are not usually sufficient in karst site investigations (Xeidakis et al., 2004). Typical methods are described in detail by Dippenaar, van Rooy and others (2019) and Kuniansky and others (2022).

Geotechnical site investigations in karst environments attempt to characterize the subsurface features associated with karstification. The site investigation needs to provide information on:

- identification of karst types,
- quantification of hazard,
- definition of appropriate geotechnical zones relating to allowable types of development,
- design methodology for foundations and infrastructure, and
- appropriate precautionary measures and risk management.

Determining where groundwater occurs and how it flows through the karst system is essential to understanding the hydrogeological processes and the heterogeneous hydrostratigraphical system. The required data depends on the karst type and the reason for the investigation and may include water supply and contamination studies, environmental impact assessments, aquifer vulnerability, and water use license applications.

Again, the investigation may be phased, and different methods and techniques are applied at different stages of project development. Given the unseen nature of groundwater systems and hydrological interactions, groundwater modeling (Tier 4) is almost always necessary to increase the confidence associated with the data and understand the regional and site-specific groundwater flow through and interaction with karst features.

The critical interactions can be assessed by quantifying infiltration, percolation, and recharge rates. Karst variability affects where and how fast water moves from the surface to the aquifer and the influence of cave systems serving as conduits and springs where groundwater leaves the karst area. Prediction of aquifer vulnerability and sinkhole risk associated with the complex karst systems can be made with confidence when the hydrogeological model is based on reliable site investigation.

Due to the morphology of a karst aquifer with groundwater present in large caves and fissures, pumping testing often produces biased values. The heterogeneity and anisotropy of karst influences precipitation, infiltration, baseflow, runoff and recharge.

The approach to site investigation is usually to start with what is known, use experience from similar karst terrains, and then decide what to do and how to find the necessary answers. Investigations may be terminated early on when initial indications are

already showing land unsuitable for the intended development or use, or further detailed investigations may be employed to collect the appropriate data for safe site development. The feasibility and design phases of investigation and their requirements are listed in Table 4. The site investigation data requirements and methods are illustrated in Figure 39.

Table 4 - Site investigation stages and techniques used in South Africa (modified from SANS, 2012a).

Method	Feasibility level investigation Requirements
Desk study	<ul style="list-style-type: none"> • Sourcing and assessment of available information. • Basic geology. • Geomorphologic features. • Existing sinkholes and subsidence. • Compile available data (e.g., geophysical surveys, borehole logs, hazard assessment, hydrogeological models).
Geophysical survey	<ul style="list-style-type: none"> • Mainly gravity surveys. • Use gravity anomalies to plan borehole positions. • Produce final residual gravity map after drilling. • Geology will dictate application of other non-destructive surveys, e.g., electromagnetic (EM), resistivity, seismic, ground penetrating radar (GPR).
Drilling and probing	<ul style="list-style-type: none"> • Typically, rotary percussion drilling. • Use geophysical, geological, geohydrological, and geomorphological data to guide drilling. • Drilling method must provide optimum sample return for every 1 m drilled. • Use of data loggers for recording drilling parameters. • Terminate borehole only after at least 6 m into solid bedrock or 15 m into non-dolomitic overburden. • All boreholes must be backfilled to prevent future preferential ingress. • Penetration testing (e.g., Cone Penetrometer Test [CPT], Dynamic Probing Super Heavy CPT [DPSH], Standard Penetration Test [SPT]).
Near surface	<ul style="list-style-type: none"> • Where appropriate, shallow dolomite bedrock areas are investigated via test pits or exploratory trenches.
Hydrogeological data	<ul style="list-style-type: none"> • Presence of groundwater compartments. • Catchment delineation (typically requires tracer tests). • Original groundwater level. • Hydrocensus (recording of available information at available boreholes). • Large scale groundwater abstraction or de-watering activities near site. • Regular groundwater related monitoring activities. • Location and yield of springs. • Spring flows, water quality, tracer testing. • When groundwater encountered in new borehole record: locality, collar elevation, depth drilled, all groundwater strike depths in borehole, static water level after 24 hours, date of each observation. • Also report all dry boreholes.
Method	Design-level investigation Requirements
General	<ul style="list-style-type: none"> • Site walkover investigations are conducted where: <ul style="list-style-type: none"> • additional information is required as identified during feasibility investigations and • additional information is required for design purposes.
Requirements	<ul style="list-style-type: none"> • A competent person shall determine the required design level investigations to confirm the inherent hazard classes.

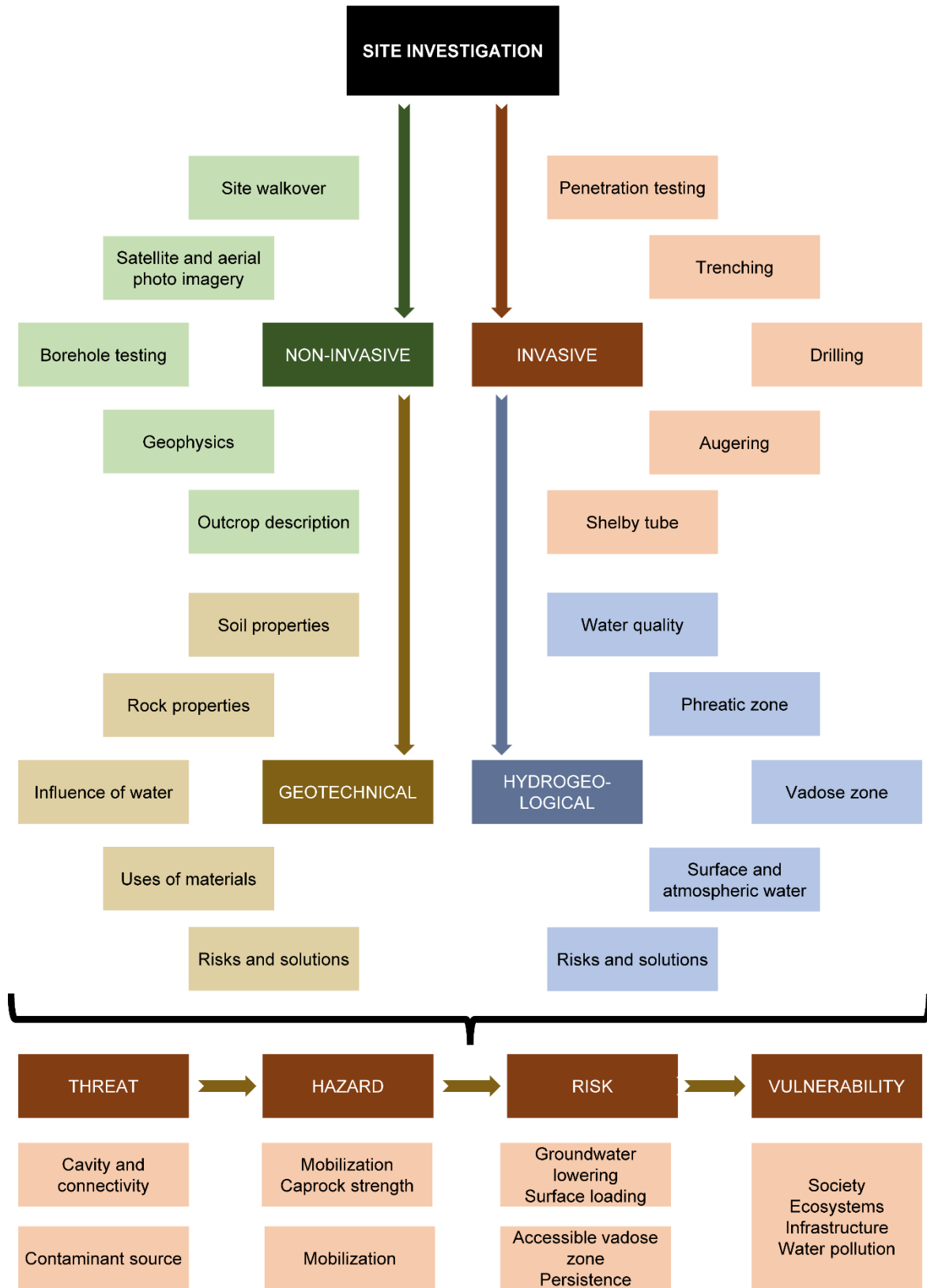


Figure 39 - Site investigation data requirements and methods for evaluating threats, hazards, risks, and vulnerabilities related to karst.

In karst terrains, site investigation outcomes should add to building of the geological model, the overburden model, and the hydrogeological model (SANS, 2012a). Challenges in karst environments are identifying the highly variable rockhead elevation, determining the properties of the materials overlying the rockhead (blanketing layer), and identifying the influence of natural and anthropogenic groundwater lowering or ingress.

Covered karst is an extremely difficult terrain to investigate and the properties and thickness of the overburden will determine the appropriate investigation methods. Geophysical techniques are quite useful under these circumstances and can be ground truthed using limited drilling records. Methods employed may include gravity surveys, ground penetrating radar (GPR) and Electric Resistivity Tomography (ERT) (Brahmi et al., 2023; Epting et al., 2009). According to Brink (1979) experimental surveys on covered karst in South Africa showed limited value of electromagnetic investigations where near surface grykes are filled with mud, although time domain electromagnetic and very low frequency methods proved useful in near-surface karst (Chalikakis et al., 2011). Magnetic surveys are useful to detect the presence of dikes and sills and to delineate groundwater compartments. Safe development areas can be identified where intrusive thickness and extent inhibit sinkhole formation. Gravity surveys in covered karst indicate rockhead contours relative to the level of the original water table (Brink, 1979). The accuracy of gravity anomalies is further increased by drilling control boreholes on or between anomalies (Brink, 1979; Waltham & Fookes, 2003). Microgravity can delineate low density fills in buried sinkholes and small sinkholes at specific depths if the grid spacing is reduced to 2 m (Waltham & Fookes, 2003; Xeidakis et al., 2004). Ground penetrating radar (GPR) produces high resolution profiles of subsurface layers but the high attenuation rates of electromagnetic energy limit its depth of investigation (Batayneh et al., 2002; Xeidakis et al., 2004). GPR is very efficient for describing the epikarst where the overburden is not electrically conductive, that is, in the absence of clay-rich sediments (Chalikakis et al., 2011). An extensive overview of the usefulness of geophysical methods in karst environments is provided by Chalikakis et al., 2011).

Recent advances in site characterization include the combination of different geophysical techniques such as electrical resistivity tomography with GPR or microgravity and GPR with vertical probing for ground truthing (Vadillo et al., 2012). Remote sensing techniques, especially differential Synthetic Aperture Radar interferometry (DInSAR), are used to detect cm to mm scale surface deformations associated with mine collapse, landslides and volcanoes and can be an effective tool to monitor karst areas susceptible to surface subsidence (Theron & Engelbrecht, 2018).

Site investigation techniques may not always be adequate to locate and minimize all hazards in karst terrain. Experience from a competent professional with expertise in karst areas may add to the final model construction and hazard determinations. In a

complex karst environment experience based on field behavior of karst systems is a valuable contribution to the factual data collected via the investigation tiers.

Geological mapping and understanding of the depositional environments and type of karst apply to all scales of investigation. Local scale investigation is based on borehole tests, measurements, and/or sampling at single boreholes. The data obtained from a borehole that penetrates conduits will be influenced by the aquifer’s diffuse flow component (non-conduit permeability). These methods are not applicable to larger scale investigations.

Conduit flow is most significant component of flow in karst aquifers, and it is controlled by the distribution and interconnection of conduits (White, 1988). Springs are the most appropriate natural sampling point for karst investigation. Water-tracing tests, spring hydrographs, and spring chemograph analyses are more appropriate than well sample analyses for understanding the character of karst aquifers because they best indicate the diffuse-versus-conduit-flow continuum.

At regional scale, covering multiple groundwater basins, appropriate methods include water level mapping, tracer tests, water quality or geochemical sampling, geological structure mapping, and geophysical methods. Under certain conditions remote sensing may be used to identify historic and current distribution of sinkholes, subsidences, springs, orientation of grykes, and bedrock structure among other features. When interpreting results, it is important to carefully consider the appropriate scale for each method. Appropriate investigation techniques for each scale are shown in Table 5.

Table 5 - Applicability of research techniques for investigation of karst aquifers. Spaced dashes indicate greater difficulty in the application due the effects of heterogeneity (reproduced from Kuniansky et al., 2022).

Method	Scale of Applicability		
	Local (Site)	Basin	Regional
	< 1 km ²	> 25 000km ²	
Hydrogeologic Mapping (surface geology, potentiometric surfaces, location of karst features, well inventories, and compilation of all existing data sets and reports on the site)	-----	-----	
Surface Geophysics (seismic, gravity, ground-penetrating radar, electromagnetics)	-----		
Single Borehole Geophysics (including flowmeter tests, tomography, packer tests, etcetera)	-----		
Multiple borehole geophysical logs and surface geophysics (combined with stratigraphic and lithologic information)	-----	-----	
Airborne Geophysics (electromagnetics, aerial infrared photography)	-----	-----	
Well hydraulic (aquifer) tests	-----		
Qualitative and Quantitative Water-Tracing Tests (artificial tracers-dyes, solutes, or microspheres)	-----	-----	
Natural Tracers (isotopes, naturally occurring dissolved solutes)	-----	-----	
Well Hydrograph/Chemograph Analysis	-----		
Spring Hydrograph/Chemograph Analysis	-----		
Mathematical Modeling (Distributed Parameter, Lumped Parameter, and Fitting Models)	-----	-----	

For karst, three-dimensional modeling, based on appropriate investigation techniques is required to provide accurate information about the karst conditions or type of karst below a structure or characteristics of the karst aquifer. Available data and data obtained during site investigations are used to create the geological model comprised of material and groundwater distribution as well as specific karstic features across a site. During well boring and completion additional data are collected and may confirm the initial conceptual models or indicate the necessity for revision of the conceptual models along with additional late-stage investigations and/or design changes.

6.3 Evaluating Understanding of Karst Site Investigation

Opportunities to assess your understanding of karst site investigation are provided by [Exercise 27](#) and [Exercise 28](#).

7 Groundwater Assessment

Groundwater studies require investigations to acquire the relevant parameter values and hydrologic estimates to make decisions and provide recommendations for optimal and relevant outcomes. Assessments provide information on the hydrogeological parameters including permeability, transmissivity, hydraulic conductivity, and storage; including estimates of the aquifer systems sustainable yield (available recharge), and safe yield (a value less than the available recharge often defined via a regulatory agency). Percolation and infiltration tests are conducted in the vadose zone to obtain relative vertical hydraulic conductivity values, aquifer pumping tests or slug and bail-down tests can acquire relative horizontal hydraulic conductivity values at the water table.

Borehole and aquifer pumping tests (described in detail in Kruseman and de Ridder, 1994) are executed to acquire many of the parameters above, but more important are the sustainable pumping rates for water supply to humans, agriculture, and industry. In karst aquifers, borehole flowmeter logging and packer testing data often indicate that small zones of the borehole are contributing most of the flow to the well. The compilation of all aquifer and slug testing data in the vicinity of the site may indicate the spatial heterogeneity of the karst system. In general, transmissivity determined from aquifer pumping tests in karst systems should be considered qualitative as the exact location of the preferential flow zone may remain unknown when borehole flowmeter logging is not conducted. Additionally, aquifer pumping tests in karst systems often require extremely large pumping rates to generate measurable drawdown.

Tracer tests entail the injection of a substance (dyes, salts, or particles) or the use of natural components of the water, and measurement of the time taken for it to reach an endpoint. This is described in detail in this section because of its immense value in understanding flow paths and flow rates through the vadose zone.

Geophysical methods are very helpful, and most notably the gravity method was and still is required to detect potential cavities or low-density zones prior to development of the land. New techniques have emerged that will provide additional data. When looking for structures and lithological contacts the normal geophysical methods like electrical resistivity profiles and magnetic anomaly traverses are sufficient. Seismic methods and ground penetrating radar are useful.

7.1 Assessing Hydrological Risks in Karst

Large springs in karst are important for aquatic ecosystems, wetlands, and stream headwaters. They are an important part of the water cycle that provides significant and substantial sources of groundwater, surface water, drinking water, and environmental water. Where karst springs are used, they are often enclosed in a collection chamber from which the needed water is pumped and the remainder freed into the environment.

As the karst evolves over time, dissolution features develop along fractures and joints, such as pipe-like conduits or bedding plane openings. These dissolution features result in preferential pathways for faster water movement. If precipitation has extreme irregularity seasonally, the pattern of karst water resources will be unequally distributed through the year. The uncertainty in timing of recharge requires time series monitoring of groundwater levels and spring discharge, especially in areas of water shortages or during summer season when evapotranspiration is greatest and groundwater withdrawals for crops may be greatest (Parise et al., 2018).

Important issues in karst hydrogeology require knowledge of flow and storage properties of the groundwater system, climatic conditions, and the current management of karst resources (Voulvoulis et al., 2017). A precise knowledge of geological and hydrogeological properties of the regional and local aquifer includes many different and not easily determined parameters. These parameters include the aquifer geometry, groundwater table, thickness of the phreatic zone, permeability, storativity, and availability of water (Stevanović, 2018).

Karst features at ground surface, such as sinkholes, fracture orientation, swallets, dolines, estavelles, and springs should be mapped. Some of these surface features are interconnected via subsurface dissolution features (conduits) to the focused discharge features, like springs or water-supply wells. It is important to analyze and map focused infiltration points such as sinkholes as they can result in surface contamination reaching springs or wells.

Groundwater vulnerability maps are crucial in decision-making and land use planning, especially in environmentally sensitive areas (Ravbar & Goldscheider, 2007). Vulnerability maps can be validated by several techniques such as tracer tests, isotope analyses, and hydrograph studies (Parise et al., 2018).

Interdisciplinary monitoring and co-operation between different specialists such as hydrologists, hydrogeologists, hydrogeologists, ecologists, and water resource managers are required to protect and manage vulnerable and exceptionally valuable aquatic and terrestrial ecosystems. When karst aquifers cross administrative borders cooperation between countries or local governments may be required to protect the recharge areas of these vulnerable aquifers.

Risk assessment is shown in Equation (8). Factors comprise the following considerations (van Westen & Greiving, 2017).

- Danger/ Threat: A natural phenomenon that could lead to damage, described by geometry, mechanical, and other characteristics
- Hazard: Probability that a particular danger (threat) occurs within a given period
- Vulnerability: Degree of loss to a given element or set of elements within the area affected by a hazard; scale 0 (no loss) to 1 (total loss)

- Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment

$$R = H V E \tag{8}$$

where:

- R = risk associated with specific danger
- H = hazard (probability of occurrence within a defined period)
- V = vulnerability, fraction of loss of elements at risk if hazard occurs
- E = expected cost if all elements at risk are lost

Vulnerability is subdivided into four factors that increase the susceptibility of communities to the impacts of the hazard as shown in Figure 40. Risk assessment is mostly based on the Source–Pathway–Receptor (or Origin–Pathway–Target) analysis as shown in Table 6 and Figure 41.

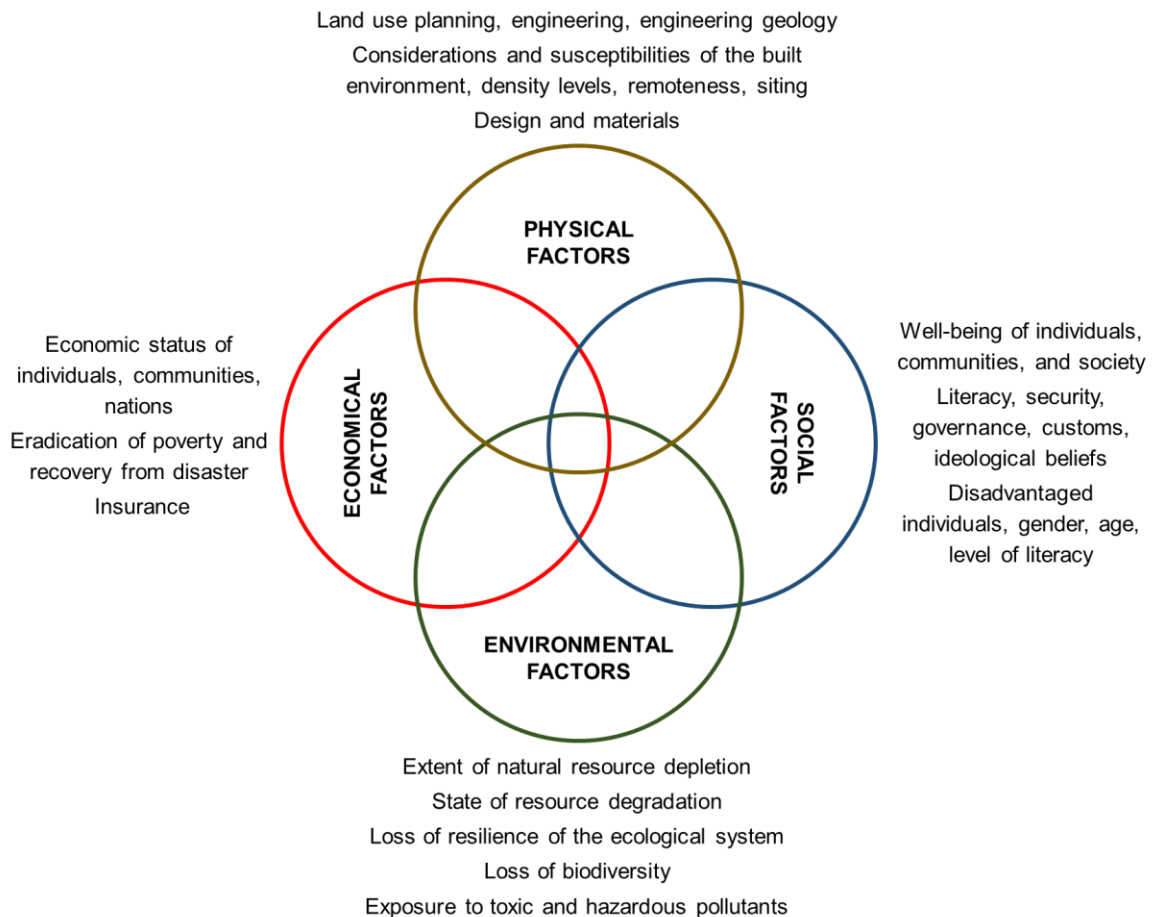


Figure 40 – Subdivision of vulnerability into four factors that increase the susceptibility of communities to the impacts of karst hazards (modified from UNISDR, n.d.).

