Karst: Environment and Management of Aquifers

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THE GROUNDWATER PROJECT

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Cover Image: Lison Spring, France; photograph by Zoran Stevanović, 2011.

Dedication

The authors of this book come from different educational systems and scientific schools and have different research backgrounds and specializations. However, they have a few things in common. Primarily, it is their love for karst and exploration of its wonders and beauties. Second, they have been members of the Karst Commission of the International Association of Hydrogeologists (IAH) for many years.

We thus dedicate this book to all those who inspired us and from whom we have learned about karst as in science "we all climb using each other's shoulders," and to the founders, and to all the past and present members of the Karst Commission including those who are no longer with us.

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The Groundwater Project Foreword

The United Nations (UN)-Water Summit on Groundwater, held from 7 to 8 December 2022 at the UNESCO headquarters in Paris, France, concluded with a call for governments and other stakeholders to scale up their efforts to better manage groundwater. The intent of the call to action was to inform relevant discussions at the UN 2023 Water Conference held from 22 to 24 March 2023, at the UN headquarters in New York City. One of the required actions is *strengthening human and institutional capacity*, for which groundwater education is fundamental.

The 2024 World Water Day theme is *Water for Peace*, which focuses on the critical role water plays in the stability and prosperity of the world. The UN-Water website↗ states that *more than three billion people worldwide depend on water that crosses national borders*. There are 592 transboundary aquifers, yet most do not have an intergovernmental cooperation agreement in place for sharing and managing the aquifer. Moreover, while groundwater plays a key role in global stability and prosperity, it also makes up 99 percent of all liquid freshwater—accordingly, groundwater is at the heart of the freshwater crisis. *Groundwater is an invaluable resource*.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, is committed to advancement of groundwater education accelerate action related to our essential groundwater resources. We are committed to *making groundwater understandable* and, thus, enable *building the human capacity for sustainable development and management of groundwater.* To that end, the GW-Project creates and publishes high-quality books about *all-things-groundwater*, for all who want to learn about groundwater. Our books are unique. They synthesize knowledge, are rigorously peer reviewed and translated into many languages, and are free of charge. An important tenet of GW-Project books is a strong emphasis on visualization: Clear illustrations stimulate spatial and critical thinking. The GW-Project started publishing books in August 2020; by the end of 2023, we had published 44 original books and 58 translations. The books can be downloaded at gw-project.org↗.

The GW-Project embodies a new type of global educational endeavour made possible by the contributions of a dedicated international group of volunteer professionals from a broad range of disciplines. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, teenagers, undergraduate and graduate students, professionals in groundwater fields, and the public. More than 1,000 dedicated volunteers from 70 countries and six continents are involved—and participation is growing. Revised editions of the books are published from time to time. Readers are invited to propose revisions.

We thank our sponsors for their ongoing financial support. Please consider donating to the GW-Project so we can continue to publish books free of charge.

The GW-Project Board of Directors, January 2024

Foreword

Karst is typified by openings in rock that are seen on and beneath the ground surface. Karst occupies 15 percent of Earth's surface and karst water resources serve the drinking water needs of 9 percent of the global population in 150 countries. Karst openings have evolved over geologic time as minerals are dissolved by water flowing in fractures. The fractures enlarge becoming channels and some channels gradually expand to form caverns. This book explains the many forms of karst that develop in response to differences in climate and geology and presents examples from around the globe. Karst presents intriguing scientific puzzles and displays many forms of natural beauty, which are the basis for the karst tourist industry. This book takes a broad look at karst that includes geology, geography, hydrology, engineering, human history, and culture. It examines what is being done and activities that need to be expanded to manage and protect karst from continuing deterioration due to human activities. The authors tell the story of karst using numerous illustrative drawings and hundreds of photographs that treat the reader to an amazing visual voyage suitable for anyone who is curious about the nature of our planet. This work presents the basic concepts and terminology that are foundational to reading other Groundwater Project books about karst such as *Introduction to Karst Aquifers* by Kuniansky and others (2022) and other karst books that are currently underway at the Groundwater Project. Karst water flow responds quickly to climate change and understanding karst is necessary for adapting to this change.

The authors are internationally recognized karst researchers who have examined karst over decades in dozens of countries and this book reflects their experience. Their stellar credentials are summarized in Section 13, *About the Authors*.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, March 2024

Preface

Karst is a complex system of rocks and water, whose interactions create landscapes and forms that cannot be found in any other rock or aquifer. That is why philosophers and scientists have been intrigued by karst ever since the times of early civilizations. Karst aquifers and their water are natural resources that are of global importance to humanity because they provide potable water and ensure health, sanitary conditions, food production, and economic development for almost one billion people on our planet. The springs emerging from karst aquifers are by far the largest, with some discharging entire underground rivers. In contrast, in some karstic terrains in arid parts of the world, or at high altitudes, there is an absence of water at the surface but rich water reserves at depth that are inaccessible to the local populations.

This book, which aims to provide an insight into karst environments and their management, also discusses many other aspects and controversies related to karst. In the early stages of writing this book we discussed the content with John Cherry and the Groundwater Project team and learned they planned to cover karst in many different ways since it manifests itself in such a variety of forms around the globe. Our target audience is very broad and includes people who have not received formal training in groundwater science, students of groundwater science, and professionals working in karst areas. We especially hope that this book provides the latter group information about some aspects of karst that they have not previously had an opportunity to learn about.

The book has a theoretical part that consists of more than 130 pages illustrated with 100 figures. It comprehensively addresses the karst environment, its surface and subsurface forms, as well as the natural processes that shape it. A brief overview of the history of the development of karstology is included. Special attention is given to karst hydrogeology and the value of karst aquifers. Finally, the vulnerability of, stresses on, and the importance of proper protection for karst aquifers are delineated. Thirty-two boxes have been prepared either to present practical examples or to visualize theories explained in the text. Over 200 references are provided for those who wish to learn more about karst. Eight exercises with solutions and 34 prepared questions and answers are provided to help readers assess their knowledge of karst.

It is sometimes said that a picture is worth a thousand words and with this in mind, in Section 9, we have incorporated 100 thousand words in the form of photographs of karst landscapes and features, all taken by the authors and chosen to show the global extent of karst. They are separated into three groups—landforms, springs, and human connections to karst. Forty-six countries are represented, about one-third, of all the countries where karst is present.

This book is a contribution to the activities of the International Association of Hydrogeologists (IAH) Karst Commission, as well as an important result of the project Karst Aquifer Resources Availability and Quality in the Mediterranean Area (KARMA), implemented within the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) program under Horizon 2020. Through it, we are among others focusing on the Mediterranean area—one of the world's richest reservoirs of karst water and the place where the scientific disciplines of karstology and karst hydrogeology were born.

Acknowledgments

We appreciate the useful reviews of this book by the following individuals:

- Eve Kuniansky, Emeritus Scientist US Geological Survey, Georgia, USA;
- Francesco Fiorillo, Department of Sciences and Technologies, University of Sannio, Benevento, Italy;
- Joanna Doumar, Department of Geology, American University of Beirut, Lebanon; and,
- Romeo Eftimi, International Consultant, Tirana, Albania.

We appreciate the contributions of Connie Bryson (Science Editor) and are grateful for Amanda Sills and the Formatting Team of the Groundwater Project for their oversight and copyediting of this book. We also thank Eileen Poeter (Colorado School of Mines, Golden, Colorado, USA) for final review, editing, and production of this book.

1 Introduction

Karst is a term that is widely used by professional geoscientists, as well as land and water explorers, engineers, and managers to describe and explain specific forms on the land surface and beneath it. Karst is the result of chemical and mechanical weathering and erosion of rocks that are generally hard but have a relatively high solubility in natural water. The dimensions, shapes, and the openings of joints, fractures, conduits, and caves are all the result of karstification. This process and its intensity depend on the rock solubility and strength in addition to internal and external factors, which may be geological, morphological, climatological, hydrological, pedological, biological, and even anthropogenic. Karst landforms and karst groundwater systems are the result of the interaction of all these factors on the two main groups of soluble karst rocks: carbonates and evaporites. This book is primarily concerned with carbonate karst, which is much more widespread than evaporite karst, forming the largest aquifers and providing water of excellent quality.

Karst groundwater systems commonly differ from, and are more dynamic than, other aquifers because of the high degree of heterogeneity and anisotropy in karst and because of the development of conduit porosity and permeability. Consequently, there are specific, commonly groundwater-related, risks associated with any construction in karst, especially creation of dams and reservoirs, tunnels, highways, and other infrastructure.

Most karst aquifers are characterised by higher velocities in the laminar, steady, and turbulent flow regimes and a higher vulnerability to pollution than in most other rocks owing to dissolution of the rock forming large conveyances (pipe-like conduits). Karst aquifers are particularly sensitive to natural and anthropogenic changes in the environment. Climate change, and especially prolonged droughts, can have significant impact, reducing recharge and groundwater availability.

Carbonates are one of the commonest rocks on earth and most have been karstified to some degree. Hence, karst is a global phenomenon, with examples on every continent and most climatic zones, the only exceptions being where liquid water is virtually absent due to hyperaridity or extreme cold. Even in these environments relict karst may be present, having formed under past, more humid, climates. The World Karst Aquifer Map (WOKAM↗), completed in 2017 (Chen et al., 2017; Goldscheider et al., 2020), is the first detailed and complete global map and geodatabase concerning the distribution of karstifiable rocks, which represent potential karst aquifers. It includes carbonate rocks, such as limestone and dolomite, and evaporitic rocks, such as gypsum. In total, 15.2 percent—20.3 million km^2—of the Earth's land surface is characterised by the presence of carbonate rocks, representing karst aquifers that have surface or near-surface exposure.

Ford and Williams (2007) estimated that about 25 percent of the global population relies, partly or entirely, on fresh water from karst aquifers. More recently, Stevanović

(2019) estimated that 9.2 percent of the world's population, approximately 670 million people, were using karst water for drinking. Even without knowing the precise number, at least hundreds of millions of people in many countries and cities rely on clean and safe fresh water from karst aquifers.

Due to favourable infiltration conditions, limited or absent surface runoff, and high transmissivity, karst aquifers often constitute abundant freshwater resources, but when withdrawal exceeds recharge, as it does in many arid regions, over-exploitation leads to rapid decline or complete depletion of these groundwater resources, followed by deterioration of the water quality. This especially applies to coastal zones, where salt intrusion inland is a common consequence of aquifer overdraft.

The establishment and maintenance of monitoring networks is necessary to prevent depletion of groundwater reserves and deterioration of their quality. Therefore, the protection and management of these valuable karst water resources is of exceptional importance and needs to be based on appropriate hydrogeological investigations and an understanding of the special properties of these aquifers. This is mainly based on knowledge of the aquifers' discharge characteristics. To this end, the WOKAS global karst spring discharge database was compiled with data from over 400 springs (Olarinoye et al., 2020). When conducting research studies, care is needed in applying investigation methods that are commonly used in other groundwater systems such as field geological mapping and modeling of aquifer systems because karst commonly exhibits different functionality (Goldscheider & Drew, 2007). Certain methods, such as groundwater tracing, have been developed primarily for the purpose of characterisation of karst aquifers. Karst and its cavities are also the only type of rock and water bearing media that humans can enter directly to explore its interior. Exploration of caves is as old as the presence of hominids on our planet. The aim of these explorations was to find safe shelters (Stevanović, 2015), and paleontological evidence from many caves all around the globe make it possible for us to investigate hominid evolution and migratory paths as well as the history of civilisation.

Another aspect of karst is its immense importance for global biodiversity and geodiversity. Consequently, the protection of surface and underground karst ecosystems is relevant to Goal 15 of the UN 2030 Agenda for Sustainable Development ("*Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*"; https://sdgs.un.org/2030agenda↗). In every nation with karst there are natural landscapes, features, and wonders that receive some degree of protection because of their scientific, environmental, or aesthetic values. At a global level, Gunn (2021) identified 86 countries that have at least one karst area in the four internationally recognised protected areas: Biosphere Reserves, UNESCO Global Geoparks and World Heritage Properties that are directly designated by UNESCO, and Ramsar Sites that are designated by International Convention with UNESCO as custodian.

Our book was written in 2021 and 2022, the years that were declared as the International Year(s) of Caves and Karst (IYCK) by the International Union of Speleology, supported by UNESCO and many other institutions worldwide. UNESCO also declared year 2022 as the International Year of Groundwater (IYG) and the theme of the 2022 World Water Day was Groundwater: Make the Invisible Visible. This book is a contribution to the IYCK and IYG, aiming to globally promote karst and its wonders and beauties but also its challenges and possible strategies for sustainably managing this precious resource.