Table 6 - Source – Pathway – Receptor Analysis.

Steps	Description
Source	Contaminant released over a large area or at a point, and as a one-time or continuous release Described in terms of persistence, bioaccumulation, and toxicity
Pathway	Vertical flow through vadose zone or lateral flow in the saturated zone Inhalation of gaseous contaminants; ingestion or dermal contact of water
Receptor	People and animals in the environment Water boreholes and water users Environmental discharge points such as springs and wetlands

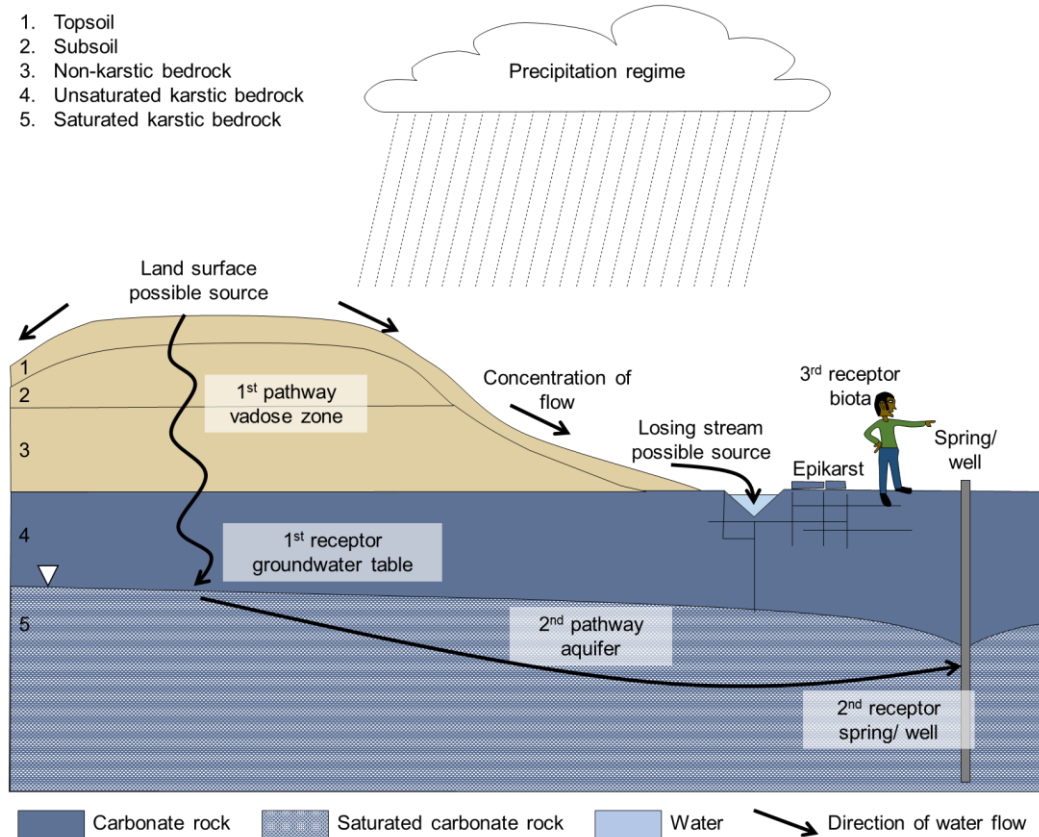


Figure 41 - Source–Pathway–Receptor analyses in risk assessment (modified from Goldscheider & Popescu, 2004).

7.2 Groundwater Tracing Tests

Groundwater tracing tests and their use in karst are discussed in detail in the review by van Wyk and others (2025) as well as Aley and others (2025). Tracing tests provide valuable insights related to vadose zone thickness, and how the vadose zone impacts residence times in different aquifer systems. Karst is unique because of its carbonate and/or evaporite geology and the associated dissolution pathways. Fluorescent dyes and natural tracers move faster in karst aquifers due to the unique characteristic of karst systems having extraordinary access to the vadose zone.

Fluorescent dyes and natural tracers are commonly employed in karst aquifer studies because they are suitable to capture and trace the rapid flow dynamics inherent to karst systems as listed here

- Fluorescent dyes provide easily detectable and visual markers suitable to track water movement through the vadose zone into the phreatic zone (aquifer).
- Natural tracers—e.g., isotopes or naturally occurring chemicals—have the advantage of mimicking the behavior of water molecules, aiding in discerning flow paths and rates in complex karst systems (van Wyk et al., 2025).
- Synthetic microsphere tracers are designed to mimic specific pathogens and can be used when concerns over transport of pathogens to water supply wells are of interest (Goldscheider et al., 2008; Harvey et al., 2008, 2017).

Single and multiple hydrological tracers improve flow estimates between the vadose zone and the groundwater table. Stable isotope tracer data show preferential flow paths influenced by rainfall characteristics. Inorganic ions and fluorescent dyes show piston-flow conditions during precipitation events, that flush tracers through the vadose zone. The connected dissolution cavities in a karst vadose zone regulate the storage and release of tracers under changing moisture contents (van Wyk et al., 2025).

Studies of artificial tracers show that, due to the short travel times in karst, they prove to be the most useful tracers to shed light on rapidly occurring processes. They can also aid in identifying flow pathways in fractured rocks, understanding transport mechanisms, determining residence times, measuring flow velocities, and understanding aquifer parameters by analyzing tracer breakthrough curves (BTCs) and tracking water movement in the vadose zone (Benischke, 2021; Cook, 2015).

Petrič and others (2018), observed that a thicker vadose zone, such as the 400 m deep one in their study, significantly enhanced the retention times of the tracer underground and facilitated dispersion. Conversely, in a 40 m thick vadose zone, the tracer reached the observed spring much earlier and exhibited a significantly higher recovery percentage—55% compared to just 8.4%. These findings provide compelling evidence that the greater the thickness of the vadose zone, the better it performs in protecting the groundwater system from contamination.

7.3 Karst Vulnerability

Aquifer vulnerability is the likelihood that contaminants can reach the groundwater table. Foster and others (2003) define vulnerability as those intrinsic characteristics of the strata that separates the aquifer from the land surface. Vulnerability determines the aquifer's sensitivity to be adversely affected by a surface-applied contaminant load and is a function of the saturated aquifer's accessibility to penetration of pollutants, and the attenuation capacity of the overlying strata.

Although the concept of groundwater vulnerability is relevant to all types of aquifers—granular, fractured, and karst—karst aquifers have unique properties which should be considered during a vulnerability assessment. Karst aquifers are affected by the addition of water to the land surface from precipitation or surface water and the

distribution of subsurface materials with different hydraulic parameters. Recharge enters the aquifer via focused recharge points, such as losing streams and sinkholes or open vertical joints where little or no filtration through a soil zone occurs. Figure 42 shows the difference between vulnerability in karst and non-karst.

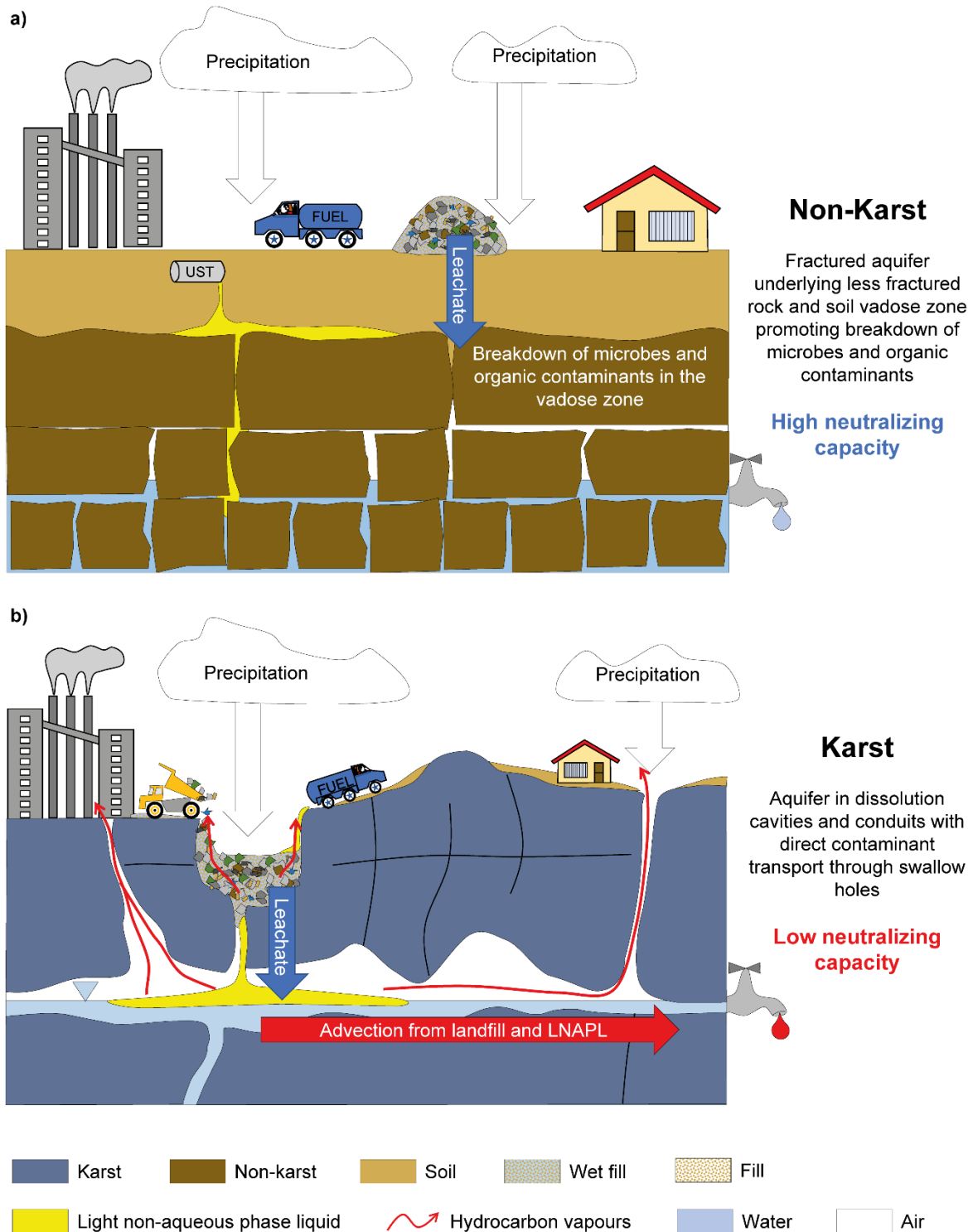


Figure 42 - Vulnerability differences between non-karst and karst aquifers. a) In non-karst environments pollutants can be neutralized in the overburden, while b) karst environments have low neutralizing capacity (modified from Ravbar & Šebela, 2015).

Karst aquifers are especially vulnerable to surface water transported contaminants because of direct connection via dolines—shallow surface depressions due to subsidence—swallow holes—sinkholes, and concentrated flow in the epikarst and vadose zone (Zwahlen, 2004).

Geological and hydrogeological attributes to be considered include the subsoils above the groundwater, point and/or diffuse recharge, and vadose zone thickness. Vulnerability depends on the following factors (Sililo et al., 2001):

- contaminant attenuation capacity in the vadose zone,
- travel time of infiltrating water and contaminants to the saturated zone, and
- relative quantities of contaminants reaching the groundwater.

The aquifer vulnerability concept assumes that the physical environment provides some protection from contaminants entering the subsurface. Vulnerability is a relative, non-measurable, and dimensionless property that can be distinguished between intrinsic and specific vulnerability (Vrba & Zaporozec, 1994). COST (1995) provides the following definitions (Figure 43):

- “The intrinsic vulnerability of groundwater to contaminants takes into account the geological, hydrological, and hydrogeological characteristics of an area, but is independent of the nature of the contaminants and the contamination scenario.”
- “The specific vulnerability takes into account the properties of a particular contaminant or group of contaminants and their mode of introduction to the system in addition to the intrinsic vulnerability of the area.”

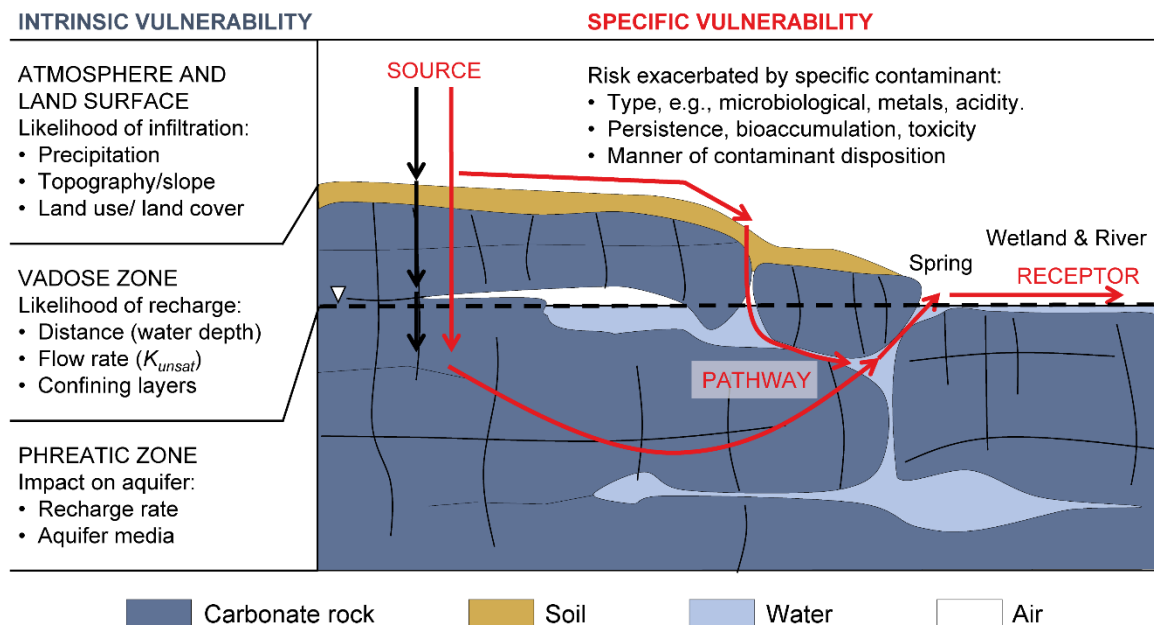


Figure 43 - Specific and intrinsic vulnerability with an example of source, possible pathways (black and red arrows), and receptors (adapted from Dippenaar et al., 2014).

Karst aquifer vulnerability can be evaluated using methods that are dedicated to karst, or methods that apply to all aquifer types but contain special methods when applied to karst areas. Intermediate conditions between a purely fractured/intergranular, and a karstic carbonate aquifer are common (Leyland, 2008). Fractured systems are more common in dolomites and intergranular systems are more common in limestones.

The steps of vulnerability assessment and its application are shown in Figure 44 and Table 7 (Iván & Mádl-Szoñyi, 2017).

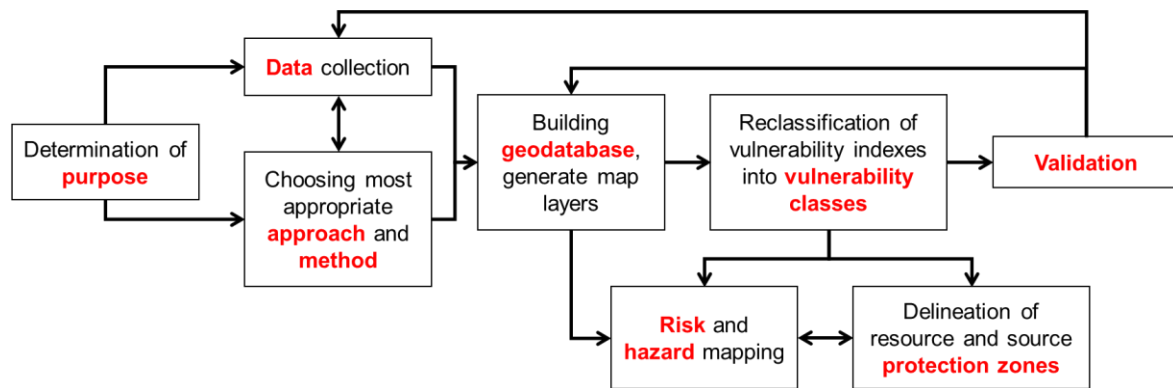


Figure 44 - Steps of vulnerability assessment and its application (reproduced from Iván & Mádl-Szoñyi, 2017).

Table 7 - Steps of vulnerability and a description for each (modified from Iván & Mádl-Szoñyi, 2017).

Steps	Description
Definition of purpose	The rate of transport to the target and the contaminant concentration need to be known.
Data collection and selection of method	The quantity and quality of the available and/or obtainable data define the scale and outcome of assessment and determine applicable approaches and methods.
Building geodatabases, generating map layers	Open-source or commercial geographic information system (GIS) software packages can be used, and map layers are easy to modify in the GIS environment making iterative mapping possible.
Reclassification into vulnerability classes	Four classes are proposed—Extreme, High, Low, Negligible—that describe potential contaminant types and required protection measures (Foster et al., 2003).
Validation	For qualitative and semi-quantitative vulnerability assessments only the adequacy of the final vulnerability needs to be validated. Physically based evaluations include providing probabilities of concentrations and travel times.
Risk and hazard mapping	Risk and hazard assessment may be useful and necessary for management purposes as opposed to less robust vulnerability assessment.

7.4 Karst Vulnerability Assessment Methods

Aquifer vulnerability is an index that is relative, dimensionless, non-measurable, and attempts to indicate the risk of contamination reaching the aquifer once it is introduced at the surface. It depends on how and how fast contaminants can move through the vadose zone to the aquifer.

Vulnerability maps are compiled based on lithological, pedological, hydrogeological, meteorological, hydrological, and geomorphological information that is presented in an understandable manner so that it supports decision making for environmental management, land use and water management, as well as communication between hydrogeologists and decision makers (Witkowski et al., 2007).

Aspects of vulnerability assessment are classified according to Iván and Mádl-Szoňyi (2017).

- 1) The **scale** of vulnerability refers to the amount of data that is required and applicable to determine the map’s content (Vrba & Zaprožec, 1994) as shown in Table 8.
- 2) The **concept** is based on the origin-pathway-target principle and is used as basic theoretical background.
- 3) The **target** is the groundwater table after vertical movement of water, followed by horizontal movement towards wells, springs, or other receptors of water from the saturated zone.
- 4) The **handling of the contaminants** is mostly used to evaluate specific vulnerability.
- 5) There are many **assessment schemes**, and the authors’ proposal is presented in Table 9.

Table 8 - Different scales of vulnerability

Reference	Description
Zaprožec (1989)	National (1:1,000,000–2,500,000) Regional (1:1,000,000–250,000) Local (1:250,000 and less) (*indicated as 25,000 in the article)
Vrba & Zaprožec (1994)	Overview or Synoptical (1:500,000 or more) Schematic (1:500,000–100,000) Operational (1:100,000–1:25,000) Specific (1:25,000 and less)

Table 9 - Steps of vulnerability assessment and their description (reproduced from Iván & Mádl-Szoňyi, 2017).

Assessment approach		Scale	Result	Validation	Examples	Scale	Data
Qualitative	Parametric system models	Matrix system	Meso- and macroscale	Classified map	Limited possibilities		
Semi-qualitative		Rating system	Meso- and macroscale	Classified map	Limited possibilities		
Quantitative	Process-based simulation models		Meso- and microscale	Transit time, concentration, pathway of transport of contaminant	Possible		
	Statistical methods		Microscale	Probabilities, classified or non-classified map	Possible		

Information obtained from the hydrogeological model allows intrinsic vulnerability to be evaluated using different procedures. Knowledge of groundwater quality conditions makes it possible to validate methods to determine the most appropriate method for a particular region. Knowledge pertaining to land use and primary economic activities of the population provides the basis for assessing the potential pollution load that could threaten

underground water quality. The danger of groundwater contamination is based on the combination of pollution load and intrinsic vulnerability. When the danger of contamination is assessed, it is necessary to calculate risk, requiring an analysis of the population’s susceptibility to adverse effects due to groundwater contamination. The risk evaluation methodology is delineated in Figure 45 (Betancur et al., 2012).

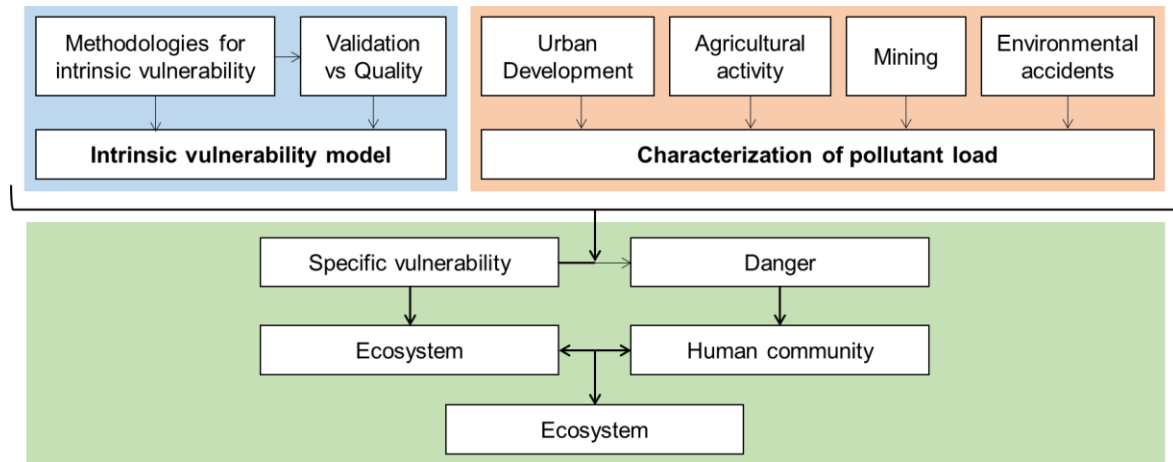


Figure 45 - Risk evaluation methodology (adapted and modified from Betancur et al., 2012).

Iván and Mádl-Szoňyi (2017) published a detailed review on karst vulnerability, as well as methods and codes for the determination of karst vulnerability (risk of contamination). They conclude by stating that the significance of carbonate terrain in global water resources cannot be disputed. Karst aquifer vulnerability assessment has four main conceptual ancestors, namely DRASTIC, EPIK, PI, and VULK. The development and relevant references to these approaches are indicated in Figure 46. The most critical issue is the physical reliability of the resulting vulnerability maps. VULK is an analytical computer program developed by the Hydrogeology Center of Neuchâtel (CHYN) as a tool for intrinsic vulnerability assessment (Jeannin et al. 2001 in Cornaton et al., 2003:155). VULK stands for **VUL**nerability and **Karst** with the basic idea to model the breakthrough curve at a defined target resulting from an instantaneous release of conservative contaminants at a given point (origin) within the system (usually located on the land-surface). Therefore, VULK uses the overlying layers and karst network development factors of the European approach but does not consider the concentration of flow in the catchment of sinking streams (Cornaton et al., 2003). The details of VULK are not discussed in this section because it is a computer program and also because it disregards the concentration of flow, a parameter that is included in most of the methods discussed in this section.

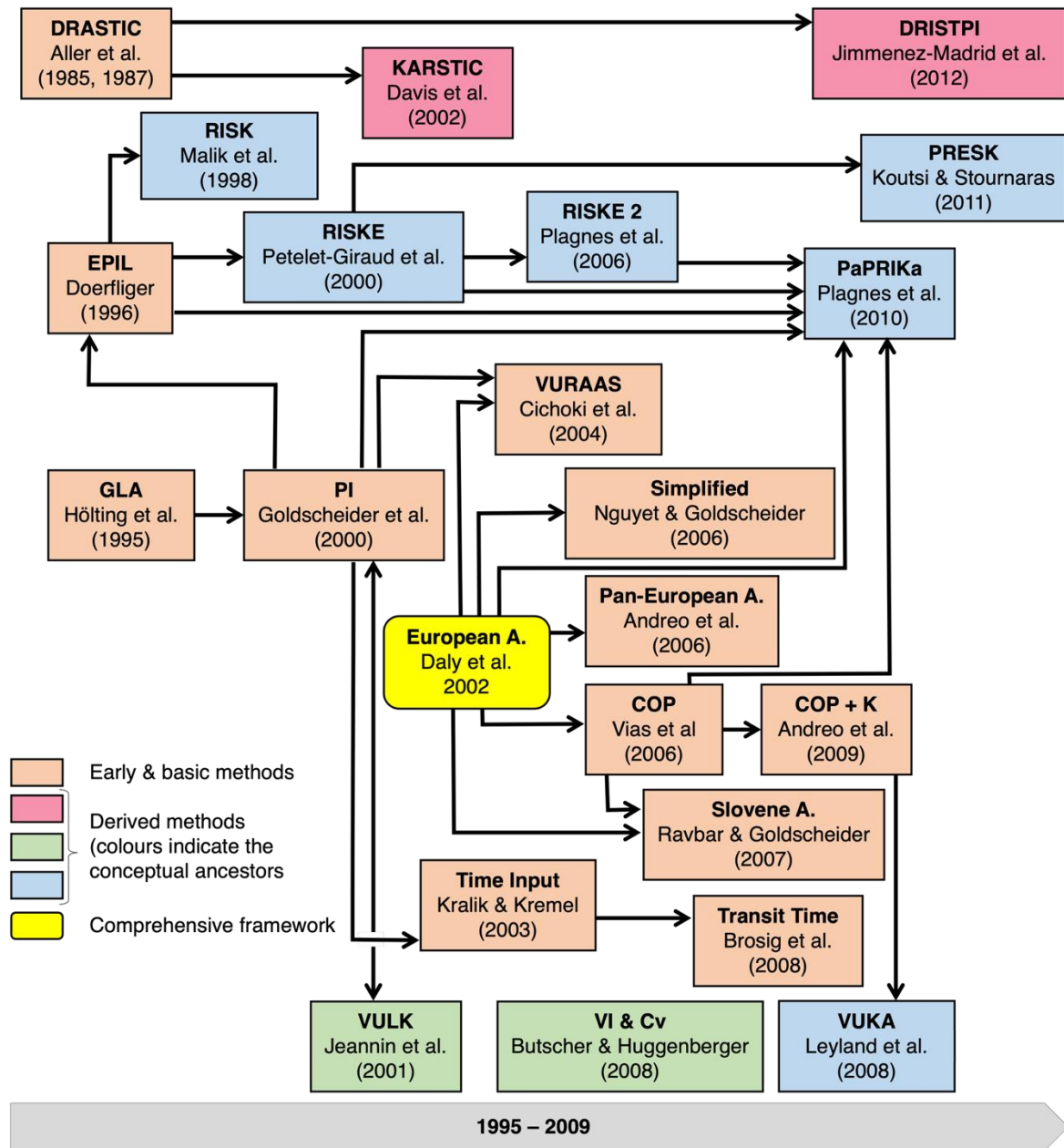


Figure 46 - History of vulnerability assessment codes and applications (Modified from Iván & Mádl-Szoñyi, 2017).

Foster and others (2003) propose that vulnerability assessment should be considered as the “best professional synthesis” of available information that is used as a screening tool, followed by quantitative process-based modeling. Different steps of vulnerability and the associated assessment approaches are shown in Table 9.

7.4.1 DRASTIC Method

The DRASTIC Method is based on weighting and rating seven parameters that influence vulnerability. The system was developed by the United States Geological Survey in the mid-1980s (Dunne, 2003). It has been adapted into KARSTIC where the *Depth to water* is replaced with *Karst development and fractures*. Calculation of the DRASTIC index (DI) is given by Equation (9) with the parameters shown in Figure 47 and supplied in Table 10.

$$DI = DRD_w + RRR_w + ARA_w + SRS_w + TRT_w + IRI_w + CRC_w \tag{9}$$

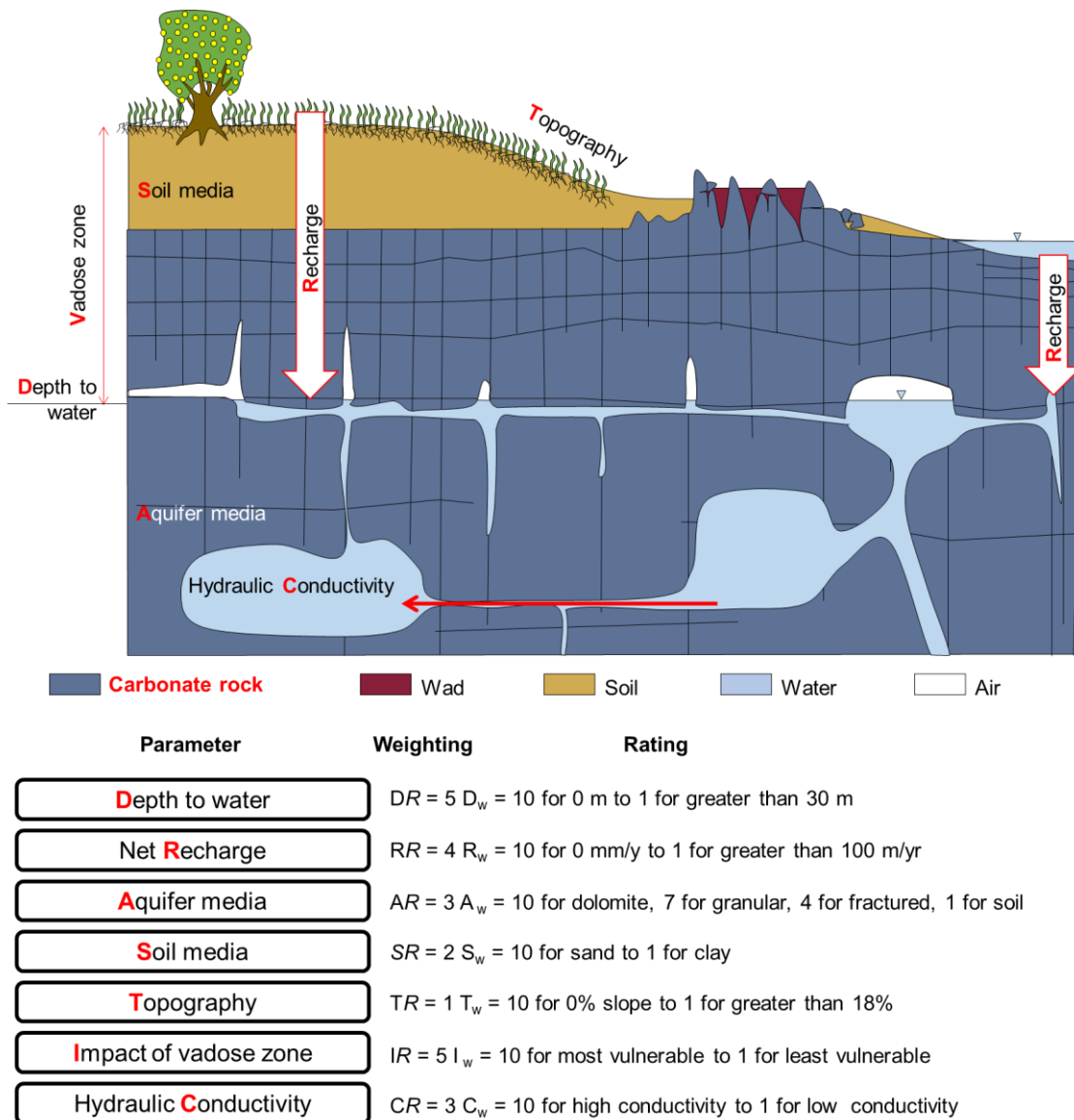


Figure 47 Parameters used in the DRASTIC Method showing the typical weighting and rating for each parameter of Equation (9).

Table 10 - Definition of parameter in Equation (9) (Iván & Mádl-Szoñyi, 2017).

Parameter	Symbol for weighting	Symbol for rating
D Depth to groundwater table	DR	D_w
R Recharge	RR	R_w
A Aquifer media	AR	A_w
S Soil media	SR	S_w
T Topography	TR	T_w
I Impact of the vadose zone	IR	I_w
C (Hydraulic) Conductivity of the aquifer	CR	C_w

7.4.2 EPIK Method

The EPIK method (Figure 48) is a multi-attribute weighting-rating method, that is an overlay and index method, to strictly assess the groundwater sensitivity of karst terrains. It is based on the analysis of four parameters (Doerfliger et al., 1999):

- E – Epikarst,
- P – Protective cover,
- I – Infiltration conditions, and
- K – Karst network development.

Four major steps are taken as listed here (Doerfliger et al., 1999).

1. The water catchment basin’s boundaries from the wells or spring are defined based on geology, hydrogeology, and tracer tests.
2. Where possible, the four attributes need to be assessed, measured, and mapped in a semi-quantitative manner by assigning numbered values.
3. GIS is used to digitize and integrate the resulting maps for attributes E, P, and I. The attribute K can be assessed globally for the entire catchment (one overall value) or regionally based on geology and tectonic context. GIS then calculates the vulnerability values for each defined cell of the map (raster) resulting in a compilation of the values that is summarized in a vulnerability map.
4. The map shows the spatial distribution of vulnerability which can be used to determine different protection zones.

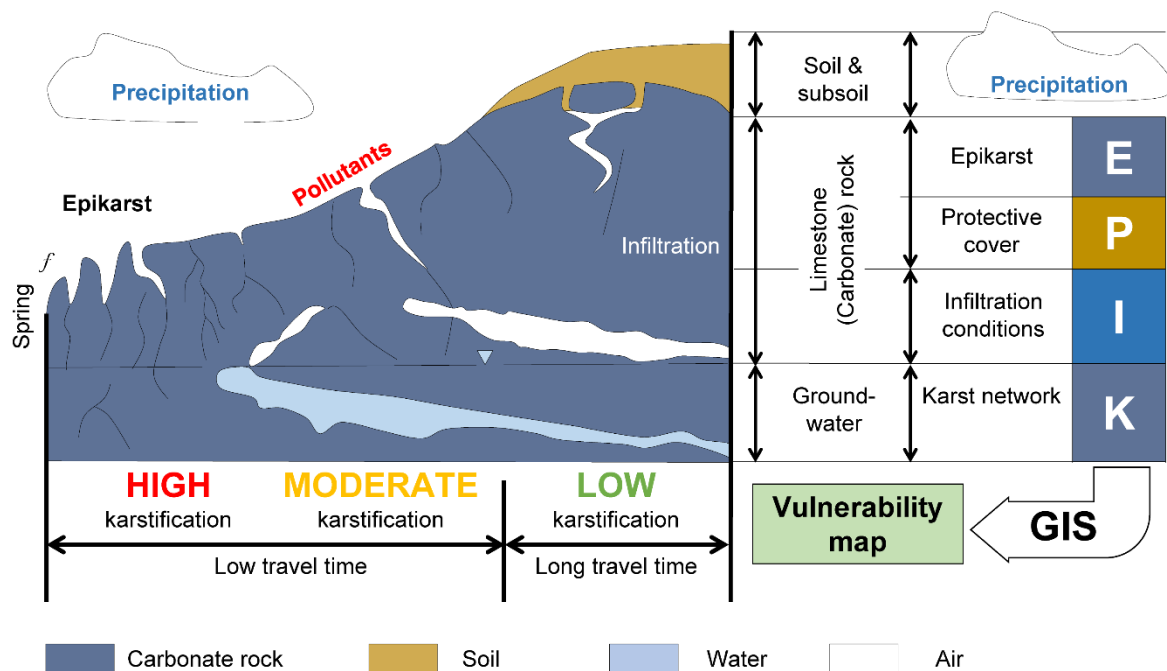


Figure 48 - Parameters of the EPIK Method (adapted and modified from Nekkoub et al., 2020).

7.4.3 PI Method

The PI Method is a GIS-based approach to mapping karst aquifer vulnerability that is based on the source-pathway-target model. The source is the ground surface, the pathway is everything between land surface and the groundwater table, and the targets can be multiple, e.g., first target is the groundwater, and second target is a spring. The protective cover (P) describes the protective function of the layers between the ground surface and the groundwater table—soil, subsoil, non karst rock and unsaturated karst rock—and therefore is equivalent to the O factor—overlying layers—of the European Approach. This protective cover consists of up to four layers including the (1) topsoil, (2) subsoil, (3) non-karst bedrock, and (4) unsaturated karst bedrock as shown in Figure 49. The P-factor is calculated according to a modified version of the German (GLA) method (Holting, et al., 1995), with P=1 referring to a very low degree of protection and P=5 referring to very thick and protective overlying layers (Goldscheider et al., 2000).

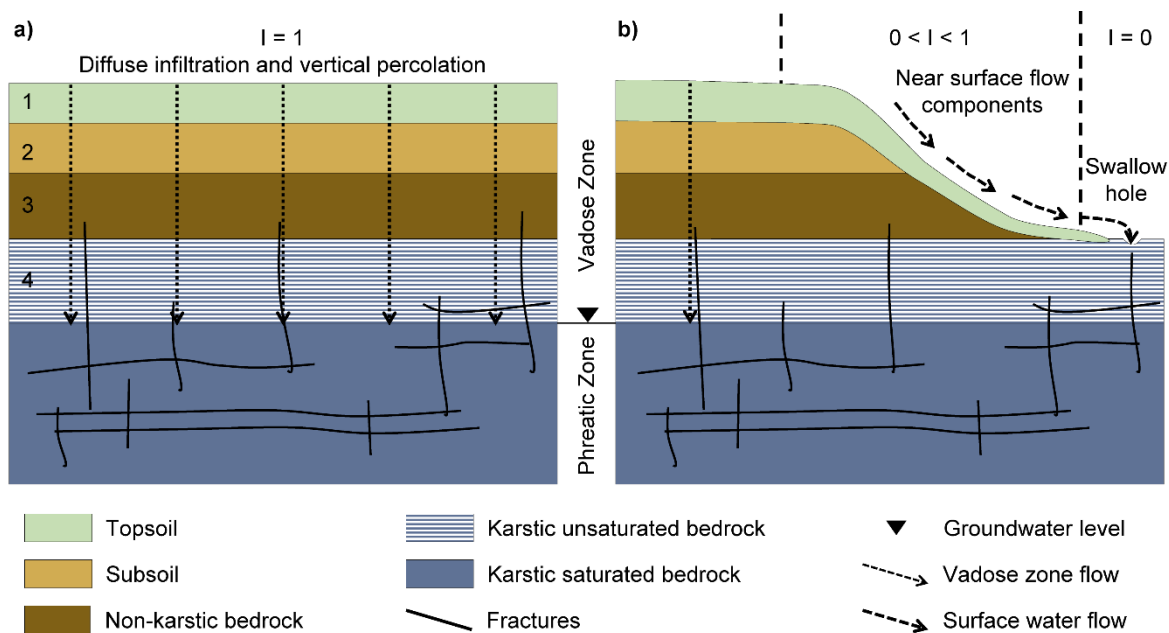


Figure 49 - Parameters of the PI method showing types of protective cover as well as a) low relief topography with uniform overburden resulting in diffuse infiltration and b) topography that leads to direct swallow hole inflow (redrawn from Goldscheider et al., 2000).

The infiltration conditions (I-factor) describe the degree to which the protective cover is bypassed due to swallow holes and sinking streams. The factor is equivalent to the C-factor of the European Approach and is given as 1 if the infiltration occurs diffusely and 0 if the protective cover is completely bypassed (Figure 49). The catchment of a sinking stream is assigned a value between 0 and 1, depending on the proportion of lateral flow components present (Goldscheider et al., 2000).

The spatial distribution of the protection factor π is obtained by multiplying the P- and I-factors with their product shown on the final vulnerability map. Small I and P maps should be printed as insets on the vulnerability map to show how the vulnerability of

particular areas are influenced by the two independent factors. The π -factor ranges between 0.0—low degree of natural protection and high vulnerability—and 5.0—high degree of natural protection and low vulnerability. All areas on each of the three maps are assigned to one of five classes symbolized by five colors ranging from red for high risk to blue for low risk as shown in Table 11 (Goldscheider et al., 2000).

Table 11 - P-map and I-map vulnerability classes (modified from Goldscheider et al., 2000).

Class	Vulnerability Map shows vulnerability of the uppermost aquifer		P-map shows effectiveness of protective cover		I-map shows degree of bypassing	
	Verbal description	π -factor	Verbal description	P-factor	Verbal description	I-factor
Red	Extreme	0–1	Very low	1	Very high	0–0.2
Orange	High	>1–2	Low	2	High	0.4
Yellow	Moderate	>2–3	Moderate	3	Moderate	0.6
Green	Low	>3–4	High	4	Low	0.8
Blue	Very low	>4–5	Very high	5	Very low	1.0

7.4.4 COP, COP+K, and VUKA Method

The COP method, developed by the Hydrogeology Group of the University of Malaga (GHUMA) Italy, assumes that contaminant transport is governed mainly by water’s ability to move through an aquifer, and that the contaminant infiltrates with rainfall. The factors are as follows (Vías et al., 2006; Živanović et al., 2021).

- The **C**-factor accounts for the surface conditions controlling water flow toward zones of infiltration.
- The **O**-factor is the capability of the vadose zone to filter out or attenuate contamination.
- The **P**-factor reflects the volumetric rate of transport through the vadose zone, which depends on the amount of precipitation.
- The **K**-factor incorporates the development of the karst network.

Figure 50 shows the COP+K method indicating the origin of the pollution and its contact with the biosphere including the following (USDA, 1986; Živanović et al., 2021).

- Water entering the aquifer or groundwater system through the vadose zone or other means like swallow holes.
- Water entering or exiting through a dug well or spring.
- Water pumped from a borehole for water supply.