The karst environment is so specific that it requires, almost as a rule, a multidisciplinary approach and engagement of specialists from various fields. This list can be very long and depends on the character and aim of the study, but in principle should include hydrogeologists, geologists (e.g., petrologists, stratigraphers, structural geologists), hydrologists, geographers, geomorphologists, speleologists, hydrochemists, climatologists, biologists, pedologists, environmental scientists, and civil engineers. However, we consider hydrogeology to be the lead discipline when it comes to studying the linkage of water and karst, not because the authors of this book all belong to that discipline but because of its fundamentally multidisciplinary character. The complexity of dealing with the hydrogeology of karst terrains has led to the establishment of specialized research groups. To collectively integrate this highly specialized branch of hydrogeology, a Karst Commission (https://karst.iah.org↗) was established in 1970 under the umbrella of the International Association of Hydrogeologists (IAH). More than 50 years later, the Commission plays a central role as the focus for the exchange of ideas for further development of karst hydrogeology. Our book is also complements the recently launched project MIKAS (Most Important Karst Springs) of the IAH Karst Commission, which aims to create the first complete list of the most important karst springs at the global, but also at the national level, and ensure their wider promotion and better protection from pollution (https://mikasproject.org↗).

This book is also a contribution to the Karst Aquifer Resources Availability and Quality in the Mediterranean Area (KARMA) project within the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) program. The project is carried out by seven institutions from six countries.

The authors acknowledge the invitation extended by John Cherry and the team that runs the Groundwater Project, which seems to be an excellent platform on which to present the characteristics and properties of aquifer systems to the wider public, including those of karst and its waters, as well as their importance for population and biodiversity.

More about karst terminology can be found in Box 1↴.

2 Karst Environment

2.1 History of Research

It is difficult to say when and how scientific research of karst began, but the two main features were always caves and springs—the former because of being utilized as places of habitation and protection and as sacred spaces, as witnessed by many artifacts such as sculptures, weapons, tools, and wall paintings, the latter because of the attempts to find sources of clean and fresh water.

Among others, it was the Assyrians (Figure 1), Greeks, Romans, Arabs, and Chinese who contributed to the early knowledge of karst and its phenomena. Inscriptions showing caves and stalagmites have been found on Assyrian cuneiform tablets dating from the eighth century BCE (Before the Common Era).

Figure 1 - Khanis Spring in northern Iraq was utilized by Assyrians as a water supply for the famous ancient city of Nineveh. A cuneiform inscription dedicated to the king Sennacherib, the son of Sargon II, is carved in the limestone. The dark form at the top of the photograph inset in the upper left is a person sitting on top of the structure to provide scale. (photograph by Z. Stevanović).

Tapping of karst water and the use of karst water for potable supply have a long history and have been crucial for the historic and economic development of many regions in which karst is present. Karst springs in northern China were used for water supply and irrigation from very early times, as evidenced by records of turtle horns and bones from the Shang Dynasty (sixteenth to eleventh centuries BCE). Hongshan Spring, southwest of the city of Taiyuan in Shanxi Province, was used during the Song Dynasty (960 to 1279 CE;

Common Era). In ancient Babylon, Persia, Israel, and Egypt are many remnants of intakes around large springs located in karst. These springs were commonly used as central places around which to create settlements. Jerusalem, for instance, is one such city, supplied by a 500 m long tunnel leading from the Gihon spring (Frumkin & Shimron, 2006). Aqueducts as architectural master works were developed and designed by the Romans to enable long-distance transportation of high-quality water. At the height of the Roman Empire, several aqueducts, mainly tapped at karstic springs up to 90 km from the city, delivered about 13 m^3/s of water to the centre of Rome (Lombardi & Corazza, 2008; Figure 2).

Figure 2 - The famous Fontana di Trevi in the centre of Rome, Italy, to which water is diverted from the Salone spring, 10 km away, using the ancient Aqueduct Vergine. It was decorated by several artists from the school of the famous architect Bernini (photograph by Z. Stevanović).

An explanation of the origin and meaning of the word *karst* is provided in Box 2. The springs of Timava near Trieste were first mentioned in the fourth century BCE, when they were described in nautical guides. Pozidonius (135 to 50 BCE) studied them in connection with the tides and the ponor Reka in the Škocjanske Jame. They are also mentioned by the Roman poet Vergilius (71 to 20 BCE) in his famous poem *The Aeneid*, when he describes the return of the soldiers from Troy, and the intermittent Lake Cerknica was mentioned by Strabo (63 BCE to 23 CE).

A typical example of the fact that major cities were created around large springs in karst is found in the Adriatic part of the Mediterranean basin. Five major settlements established by the Romans are linked to karst springs (Figure 3): Trieste - Timavo spring;

Rijeka - Zvir springs; Split - Jadro spring; Dubrovnik - Šumet and Ombla springs; and Kotor - Gurdić, Škurda, and Tabačina springs (Stevanović & Eftimi, 2010).

Figure 3 - Karst springs at the Adriatic Sea shoreline: a) Jadro spring near Split (Croatia), used continuously since Roman times. The spring intake was reconstructed in 1886; b) Tabačina spring and pumping station, utilized for the city of Kotor (Montenegro); c) Ombla spring near Dubrovnik (Croatia) (photographs by Z. Stevanović).

The Chinese also made many contributions to the knowledge of caves and karst including a book from 221 BCE that describes caves and hydrology. Xu Xiake, known as the "father of karst studies in China," lived from 1586 to 1642 CE, during the Ming Dynasty. He visited and described some 340 caves in southern China in his book *Xu Xiake's Travels* [Xu Xiake Youji], which was published after his death. He devoted himself to the exploration of the subterranean world and described underground rivers and lakes as well as water resources. He first described various types of tropical karst and focused on the characteristics and reasons for the formation of tower hills. He introduced the term *fenglin* [peak forest], which is still used in scientific literature (Figure 4).

Figure 4 - Wanfenglin, Xingyi Geopark, Guizhou, China. The term fenglin [peak forest] was introduced by Xu Xiake (photograph by J Gunn).

Several documents confirm that research in Europe in the late seventeenth and early eighteenth century was focused on certain karst phenomena and occurrences. German explorer Melchior Goldast described Blautopf, one of Germany's largest karst springs (LaMoreaux, 1991). Janez Vajkard Valvasor (1689) described the intermittent lake of Cerknica and published his explanation of the lake's occurrence in 1687 in the *Philosophical Transactions of the Royal Society of London* and in 1689 in the *Acta Eruditorium*—two of the oldest and most important scientific journals of the time (Figure 5). Based on his paper and related work, he was elected as a Fellow of the Royal Society. Later, Balthazar de la Motte Hacquet described numerous karst phenomena in Slovenia and Austria in the late 1700s (Kranjc, 2006). The discharge of the spring of Vaucluse, France, which lends its name to the ascending type of spring, has been measured at regular intervals since 1854, and this spring has the longest data record in the world. The first large quantitative tracer experiment, during which tracers were injected into sinks of the Danube River in Germany, was conducted in 1878. The late nineteenth century was marked by intensive cave investigations, and many karst explorers of that time considered the French lawyer and caver Edouard-Alfred Martel to be the "father of speleology" (Kranjc, 1997).

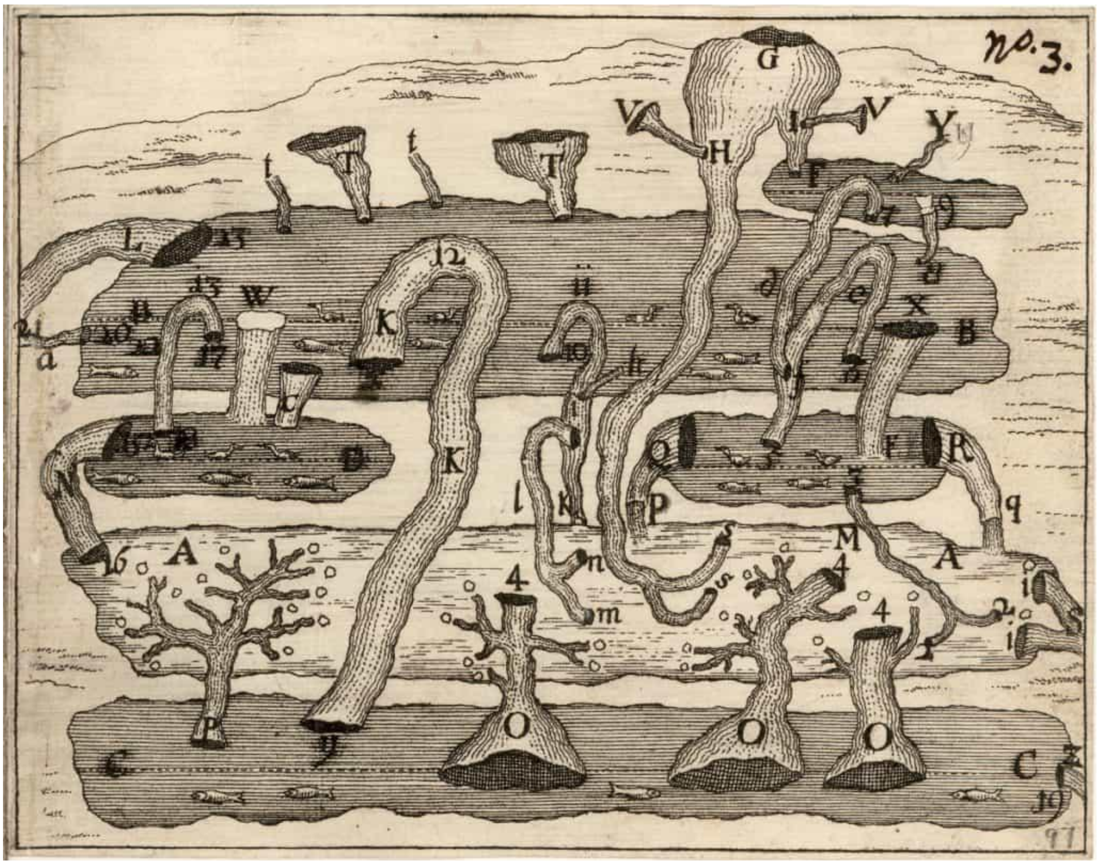

Figure 5 - Valvasor's hydraulic model of the appearance and disappearance of the intermittent lake of Cerknica (Valvasor, 1689).

The first discoveries of cave animals in the eighteenth and nineteenth centuries paved the way for biospeleology as a scientific discipline. The cave amphibian *Proteus anguinus* was described by J. N. Laurenti in 1768 and F. Schmidt wrote the first formal study of cave organisms when he described the cave beetle *Leptodirus hochenwartii* (Shaw & Čuk, 2015). In 1907, Emil Racovita published *Essai sur les Problèmes Biospéologiques* [Essay on Biospeological Problems].

Finally, Jovan Cvijić is often called the "father of karst geomorphology and hydrology" (Ford, 2005) as result of his doctoral dissertation *Das Karstphänomen* (1893).

More extensive descriptions of historical development, old documents, and evidence of the importance of karst are presented in detail in the works of LaMoreaux (1971, 1991), LaMoreaux and LaMoreaux (2007), Ford and Williams (2007), Bakalowicz (2005), Shaw (2008), Krešić (2013), LaMoreaux and Stevanović (2015) and Shaw and Čuk (2015).

2.2 Karstification and Karst Distribution

The two main physical characteristics of karst aquifers are anisotropy and heterogeneity. *Anisotropy* means that one physical property varies with direction. *Heterogeneity* is the variation of a property from one site to another within the same formation (Figure 6).