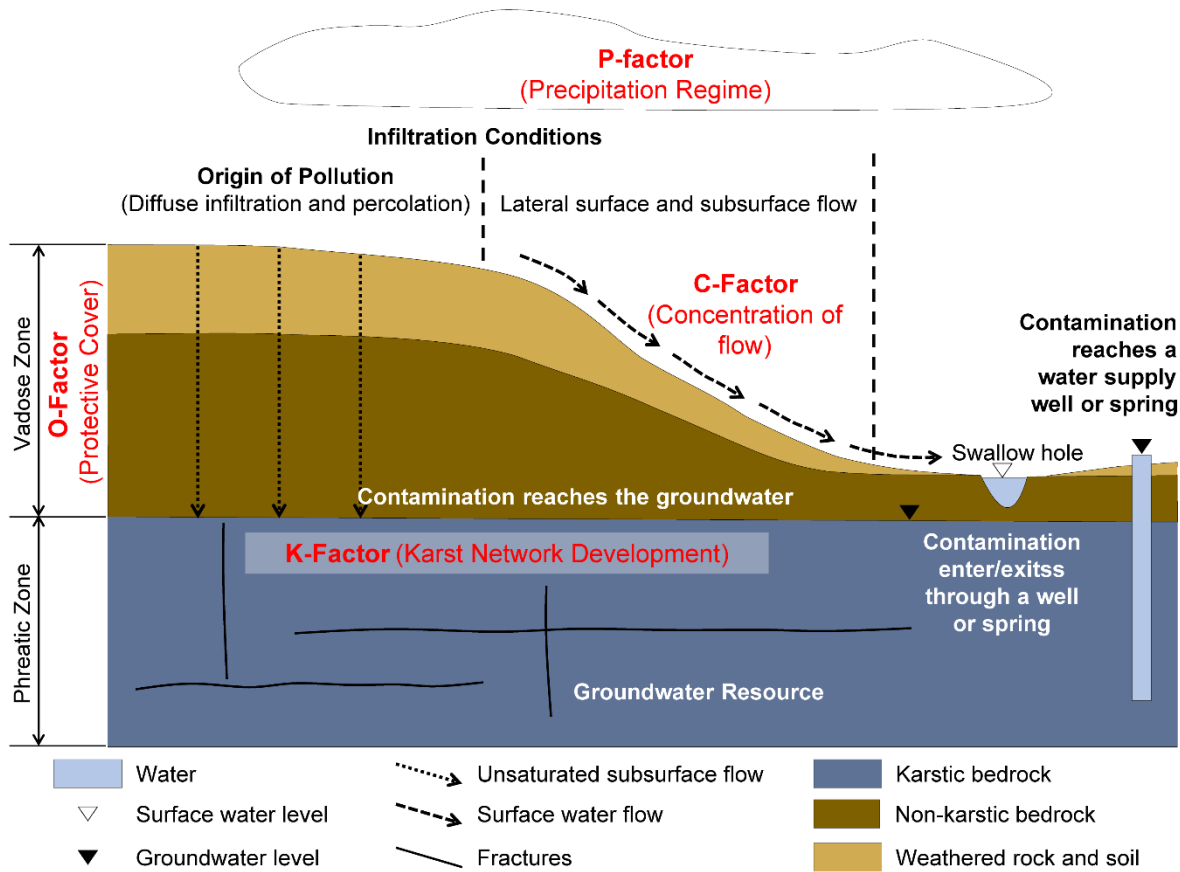


Figure 50 - Parameters of the COP+K method (adapted and modified from USDA, 1986; Živanović et al., 2021).

The VUKA method (Leyland et al., 2008) is modified from the COP aquifer vulnerability method and was specifically adapted to South African karst. It requires determination of the protection of the aquifer offered by the vadose zone against contamination, and the ability of the vadose zone to attenuate or filter contamination through various processes, thereby reducing adverse effects (Vías et al., 2006). The O-factor is subdivided into a soil sub-score and rock sub-score and the sum of the two constitutes the O score (Leyland et al, 2008). The other two factors modifying the degree of protection of the overburden are then considered namely the C-factor, which accounts for surface conditions controlling water flow and the P-factor taking the characteristics of the agent (e.g. water) transporting the contaminants through the vadose zone into account. The final vulnerability index is obtained by multiplying the three C-, O-, and P-factors, and it is then classified into five classes ranging from Very Low to Very High (Leyland, et al, 2008). The changes to the O-factor consider the differences in ground profiles occurring in the northern hemisphere, where the method was developed and southern hemisphere where recent glaciation is absent.

7.4.5 Groundwater Modeling

Groundwater modeling can be accomplished using numerical methods, such as analytical solutions for the partial differential equations for flow and transport or more complex methods of finite element, finite differences with or without unstructured grids,

and the control volume finite difference method. The more complex methods require specialized skills. These complex models simulate flow and transport at a site based on field and laboratory data to develop an approximation of the aquifer system through a calibration process (matching field observations with simulated results). Thus, numerical models provide a way to represent an aquifer system in a form that can be used to investigate a system’s response under certain conditions, or to predict the future behavior of the system. Simpler mathematical models based on statistical regression fitting of observed data to functions can also be applied to karst aquifers and are frequently used in hydrology and hydrogeology. These models fit specific datasets and do not simulate the details of the aquifer system and are not discussed here.

Models are used for water resource management, protection of groundwater, and remediation. Models are useful in hydrogeology albeit imperfect approximations of the aquifer system. Model development remains unchanged despite the complexity of the model used. The stepwise methodology of modeling is shown in Figure 51 (Baalousha, 2009). A more complete overview with example applications of all types of mathematical models for karst aquifer systems is provided in Chapter 6 of *Introduction to Karst Aquifers* (Kuniansky et al., 2022). Provided herein is a very simple overview as entire textbooks are devoted to analytical models often used in aquifer pumping test analysis (Kruseman & de Ridder, 1994) and to numerical models (Anderson et al., 2015).

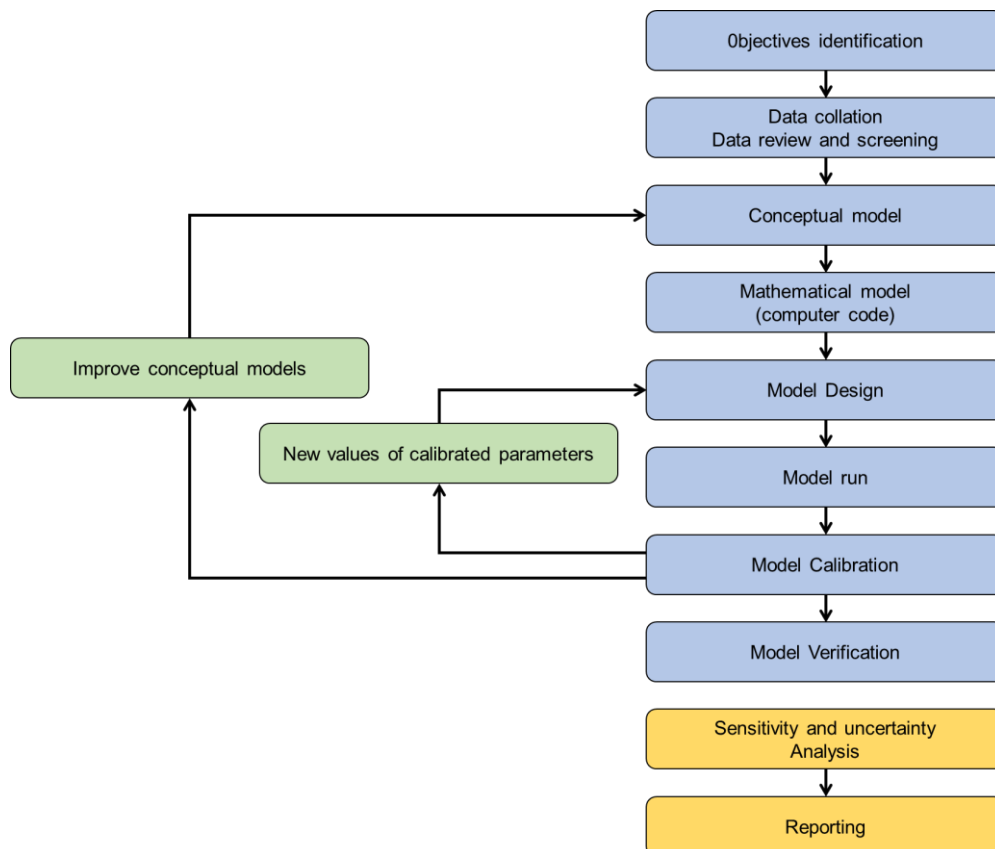


Figure 51 - Stepwise methodology of groundwater modeling (modified from Baalousha, 2009).

The objectives of groundwater modeling are outlined by Baalousha (2009) as follows.

- Predict groundwater flow and groundwater head spatially and temporally.
- Investigate the effect of groundwater abstraction at a borehole that is in the flow regime and can predict the resulting drawdown.
- Investigate the consequence of human activities (such as wastewater discharge, landfills, and agriculture) on groundwater quality.
- Analyze different management scenarios, both quantitatively and qualitatively, on groundwater scenarios.

A conceptual model is the most important part of groundwater modeling after objectives of the modeling are identified. The key features of a conceptual model are listed here (modified from Baalousha, 2009).

- Geometry of the aquifer and semi confining units and the model domain (i.e., the plan area and subsurface volume) required to address the problem under investigation.
- Aquifer parameters (e.g. hydraulic conductivity or permeability, storativity, transmissivity, and porosity if transport is simulated).
- Boundary conditions (specified head, specified flux, or head-dependent flux for groundwater flow modeling, if transport is simulated specified concentration or mass).
- Groundwater recharge (specified flux reaching the water table).
- Evapotranspiration (a head-dependent flux describing the rate of loss of water from the saturated zone based on the depth of the water table).
- Identification of sources (recharge, injection wells, irrigation return flow, losing streams) and sinks (pumping wells, springs) and their spatial distribution.

Development of the conceptual model is followed by model calibration, verification, and validation, with the latter never being possible (Konikow & Bredehoeft, 1992), so in this sense validation means determining whether the resulting model applies to other datasets. There are three categories of models: physical, analog, and mathematical. Physical models include, for instance, sand and acrylic models that demonstrate flow and contaminant transport. Physical models cannot be constructed to represent complicated field problems. Analog models use surrogates that are governed by the Laplace Equation such as electrical flow and heat flow to represent groundwater flow in homogeneous, isotropic porous media. Analog models cannot represent complicated field problems. Mathematical models use partial differential equations to describe groundwater flow. These can be analytical models simple geometry and symmetry often used in aquifer test approximations that are limited in their representation of complex field systems; or numerical models that can represent complex systems where fully three-dimensional groundwater flow and transport is necessary to evaluate the problem (Baalousha, 2009).

Numerical groundwater flow models divide a groundwater system into discrete volumes (e.g., a finite element or finite difference cell) that are assigned hydraulic properties representing that portion of the system. They are called distributed parameter models. Initial conditions are applied to each volume. Boundary conditions are assigned to the external surface of the model domain and at locations where there is a flux (e.g., recharge, well pumping, or evapotranspiration) or where a water level controls water exchange (e.g., a lake, stream, or drain).

7.5 Evaluating Understanding of Karst Vulnerability

Opportunities to assess your understanding of hydrological risk in karst are provided by [Exercise 29](#), [Exercise 30](#), [Exercise 31](#), [Exercise 32](#), [Exercise 33](#), and [Exercise 34](#). An opportunity to assess your understanding of tracer tests is provided by [Exercise 35](#). An opportunity to assess your understanding of karst vulnerability is provided by [Exercise 36](#). Opportunities to assess your understanding of karst vulnerability assessment methods are provided by [Exercise 37](#) and [Exercise 38](#).

8 Geotechnical Assessments for Sinkholes

8.1 Risk Assessment

When assessing risk, it is important to know and understand the source of potential harm or hazard. Typical damage to infrastructure and residential developments are caused by sinkholes that are larger than 5 to 6 meters in diameter (Buttrick et al., 2011). The risk is then expressed in terms of a combination of the consequences of an event and the likelihood of occurrence.

Due to the complexity of karst systems, risk assessments tend to be region or site specific. Our preferred engineering description of karst for risk assessment includes the five karst types or classes (Figure 15) and parameters such as sinkhole density, cave(s) size, fissuring, and rockhead relief (Waltham & Fookes, 2003). Site investigations should be aligned to provide data to describe each of the relevant parameters. Finding subsurface cavities in karst is the biggest challenge and there are few alternatives to assessment via use of detailed geophysics and closely spaced drilling/probing (Waltham & Fookes, 2003). The ground model is important to identifying the expected type and size of sinkholes and the groundwater flow regime. Risk determination is only possible if the hazard—e.g., sinkhole size and recurrence periods or aquifer vulnerability—is known.

Risk factors contributing to potential sinkhole hazard depend on the geology and hydrology and each karst site has a unique set of factors that may contribute to the hazard of sinkhole formation. Nawaz and others (2020) considered the general influencing factors for sinkhole development and reduced these for application to a specific site in Saudi Arabia, then compiled a reduced list of factors that contribute to the hazards.

Geological factors refer to the following (Nawaz et al., 2020).

- Depth to bedrock
- Groundwater depth and potential for desiccation of overburden soil
- Potential for near-surface bedrock
- Fracturing and quality of rock in the upper 5 m of bedrock
- Presence and size of known voids in the soil
- Presence, size, and locality of voids in the rock
- History of sinkholes and subsidences
- Soft zones in underlying soil

Groundwater factors include the following (Nawaz et al., 2020).

- Groundwater depth
- Groundwater pumping history
- Evidence of historical near surface groundwater flow

Surface water and infiltration factors include the following (Nawaz et al., 2020).

- Existing and historic pipe leaks

- History of effluent discharge
- Storm water ponding and runoff on site.

Site feature factors include the following (Nawaz et al., 2020).

- Existing and historical buried services and utilities
- Disturbance of soil due to site activities
- Impervious surfaces.

A risk assessment matrix is presented in Table 12. The four phases in evaluating qualitative risk, based on the approach used by the US Army Corps of Engineers to evaluate earth and similar structures, are shown in Figure 52 (Nawaz et al., 2020).

Table 12 - Risk assessment matrix (reproduced from Nawaz et al., 2020).

		Impact		
		Low	Moderate	High
Likelihood	Very likely	3	4	5
	Likely	2	3	4
	Unlikely	1	2	3



Figure 52 - Risk assessment matrix (reproduced from Nawaz et al., 2020).

Nam and others (2020) identified the critical factors causing sinkholes in Florida’s karst in the USA as: the hydraulic head difference between the water in the surface aquifer system and the deeper Floridan aquifer; soil permeability; overburden thickness; thickness of the unconfined permeable hydrostratigraphic unit; thickness of aquitard between the surficial aquifer and Floridan aquifer; and the proximity to old sinkholes. A statistical analysis of these contributing factors revealed nonlinear relationships and indicated they could not be treated as independent variables but could be used to develop a probabilistic prediction model for sinkhole occurrence (Nam et al., 2020).

In karst environments where it is possible to enter underground cavities or caves it is important to map the cave, because karst aquifers are vulnerable to pollution due to the direct connection between surface water and water flow in caves (Parise et al., 2015). This is referred to as a speleological survey.

Hazard assessment in karst areas is an empirical science that relies on experience and historical records. The hazard is surface subsidence. Inherent hazard refers to the geological susceptibility to an event with the size of event relating to the diameter of the surface subsidence, or sinkhole. Factors used in the evaluation of sinkhole risk are: installation of wells or boreholes in the overburden and/or bedrock; mobilizing activities (e.g., dewatering or water ingress); the nature of the overburden; potential for the overburden to mobilize; and bedrock morphology (Buttrick et al., 2001).

8.2 Sinkhole Hazard Assessment

It is important to realize that sinkhole occurrence is not due to present day dissolution. The cavities and erodible blanketing layer are related to processes and events that happened over geologic time scales (Parise et al., 2015). Present day human activities may cause sudden changes that lead to unstable conditions that may result in sinkhole development. Additionally, climatic factors such as drought and flooding contribute to falling and rapidly rising groundwater levels. Drought may result in collapse of overlying material into previously saturated caverns, and sudden water level rise from flooding may destabilize overburden above subsurface voids.

Once the site assessment has been completed with the hazard size (e.g., small, medium, and large sinkholes) and probability determined, foundations should be designed to limit loss of life in the event of sinkhole formation.

Theoretically the sinkhole size, also referred to the maximum potential sinkhole, is determined by using the internal friction angle to determine the angle of draw. The angle of draw is the angle at which earth materials will form a stable sidewall. If all the material within this space is mobilized the sinkhole will develop to its maximum size. Sinkholes rarely reach their maximum size due to a number of factors, for example the throat may get blocked and prevent materials from being eroded into the cavity, the cavity may not be large enough to accept all the eroded material, or the eroding agent is removed (e.g., a burst water pipe repaired), among other possibilities. The grey area in Figure 53a is an example of a sinkhole showing the condition where the total volume of overburden materials was not eroded into the cavity. If there are different soil and/or rock horizons occurring between the throat of the cavity and the natural ground level the angle of draw of the different horizons can be used to determine the area within which a sinkhole may likely occur (Figure 53b) as well as the maximum development space if all the material within the development space is eroded (Buttrick et al., 1995).

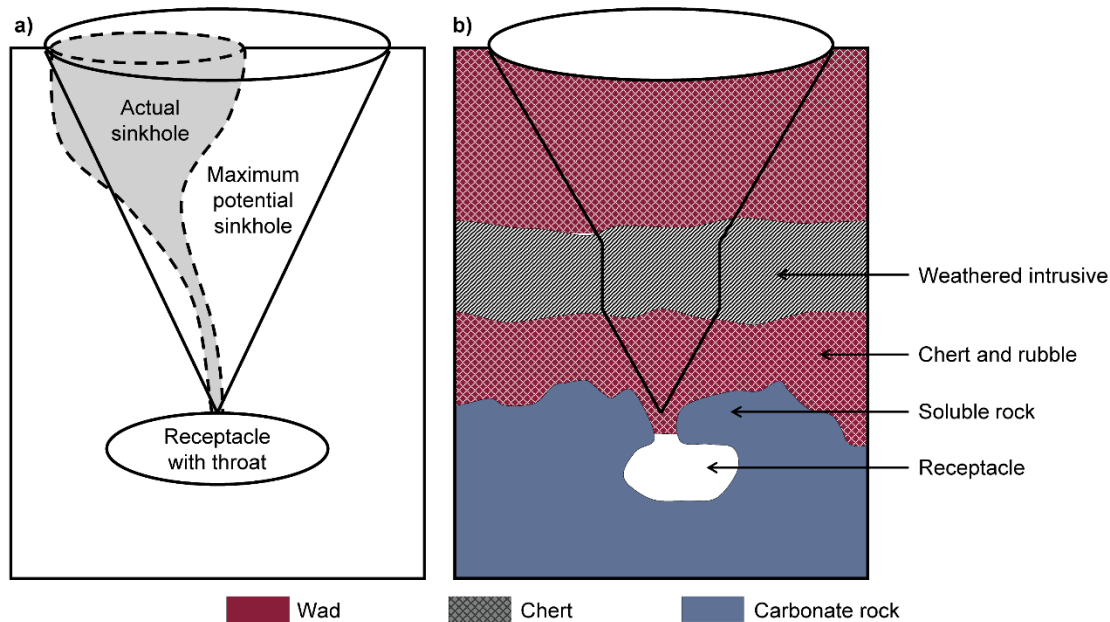


Figure 53 - Actual sinkhole size within the maximum potential development space. a) Mobilization volume of material within the maximum potential sinkhole development area determines the potential sinkhole size. b) Angles of draw of the different horizons determine maximum potential sinkhole size (redrawn and modified from Buttrick & van Schalkwyk, 1998; Buttrick et al., 1995).

Risk assessment is usually mandatory in urban areas and can be expressed as the specific probability of sinkhole development per unit area per unit time taking the probable economic, social, and environmental aspects of damage into account (Tolmachev, 2013). Probability is based on environmental conditions applying stochastic laws of sinkhole development in time and space and including the type of development (SANS, 2012a). This probability of sinkhole formation within a unit surface area over a unit time can be regarded as the predicted risk. Once the risk is predicted, a multidisciplinary team of designers, lawyers, economists, insurers, environmentalists, and engineering karstologists usually define the acceptable risk for a specific structure. The ratio between predicted and acceptable risk serve as a meaningful karst-risk-level indicator for the purposes of development on karst and can be used to develop a risk management program (Tolmachev, 2013).

Risk assessment in areas where caves are present use the geographic location of the caves followed by cave mapping (speleological survey), highlighting all discontinuities in the rock mass, and all other factors that may contribute to instability such as weathering, previous failures, water flow, and previous stabilization of sinkholes (Parise et al., 2015).

Buttrick and others (2001) propose the use of a set of simple factors to assess the hazard and inherent risk in dolomite land. The factors include the thickness and nature of the dolomite overburden (blanketing layer); presence of voids (cavities) in both the overburden and dolomite bedrock; the mobilization potential; expected agents of subsurface erosion; and the maximum potential development space for a specific profile. They distinguish between the hazard—the sinkhole size—and the inherent risk that reflects

on the geotechnical characteristics of the blanketing layer and depends primarily on the susceptibility of this material to mobilize.

The risk analysis for infrastructure development on karstic limestones in Saudi-Arabia follows a similar approach (Nawaz et al., 2020). Depth to bedrock, overburden erodibility and shrinkage on desiccation, presence of a capstone layer, degree of bedrock fracturing and presence of cavities, depth to groundwater, distribution of historic sinkholes, and various anthropogenic influences are assessed and combined in a risk matrix.

Statistics from various parts of the world, including China, the USA, and South Africa, indicate that the majority (75%–90%) of current day sinkholes form due to anthropogenic activities (Lei et al., 2002; Oosthuizen & van Rooy, 2015). Sinkholes therefore occur mainly in urban environments where leaking pipes and disturbed surfaces lead to water ingress and over pumping of aquifers lead to groundwater lowering. Both these processes are known to trigger surface instability that result in sinkholes or gradual subsidence.

Human development on karst is exposed to hazards related to geological and anthropogenic processes that may cause sinkholes. It is generally not possible to predict exactly where surface events will occur and, consequently, there is always some risk of loss of infrastructure or life. Buttrick and others (2001) classified risk as low when 0 to 0.1 events are anticipated per hectare for a period of 20 years, medium for an expected 0.1 to 1 event per hectare per 20 years, and high if more than 1 event is anticipated per hectare per 20 years.

8.3 Risk Management

Urban development, dewatering of karst aquifers and mining, amongst other anthropogenic activities invariably disturbs the meta-stable conditions in karst terrains.

Human development on karst is increasing due to increasing infrastructure and shortage of land for development. Investigation and identification of low-risk areas for development are no guarantee that the karst processes enhanced by anthropogenic activities and effects may not alter the original system and cause a change in stability.

The main activities that may influence the initial stability of karst terrains are related to groundwater dewatering, surface water ingress, and changes in the ground profile due to construction activities. All of these may increase risk and may result in additional remedial foundations and other measures to be implemented.

Effective risk management includes implementing the following.

- Restriction of land-use to appropriate development related to hazard class.
- Management of surface drainage and sealing of surfaces to reduce infiltration.
- Control of groundwater lowering (i.e., limiting dewatering).

- Prevention or control of water use such as irrigation and drain fields for septic disposal.
- Requirement of subsurface water-bearing infrastructure and drainage.
- Design requirements that allow safe evacuation of occupants in the event of sinkhole formation.
- Rehabilitation and grouting of sinkholes.

Engineering measures that may prevent sinkhole development include the following (Parise et al., 2015).

- Induce collapse of shallow cavities.
- Improve mechanical properties of overburden/blanketing layer.
- Seal openings in rockhead.
- Fill cavities via grouting.
- Rigid foundations to span potential sinkholes.
- Piles to bedrock below cavernous zone.

It is statistically significant that sinkholes tend to occur in association with waterborne services and specifically within a 20 m corridor on either side of the service. The probability of sinkhole formation in dolomite is significantly reduced when management is based on identification of the hazard, quantification of the inherent hazard, and implementation of appropriate land-use and precautionary measures relating to the hazard (Buttrick et al., 2011).

Hazard assessment of dolomite land may follow a hierarchical approach where the hazard is first determined to be within acceptable levels, the land-use presents a tolerable hazard rating, the probability of sinkhole occurrence is low, and various compliance remedial measures are implemented (Watermeyer et al., 2008).

Although risk management and mitigation measures may reduce the risk of sinkhole formation, certain anthropogenic and natural processes, or catastrophic events, such as burst water mains, earthquakes, flooding, may cause sinkholes to develop notwithstanding the risk assessment and low probability of sinkhole development. Foundation design to accommodate a specified size of event and to allow the safe evacuation of residents are seen as a necessary component of risk management (Wagener, 1985; Xeidakis et al., 2004).

The depth to rockhead and properties of the blanketing layer are important conditions to consider when deciding on foundation remedial measures. Figure 54 provides examples of foundation solutions where shallow pinnacled rockhead or variable depth to rockhead exists (Wagener, 1985).

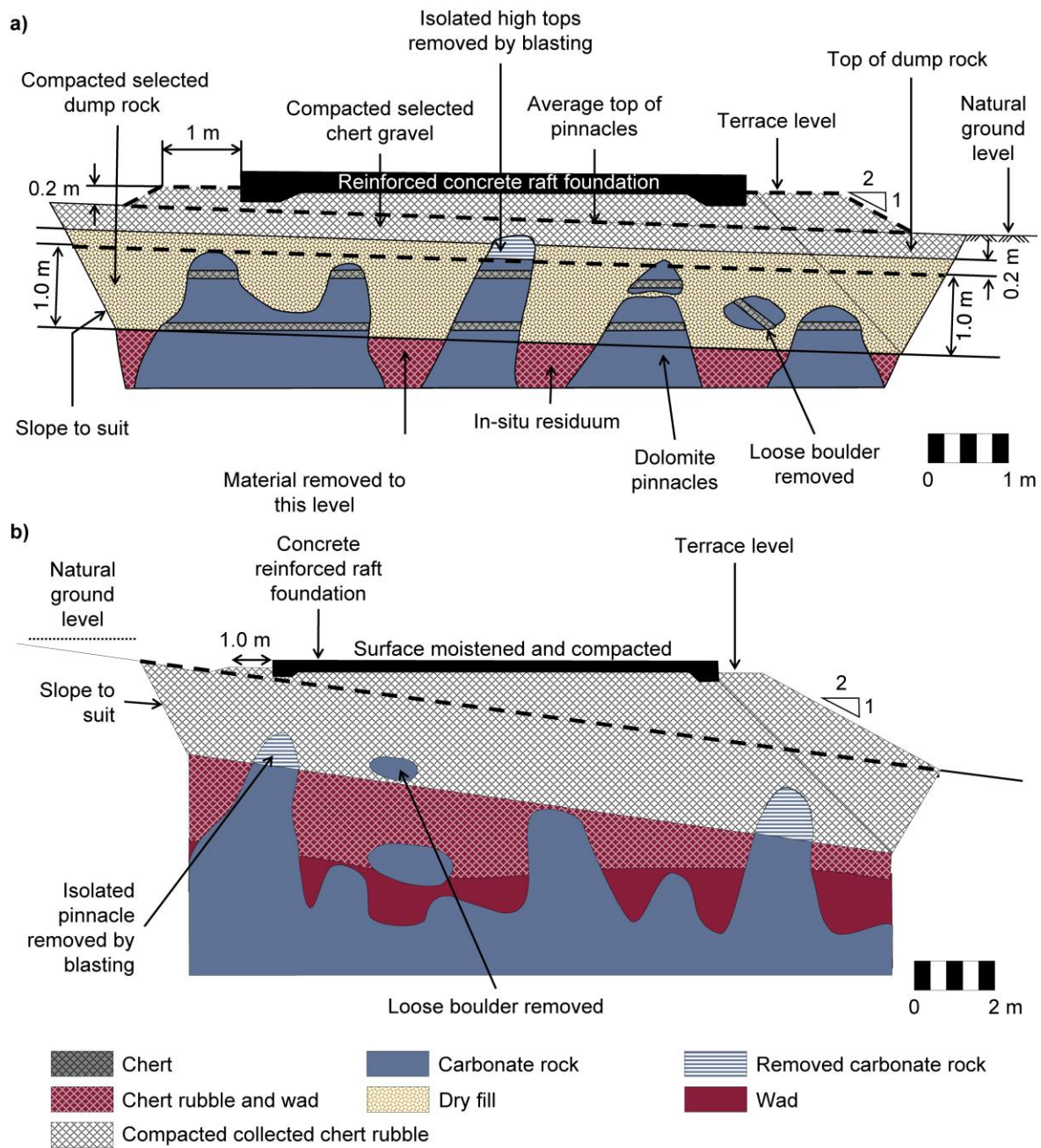


Figure 54 - Examples of foundations in areas with a) shallow pinnaced dolomite and b) variable shallow and deep rockhead (reproduced from Wagener, 1985).

Available foundation remedial measures are linked to the type of karst for which they are appropriate as follows.

- For shallow rockhead with small fissures, spread footings or use reinforced beams across small voids or grykes.
- For moderate depth to rockhead with extensive fissuring, use beams, heavy geogrid, or preparatory grouting (mainly compaction grouting).
- For pinnaced rockhead with deep foundations on solid rock, use drilled shafts and piles.

- For any setting, drilled shafts and piles are no risk options, however they are expensive and only viable for larger and more expensive structures.

Examples of foundation preparation are shown in Figure 55.

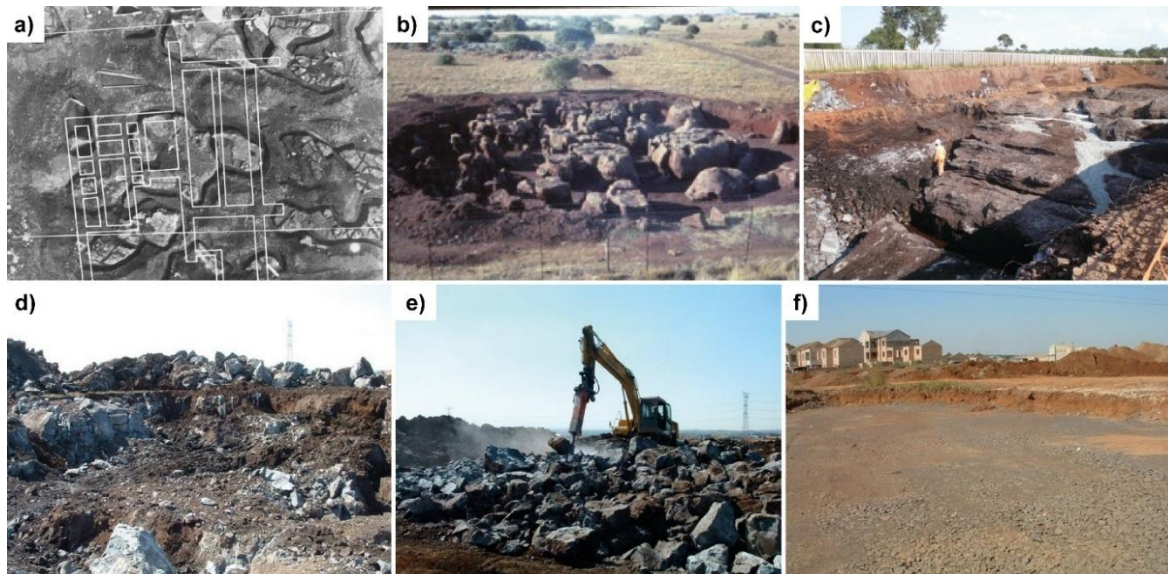


Figure 55 - Examples of construction in dolomite terrain: a) layout of reinforced ground beams supported by pinnacles; b) exposed building footprint area; c) mass concrete infill of shallow grykes below new rapid rail track; d) removal of gryke infill; e) leveling by removal of hard-rock pinnacle heads; and f) compacted level platform prior to start of construction ((a) and (b) from Brink, 1979; (c) through (f) photographs by van Rooy).

Although site investigation, risk assessment, and risk management ensure acceptable risk for development on dolomite the complex karst environment and longer-term influences of anthropogenic activities call for ongoing monitoring and review of possible hazards occurring; as well as reassessment of the initial risk mitigation and management strategies (Potgieter, 2017). In South Africa, a dolomite risk management program is mandatory (SANS, 2012c).

The implementation of such a program starts with the establishment of risk evaluation criteria, identification of the hazard, and a risk analysis. If the risk is acceptable for development of the particular site and development type, it can proceed with appropriate remedial and risk reduction measures. If the risk is unacceptable the development may be abandoned or risk treatment options may be implemented (SANS, 2012b, 2012c).

Ongoing monitoring also assists with possible early warning of deep-seated ground movement where subsurface erosion may lead to a surface event. Monitoring measures may include high-precision level surveying of critical infrastructure—e.g., roads, buildings, water lines—with reference to a static base point—e.g., a rock-embedded elevation base or telescopic bench marks (Figure 56). In addition, visual assessment of expected unstable areas is necessary including monitoring cracks in buildings, road surfaces, and ground surface.



Figure 56 - Telescopic benchmark anchored in rock, and two higher elevated horizons (Photograph Wolmarans, 1984).

The two main factors contributing to development of a risk management program on karst terrain are the physical environment—geology, hydrogeology, and engineering geology—as well as the anthropogenic environment—existing infrastructure, land-use planning, and social structure. It is imperative to involve the local community in discussion of the risk assessment, decision making, and continued monitoring. The social structure needs to be considered to ensure all members of the community have input. In addition, it is essential that the relevant authorities take ownership of the continued monitoring program. The development of a dolomite risk management program can only be effective if it is based on the following (Potgieter, 2017).

- Historic and current data on the susceptibility of an area to and occurrence of sinkholes (hazard identification).
- Risk analysis related to existing development (i.e., land use) and anticipated future expansion.
- Implementation and control of land-use limitations and mitigation measures (e.g., repair or replacement of leaking services).
- Monitoring of surface indicators to subsidence such as water ingress locations.

8.4 Rehabilitation

Mitigation of sinkholes may include rehabilitation of existing holes and implementation of measures to prevent their reactivation in future (Zhou & Beck, 2008). Evaluation of a specific sinkhole and the geological model pertaining to a specific collapse event guide the appropriate rehabilitation and remedial measures. An overriding factor determining the design of rehabilitation is the depth to which subsurface has influenced the overburden divided into shallow (8 m), intermediate (8–15 m), and deep (15 m) influence according to Kleinhans and van Rooy (2016). Zhou and Beck (2008) divide

sinkholes into shallow and deep sinkholes for mitigation purposes. Shallow sinkholes are, according to them, those that are less than 10 m deep. Their base can be reached by a regular backhoe. Deep sinkholes are more than 10 m deep and drilling rigs are needed to reach their base.

The success of sinkhole rehabilitation and mitigation measures boils down to the efficacy to which the mechanical erosion processes are eliminated in the overburden. Successful sinkhole rehabilitation includes treatment of the throat to the receptacle, backfill of the collapsed space, and placement of a sinkhole cap (Zhou & Beck, 2008).

The factors determining the rehabilitation method are as follows.

1. Cause of sinkhole formation (water ingress or dewatering).
2. Complexity of the geological model:
 - Blanketing layer (overburden composition, thickness, and properties; presence of intrusive or cap rock; presence of faults or shear zones; and presence of paleo-sinkholes)
 - Depth to rockhead because this influences maximum size of sinkholes.
 - Depth to groundwater as well as consideration of the susceptibility of overburden to mechanical erosion; compaction subsidence; containing water filled voids.
3. Lateral extent of area to be rehabilitated.
4. Triggering mechanism.
5. Impact on existing infrastructure.
6. Post-rehabilitation land-use.

The different methods of sinkhole rehabilitation include the following (Kleinmans & van Rooy, 2016).

- Inverted Filter (Figure 57) which involves excavating a sinkhole to a stable base, then refilling it with layers of progressively smaller rock to create a filter, covering it with a geotextile to prevent fine soil from migrating into the rock fill, then backfilling the area with soil.
- Dynamic Compaction (Figure 58) which involves increasing the density of soil and collapsing subsurface voids by repeated impact using a dropped weight.
- Combination of Inverted Filter and Dynamic Compaction.
- Combination of Inverted Filter and Compaction Grouting which involves injecting low-mobility grout (e.g., a sand-cement-fly ash mix) into the soil under high pressure to increase the density of soil, fill voids, and stabilize the ground.
- Combination of Dynamic Compaction and Compaction Grouting.
- Self-compacting concrete or soil-cement mix.

- Chemical grouting involves injecting a fluid such as polyurethane foam into soil to fill voids, stabilize, and bind soil particles together.

Illustrative examples of sinkholes being excavated and backfilled for rehabilitation are shown in Figure 59 and Figure 60. Sinkhole rehabilitation depends on the complexities and unique setting at each sinkhole occurrence.

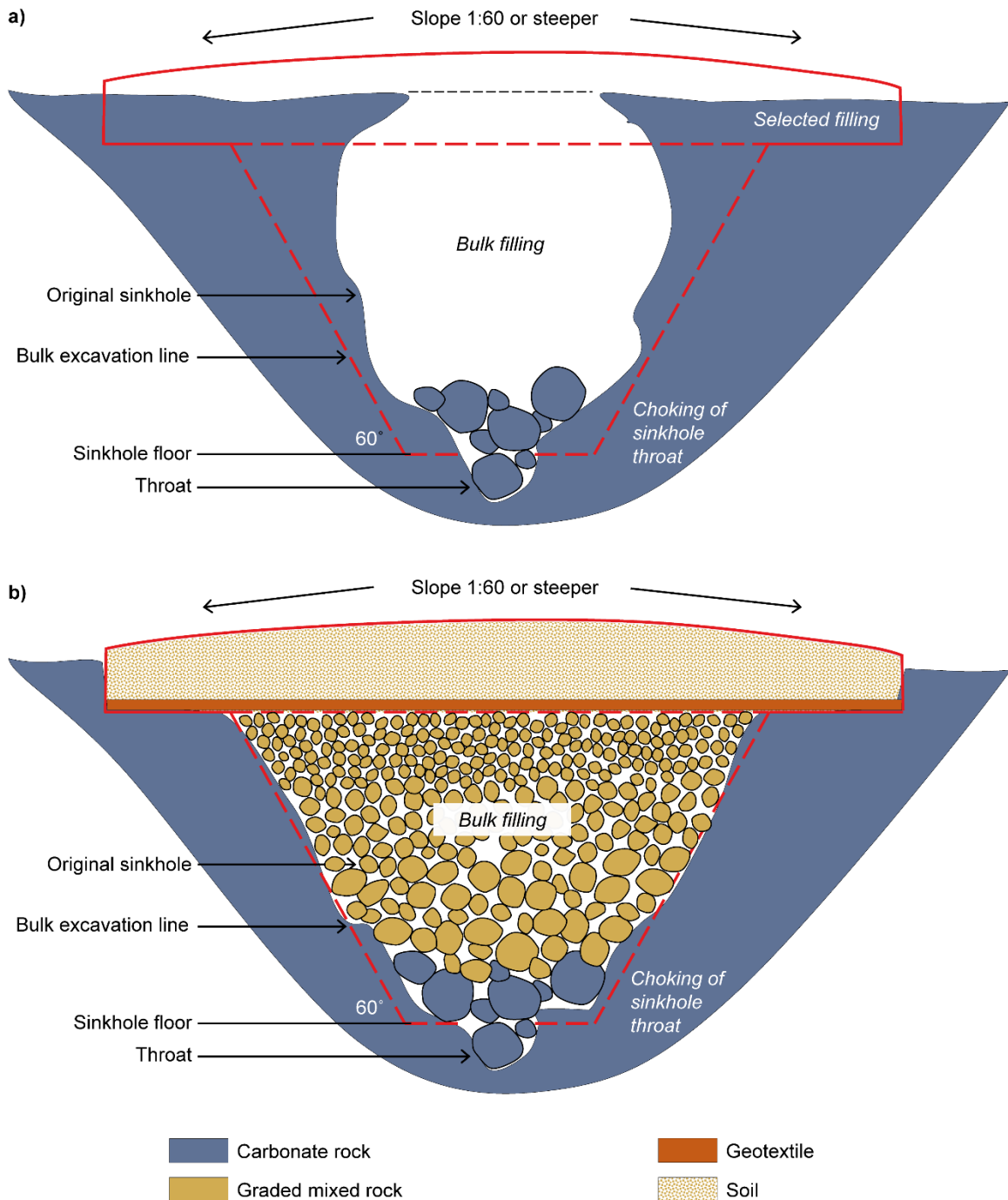


Figure 57 - Inverted Filter. After excavating the sinkhole to a stable base, it is refilled with layers of progressively smaller rock to create a filter. A geotextile fabric is placed over the rock layers to prevent finer soil from migrating into the rock, and the area is then covered with soil ((a) reproduced from Kleinhans & van Rooy, 2016); (b) original for this book).

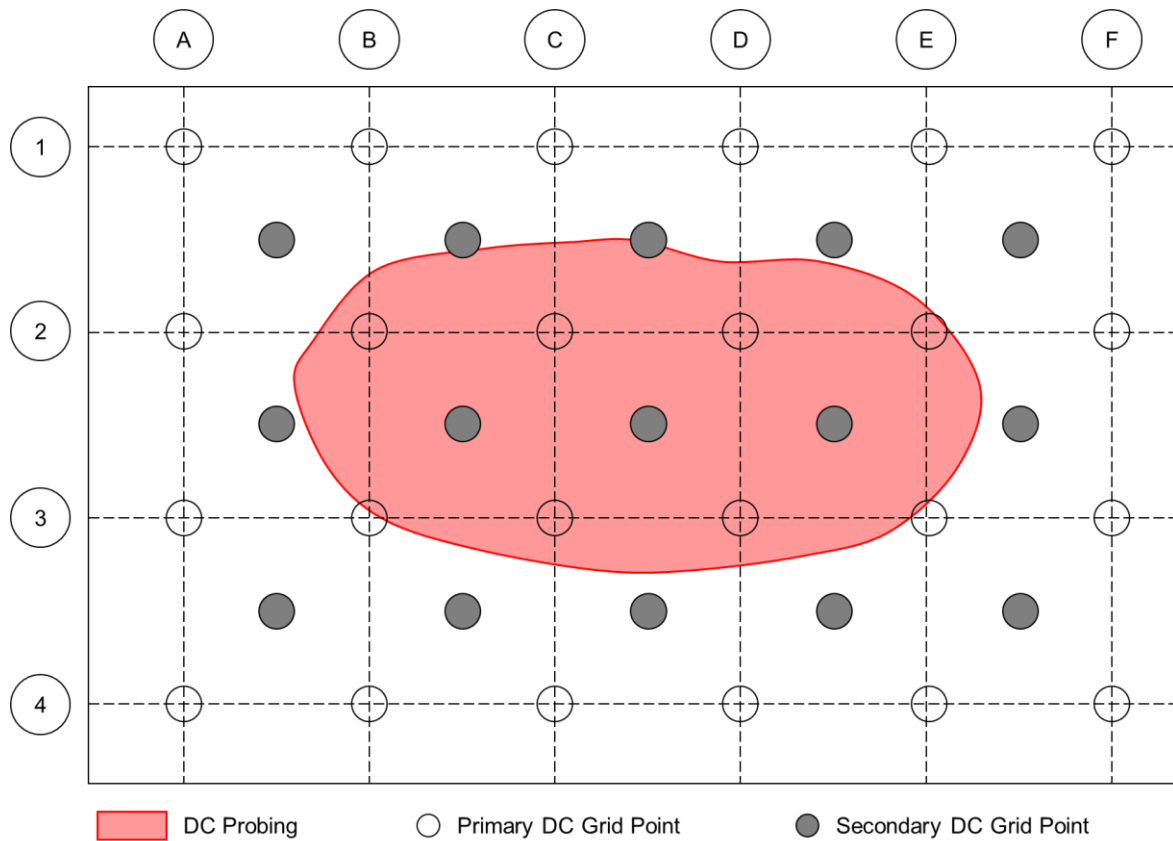


Figure 58 - Dynamic compaction (DC) probing area and grid. DC probing is initially applied to collapse the sinkhole roof or cavities not daylighting and to choke the sinkhole throat. The primary grid has a wide spacing for deeper compaction then additional impact is applied at secondary points to compact the shallower soil layers (reproduced from Kleinhans & van Rooy, 2016).