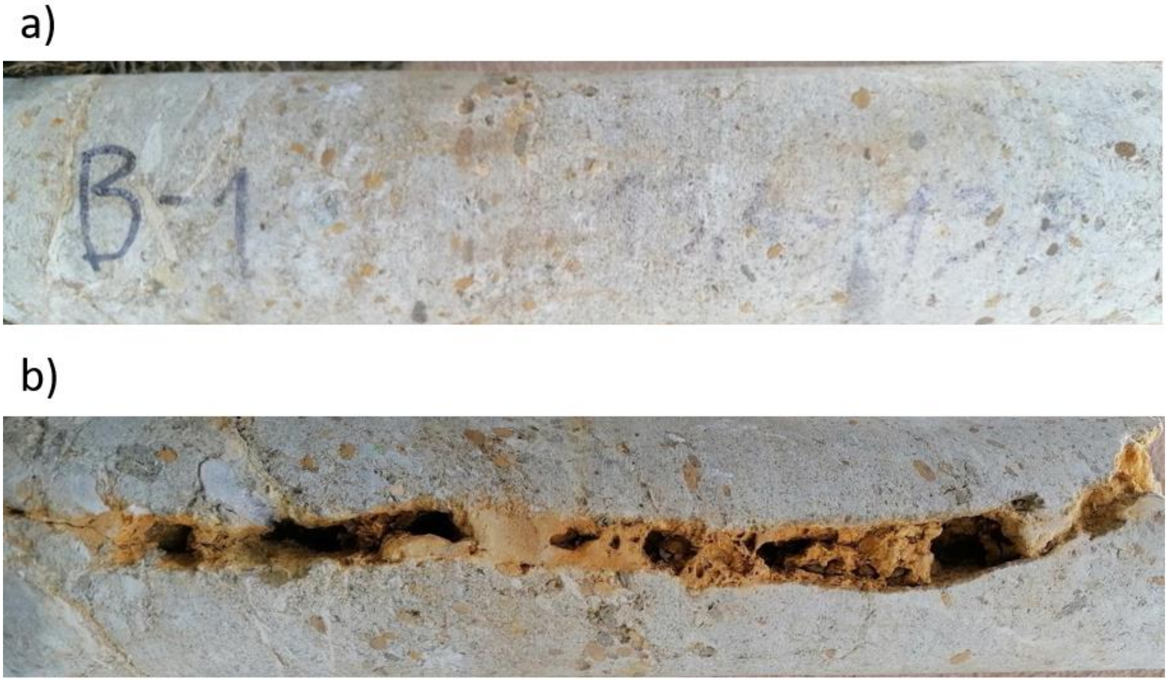

Figure 6 - Two limestone cores taken from the same geological formation: a) one with only matrix porosity and b) another with cavities partly filled with crystallized plug. The difference between the two cores illustrates heterogeneity, while the direction of the cavity indicates anisotropy, that is, much higher hydraulic conductivity in the direction of this conduit (photographs by Z. Stevanović).

In common with other rocks, most carbonate and evaporite rocks have a primary intergranular porosity (sometimes called a microscopic porosity) that relates to the time of rock formation (diagenesis). In most carbonates, this porosity is very low, and in those carbonate rocks that do have a high intergranular porosity—such as chalks—the pores are commonly so small that there is little to no intergranular permeability. Hence, in carbonate rocks it is important to distinguish between *total porosity,* the ratio between the total volume of voids and the total volume of rock, and *effective porosity,* the volume of interconnected voids that are large enough to permit water transfer, relative to the total volume of rock. Water movement driven by gravity is only possible through these larger and interconnected pores.

Another similarity with non-karst rocks is the fact that most carbonates and evaporites have a secondary porosity, sometimes called the macroscopic porosity, that consists of voids on bedding planes, joints, fissures, and fractures. This porosity and the permeability that it imparts is largely a product of the tectonic history of the rock following diagenesis.

However, the feature that distinguishes karst groundwater systems from other aquifers is the development of another form of porosity and permeability (Figure 7). This third type of porosity is a result of the rock dissolution process, and it takes the form of an integrated network of dissolutionally enlarged conduits. Hence, some authors consider karst to be a triple porosity—and permeability—system:

1. intergranular;
2. fracture / fissure / bedding plane; and
3. conduit.

Figure 7 - Core samples that were taken during the drilling of karstic rocks and are different in genesis, degree of dissolution, and porosity: halite (left), carbonate breccia (middle), and travertine (right) (photograph by Z. Stevanović).

It may be more convenient, particularly for groundwater flow modeling, to group the first two and refer to them as the *fissured rock matrix* porosity/permeability group with conduit porosity/permeability as a second group only found in karst.

Water is the main agent responsible for the creation of karst, while the entire process of transformation of hard and compact rock into permeable water-bearing media is called the process of *karstification*, which will be explained in greater detail later in this section. As this process results in an underground drainage system with water flow through conduits, some of which become large enough for human exploration (caves), *karstification* and *speleogenesis* are virtually synonymous. Karstification and speleogenesis are self-amplifying processes. The initial karstification of a narrow fissure is a very slow process, but increasing carbonate dissolution leads to wider fissure apertures, increasing throughflow, and acceleration of the karstification process, eventually resulting in a "breakthrough." Therefore, the initial fissure aperture has a major influence on the breakthrough time. The wider the fissure, the shorter the breakthrough time. Exercise 1↴ explores assessment of the time required to fill a cave system with water.

2.2.1 Rock solubility and deformation

Karst rocks are, by definition, of sedimentary origin although some such as marble have been metamorphosed (they are sometimes called metacarbonate, metalimestone, and metadolomite). Voids and cave systems (lava tubes) are commonly found in volcanic rocks, primarily those of the basaltic type, but these are not classed as karst because they are not a product of dissolution. The deposition of various inorganic and organic sediments in the marine environment (Figure 8) can be a very long process, even viewed in geological terms, which usually ends with sea retreat (regression), commonly as part of *epeirogenic* or *orogenic* movements. Epeirogenic processes are generally gentle, producing extensive plains with minor tilting, warping, or faulting. In contrast, most orogenic belts are characterized by greater folding and fracturing.

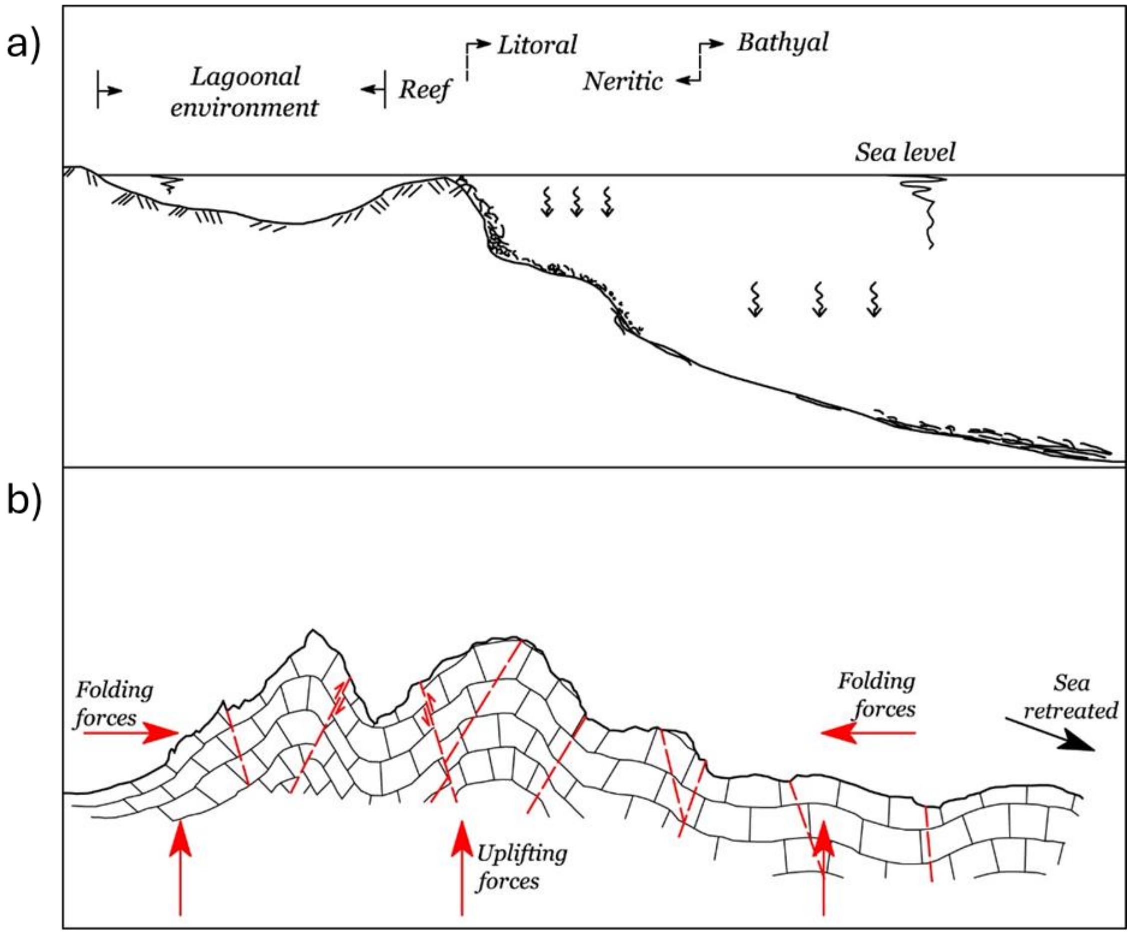

Figure 8 - a) A typical marine sedimentary basin consists of shallow parts (lagoonal, reef, littoral, and neritic) and a deep (bathyal) sedimentary environment (also known as a geosyncline). b) Orogenic processes of a fold and thrust belt consisting of carbonate rocks undergo intense fracturing that facilitates the karstification process.

The two main group of karst rocks are carbonates and evaporites. In addition, under certain conditions, silicate rocks (mainly quartzites and siliceous sandstones) are sufficiently soluble that karst surface landforms and caves may form (Ford & Williams, 2007). Silicate karst is not discussed in this book.

Carbonate rocks are formed from calcium and magnesium minerals, with calcite and dolomite being the most important rock-forming minerals, while aragonite and magnesite are much less widespread and relevant. Carbonates are among the most abundant sedimentary rocks. A discussion of the distribution of karstifiable rocks is presented in Section 2.2.3. Carbonate rocks are commonly classified according to the proportions of calcite, dolomite, and impurities. Limestone, in the narrowest sense, contains over

90 percent calcite (i.e., calcium carbonate), whereas dolomite (sometimes called dolostone) contains over 90 percent dolomite mineral (i.e., calcium magnesium carbonate). The term *dolomite* is used both for the mineral and the rock, whereas the term *dolostone* refers unambiguously to the rock. Other groups include impure limestone (50 to 90 percent calcite), impure dolomite (50 to 90 percent dolomite), dolomitic limestone (50 to 90 percent calcite with 10 to 50 percent dolomite, respectively) and calcareous dolomites (50 to 90 percent dolomite with 10 to 50 percent calcite). Clastic sedimentary rocks in which carbonates make up less than 50 percent of the total are given names such as calcareous sandstone and dolomitic mudstone. Chalk is a fine-grained sedimentary carbonate rock that is white and has a high total porosity but low effective porosity.

Travertine and tufa are freshwater carbonates formed by the chemical (and, in most cases, biochemical) precipitation of calcium carbonate at and downstream of springs and in rivers and lakes. Some workers reserve tufa for carbonate precipitated by cold water and travertine for carbonate precipitated by warm water, but others use the terms interchangeably.

All types of sedimentary carbonate rocks may be subject to metamorphism to form metacarbonates. Marble is the most common type of metacarbonate, but care is needed when using the term because the word marble is used by the dimensional stone industry to describe all rocks that can be polished. Hence, some rocks described by stone masons as being marble may be neither metamorphosed nor carbonates. Just as with sedimentary carbonates, there are impure metacarbonates such as calcite schist.

All these carbonate rocks are karstifiable to some degree, but the finest surface karst landforms and the most extensive caves are developed on and in limestone of high purity.

Rocks and minerals that contain SO_4^{2-} or Cl^- anions belong to the evaporite group including:

- anhydrite ($CaSO_4$),
- gypsum ($CaSO_4 \cdot 2H_2O$),
- halite ($NaCl$), and
- sylvite (KCl).

The ranking list established by Freeze and Cherry (1979) for some representative minerals, shows that calcite is six times less soluble than gypsum and about 1,000 times less soluble than halite (Figure 9). In addition, the evaporite rocks are soluble in pure water, whereas the carbonate minerals have low solubility in pure water. The formation of karst landforms and drainage depends on dissolved carbon dioxide (carbonic acid). Strong acids may also play an important role, particularly at the earliest (inception) phase of karstification. In this book, we only discuss karst developed on carbonate rocks.

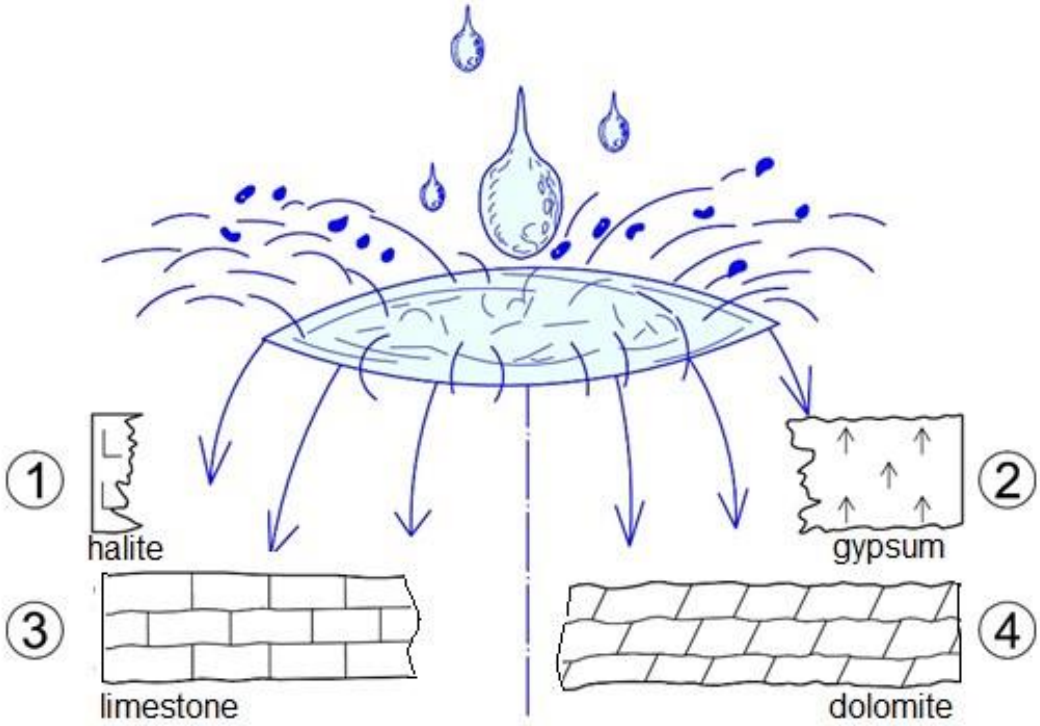

Figure 9 - Artistic impression of water dissolving rock along with the relative solubility of karstic rocks under identical physicochemical circumstances ordered by decreasing solubility: 1. halite; 2. gypsum; 3. limestone; 4. dolomite.

The primary karst process is aqueous dissolution. Mechanical processes may play a minor role once a karstic groundwater system has been established, but it is the dominance of dissolution that distinguishes karst from other aquifers. Carbonate rocks are only slightly soluble in pure water, but when rain falls through the atmosphere it dissolves carbon dioxide, forming a weak carbonic acid. This can dissolve more carbonate than pure water and the process results in a solution that contains calcium (and magnesium if present in the rock) ions and hydrogen carbonate ions. The dissolution process is complex but may be summarized by Equation (1), which describes the dissolution of limestone, and Equation (2), which describes the dissolution of dolomite/dolostone.

$$\mathrm{CaCO_3 + H_2O + CO_2 = Ca^{2+} + 2HCO_3} \tag{1}$$

$$\mathrm{CaMg(CO_3)_2 + 2H_2O + 2CO_2 = Ca^{2+}Mg^{2+} + 4HCO_3} \tag{2}$$

Wherever there is a soil cover, there is a marked increase in carbon dioxide, which is produced by microbial processes, soil fauna, and plant roots. It is this source of carbon dioxide that drives the dissolution process in most karst areas. Percolation water that has dissolved carbon dioxide as it passes through the soil is commonly referred to as being aggressive because it is able to dissolve limestone. In most caves the concentration of carbon dioxide in the air is markedly less than the concentration in the overlying soil, so when water emerges into a cave it rapidly loses carbon dioxide to the atmosphere within the cave, becomes supersaturated in $CaCO_3$, and deposits the calcium carbonate as speleothems. This process is discussed further later in this section.

Carbonate rock solubility is also influenced by chemical and mineralogical impurities as well as the size of mineral crystals. Chemical impurities (such as traces of magnesium in calcite) increase solubility, as they destabilize the crystal lattice. By way of contrast, mineralogical impurities (such as clay or sand particles in the carbonate rock) decrease solubility. Solubility decreases with increasing crystal size, as larger crystals are more stable and have a lower specific surface area than smaller crystals.

While carbonic acid is by far the most common solvent in karst areas, other acids may contribute to rock dissolution, particularly at early (inception) stages in the karstification process. Of primary importance is the generation of sulfuric acid by oxidation of iron sulphide minerals such as pyrite, which are commonly present in shales.

2.2.2 Karst classifications and typology

There are many classifications using different criteria such as karstification processes and driving mechanisms, morphological forms, lithology, or climatic conditions. In some classifications, the criteria are mixed.

As regards the environment in which carbonate or evaporitic sediments are deposited, we commonly distinguish between *karst in orogenic belts* (also known as *geosynclinal*) and *platform* karst. Box 3↴ describes the Earth's largest karst system in an orogenic belt. The former includes mountain ranges formed by the tectonic compression and uplift of large sedimentary basins, characterized by folds, faults, and a high degree of rock deformation and fracturing, while the latter is characterized by "quieter" tectonic movements and less deformed (sub-horizontal) strata.

The Köppen-Geiger classification of climate suggests five broad climatic zones: tropical, arid, temperate, cold, and polar. There has been considerable debate as to the extent to which climate influences karst processes and resulting landforms and drainage. For example, Corbel (1959) argued that cold, high mountains were the most favourable environment for carbonate dissolution and that for a given annual rainfall the solutional erosion rates in cold regions were up to ten times higher than in hot regions. These findings were contrary to morphological evidence, and they provoked many field studies of solutional erosion rates in different climatic zones together with theoretical studies. The key conclusion is that runoff (and hence recharge) explains between 50 and 75 percent of the variation in global solutional erosion rates and most of the remaining variation is due to differences in solute concentration. The present consensus is that climate is important because it determines the water surplus (precipitation minus evapotranspiration) and the production of carbon dioxide in the soil, which is the key driver of carbonate dissolution. Box 4 provides photographs of karst in different climatic settings.

Classification systems based on the development and presence of surface and underground karst landforms commonly distinguish between *fully developed karst* (the *holokarst* of Cvijić, 1918), *non-fully developed karst* (*merokarst*), and *transient karst*, which is somewhere between the two. However, these definitions are not helpful for hydrogeologists because conduit permeability is present in both merokarst and holokarst, the primary difference between the two being an absence of caves and less-well developed surface landforms in merokarst. Another classification system separates surface landforms (*exokarst*) and underground landforms (*endokarst*).

Klimchouk (2015) set out a modern approach to classifying karst settings and their hydrogeological significance (Figure 10). *Syngenetic (eogenetic)* karst develops soon after the rock is formed. For example, on some tropical islands, there is karst groundwater circulation with conduit permeability and caves in limestones that are 1- to 2-million years old (Lowe & Gunn, 1986; Mylroie & Carew, 1995). At the opposite end of the spectrum of settings, *deep-seated* karst develops while the rock is deeply buried and, in most cases, when it is overlain by non-karst rocks. In this case, it is likely the processes will be hypogenic as opposed to epigenic processes that operate closer to the land surface. These terms are discussed further in Section 2.3. Over time, the deeply buried rocks move closer to the surface by a combination of uplift and erosional removal of cover rocks. When the cover rocks are locally breached, allowing direct inputs of water from the surface, the setting is called a *subjacent* karst.

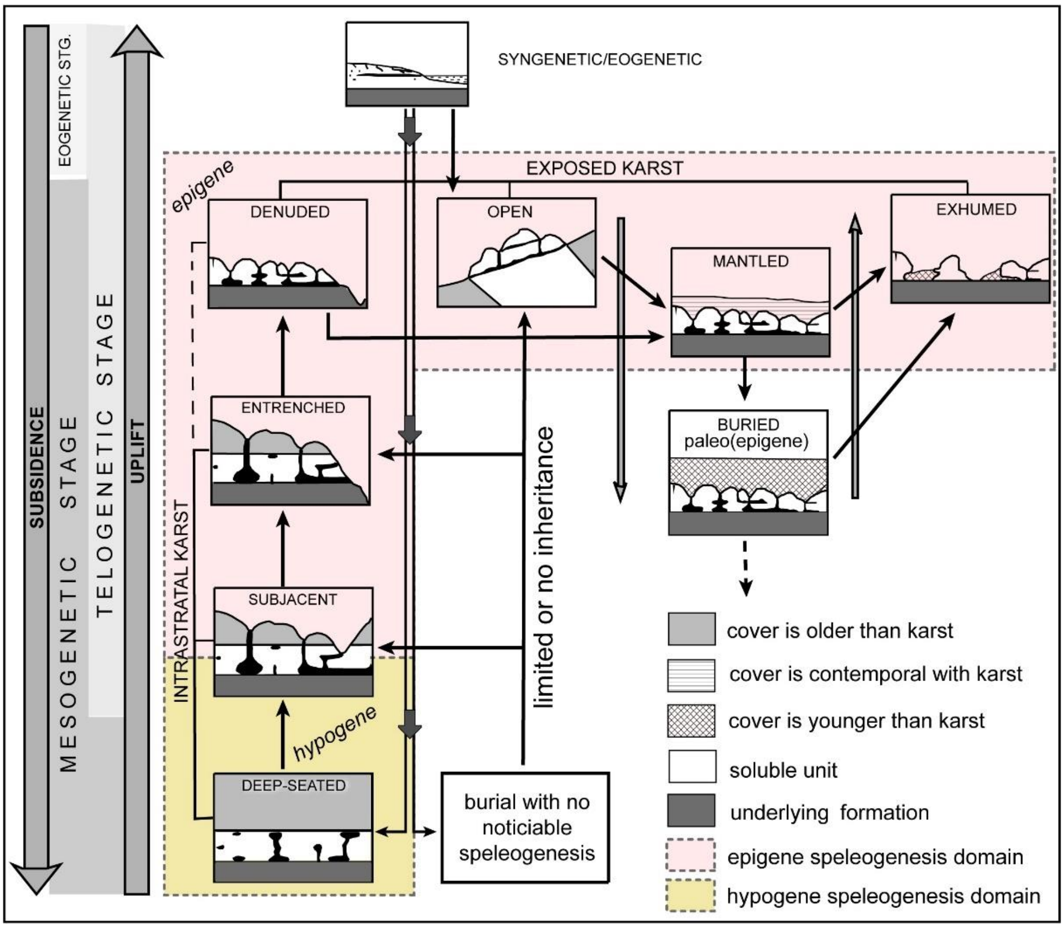

Figure 10 - Evolutionary types of karst and speleogenetic environments (from Klimchouk, 2015). The background colours indicate the domains of epigenic and hypogenic speleogenesis.

Continued uplift and surface lowering may produce an *entrenched* karst where the deepest valleys have cut down onto less permeable rocks below the karst sequence, but—for the most part—the cover rocks crop-out at the surface. Deep-seated, subjacent, and entrenched karst are grouped as *intrastratal karst*. In a *denuded* karst, the cover rocks have been completely removed. An alternative setting is *open* karst of which there are two types: one in which the karst rock was never buried and one in which the rock was buried, but karst processes did not operate until the cover rock had been removed. In both denuded karst and open karst, the rocks are exposed at the surface (possibly beneath a soil cover), and these are *exposed* karst settings.

During the phase of active karstification, both denuded karst and exposed karst may be mantled by cover deposits such as aeolian sediments (loess), glacial till, or volcanic ash. Over longer periods of time, the karstified rocks may be buried by younger rocks and both mantled and buried karst may later be exhumed. Groundwater can continue to circulate in all these settings, but in the case of mantled and buried karst the conduits may become filled with sediment, preventing water circulation and effectively fossilizing the conduit. This is referred to as *paleokarst*.

Caves and associated landforms such as collapse dolines are also present in rocks other than carbonates and evaporites. Caves that are formed by processes other than dissolution—for example, lava caves and caves formed by the mechanical action of waves—are commonly classed as being *pseudokarst*. The term has also been applied to caves and landforms formed by dissolution of silica-rich rocks such as sandstone, quartzite, or even some igneous rocks such as granites, although some consider these to be true karst.

2.2.3 Distribution of karstifiable rocks

According to global analysis conducted under the WOKAM project (Chen et al., 2017; Goldscheider et al., 2020) about 15.2 percent of the global land surface is underlain by karstifiable rocks with 9.4 percent continuous carbonate rocks and 5.8 percent discontinuous carbonate rocks or mixed karst. The spatial extent of non-exposed (i.e., deep, confined) karst aquifers could not be quantified but is displayed on the full-scale map in a generalized way. Some rock outcrops were too small or too complex in shape to be displayed on WOKAM. Therefore, areas with more than 65 percent of carbonate rock were classified as *continuous*; areas between 15 and 65 percent were mapped as *discontinuous*; and areas containing more than 15 percent of carbonate and more than 15 percent of evaporite rock were displayed as *mixed karst*. The data and analysis presented in this section are based on the study by Goldscheider and others (2020) and focus on carbonate rocks because these rocks are more important in terms of water resources than evaporitic rocks. Figure 11 shows a generalized version of WOKAM. The detailed map is freely available for download in different formats on the WHYMAP↗ (World-wide Hydrogeological Mapping and Assessment Program) server of Bundesanstalt für Geowissenschaften und Rohstoffe [BGR: German Federal Institute for Geosciences and Natural Resources].