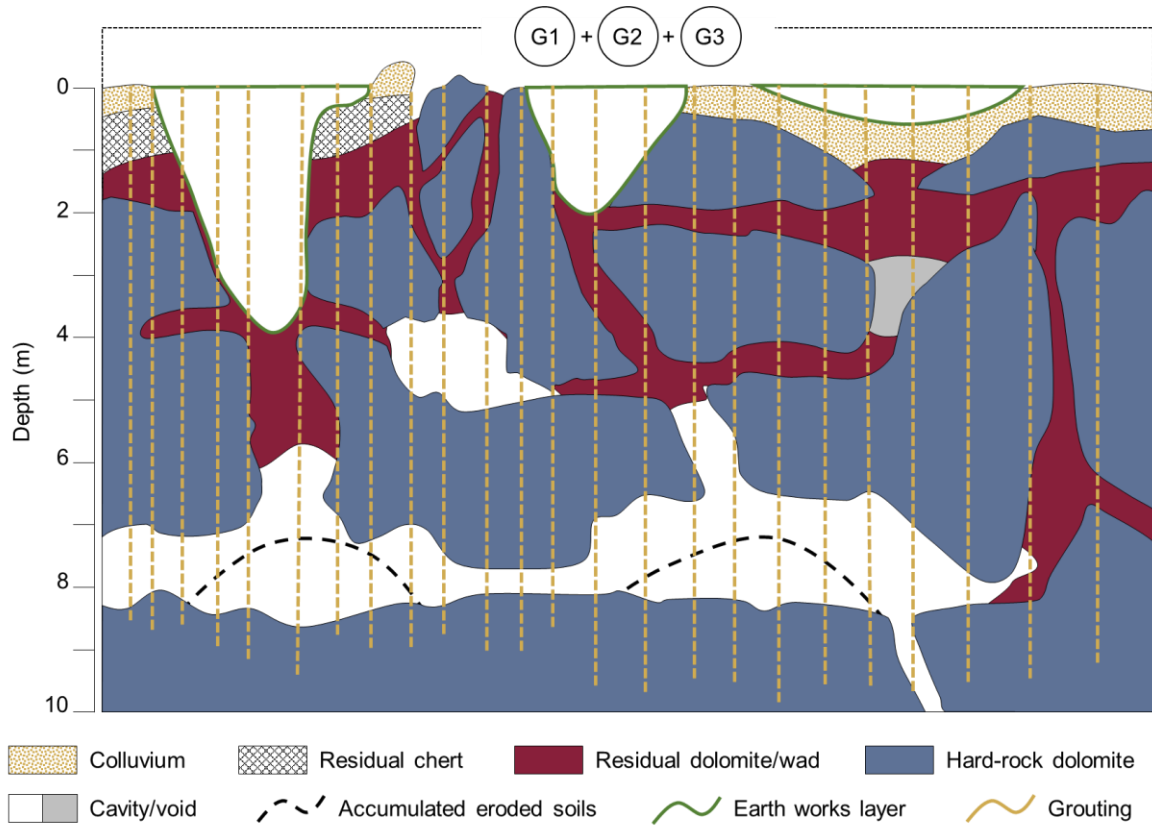
Figure 59 - Rehabilitation of a sinkhole in Pretoria: a) removal of collapsed overburden and b) excavated sinkhole showing maximum development space (photographs by van Rooy).



Figure 60 - Illustration of the rehabilitation process: a) original sinkhole, b) excavation of slumped overburden material and c) dynamically compacted rockfill base prior to complete backfill (photographs by van Rooy).

An example of the rehabilitation approach in the case of a complex geological model including grouting of cavities and voids and surface earth works is shown in Figure 61. The rehabilitation measures should be customized to produce the most economical and safe outcome. The diagram in Figure 61 shows deep cavities (caves); shallow cavities and voids; low density residual dolomite; and a highly variable dissolution pattern in the bedrock with some outcropping pinnacles. Remedial actions therefore include deep and shallow grouting as well as surface backfill of open sinkholes and soil-cement mix cover. The examples of rehabilitation methods in Table 13 illustrate the complexity of the process (Kleinhans & van Rooy, 2016). The investigation and rehabilitation of numerous sinkholes and subsidences on the East Rand, South Africa, made it possible to develop an understanding of the different dolomite environments, their susceptibility to sinkhole and subsidence formation, and best-practice rehabilitation methods. Generic geological models

are presented in Table 13 and linked to most appropriate rehabilitation methods to serve as a guideline for sinkhole and subsidence rehabilitation in karst environments. The influencing factors considered to determine the most appropriate rehabilitation method based on the three depths of influence of the sinkhole are included in Table 13.



EARTHWORKS			
Number	Material Type G-quality materials, COLTO 1996)	Layer Thickness	Compaction (% of Mod AASHTO)
1	Boulders and soilcrete (5% cement added)	Varies	Excavator bucket
GROUTING			
Number	Upstage Grouting Sequence		Grout Type
G1	Primary Grouting on 3 m Grid Spacing		2 MPa
G2	Secondary Grouting, placed midway Primary Positions		2 Mpa
G3	Tertiary Grouting, infilled between Primary and Secondary		2 MPa

Figure 61 - Rehabilitation approach for a complex geological model (Kleinhans & van Rooy, 2016).

Table 13 - Recommended rehabilitation for sinkholes (Kleinhans & van Rooy, 2016). Dark green lines are earth works. Bright green lines are grout holes. The solid red line is the bulk excavation area, the dashed red line is the position of wet service, the squiggly red line is the position of the broken wet service post sinkhole development. Subsurface materials are indicated by the legend of Figure 61.

Influencing Factors and Models	Case 1	Case 2	Case 3
	Dropout sinkhole impact to 8 m	Buried sinkhole impact to 15 m	Caprock sinkhole impact to greater than 15 m
Cause/ Trigger	Multiple cracks and disconnected 160 mm diameter uPVC sewer line at 4 m depth, 20 m section of pipe dysfunctional.	Broken 150 mm diameter vitrified midblock sewer line at 3.5 m depth, point source.	Dewatering of the dolomite compartment to 50 m exposing cavities at depth and material with high mobilization potential. Surface water ponding. Potential for sinkhole diameter increase.
Geological Model Complexity	Intermediate to complex, highly variable bedrock profile.	Intermediate to complex, weathered rock above and within dolomite residuum.	Complex, deep profile susceptible to instability.
Blanketing Layer	Colluvium, chert and dolomite residuum (wad) with dolomite floaters and voids.	Chert residuum, dolomite residuum with a horizon dolomite rock. No voids encountered. Inaccessible to drilling rig.	Colluvium, shale, chert residuum, dolomite residuum (wad) absent in subareas. No voids encountered.
Bedrock	Pinnacled dolomite rockhead (1–8 m), adjoining V-shaped grykes. Cavities present.	Variable depth of 3 to 15 m. No cavities encountered.	Variable depth of 8 to 40 m. A number of interconnected cavities encountered.
Instability Feature Dimensions	4 m diameter, 4 m deep sinkhole.	4.5 m x 2 m, 2.5 m deep sinkhole.	50 m diameter, 25 m deep sinkhole.
Impact on Infrastructure	Located in sewer service area and affecting suburban road.	Extends partially below two-story house, overhead electrical cables and a subsurface water line.	Road in agricultural area.
Rehabilitation Method(s)	Inverted Filter Method because space is available for bulk excavation, backfill, and compaction.	Compaction Grouting Method after structure is stabilized with mass concrete sinkhole infill.	Sterilization of land by fencing off and building a soil berm to divert runoff, thus preventing expansion of feature.
Land Use after Rehabilitation	Road, sewer service, and garden area of residential stands.	Existing residential structure stabilized.	Agriculture.
Sinkhole Model			
Rehabilitation Model			

In summary, the rehabilitation process includes the removal of the cause, filling of the void, prevention of future triggers, and a decision on appropriate post event land-use (Kleinhans & van Rooy, 2016). In some circumstances it may be excessively expensive to fill the void and, if property and/or lives are not immediately threatened, the sinkhole may be isolated and left with only local surface water measures implemented. A similar sized event in an urban area will be rehabilitated at enormous cost.

8.5 Evaluating Understanding of Geotechnical Assessment of Sinkholes

Opportunities to assess your understanding of geotechnical assessment of sinkholes are provided by [Exercise 39](#), [Exercise 40](#), [Exercise 41](#), [Exercise 42](#), [Exercise 43](#), [Exercise 44](#), [Exercise 45](#), and [Exercise 46](#).

9 Case studies from South Africa

9.1 Case Study Far West Rand, South Africa

Gold mining history on the Far West Rand in South Africa started in a geological setting where the gold bearing reefs of the Witwatersrand Supergroup underlie the dolomite and chert of the Chuniespoort Group. Water storage is in the dolomite residuum and caverns where the water table is above bedrock, and in caverns where the water table is in the bedrock (Brink et al., 1990). Water inflow from dolomite cavities into the mine workings necessitated dewatering of the karst aquifers.

The interface between the dolomite bedrock and overburden is highly irregular. The area is divided into groundwater compartments by several syenite dikes, and prior to dewatering, the overflow from one compartment to the next occurred at the lowest point of the particular dike where water flowed to springs. Most of the groundwater is stored in the overburden, leached fault zones, and fracture zones. Between the highly leached zones groundwater is stored in the residuum and relatively shallow dolomite bedrock. Due to the nature of leaching in the bedrock most of the water is stored in highly leached fracture zones in the first 100 m below the water level of the main dolomite aquifer. Storage capacity has been estimated by De Kock (1964) at 10% in the first 30 m, 2% in the next 30 m and less than 1% deeper in the bedrock (Kleywegt & Pike, 1982).

The collapse of a three-story crusher plant at the West Driefontein mine, 100 km west of Johannesburg where twenty-nine people lost their lives, was one of the early, very large, sinkholes that developed due to the dewatering. Lowering of the groundwater level by hundreds of meters caused numerous sinkholes and surface compaction subsidence (Brink et al., 1990).

Lowering of the water table resulted in the consolidation of the wad and gradual surface subsidence. Surface water flowing into cracks concentrated along grykes in the bedrock started headward erosion of the unconsolidated overburden materials resulting in cavities that may grow larger and eventually form sinkholes when the cavity roof collapses (Brink et al., 1990).

In some areas younger shale and sandstone sediments of Karoo Age cover the dolomite bedrock and large caprock sinkholes developed due to the undermining and collapse of the insoluble caprock (Waltham & Fookes, 2003). An example of a large cap rock sinkhole that developed due to collapse of the Karoo shale and sandstone covering into open cavities post dewatering is shown in Figure 62.



Figure 62 - Sinkhole in the Far West Rand (South Africa) (photograph by van Rooy).

No sinkholes were known in this area prior to mine dewatering. Approximately 700 sinkholes were recorded over a period of 20 years post dewatering due to surface water concentration at slimes dams, mine shafts, and urban developments. This also resulted in more than 25,000 ha of unsafe land that were evacuated and purchased by the mines and government (Brink et al., 1990).

The rewatering of compartments after mining ceased caused further sinkholes to develop due to reactivation (Beukes, 1987). The recharge rate increased due to the swallow holes and sinkholes that formed during dewatering and the dewatering affected the natural flow of groundwater. The large discharge of sediment-containing mine water clogged surface streams and aquifers causing a dramatic increase in flow rates of previously perennial streams, changing them into rivers or permanent swamps (Durand, 2012).

9.2 Case Study Centurion (ingress water in an urban setting), South Africa

The Centurion Central Business District (CBD) is in the southern part of the Tshwane (Pretoria) Metropolitan Municipality and is underlain by dolomite and dolomite interbedded with chert of the Chuniespoort Group of the Transvaal Supergroup. An estimated 2,500,000 people live on dolomite in the Centurion area where more than 800 sinkholes have occurred (Buttrick et al., 1995).

The dolomite in Centurion is a typical example of deeply weathered linear fractures (grykes) with highly variable bedrock topography in a pinnacled dolomite setting. The groundwater level is usually deep and below the bedrock surface with a relatively thick

vadose zone. As opposed to the subsidence experienced in groundwater lowering cases, for example, in the Far West Rand of South Africa, most surface instability events in the Centurion area are due to concentrated water ingress through the vadose zone. The composition, thickness, and properties of the vadose zone is therefore crucial when determining the risk of sinkhole or subsidence development.

In the dolomite groundwater compartment of the aquifer below the CBD, the groundwater level is 48 to 91 m below surface with a very low hydraulic gradient and a high transmissivity (Oosthuizen & van Rooy, 2015). Groundwater investigations for infrastructure developments also indicate that current groundwater extraction by the municipality does not have any influence on the aquifer and it can be regarded as not being dewatered. Nearly 120 sinkholes developed in the early 1970s and continued through 2012. These events led to the demolition of seven residential houses, financial loss to landowners, and the loss of three lives during an attempted sinkhole rehabilitation project.

The vadose zone comprises residual soils of which the in-situ strength is contrary to most natural profiles, usually decreasing with depth from the near-surface, competent chert gravels to the compressible wad directly above the bedrock (Wagener, 1985). The dolomites south of Pretoria are subdivided based on the presence of interlayered chert into four stratigraphic units making up the Malmani Subgroup (i.e., the Oaktree, Monte Christo, Lyttelton, and Eccles Formations) (Brink, 1979). As shown in Figure 63 the Oaktree and Lyttelton Formations are without prominent chert layers. It is thought that the presence of chert layers “protect” the residual dolomite soil to some extent from erosion and also forms a brecciated residuum if the chert bands fail due to reduction in strength where dolomite weathers between the chert bands. This forms a high permeability soil compared to residuum without chert. Conditions for the mobilization of overburden is therefore favorable in higher permeable soils with chert gravel compared to silty and clayey residual dolomite with no or very little chert.

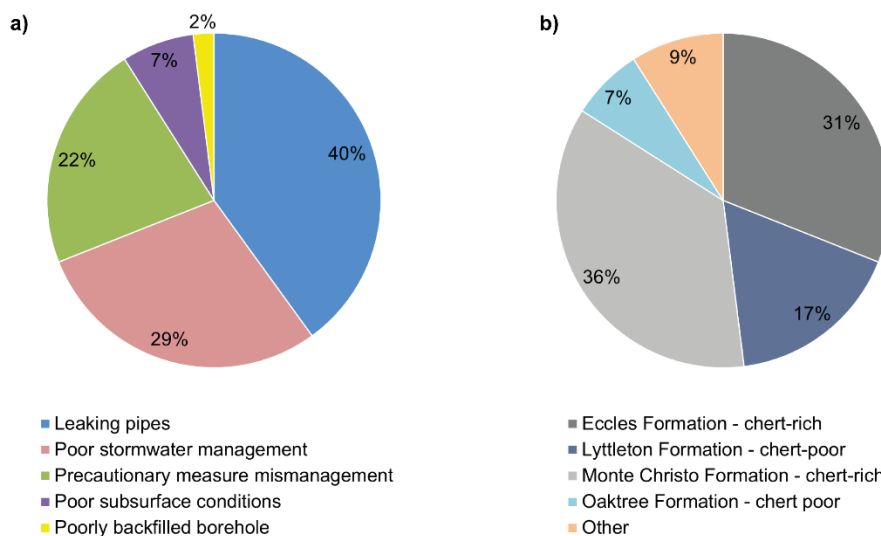


Figure 63 - Distribution and causes of sinkholes in the Centurion CBD a) due to human impacts and b) correlated with stratigraphic formations with differing chert content (Oosthuizen & Van Rooy, 2015).

Figure 63 shows the distribution of the different types of sinkholes and their causes. Most instability events are sinkholes with surface subsidences and cracks making up 36% of events. Although sinkhole causes are not reported in historic data, available data show more than 90% of the events occurred as a result of anthropogenic disturbance, e.g., leaking pipes or poor stormwater management (Oosthuizen & van Rooy, 2015). Water ingress resulting in the downward erosion of vadose zone material into connected solution cavities in the bedrock is the primary mechanism causing these surface features, so the formation of sinkholes is directly linked to the underlying karst where a deep groundwater level is present. The karst system is in equilibrium due to the land surface being uplifted and natural groundwater lowering during recent geological time.

9.3 Compaction Grouting of a Road Section Between Westonaria and Carletonville (South Africa)

Dolomites of the Chuniespoort Group, overlie the gold-bearing sedimentary rocks of the Witwatersrand Supergroup in the Far West Rand of South Africa. The broad valley occupied by the dolomites is divided into several groundwater compartments by impervious intrusive dikes and surface drainage is by the Wonderfontein Spruit. The deep mines in gold-bearing conglomerates occurring below the dolomites experienced hazardous and uncontrollable water inflows along geological discontinuities, threatening the viability of the mines. The karstic dolomites also serve as an important aquifer due to the extensive near-surface dissolution. Dewatering to limit groundwater inflows from the dolomites into the underground mine workings resulted in rapid artificial lowering of the groundwater table (Kleywegt & Pike, 1982). This resulted in accelerated development of surface subsidences (sinkholes). The catastrophic disappearance of the crusher plant at the West Driefontein Mine in 1962 (Figure 64), highlighted the necessity to delineate high risk areas where sinkholes could form due to the dewatering. After weighing the economic value of the remaining gold ore against the devastating surface effects of dewatering, the government and mines adopted a policy curtailing excessive pumping from underground mines (Gregory et al., 1988).

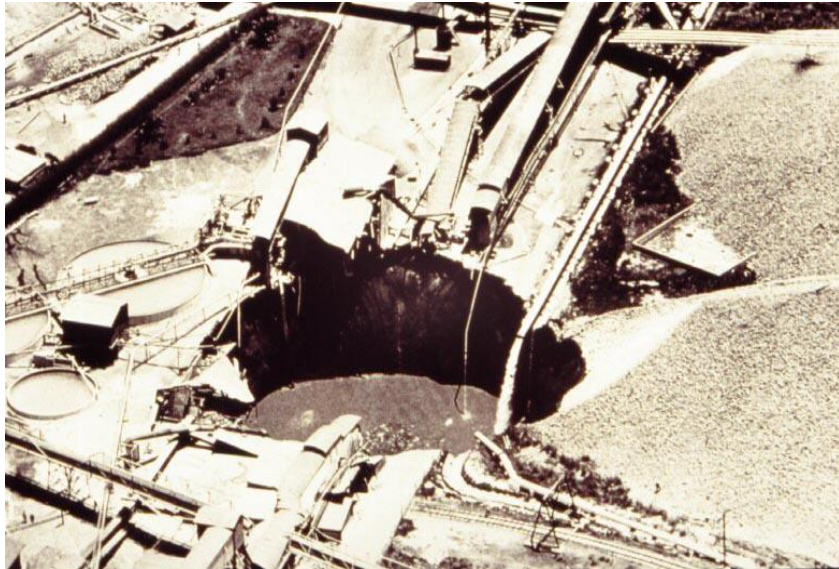


Figure 64 - Sinkhole engulfing crusher plant, West Driefontein mine (photograph by Rand Daily Mail from Brink, 1979).

A risk assessment was carried out for one of the major traffic routes traversing the dewatered Gembokfontein Compartment and the viability of grouting to reduce the subsidence risk was investigated during a field trial (Gregory et al., 1988). At the time the method of pressure grouting was considered due to success achieved in other parts of the world (Ortiz-Suarez et al., 1982; Ryan 1984). This method uses the principle of sealing off and filling cavities, where present, in the dolomite bedrock and overburden reducing the risk of sinkhole development (Figure 65).

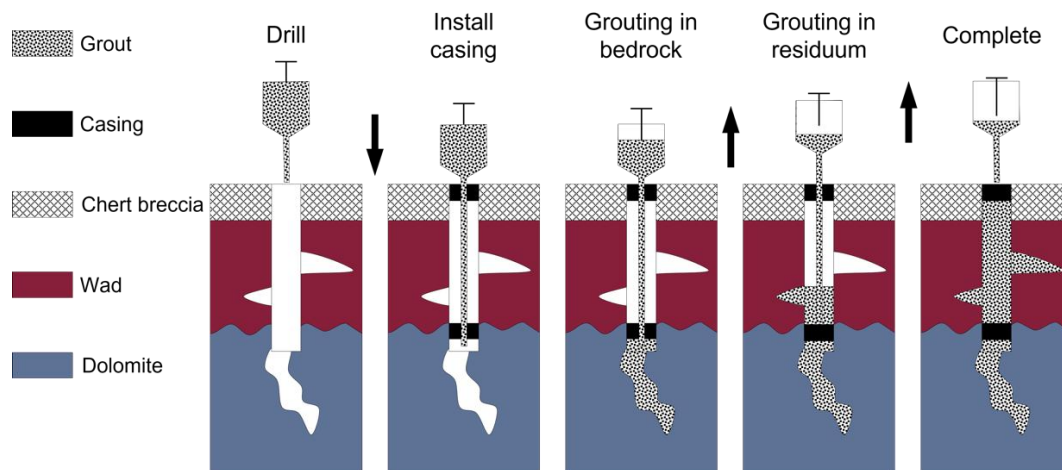


Figure 65 - Idealized soil profile showing grouting principle (Gregory et al., 1988).