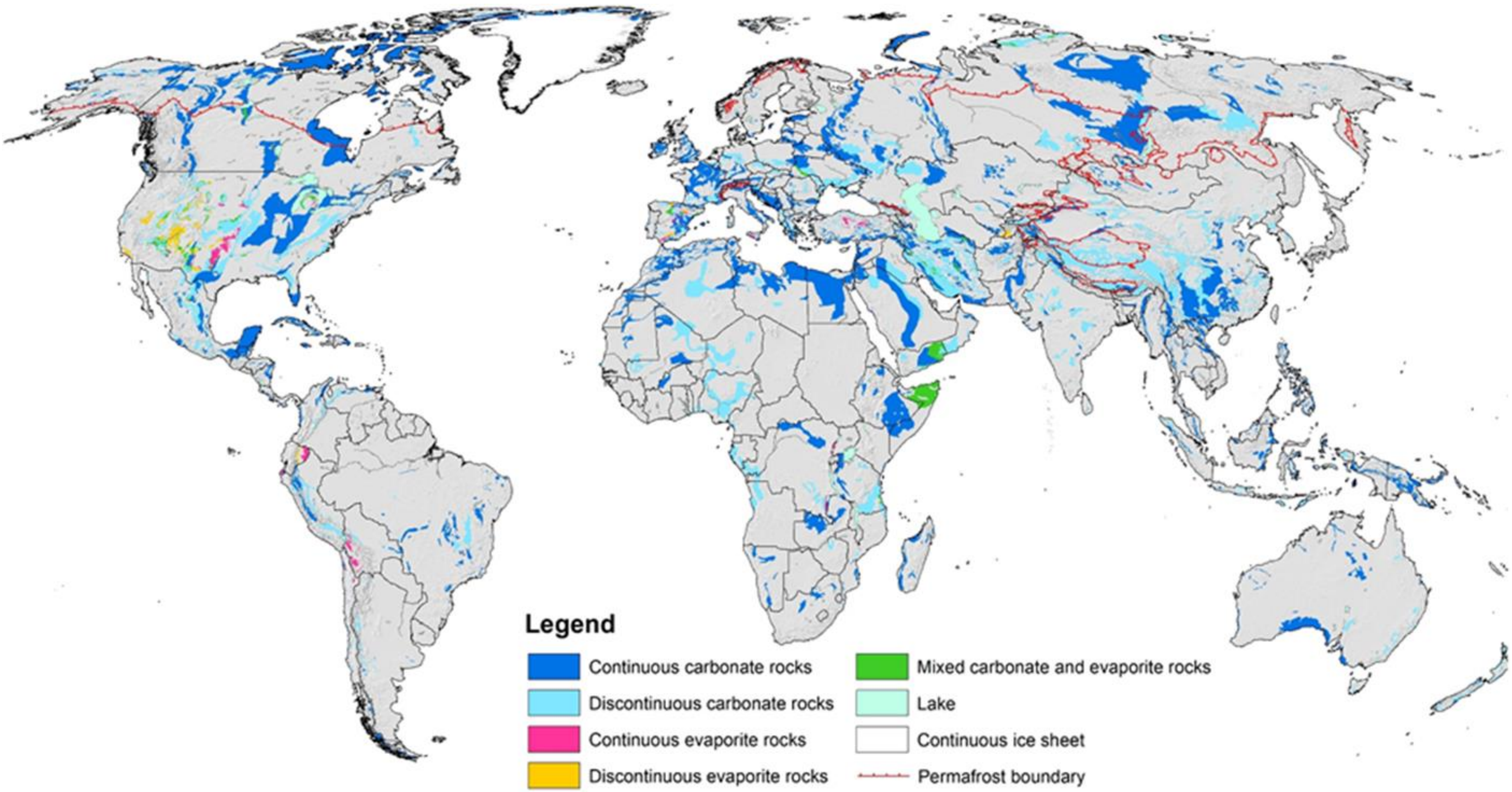

Figure 11 - Generalized WOKAM map of global distribution of various types of karstified rocks (after Goldscheider et al., 2020).

Karstifiable carbonate rocks are present on all continents (Table 1; Figure 11). The largest absolute area is found in Asia—8.35 million square kilometres (M.km^2) which is 18.6 percent of the land surface—and the highest percentage of karst is in Europe — 21.8 percent of the land surface (2.17 M.km^2). Substantial amounts of carbonate rocks also occur in North America (19.6 percent; 4.43 M.km^2) and Africa (13.5 percent; 4.05 M.km^2) but much smaller percentages are present in Australia and Oceania (6.2 percent; 0.50 M.km^2) and South America (4.3 percent; 0.77 M.km^2).

Table 1 - Distribution of carbonate rock areas and population living on karst (in 2015), on all continents and globally. Total areas in million km^2 (M.km^2) and percent (%); population in million people (M) and percent (%) (modified after Goldscheider et al., 2020).

Continent	Carbonate rock area		Population on karst	
	M.km^2	%	M	%
Europe	2.17	21.8	172.1	25.3
Africa	4.05	13.5	174.4	16.7
Asia	8.35	18.6	661.7	15.1
Australia & Oceania	0.50	6.2	4.4	13.1
North America	4.43	19.6	134.2	23.5
South America	0.77	4.3	34.3	8.2
World	20.27	15.2	1,181.1	16.5

Table 1 also presents the absolute numbers and percentages of people living on karst based on population data from 2015. Globally, 1.18 billion people (16.5 percent of the global population in 2015) live on karst. The highest absolute number occurs in Asia (661.7 million), and the highest percentages are in Europe (25.3 percent) and North America (23.5 percent) (Goldscheider et al., 2020).

China and Russia are the countries with the largest (and nearly identical) absolute karst surface areas, 2.55 and 2.51 M.km^2, respectively, corresponding to 26.5 and 14.7 percent of their land surfaces. Among the ten largest countries, China also has the highest percentage of karst, but the USA (21.3 percent) and Canada (16.6 percent) also have large areas characterized by karstifiable carbonate rock outcrops. Some smaller countries in the Dinaric region of Europe have much higher percentages of karst areas, such as Montenegro (80.1 percent), Bosnia and Herzegovina (60.5 percent), and Slovenia (49.5 percent). Carbonate rocks are also widespread in other Mediterranean countries such as Spain (29.2 percent), France (35.0 percent), Italy (28.1 percent), Greece (41.0 percent), Turkey (18.0 percent), Egypt (45.2 percent), Libya (22.1 percent), and Algeria (15.4 percent) (Chen et al., 2017; Goldscheider et al., 2020). The Mediterranean Karst Aquifer Map (MEDKAM↗), completed in 2022, provides further details on Mediterranean karst (Xanke et al., 2022).

Using a global digital elevation model (DEM)↗, it is possible to differentiate between three broad topographic settings: plains, hills, and mountains. By combining this type of GIS (Geographic Information System) analysis with WOKAM, it was possible to determine that 31.1 percent of all carbonate rocks occur in areas with extensive plains, 28.1 percent in hilly areas, and 40.8 percent in mountainous areas (Goldscheider et al., 2020). Australia has the highest percentage of karst in plains (55.3 percent), with the Nullarbor Plain as the most prominent example. South America has the largest percentage of mountainous karst (68.5 percent), mostly located in the Peruvian Andes and Patagonia.

Hundreds of millions of people live in coastal areas, which are particularly threatened by sea-level rise and salt-water intrusions into coastal aquifers caused by over-pumping (Ferguson & Gleeson, 2012). Therefore, it is particularly important to quantify the occurrence of coastal karst aquifers. According to Goldscheider and others (2020), 151,400 km or 15.7 percent of marine coastlines are characterized by carbonate rocks. About one quarter of all coastal carbonate rocks occur in the Canadian Arctic and Hudson Bay, far from human populations and with largely unknown aquifer properties. Important examples of coastal karst with high relevance in terms of water resources include the Dinaric Karst along the Adriatic Coast (2,707 km), Florida in the USA (2,220 km), and the Yucatan Peninsula in Mexico, Belize, and Guatemala (1,807 km).

Globally, following the Köppen-Geiger classification, about 34.2 percent of all carbonate rock areas occur in arid climates, followed by 28.2 percent in cold, 15.9 percent in temperate, 13.1 percent in tropical, and 8.6 percent in polar climates. It is also possible to quantify the proportion of karstifiable rocks in each climatic zone individually: The highest percentage of karstifiable rocks occurs in temperate climates (19.1 percent), followed by cold (16.8 percent) and arid (14.8 percent) climates, whereas only 8.8 percent and 7.7 percent of the land surface in the tropical and polar regions consists of carbonate rocks. It is important to understand that these distributions relate only to the present-day climate in these regions, whereas the karst now present may have formed under different climatic conditions. For example, some regions that are presently arid—such as the Nullarbor Plain in Australia—contain extensive cave systems that formed under past pluvial conditions (Figure 12). Similarly, many presently temperate regions were subject to repeated glaciations during the Quaternary, while polar regions have evidence of karst that formed during warmer conditions in the Paleogene and Neogene.

a)

b)

Figure 12 - Karst features in the arid Nullarbor Plain in Australia: a) collapse doline entrance to Koonalda Cave; b) Weebubbie Cave with fossil groundwater that recharged during past pluvial conditions (photographs by J. Gunn).

2.3 Karst On and Beneath the Earth's Surface

2.3.1 Driving forces - Epigene and hypogene karst

From a hydrogeological perspective, the process of karstification is essentially the growth of a dissolutionally enlarged, organized, and spatially integrated void–conduit system that imparts a tertiary porosity–permeability to a rock mass. This process may also be described as speleogenesis, although only a small percentage of the conduits ever become large enough to be caves that can be entered by humans. Groundwater is the driving force for speleogenesis and for most aspects of karstification, the exceptions being karst landforms that are solely formed by water flowing on the Earth's surface.

The nature of the groundwater circulation allows two broad genetic types of karst to be defined: *epigene* (also referred to as epigenic, epigenetic, or hypergene) and *hypogene* (synonyms: hypogenic, hypogenetic). In epigene karst, CO_2 and water from the atmosphere are the driving forces of karstification, while hypogene karst relates to deep or confined groundwater circulation, commonly with other sources of acidity and often in large artesian basins.

At its simplest, epigenic karst is formed in areas where dense, well-lithified karst rocks (sometimes referred to as *telogenetic*) crop out at the surface (*open karst*) or underlie a cover of soils and superficial deposits (*covered karst*). There is little or no surface runoff and meteoric water containing carbon dioxide enters the rock either as dispersed autogenic recharge or—where closed depressions (dolines, discussed in the next section) have developed—as concentrated autogenic recharge (Figure 13). Autogenic recharge is sourced entirely from precipitation that falls on the karstic area. Dissolution (by carbonic acid) is focused in the upper layers of rock (*epikarst*), particularly in areas of covered karst where soil carbon dioxide is generated. Hence, the epikarst is a zone of enhanced permeability in which there is commonly lateral groundwater flow toward conduits that channel recharge vertically. If the karst rock outcrop is bordered by higher-elevation, non-karst rocks then surface streams with their headwater on those rocks drain onto the karst and commonly sink (i.e., flow into the groundwater system), providing concentrated allogenic recharge that immediately enters conduits. Allogenic recharge is water that has flowed over or through non-karst rocks before reaching a karstic area. In rare situations, groundwater percolating through permeable non-karst rocks overlying karst rocks provides dispersed allogenic recharge (Figure 13).

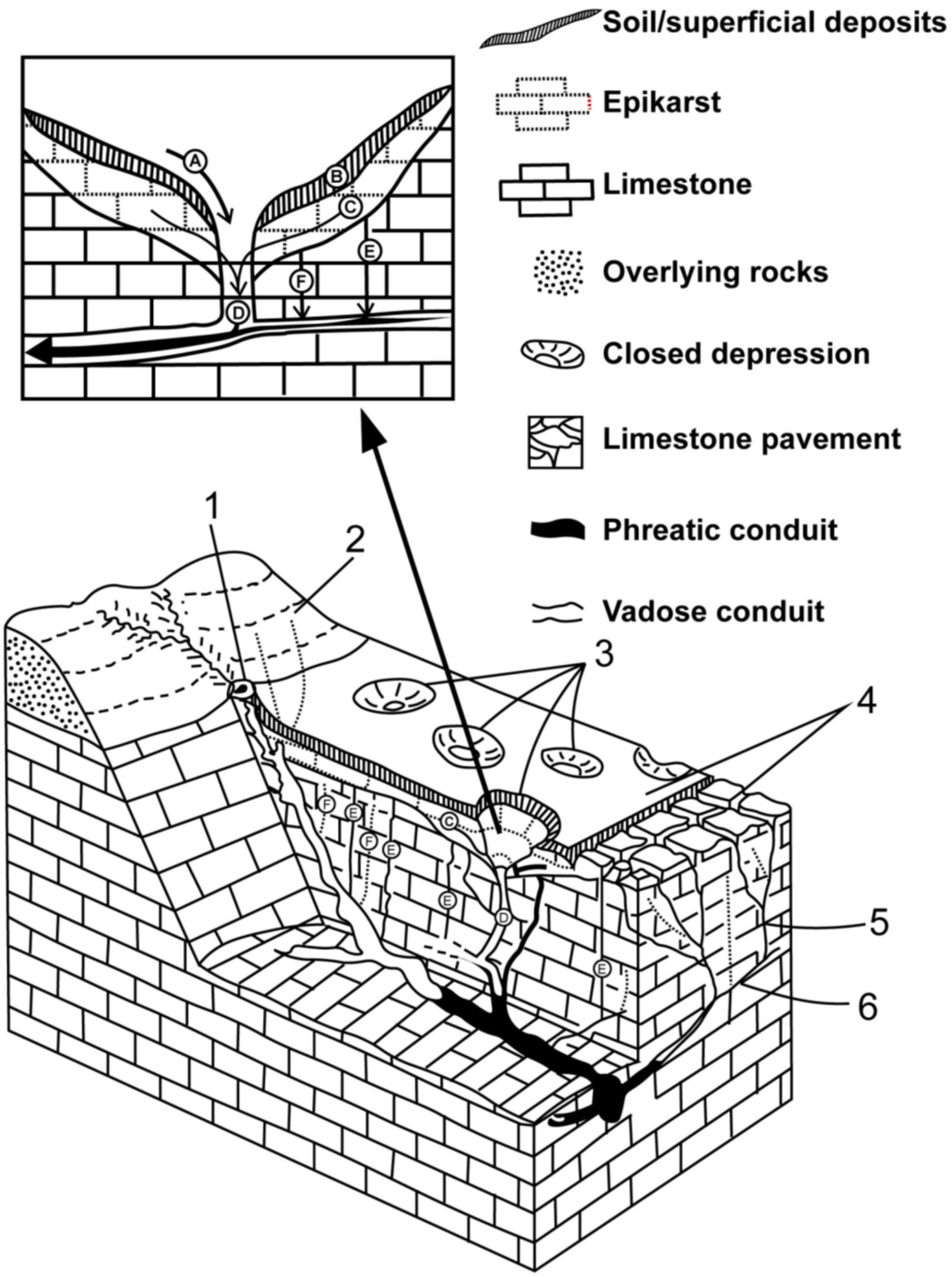

Figure 13 - A simple recharge model for an epigenic karst. (1) Water enters the karst groundwater system as concentrated allogenic recharge where a stream with headwater on non-karst rocks sinks. (2) If the non-karst rocks are permeable, groundwater entering those rocks will provide dispersed allogenic recharge. (3) Solution dolines provide concentrated autogenic recharge and (4) rain falling onto bare or soil-covered karst rocks forms dispersed autogenic recharge. The slopes of dolines have three broadly lateral pathways that concentrate recharge: (A) overland flow, (B) throughflow in the soil, and (C) epikarst flow in the upper bedrock. The lateral pathways focus recharge toward vertical flowpaths that range in size from shafts (D), which are open conduits that may be large enough for human exploration, through smaller conduits (E) with vadose flow, to the smallest channels (F) that transmit water as vadose seepage. Rain falling on bare limestones enters the epikarst directly, commonly along major joints that supply vadose flows (E). These may become concentrated in the vadose zone (5) and form percolation streams (6) that are tributary to the primary conduits that drain sinking streams and dolines (from Gunn, 1986a).

Beneath the epikarst, groundwater passes through the vadose zone where evidence from caves shows there is commonly much greater sub-horizontal flow than is the case in non-karst rocks. Some active stream caves remain in the vadose zone for their entire pathway to a spring—but, more commonly, groundwater descends to a phreatic zone. The phreatic zone in karst differs from that in equivalent porous medium rocks in that conduits through which there is rapid groundwater flow commonly descend tens and sometimes hundreds of metres below the land surface and are surrounded by rock that has a much lower permeability. In epigene karst systems, the scale of groundwater flow is most commonly local (up to around 10 km) although some epigenic flow systems are of intermediate (10 to 50 km) or regional (> 50 km) extent. Flow is generally convergent on a spring or spring-group, but divergent flow is also common in epigenic systems where recharge at a particular point may flow to springs that are several kilometres apart.

One common complication of the simple epigenic model occurs where a conduit system fed by meteoric water extends beneath lower permeability non-karst rocks. In hydrogeological terms, it could be said that the water is confined, but there are many cases where a free-surface stream flows within the vadose zone in a cave system that extends for several kilometres beneath non-karst rocks (Figure 14) and, even if a conduit is water-filled, that does not necessarily mean the groundwater is confined by overlying rocks. This type of system is best described as being epigenic *intrastratal* karst.

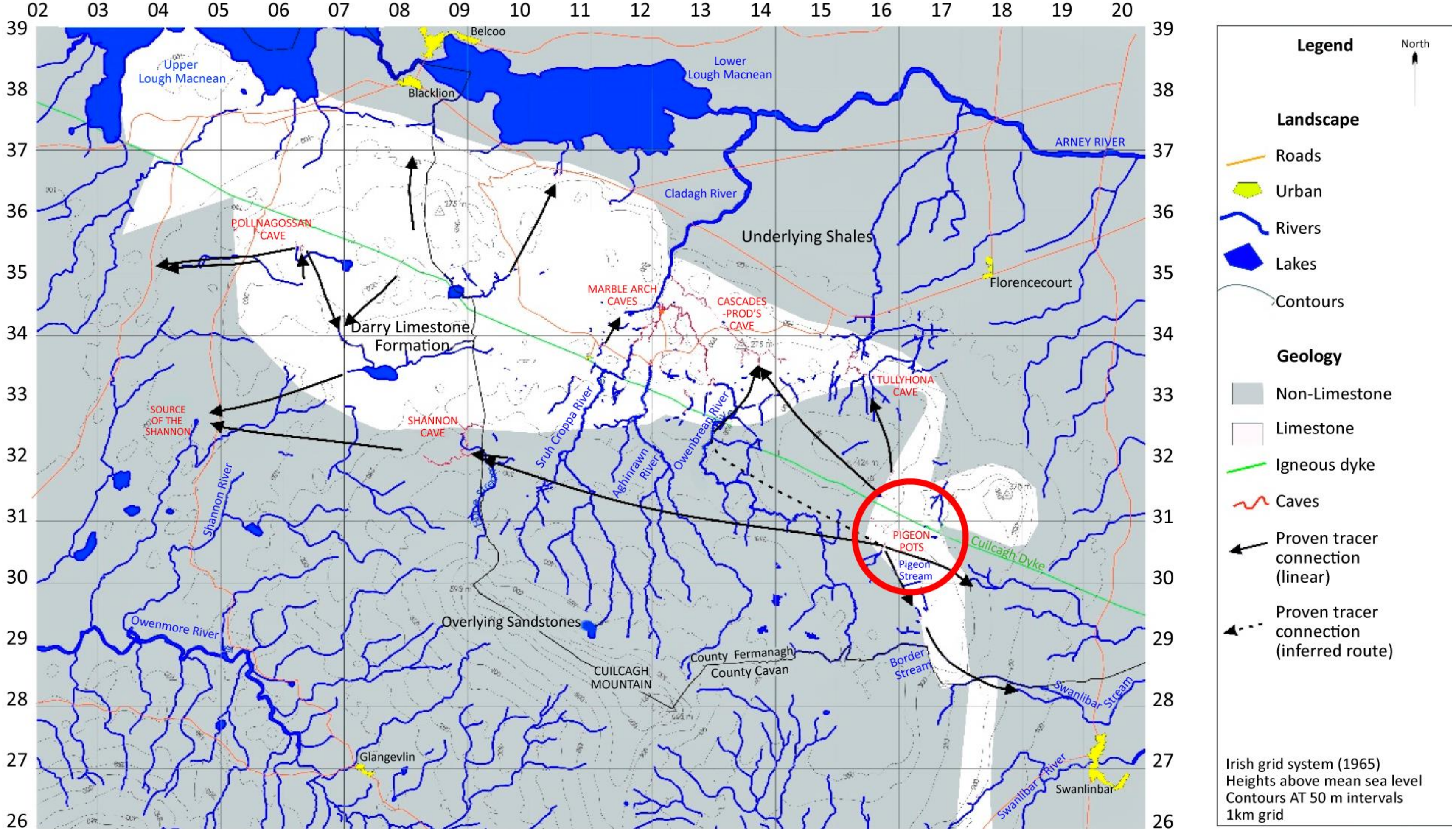

Figure 14 - Epigenic open and intrastratal flow in the Cuilcagh karst on the border between Northern Ireland (UK) and the Republic of Ireland. Water tracing experiments using fluorescent dye show that flow is convergent on springs but also divergent with dye injected at a single sink flowing to different springs. The Pigeon Pots (shown by red circle) provide a particularly good example as dye was recovered from springs to the east, southeast, northwest, and west. Between Pigeon Pots and Shannon Pot to the west groundwater flows over 10 km between mudstones and sandstones and passes through Shannon Cave where almost all the explored passage lies beneath non-limestones (modified from Brown, 2005).

Another complication to the simple epigenic model occurs in geologically young carbonate rocks that are commonly but not solely found in coastal regions (these are sometimes referred to as *eogenetic* or *syngenetic* settings). In most cases, these rocks were never compacted or tectonically deformed, and some are still undergoing diagenesis. Consequently, they commonly have a high primary porosity, although this does not always mean a high primary permeability. As is the case in telogenetic settings, groundwater flow is gravity-driven from topographically high recharge areas to lower elevation springs. However, the greater primary permeability means that conduits large enough to be explored by humans (caves) tend to be less common in these rocks. A common error in the past was to assume that absence of caves means absence of karst. For example, the Cretaceous limestones (the Chalk) in England were once regarded as being non-karstic because of an absence of caves. However, the Chalk receives concentrated allogenic and autogenic recharge that is convergent on large springs, and water tracing experiments have shown that groundwater velocities in conduits in the Chalk are similar to velocities in British Carboniferous limestones in which there are many cave systems (Maurice et al., 2021).

Broadly speaking, epigene karst is "top down," whereas hypogene karst is "bottom-up" in the sense that it is driven by rising rather than descending groundwater. Hence, hypogene karst is largely independent of recharge from overlying rocks and is instead driven by upwelling fluids from hydrostratigraphically lower units. The fluids are derived either from deep sources (commonly thermal) or from distant recharge that has been confined by lower permeability units. Carbonic acid, the main driver for epigene karstification of carbonate rocks, may also play a significant role in the hypogene karstification of carbonate rocks, but the carbon dioxide source is different. In epigene systems, carbon dioxide is dominantly produced in the soil zone, but in hypogene systems the carbon dioxide is produced at depth by a variety of processes including metamorphism, devolatilization reactions, thermal degradation, and oxidation of deep-seated organic compounds. Another feature of hypogene karstification is that other acids, most notably sulfuric acid, may play a more dominant role than carbonic acid. One important source of sulfuric acid is dissolution of hydrogen sulphide (H_2S); the process is particularly potent where water with dissolved H_2S rises and interacts with oxygenated shallow groundwater. Oxidation of iron sulfides provides another source of sulfuric acid.

Conduit–void systems that formed under deep-seated hypogenic conditions are brought closer to the surface by a combination of uplift and erosion of overlying strata; ultimately, this may allow epigene groundwater to invade, and modify, the hypogene system. Subjacent karst, entrenched karst, and degraded karst may represent phases in the uplift of an originally hypogenic system but can also form under epigenic conditions where there is a relatively thin low-permeability layer in a carbonate rock sequence.

2.3.2 Surface karst landforms

All karst landforms are associated with water as it flows over, into, through, or out of the ground. The majority are largely a product of dissolution by groundwater, although mechanical erosion and dissolution by surface water contribute to varying degrees. Here we discuss landforms on the earth's surface while the following section goes beneath the surface to the world of caves. Figure 15 provides an illustration of how the surface and underground landforms fit together and relate to the flow of water. The three primary groups of surface karst landforms are karren, valleys, and closed depressions (dolines and poljes).