The test section along the Randfontein to Vereeniging dual carriageway was selected based on the results from a gravity survey and exploratory drilling (Gregory et al., 1988). The profile indicated very soft residual dolomite (wad) occurring below the water table that was yet to be exposed to groundwater lowering. During grouting of the test section most of the grout was injected within the cavernous dolomite or on the dolomite/wad interface. Typical profiles and grout take are presented for two boreholes in

the test section indicating most of the grout either injected in cavernous dolomite (hole E2) or at the wad/dolomite (hole E1) interface (Figure 66).

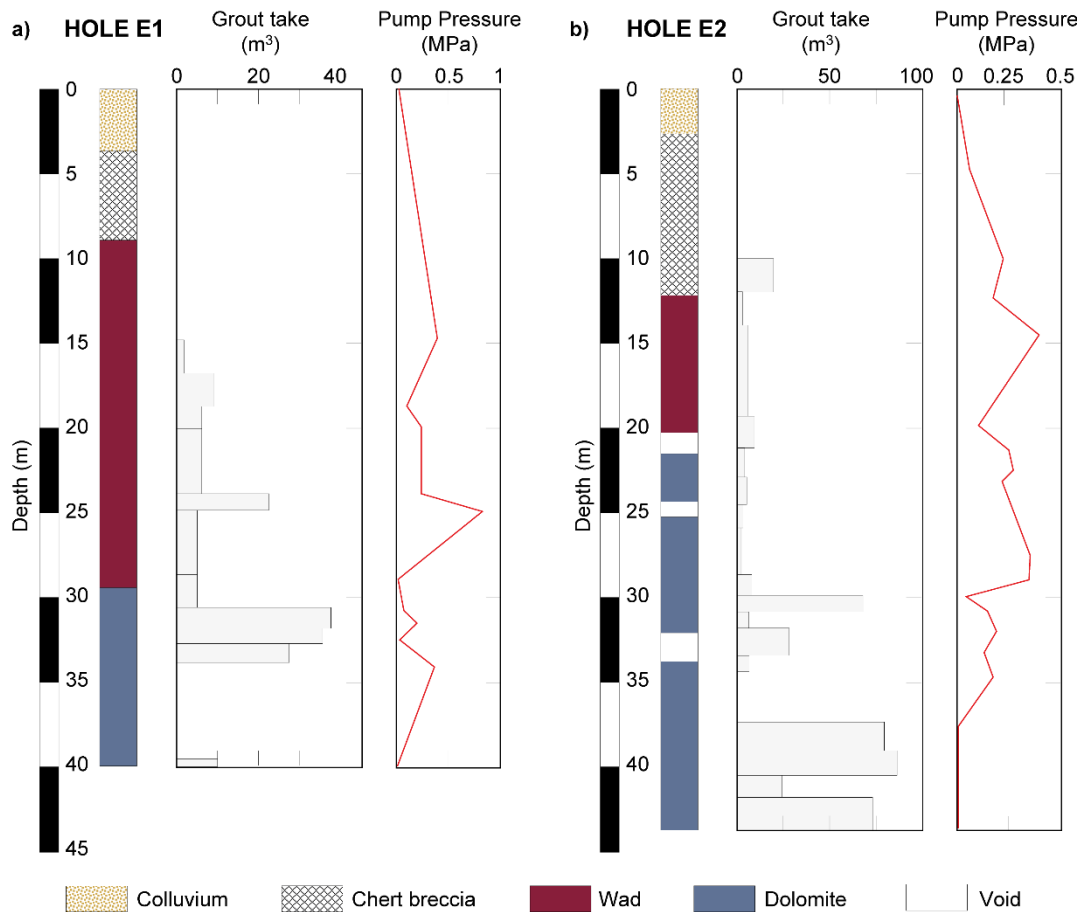


Figure 66 - Typical grout hole profiles: a) indicating higher grout takes in low density wad and contact zone between wad and dolomite in borehole E1; and b) with higher takes in in cavernous dolomite bedrock of borehole E2 (Gregory et al., 1988).

Surface settlements and cracks were recorded during the grouting process, and the process was then terminated to assess the reasons. The bedrock dips steeply to the east and it was postulated that the grout flowing on the rockhead was disturbing and eroding the residual dolomite horizon and that this may cause the surface settlements. Additional grout holes were drilled to block off or fill the cavity to which the grout was migrating along the rock surface. The grouting injection was also switched between surrounding holes and arrested the surface settlement between holes, which supported the assumption that grout successfully penetrated the trial area. Grout take data correlated with the borehole profiles indicated that the largest quantities of grout penetrated the zone near the dolomite/wad interface and the cavities in the upper bedrock zone.

The main grouting project used the experience gained during the trial. Grouting started in those boreholes where the deepest dolomite or cavities occurred with primary holes drilled at 20 m centers, and areas where additional secondary or tertiary grout holes

were necessary could be identified based on surface settlements (Gregory et al., 1988). Figure 67 shows the grouting activity.



Figure 67 - Grouting operation along the closed left lane of the dual carriageway (Photograph by van Rooy).

The final contract ran for six months with 44,000 m³ of grout placed along the 2.7 km of dual carriageway. As soon as surface settlements were observed grouting was ceased and grouting commenced in the center of each settlement zone. Mine dewatering in this grouted area caused a drop of 12 m in the groundwater level without any subsidences or sinkholes occurring in this high-risk zone.

10 Living with Karst

The overlapping of human habitation and geological processes may lead to negative impacts on humans and is referred to as geological hazards (geohazards). Karst landscapes were shaped over geological time, but recent anthropogenic impacts also influence these environments. The presence of springs caused humans to settle near and on karst areas. The potential hazards to human habitation on karst include surface subsidence, catastrophic sinkholes, and contamination of groundwater from fertilizers, pesticides, and other pollutants entering these highly vulnerable and sensitive aquifers from surface runoff. It is therefore necessary to identify and manage those critical factors that may cause a sinkhole to develop or cause pollution of these vulnerable aquifers. The factors vary depending on the specific karst terrain but include the depth to rock head, depth to groundwater, mechanical and hydraulic properties of the vadose zone—specifically of the blanketing layer—as well as number of and distance from historic sinkhole occurrences.

Therefore, geotechnical and hydrogeological site investigations are critical to assess the parameters that may influence surface stability and determine aquifer properties that influence vulnerability before any potential land-use change. The ultimate level of vulnerability of the land surface to instability and aquifer pollution will determine the acceptable types and safety of development. Site investigation, risk assessment, and risk mitigation are necessary to safely living with karst.

Development on karst terrains is inevitable, and it is not always possible to prevent densification of infrastructure and population increase as many of these areas are part of the central business districts or urban spread of large cities. Prohibiting development is also not an option, as, for instance, more than 5 million people live on dolomite in South Africa, and the only feasible way to sustain a safe living and working environment is through risk mitigation measures (Buttrick et al., 2011). The type of development and surface cover may change over time. Integrity of municipal water services deteriorate after a decade or two, and it is a universally accepted fact that periodic replacement of services is not economically viable.

The slow deterioration of the initial “safe” conditions under which a development took place is difficult to manage if the site was initially marginal. It is therefore essential to only allow development that is suitable to those karst conditions of a particular site and to add a factor of safety, emphasizing the importance of risk assessment and mitigation measures.

The number of sinkholes of a dolomite area in South Africa was reduced by 90% after implementation of risk management strategies. This area saw 50 events per year prior to implementation of a risk management strategy that reduced frequency to 5 events per year (Buttrick et al., 2011). The hazard rating for this area was intolerable but, with risk mitigation, is now considered tolerable. This risk management strategy included a holistic

approach to sensitize the community resulting in use of scientific, planning, and engineering procedures to manage the risk.

The best-practice approach to safely living with karst depends on selection of the appropriate site and type of development, preventative, and mitigation measures. An approach used by the US Army Corps of Engineers (modified in Nawaz et al., 2020) comprises four phases.

1. Hazard analysis
2. Probabilistic risk analysis
3. Failure potential
4. Consequence evaluation.

Although there are advances in scientific understanding of complex karst systems Gutiérrez et al. (2014) predict increased environmental problems due to more people being exposed to hazards on karst, greater pressure on karst aquifer systems, and political decisions taken without due cognizance of the complexity of karst. Prediction, investigation, and hazard modeling of sinkhole subsidence needs to be improved.

Living with karst is comparable to living with any other geohazard. Tolerable risk can be achieved if risk mitigation measures and monitoring are continuously implemented at the community level. Advances in site risk assessment as well as remedial and mitigation engineering measures add to safe development on karst. Above all, changes in public perception are necessary. For example, the perception that visible surface water sources, like rivers and reservoirs, are preferable, when in fact 96% of fresh water is groundwater, its quality is generally better than surface water, and it is free from evapotranspiration unlike surface water.

It is extremely difficult to convey the intricate and highly variable karst models to the general public due to solution cavities, caves, variable rockhead and other karst features not always being visible in most instances. Safe development on karst is however possible with appropriate input and continued risk management by the dedicated geo-professionals working on karst and with the involvement of communities living on karst.

11 Exercises

11.1 Exercises from Section 2

Exercise 1

Name and give the chemical formula of four minerals that form from precipitation.

[Solution to Exercise 1](#) ↴

[Return to where text linked to Exercise 1](#) ↲

Exercise 2

Compare evaporites and carbonates in terms of their dissolution and precipitation.

[Solution to Exercise 2](#) ↴

[Return to where text linked to Exercise 2](#) ↲

Exercise 3

Show or describe the dissociation and precipitation of calcite in carbonic acid.

[Solution to Exercise 3](#) ↴

[Return to where text linked to Exercise 3](#) ↲

Exercise 4

Write down the equation for the dissolution of dolomite.

[Solution to Exercise 4](#) ↴

[Return to where text linked to Exercise 4](#) ↲

Exercise 5

List and distinguish between six types of carbonate rocks according to Dunham's classification.

[Solution to Exercise 5](#) ↴

[Return to where text linked to Exercise 5](#) ↲

11.2 Exercises from Section 3

Exercise 6

Provide a universal definition for karst.

[Solution to Exercise 6](#) ↴

[Return to where text linked to Exercise 6](#) ↲

Exercise 7

What is pseudokarst?

[Solution to Exercise 7](#) ↓

[Return to where text linked to Exercise 7](#) ↑

Exercise 8

Karst systems comprise certain surface, rockhead, and underground features that form different landscapes. Name the five types that it can be classified in.

[Solution to Exercise 8](#) ↓

[Return to where text linked to Exercise 8](#) ↑

Exercise 9

Name five (5) factors that affect karstification.

[Solution to Exercise 9](#) ↓

[Return to where text linked to Exercise 9](#) ↑

Exercise 10

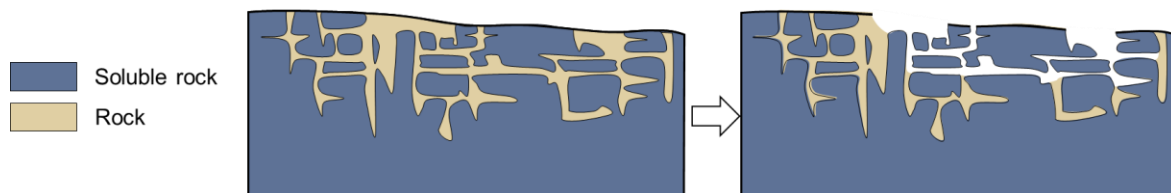
Distinguish between karstification and ghost-rock karstification.

[Solution to Exercise 10](#) ↓

[Return to where text linked to Exercise 10](#) ↑

Exercise 11

Briefly explain the process shown on the figure.



[Solution to Exercise 11](#) ↓

[Return to where text linked to Exercise 11](#) ↑

Exercise 12

Name and distinguish between two types of caves.

[Solution to Exercise 12](#) ↓

[Return to where text linked to Exercise 12](#) ↑

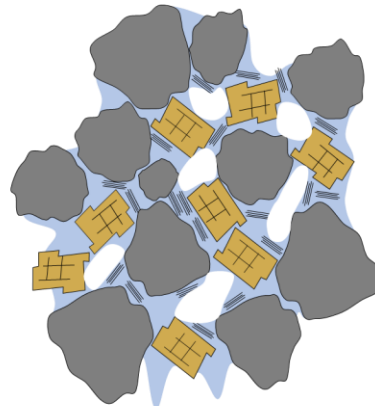
11.3 Exercises from Section 4

Exercise 13

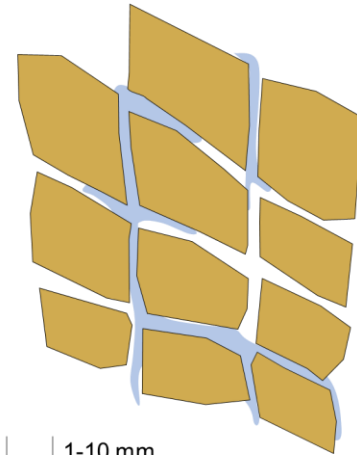
Name the type of porosity and describe the formation or disposition of the porosity and how water is stored in it.



□ >10 m



□ 0.1-1 mm



□ 1-10 mm

[Solution to Exercise 13](#) ↓

[Return to where text linked to Exercise 13](#) ↑

Exercise 14

The conduit network or cave pattern depends on two drivers. Name the two drivers and state what they depend on.

[Solution to Exercise 14](#) ↓

[Return to where text linked to Exercise 14](#) ↑

Exercise 15

Name and describe the four types of groundwater recharge in karst.

[Solution to Exercise 15](#) ↓

[Return to where text linked to Exercise 15](#) ↑

Exercise 16

What is the difference between epikarst and pinnacled karst?

[Solution to Exercise 16](#) ↓

[Return to where text linked to Exercise 16](#) ↑

Exercise 17

What minerals and soils can exist as residual material in the dissolution of dolomite.

[Solution to Exercise 17](#) ↓

[Return to where text linked to Exercise 17](#) ↑

Exercise 18

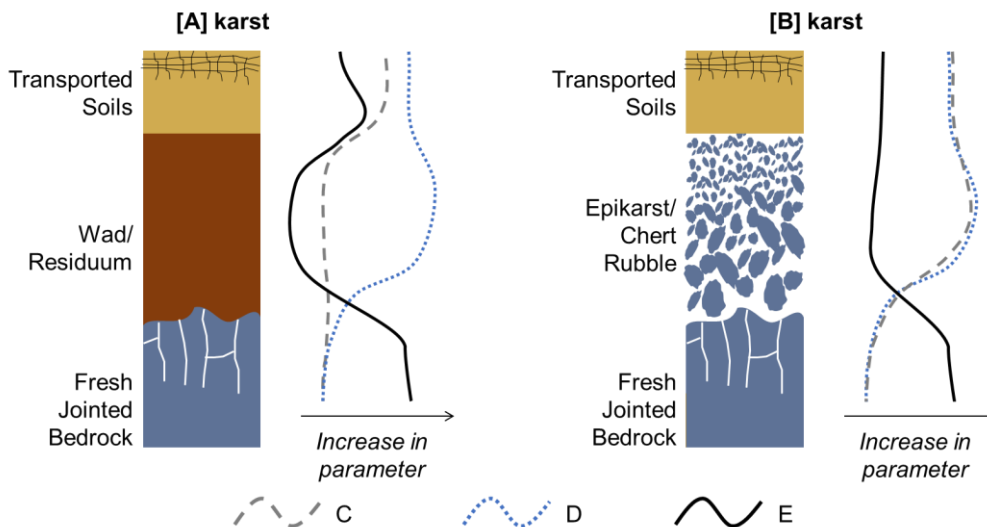
What do you call the metamorphosed rock when carbonate rock is intruded by an igneous body?

[Solution to Exercise 18](#) ↓

[Return to where text linked to Exercise 18](#) ↑

Exercise 19

Label karst types and parameter curves [A] to [E]



[Solution to Exercise 19](#) ↓

[Return to where text linked to Exercise 19](#) ↑

11.4 Exercises from Section 5

Exercise 20

What are the influences of climatic extremes such as droughts and floods on the possible land subsidence on carbonate rocks with large voids or bedding plane conduits that is a specific hazard for land use development?

[Solution to Exercise 20](#) ↓

[Return to where text linked to Exercise 20](#) ↑

Exercise 21

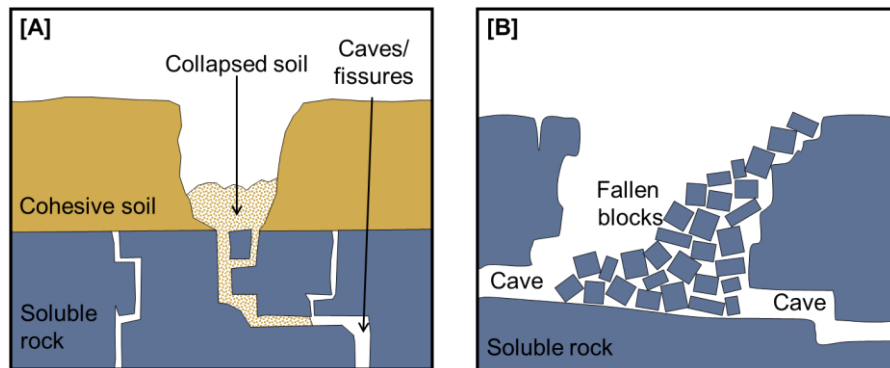
Name the three types of sinkholes forming in rock and give an indication of the size of each.

[Solution to Exercise 21](#) ↓

[Return to where text linked to Exercise 21](#) ↑

Exercise 22

Name the types of sinkholes label [A] and [B] in the images below and explain how they form.



[Solution to Exercise 22](#) ↓

[Return to where text linked to Exercise 22](#) ↑

Exercise 23

What are the two water-related scenarios that can form sinkholes, and how do the failures occur?

[Solution to Exercise 23](#) ↓

[Return to where text linked to Exercise 23](#) ↑

Exercise 24

List the nine potential triggers of sinkhole development and give an effect for each.

[Solution to Exercise 24](#) ↓

[Return to where text linked to Exercise 24](#) ↑

Exercise 25

Name the three types of flooding sinkholes due to precipitation.

[Solution to Exercise 25](#) ↓

[Return to where text linked to Exercise 25](#) ↑

Exercise 26

What does the Kentucky Geological Survey regard as two general causes of sinkhole flooding?

[Solution to Exercise 26](#) ↓

[Return to where text linked to Exercise 26](#) ↑

11.5 Exercises for Section 6

Exercise 27

What information needs to be provided in a geotechnical site investigation to characterize subsurface features associated with karstification?

[Solution to Exercise 27](#) ↓

[Return to where text linked to Exercise 27](#) ↑

Exercise 28

Distinguish between local scale and regional scale investigations in karst terrain.

[Solution to Exercise 28](#) ↓

[Return to where text linked to Exercise 28](#) ↑

11.6 Exercises from Section 7

Exercise 29

List the six hydrological parameters required for groundwater assessment.

[Solution to Exercise 29](#) ↓

[Return to where text linked to Exercise 29](#) ↑

Exercise 30

What vadose zone tests can give you approximate vertical hydraulic conductivity of the vadose zone, and what tests can give you an estimate of horizontal hydraulic conductivity at the water table?

[Solution to Exercise 30](#) ↓

[Return to where text linked to Exercise 30](#) ↑

Exercise 31

List the parameters required to establish knowledge of the regional and local aquifer hydrogeological properties.

[Solution to Exercise 31](#) ↓

[Return to where text linked to Exercise 31](#) ↑

Exercise 32

Define Danger/Threat, Hazard, Risk, and Vulnerability.

[Solution to Exercise 32](#) ↓

[Return to where text linked to Exercise 32](#) ↑

Exercise 33

Provide the equation for risk and define what the parameters represent.

[Solution to Exercise 33](#) ↓

[Return to where text linked to Exercise 33](#) ↑

Exercise 34

What do you understand under Source–Pathway–Receptor analyses?

[Solution to Exercise 34](#) ↓

[Return to where text linked to Exercise 34](#) ↑

Exercise 35

Distinguish between the different types of tracers.

[Solution to Exercise 35](#) ↓

[Return to where text linked to Exercise 35](#) ↑

Exercise 36

Provide the three factors that vulnerability depends on.

[Solution to Exercise 36](#) ↓

[Return to where text linked to Exercise 36](#) ↑

Exercise 37

Write the equation and define the parameters for the DRASTIC model.

[Solution to Exercise 37](#) ↓

[Return to where text linked to Exercise 37](#) ↑

Exercise 38

Provide the key issues that have to be incorporated into a conceptual model.

[Solution to Exercise 38](#) ↓

[Return to where text linked to Exercise 38](#) ↑

11.7 Exercises from Section 9

Exercise 39

Explain what is regarded as the hazard and what is risk on karst terrain.

[Solution to Exercise 39](#) ↓

[Return to where text linked to Exercise 39](#) ↑

Exercise 40

List at least 5 risk factors that are regarded by Nawaz (2020) as contributing to sinkhole development.