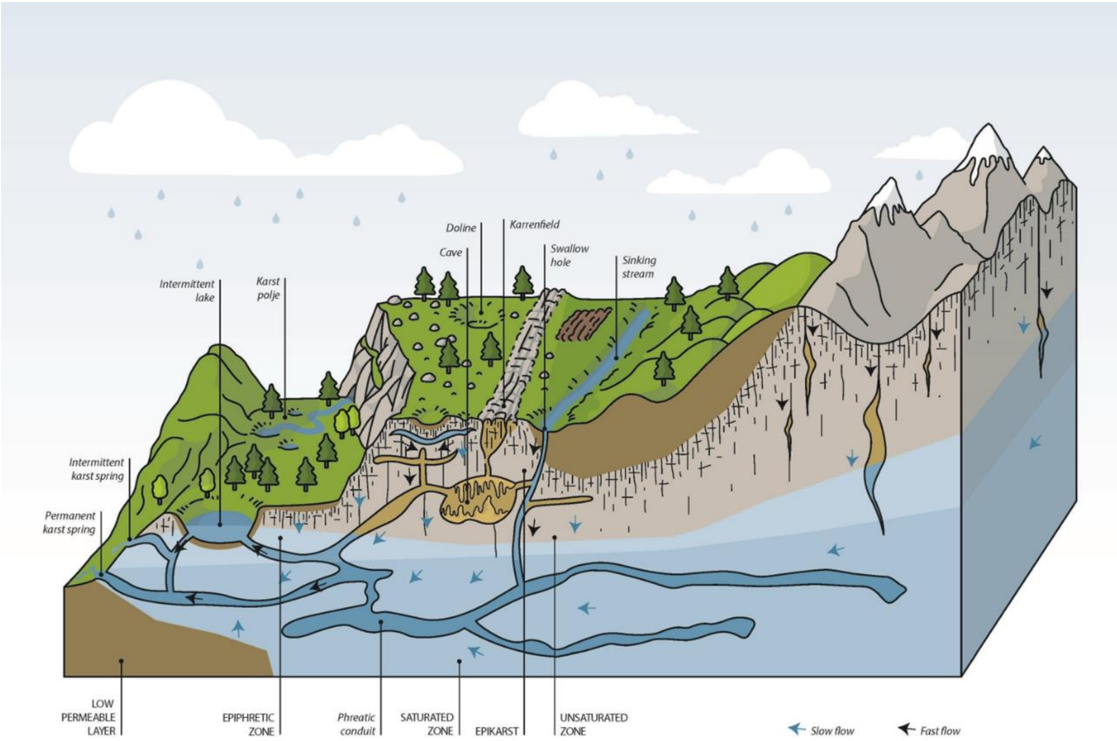

Figure 15 - Schematic three-dimensional diagram (not to scale) showing how surface and underground karst landforms relate to each other and to the flows of water (from Ravbar and Šebela, 2015).

Karren

When carbonate or evaporite rocks are exposed at the surface, they are commonly dissected by channels and pits that are given the collective name *karren*, a German term that is now widely used by karst scientists (*lapies* in French). Most karren are formed by dissolution effected by direct rainfall and overland flow (both as sheet flow and in microchannels), although they may also form by dissolution beneath soil or superficial deposits and be subsequently exposed when these deposits are removed by erosion. There are many different karren forms ranging in size from a few millimetres to giant karren over 10 m tall (Figure 16; Figure 18). Karren may be individual forms occupying a small area but, in some karsts, there are extensive karren fields that extend from a few hectares to over one hundred square kilometres in area (Figure 17; Figure 18). In these areas, most rain is rapidly absorbed, although some may be stored in *kamenitzas* (solution pans) and returned to the atmosphere by evaporation. As there is very little vegetation, there is also little evapotranspiration, and a greater proportion of annual rainfall becomes groundwater than would be the case in a karst area where there is a soil (and hence vegetation) cover.

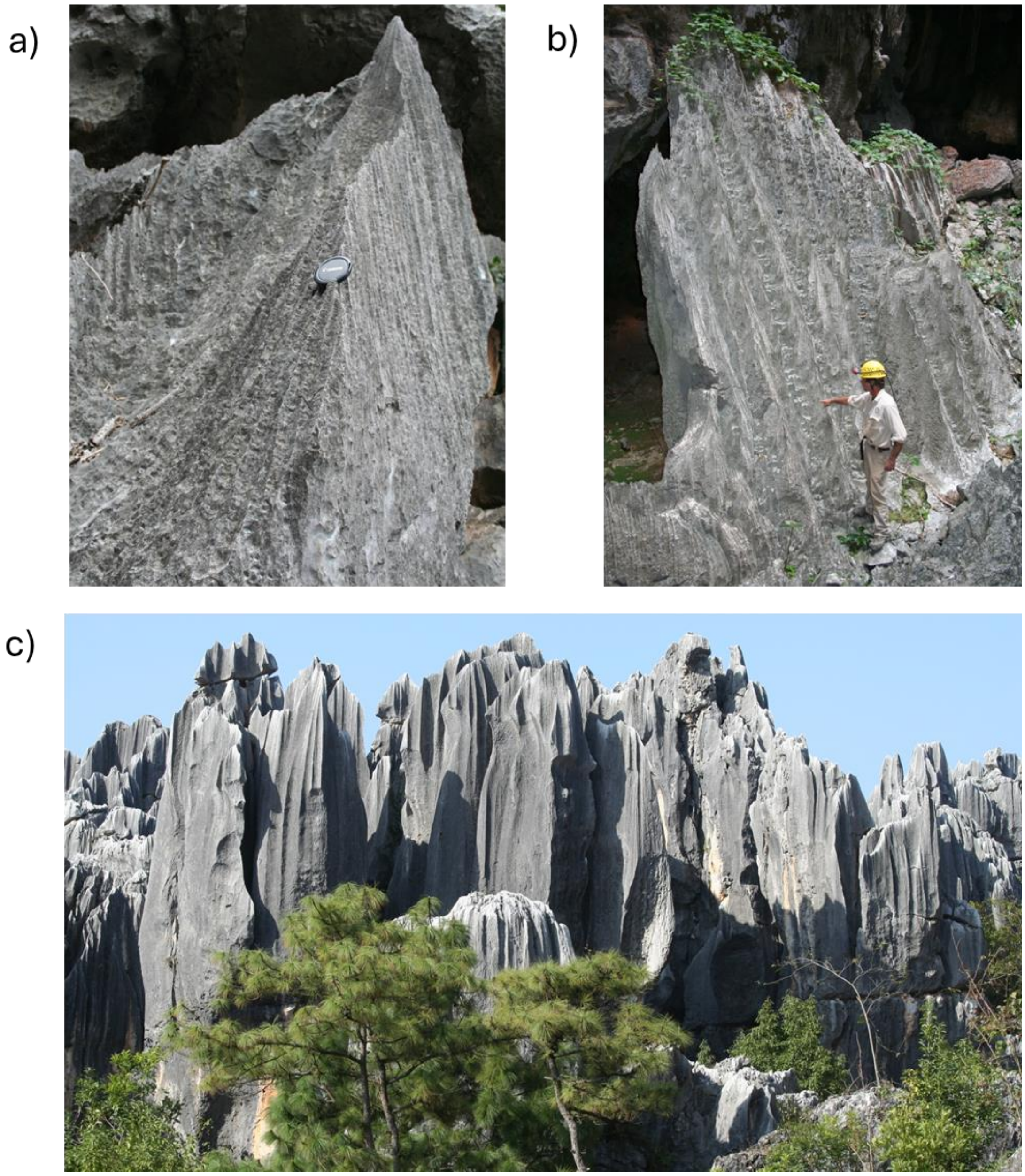

Figure 16 - Examples of karren: a) rillenkarren, very sharp, small, (lens cap is 65 mm) features formed by direct rainfall; b) larger rinnenkarren with steps (trittkarren) formed by channelled water flow (both examples are from Chillagoe, Queensland, Australia); c) giant karren over 10 m tall that are part of a stone forest at Shillin, Yunnan, China (photographs by J. Gunn).

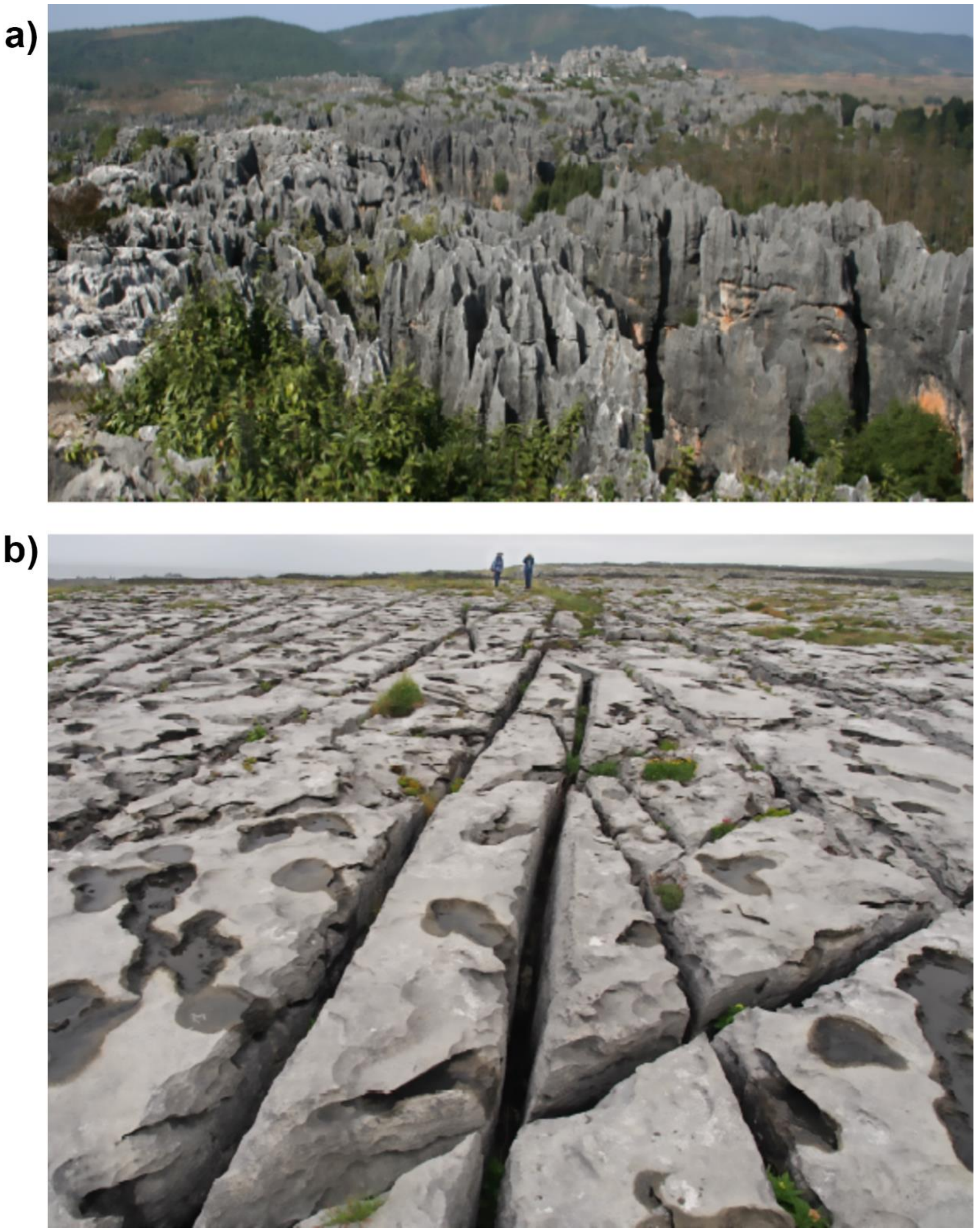

Figure 17 - Examples of karrenfields: a) part of a stone forest at Shillin, Yunnan, China, showing deeply dissected forms with no surface water storage; b) limestone pavement in the Burren, County Clare, Republic of Ireland. The dissolutionally enlarged joints are called grikes and the slabs between them are called clints. There are kamenitza on the clint surfaces, some being totally enclosed basins that are partially filled with rainwater and some draining into grikes. The patchy vegetation has formed on remnants of a formerly more extensive cover of glacial deposits (photographs by J. Gunn).

Figure 18 - Karrenfield in the temperate zone with forest vegetation cover; example is of Ždrocle, southwest Slovenia (photograph by N. Ravbar).

Valleys in Karst

Mechanical erosion is the dominant process in valleys cut by surface rivers (Figure 19); hence, it can be argued that valleys are not produced by true karst processes (dominantly dissolution). In addition, karst drainage is dominantly underground and karst areas typically have an absence of surface drainage. Closed depressions (dolines, poljes) are the diagnostic karst landform, but valley forms are present in many karst areas and there are some fluviokarst areas where valleys are the dominant landform. Four broad types of karst valley are commonly recognized:

1. through (allogenic) valleys,
2. blind and semi-blind valleys,
3. dry valleys, and
4. pocket valleys.

a)

b)

Figure 19 - Mechanical erosion is the dominant process in valleys cut by surface rivers. a) The Kolpa River in south Slovenia cuts its way between high karst plateaus (photograph by N. Ravbar). b) Crnojevića Rijeka in Montenegro has a low gradient and the river mouth has been submerged by Skadar Lake water (photograph by Z. Stevanović).