[Solution to Exercise 40](#) ↓

[Return to where text linked to Exercise 40](#) ↑

Exercise 41

Explain why sinkholes may develop in one area and not in another using the parameters listed by Buttrick and others (2001).

[Solution to Exercise 41](#) ↓

[Return to where text linked to Exercise 41](#) ↑

Exercise 42

Why do you think the actual sinkhole size and so-called maximum potential sinkhole size may not always be the same?

[Solution to Exercise 42](#) ↓

[Return to where text linked to Exercise 42](#) ↑

Exercise 43

Sinkholes develop if several different factors are present. Explain which factors are used in sinkhole risk assessment.

[Solution to Exercise 43](#) ↓

[Return to where text linked to Exercise 43](#) ↑

Exercise 44

Risk management on karst terrain includes land zoning and engineering measures. List the most important principles for both land-use planning and engineering measures.

[Solution to Exercise 44](#) ↓

[Return to where text linked to Exercise 44](#) ↑

Exercise 45

Discuss three general methods used to rehabilitate sinkholes.

[Solution to Exercise 45](#) ↓

[Return to where text linked to Exercise 45](#) ↑

Exercise 46

The complexity of rehabilitation is summarized in Table 13. Study this table and specifically notice the methodologies used in areas with different sinkhole depths.

[Solution to Exercise 46](#) ↓

[Return to where text linked to Exercise 46](#) ↑

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13 Exercise Solutions

Exercise Solution 1

The following minerals form from precipitation:

- Halite: NaCl
- Gypsum $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
- Calcite CaCO_3
- Dolomite $\text{CaMg}(\text{CO}_3)_2$

[Return to Exercise 1](#) ↑

[Return to where text linked to Exercise 1](#) ↑

Exercise Solution 2

Evaporites are more prone to continuous dissolution than carbonates because carbonates take longer to dissolve. Salt precipitates from water to form evaporites and the type of salt that precipitates depends on the amount of evaporation of trapped seawater in the basin:

- 80% forms gypsum
- 90% forms halite
- 100% forms 80% halite
- 13% gypsum, and some minor salts and carbonates

Carbonates form through biochemical processes, and they are composed of physical remains that include shells of organisms, or through chemical processes where they form due to precipitation from aqueous solutions. Carbonates are minerals with a carbonate anionic group (CO_3^{2-}) such as:

- Calcite CaCO_3
- Dolomite $\text{CaMg}(\text{CO}_3)_2$

[Return to Exercise 2](#) ↑

[Return to where text linked to Exercise 2](#) ↑

Exercise Solution 3

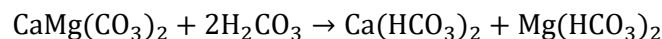
These are the five different types of limestone according to Dunham's classification:

1. Mudstone contains less than 10% grains and generally indicates that it was formed in calm water with apparent inhibition of grain-producing organism that is associated with a low-energy deposition setting.
2. Wackestone contains more than 10% grains and is subdivided into mud-dominated with pore spaces of mud.
3. Packstone is a grain-supported carbonate rock that is divided into mud-dominated with pore spaces filled with mud representing low-energy processes, and grain-dominated with some inter-grain pore spaces free of mud representing high-energy processes.
4. Grainstone is a grain-supported mud-free carbonate rock deposited in moderate-energy to high-energy, grain-producing environments with variable hydraulic significance.
5. Boundstone shows signs of binding during deposition and there is a three-fold classification based on the fabric.
6. Crystalline carbonates lack evidence of depositional texture for classification, and dolomitization obliterates the original limestone texture.

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Exercise Solution 4



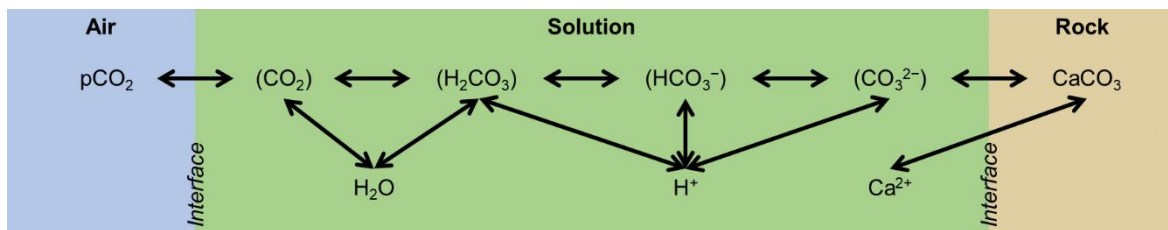
[Return to Exercise 4](#) ↑

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Exercise Solution 5

Given the partial pressure of carbon dioxide ($p\text{CO}_2$), CO_2 dissolves in rainwater to form carbonic acid (H_2CO_3). Carbonic acid dissolves to form bicarbonate (HCO_3^-) and, as pH increases, eventually carbonate (CO_3^{2-}). When hydrogen (H^+) and calcium (Ca^{2+}) ions are dissolved in water (H_2O), they precipitate to form calcite (CaCO_3). The opposite happens with dissolution where solid calcite dissolves to form carbonate in the aqueous phase, then bicarbonate in the aqueous phase, and eventually gas carbon dioxide.

This is shown visually as:



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Exercise Solution 6

The term karst is used to refer to the landscape (karst terrain), geologic or hydrogeologic setting (karst terrane), or groundwater system (karst aquifer) in areas underlain by soluble bedrocks.

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Exercise Solution 7

Pseudokarst is karst topography that does not apply to soluble rocks. Pseudokarst is found in rocks like quartzites, granite, and basalt despite their low solubility. This can look like epikarst and sinkholes.

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Exercise Solution 8

Karst can be subdivided into the following five classes (in the correct sequence become increasingly more karstified):

1. Juvenile Karst kI
2. Youthful Karst kII
3. Juvenile Karst kIII
4. Mature Karst kIV
5. Complex Karst kIV

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Exercise Solution 9

The five factors that affect karstification are the pH of precipitation, pCO₂, hydraulic gradient, climate, and properties of the karst including the extent and degree of its fracturing.

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Exercise Solution 10

Karstification is total removal and requires considerable chemical energy for the dissolution of carbonates and considerable hydrodynamic energy for the removal of undissolved particles. Ghost-rock karstification requires considerable chemical energy for the dissolution of the carbonates but only limited hydrodynamic energy to remove the dissolved species without removing all the undissolved particles thus leaving some behind in the cavities.

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Exercise Solution 11

The diagram shows ghost-rock karstification resulting from significant dissolution but low hydrodynamic erosion. It requires considerable chemical energy for the dissolution of the carbonates but only limited hydrodynamic energy to remove the dissolved species without removing most of the undissolved particles.

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Exercise Solution 12

There are two types of caves, fluvial caves, and corrosion or solution caves.

- Fluvial caves are predominantly formed by erosion of turbulent streams, and thereby form features such as potholes, subsurface canyons, and natural bridges.
- Corrosion caves or solution caves are the most widespread and are formed by chemical erosion. They have smaller diameters and lengths.

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Exercise Solution 13

Left: Karstic or tertiary porosity formed by dissolution that creates solution cavities with high water storage capacity and is self-confined. Water moves mostly under gravity through cohesion.

Middle: Interstitial or primary porosity that has openings between grains in soil or rock with voids connected by narrow throats. Initially adhesion occurs then as the water content increases becomes cohesion and water drains driven by gravity.

Right: Fractured or secondary porosity with apertures that are kept open due to roughness and infill. This setting is more prone to cohesion and drainage occurs more readily.

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Exercise Solution 14

Local scale drivers relate to the type of porosity and the type of recharge. Regional or system scale drivers depend on the hydraulic gradient, and the relationship between the direction of the hydraulic gradient and the drainage planes or fracture orientation.

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Exercise Solution 15

Allogenic recharge refers to surface water that flows in a stream on a non-karst area onto a karst landscape where infiltration occurs into the karst.

Autogenic recharge is precipitation that falls on a karst landscape and infiltrates directly into the karst.

Concentrated recharge occurs where surface water runoff flows directly into large openings into the karst bedrock. This is typically related to high intensity rainfall events or large storms.

Diffuse recharge occurs as infiltration directly into small openings in the karst bedrock at low volumetric rates.

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Exercise Solution 16

In epikarst the weathered soluble rock forms a very well-drained, coarse-grained horizon that behaves differently than typical residual horizons. A gravelly horizon develops above fresher bedrock that forms a high-storage, gravelly layer from which diffuse flow is slowly released causing deeper percolation into the bedrock.

Pinnacled dolomite develops in response to climate and geological history. Rockheads form in humid tropical climates with ample time and the appropriate environment to mature fully. At advanced stages, solid rock pinnacles form. Deeply weathered grykes form between the pinnacles and are filled with residual material such as wad and chert rubble that forms from collapse of the silica that remains after dissolution of soluble rock, transported soils, or younger rocks.

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Exercise Solution 17

Chert forms chert rubble, and manganese enrichment forms minerals such as birnessite and residual dolomite like wad.

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Exercise Solution 18

Skarn.

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Exercise Solution 19

[A] Pinnacled; [B] Epikarstic; [C] Hydraulic Conductivity; [D] Porosity; [E] Density.

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Exercise Solution 20

Drought and groundwater development lower the groundwater levels and increase the effective stress on the supporting rock and drain the water-filled cavities that can result in sinkholes. This is exacerbated by precipitation and floods following a drought period that increases karst sinkhole formation through vertical erosion of overburden materials.

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Exercise Solution 21

Solution sinkhole: < 1000 m across and 100 m deep.

Collapse sinkhole: < 300 m across and 100 m deep.

Caprock sinkhole: < 300 m across and 100 m deep.

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Exercise Solution 22

[A] Dropout sinkhole – soil collapse into void formed over bedrock fissure.

[B] Collapse sinkhole – rock roof failure into underlying cave.

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Exercise Solution 23

Dewatering removes basically incompressible water to replace it with air. Ingress can follow dewatering where the water ingress causes the soil or fractured rock to lose its shear strength and fail.

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Exercise Solution 24

- Increased water into ground: Increases percolation accelerating suffusion. Favors dissolution. Increases the weight of sediments. May reduce the mechanical strength and bearing capacity of sediments.
- Water table decline: Increases the effective weight of the sediments. Slow phreatic flow is replaced by more rapid downward percolation favoring suffusion. Accelerates groundwater flow in areas affected by cones of depression. May reduce mechanical strength by desiccation and crystallization of salts. Hydrofracturing of poorly drained deposits surrounding cavities. Suction effect. Loose fine-grained deposits may be dragged with the pumped water causing internal erosion.
- Impoundment of water: May create extremely high hydraulic gradients leading to rapid turbulent flows favoring internal erosion and dissolution. The base level rise may change groundwater flow paths and location of discharge zones. Major and continuous changes in the water table causing repeated flooding and drainage of karst conduits. Imposes a load.
- Surficial erosion or shallow excavation: Reduces the thickness and mechanical strength of cavity roofs. May concentrate runoff. May create a new base level changing the path and rate of groundwater flows.
- Underground excavation: Disturbs groundwater flow. May intercept phreatic conduits and distort groundwater flow paths. May cause sudden inrushes of water and flooding in underground openings involving accelerated internal erosion and karstification. May weaken sediments overlying voids.
- Static load: favors the failure of cavity roofs and compaction process.
- Dynamic load: favors the failure of cavity roofs and may cause liquefaction-fluidization processes involving a sharp reduction in the strength of soils.
- Vegetation removal: Reduces mechanical strength of cover deposits (root cohesion). Increases infiltration.
- Thawing of frozen ground: Favors dissolution. Significant reduction in the strength of the sediments.

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Exercise Solution 25

- 1) Rate of stormwater flow exceeds capacity of sinkhole.
- 2) Underground karst system is unable to drain the total stormwater flow.
- 3) Groundwater level rises rapidly due to diffuse infiltration.

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Exercise Solution 26

According to the Kentucky Geological Survey sinkhole flooding can be caused when the inflow rate to the sinkhole due to rain or snowmelt exceed that water flow rate through the swallow hole, dissolution cavities, and fractures. The second cause is where the flow of water is reversed because other parts of the basin are flooded causing water to back up into the sinkhole.

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[Return to where text linked to Exercise 26](#) ↑

Exercise Solution 27

The information required to characterize a karst site includes identification of karst types, quantification of hazards, definition of appropriate geotechnical zones related to the development type, design methodology for infrastructure like foundations, and appropriate precautionary measures and risk assessment.

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Exercise Solution 28

Local scale investigations work with individual boreholes that include single well tests, and measuring or sampling the borehole. Regional scale investigations cover multiple groundwater basins and methods include mapping water levels, tracer tests, water quality or geochemical sampling, geological structure mapping, and geophysical methods. Remote sensing can also be employed.

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Exercise Solution 29

Permeability, transmissivity, hydraulic conductivity, storage, sustainable yield, and safe yield.

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Exercise Solution 30

Percolation tests and infiltration tests are conducted in the vadose for vertical hydraulic conductivity. Aquifer pumping tests or slug and bail-down tests are conducted below the water table for horizontal hydraulic conductivity.

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Exercise Solution 31

The parameters include aquifer geometry, groundwater table, thickness of phreatic zone, permeability, storage, and availability of water.

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Exercise Solution 32

- Danger/Threat: A natural phenomenon that could lead to damage, described by geometry, mechanical and other characteristics.
- Hazard: Probability that a particular danger (threat) occurs within a given period.
- Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment.
- Vulnerability: Degree of loss to a given element or set of elements within the area affected by a hazard; scale 0 (no loss) to 1 (total loss).

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Exercise Solution 33

$R = H V E$ where R = risk associated with specific danger; H = hazard; V = vulnerability of those elements at risk (i.e., the fraction of threatened elements that would be lost if the hazard occurred); E = expected cost of total loss of elements at risk.

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Exercise Solution 34

The source is the contaminant that is released diffusely over an area or at a point, as either a once-time or a continuous release, and is described in terms of persistence, bioaccumulation, and toxicity. The pathway is the movement of the contaminant vertically down through vadose zone or laterally in the saturated zone. The pathway can also include inhalation of gaseous contaminants, ingestion or dermal contact of water by the receptors that include people and animals in the environment, water boreholes and water users, as well as environmental discharge points such as springs and wetlands.

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[Exercise 34](#) ↗

Exercise Solution 35

The three types of tracers occur and behave differently. Fluorescent dyes provide easily detectable and visual markers making it possible to track water movement through the vadose zone into the phreatic zone (aquifer). Natural tracers such as isotopes or naturally occurring chemicals have the advantage of mimicking the behavior of the water molecules, to aid in discerning flow paths and rates of travel in complex karst systems. Synthetic microsphere traces are designed to mimic specific pathogens and can be used when concerns over transport of pathogens to water supply wells are of interest.

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Exercise Solution 36

Vulnerability depends on contaminant attenuation capacity in the vadose zone; travel time of infiltrating water and contaminants to the saturated zone; and relative quantities of contaminants reaching the groundwater.

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Exercise Solution 37

D – depth to water; R = (net) recharge; A = aquifer media; S – soil media; T – topography; I – impact of vadose zone; C – hydraulic conductivity. With the letter followed by an R as the symbol for the rating and the letter with a subscript w for the weighting.

$$DI = DRD_w + RRR_w + ARA_w + SRS_w + TRT_w + IRI_w + CRC_w$$

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Exercise Solution 38

The key issues to be incorporated into a conceptual model include geometry of the hydrostratigraphic units and the model domain, boundary conditions (e.g., groundwater recharge, definition of sources and sinks), and hydrostratigraphic unit property values.

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Exercise Solution 39

The hazard is regarded as surface subsidence and can be regarded as the source of potential harm. Risk on the other hand is described with respect to the consequences, e.g., size of sinkhole and the probability that an event of a specific size will occur. There is usually also a period or time within which a sinkhole is expected to occur with a specific size specified.

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Exercise Solution 40

Risk factors that contribute to sinkhole development include depth to bedrock; groundwater depth; potential for desiccation of overburden soil; potential for near-surface bedrock; fracturing and quality of rock in the upper 5 m of bedrock; presence and size of known voids in the soil; presence, size and locality of voids in the rock; history of sinkholes and subsidence; soft zones in underlying soil.

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Exercise Solution 41

For a sinkhole to develop, a combination of the listed factors are necessary—e.g., a sinkhole will not form if there are no cavities (receptacles) present into which the overburden material can collapse or be eroded into or if there are no triggering mechanisms such as a water-bearing pipe.

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Exercise Solution 42

The material that needs to be mobilized to create the space for the sinkhole may not fit into the available void in the bedrock; the trigger mechanism may cease to exist (no more water ingress to erode overburden downward when, for instance, a leaking pipe is repaired); the throat from the sinkhole to the cavity may become clogged.

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Exercise Solution 43

Depth to bedrock, overburden erodibility and shrinkage on desiccation, presence of a capstone layer, degree of bedrock fracturing and presence of cavities, depth to groundwater, distribution of historic sinkholes, and various anthropogenic influences.

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Exercise Solution 44

For effective risk management, the following apply.

- Restrict land-use to appropriate development related to hazard class.
- Management of surface drainage, reduction of infiltration, and sealing surfaces.
- Control of groundwater lowering (i.e., limiting dewatering).
- Prevention or control of water use such as irrigation and drain fields for septic disposal.
- Requirements for subsurface water-bearing infrastructure and drainage.
- Design requirements that allow safe evacuation of occupants in the event of sinkhole formation.
- Rehabilitation and grouting of sinkholes.

Engineering measures that may prevent sinkhole development include the following (Parise et al., 2015).

- Induce collapse of shallow cavities.
- Improve mechanical properties of overburden/blanketing layer.
- Seal openings in rockhead.
- Fill cavities via grouting.
- Rigid foundations to span potential sinkholes.
- Piles to bedrock below cavernous zone.

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Exercise Solution 45

Inverted Filter; Dynamic Compaction; combination of Inverted Filter and Dynamic Compaction method; combination of Inverted Filter and Compaction Grouting; combination of Dynamic Compaction and Compaction Grouting; self-compacting concrete or soil-cement mix; chemical grouting. The specific method or combination of methods depends on the specific conditions as in the solution to Exercise 46.

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Exercise Solution 46

Self-study of Table 13.

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14 Glossary

<i>Cave</i>	subsurface karst where sub-horizontal and sub-vertical conduits along faults, fractures, and bedding planes intersect fluvial caves form due to erosion by turbulent streams corrosion or solution caves form by chemical erosion
<i>Dolomite</i>	rock formed primarily from the mineral dolomite ($MgCO_3$)
<i>Epikarst</i>	well-drained, high-storage, coarse-grained horizon overlying fractured karst that overlies fresh rock containing fractures and cavities
<i>Evaporite</i>	rocks formed from minerals that precipitate from solution, most common are evaporites such as halite and gypsum, or carbonates such as calcite
<i>Gryke</i>	crevice or crack in rock widened by natural forces (weathering or solution)
<i>Hazard</i>	source of potential harm
<i>Karst</i>	may refer to the landscape (karst terrain), geologic or hydrogeologic setting (karst terrane), or groundwater system (karst aquifer) in areas underlain by soluble bedrocks, characterized by distinctive features such as sinkholes, caves, and springs often lacking in perennial stream networks, ponds, wetlands, or lakes
<i>Limestone</i>	rock formed primarily from the mineral calcite ($CaCO_3$)
<i>Rockhead</i>	surface of bedrock beneath soil cover; the upper boundary of bedrock
<i>Sinkhole</i>	feature that occurs suddenly and manifests itself as a hole in the ground
<i>Subsidence</i>	gradual sinking of an area of land or sudden caving in of land forming a sinkhole
<i>Vulnerability</i>	likelihood that contaminants can reach the groundwater table
<i>Wad</i>	dark, fine-grained, insoluble material formed from weathering of manganese-rich dolomite

15 About the Authors



Louis van Rooy retired as associate professor in Engineering Geology and Rock Mechanics at the University Pretoria which he joined in 1985. He started his career in the “dolomite section” of the then Geological Survey of South Africa. His research covers hazards in karst, engineering properties of basic igneous rock in civil engineering infrastructure, and prediction of flow mechanisms through rock masses based on engineering rock mass characterization. The photo was taken at the Bangweulu wetlands (Zambia).



Matthys Dippenaar is an associate professor in Engineering Geology and Hydrogeology at the University Pretoria. He joined the university in 2007 following six years working in industry. His research focus is the intermediate vadose zone where air and water fill the void space of intergranular, fractured, and karst systems. His projects incorporate societal and environmental matters as well as establishment of regional groundwater monitoring, and impacts of anthropogenic changes. He enjoys compiling figures and graphics for his research output and teaching. The photo was taken at Wondergat (South Africa).

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Modifications to Original Release

Changes from the Original Version to Version 2

Original Version: March 24, 2026, Version 2: April 6, 2026

General: updated the Table of Contents to include this modification section

Page numbers refer to the original PDF.

page ii, added Version 2

page 12, Figure 10 modified so that a) and b) are in the GW-Project format

page 28, Figure 22 modified so that a) and b) are in the GW-Project format

page 32, Figure 25 modified so that a) and b) are in the GW-Project format and the third box in part (a) was adjusted to include the word intrusion inside the box

page 60, Figure 42 modified so that a) and b) are in the GW-Project format

page 68, Figure 49 modified so that a) and b) are in the GW-Project format

page 80, Figure 54 modified so that a) and b) are in the GW-Project format

page 84, Figure 57 modified so that a) and b) are in the GW-Project format

Changes from the Version 2 to Version 3

Version 2: April 6, 2026, Version 3: April 7, 2026

General: Revised cover to include first initial of first author

Page numbers refer to the version 2 PDF.

page ii, revised to Version 3