Through valleys are formed by rivers that have their origins on non-karst lithologies and maintain perennial flow through the karst to the output boundary. Most through valleys are steep-sided, and gorges are more common in karstic rocks than in other lithologies, partly because most carbonate rocks are mechanically strong and partly because of a general absence of surface runoff and consequent reduction in mass wasting. Antecedent gorges form where uplift occurs at a rate less than the river's capacity to incise. There are four main reasons for the development of through valleys. First, karstification may not yet be sufficiently advanced; that is, the input from outside the karst exceeds the present capacity of the limestones to absorb it. In this case, the river will usually be influent, with discharge decreasing both downstream and progressively over time. Second, the allogenic river may transport and deposit sufficient clastic material onto the karst to render the riverbed virtually impermeable. In the third situation, the riverbed is rendered impermeable by permafrost, but downcutting continues during summer melt periods. A fourth situation occurs where the hydraulic gradient is low and the river is at the local base level for drainage. In this case, the river will usually be effluent, with discharge increasing downstream due to inputs from springs and direct recharge through the bed.

Some influent rivers lose water to the karst over a long reach, commonly via a series of more or less distinct sink points that may not always be active or clearly visible. The upper Danube in Germany (Figure 20) and the Takaka in New Zealand are good examples. However, it is much more common for flow to be lost at a point, or series of points, commonly termed ponors or swallow holes. The processes of dissolution and transport of clastic sediment underground result in a gradual lowering of the bed at these sink points; downstream of them, the river has less erosive power. Hence, over time an upward step develops at the sink point. Underground, the capacity of the conduits increases as they enlarge and ultimately the lowest sink may be able to accommodate the entire base flow. This is the first stage in the formation of a *blind valley*, but as the sink is overtopped at discharges greater than base flow it is commonly called a half-blind or semi-blind valley. With further time, the conduit system may enlarge sufficiently for the sink to take even the highest of flood flows forming a true blind valley (Figure 21a, b; Figure 22). If the sink point migrates upstream, then the height of the closure at the end of the blind valley may be just a few metres, but—if a large river continues to sink at the same point for many years, and the hydraulic gradient is high—the closure may grow to several hundred metres.

Figure 20 - The upper Danube (flowing toward the person in the centre of the photograph) loses flow to the underlying limestone. When the discharge exceeds the losses, there is continuous flow, but the channel down-valley is dry during periods of low discharge (photograph by J. Gunn).

a)
b)
c)
d)
e)

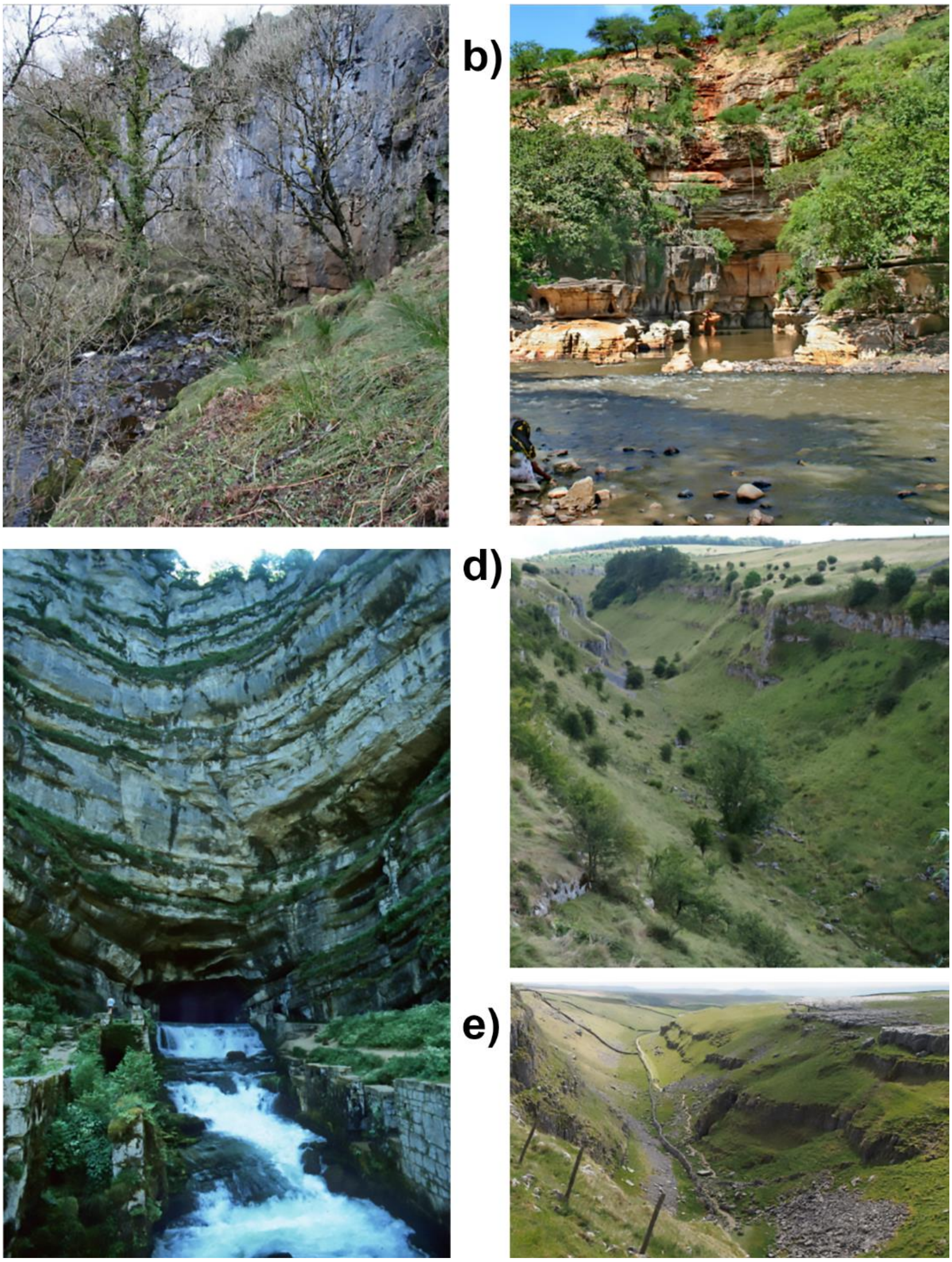

Figure 21 - Rivers sinking at the end of blind valleys are shown in a) Aghinrawn River sinking at Monastir, County Fermanagh, UK and b) Webb River sinking at Sof Omar, Ethiopia. c) A pocket valley downstream of Source du Loue (France). Dry valleys are shown in d) Lathkill Dale, Derbyshire, UK and e) Watlowes, Yorkshire, UK (photographs by J. Gunn).

Figure 22 - The Brezovica blind valley in southwest Slovenia. Water flows from the non-karst Brkini hills in the background and sinks close to the contact with the karst beneath the steep cliff from which the photograph was taken. The stream flows on the left side of the depression but is not visible because it is overgrown by bushes (photograph by N. Ravbar).

Pocket valleys (or steepheads) are the reverse of blind valleys since they occur in association with large springs close to the margins of karst areas. They are commonly short and most are formed by headward recession as water from the spring undermines the rock above it or by cavern collapse (Figure 21c).

Long, well-developed dry valleys are found in many karst areas, particularly where there are, or were, allogenic inputs; they are commonly similar in cross section to through valleys (Figure 21d, e). Three major groups of hypotheses have been suggested for their formation:

1. differing climates in the past, with either greater rainfall or permafrost;
2. superimposition from non-karst strata followed by karstification of drainage; and
3. a fall in the level of the potentiometric surface due to uplift of the land mass, incision of major valleys, or scarp recession.

To these should be added the progressive desiccation of a through valley as the sink-point migrates upstream. Over time, the floor of a dry valley may become dissected by dolines and the original fluvial form may be lost completely, as has happened in the Waitomo area of New Zealand (Box 5↴). Alternatively, a substantial increase in surface discharge, following climate change or blockage of underground conduits by sediment deposition, may result in previously relict dry valleys becoming re-activated.

Closed Depressions

Internally draining enclosed depressions are the fundamental unit of topographic relief in many karst areas, replacing the valleys that are the primary units in fluvial areas.

The depressions serve a similar function to the drainage basin of a surface river in that they channel water, solutes, and sediments to an outlet point or points and thence underground. A distinction is commonly made between enclosed hollows of moderate dimensions (< 1 km-long axis), commonly known as *dolines*, and closed depressions of large dimensions (> 1 km-long axis), commonly known as *poljes*. The term *turlough* is applied to an intermediate form of closed depression with an ephemeral lake (Box 6↴).

The term *sinkhole* is sometimes applied to dolines, particularly in North America and by engineering geologists. However, this term is also commonly applied to collapse features that are not karst but are associated with human activities such as mining or leakage of water pipes. It is also sometimes applied to the point where a stream sinks underground, so care is needed to understand the context in which the term sinkhole is used.

Dolines

Dolines are sub-circular in plan, and range from a few to one thousand metres in their long-axis. In profile, they range from shallow depressions that are a few metres deep with gently sloping sides to voids that are up to 650 m deep with steep to vertical sides. There is a varied nomenclature, and several classification schemes have been proposed, but one that is commonly employed is that of Waltham and Fookes (2003) who recognized six categories on the basis of the mechanism of ground failure and the nature of the material that fails or subsides (Figure 23).

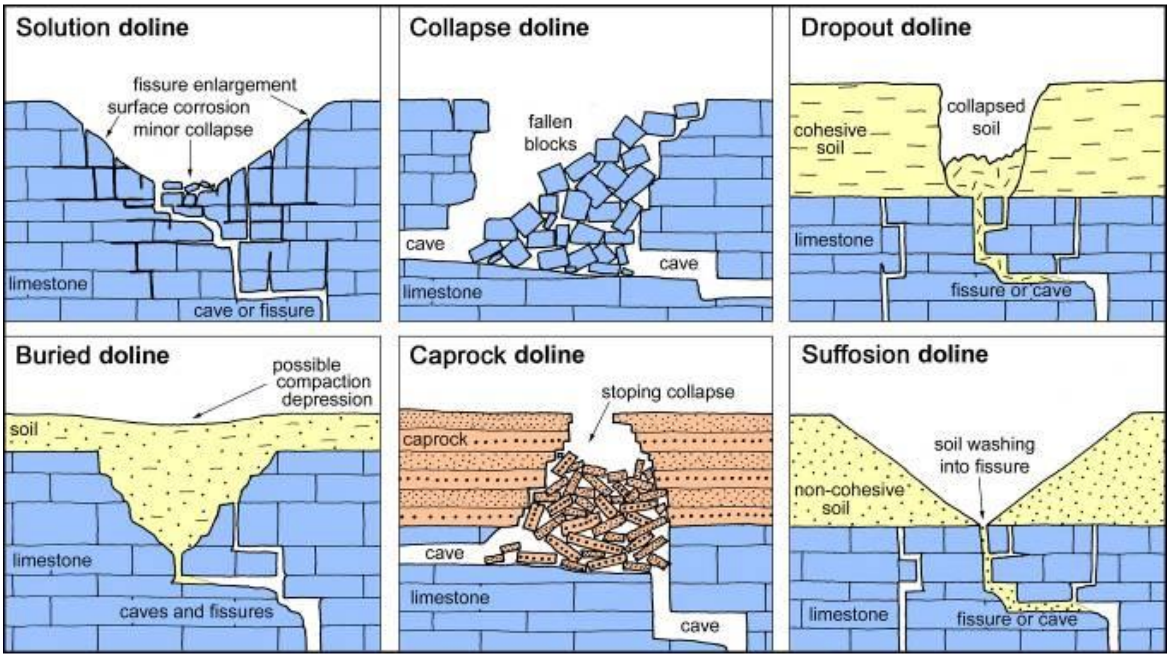

Figure 23 - Classification of dolines (sinkholes) based on the mechanism of ground failure and the nature of the material that fails or subsides (from Waltham & Fookes, 2003; drawn by Tony Waltham).

Solution dolines (Figure 23, Figure 24) form in the epikarst (the upper layer of dissolutionally weathered bedrock) where there is lateral groundwater flow toward a point or points of enhanced vertical permeability, commonly at fracture-intersections (Figure 13). As solutional erosion is greatest where flow is highest, vertical conduits (i.e., shafts labelled D in Figure 13) form at these points and the surface is lowered preferentially. In some areas, solution dolines extend laterally until their rims abut and they form a polygonal karst (Figure 24a). In contrast to solution dolines that enlarge downwards from the surface, *collapse dolines* are dependent on voids that form underground and enlarge upwards until their roof becomes unstable and collapses (Figure 23). In epigenic settings, the initial void is always associated with an underground river that removes debris formed by collapse; without a removal mechanism, material will accumulate, filling the void. Collapse dolines may also form where the roof of a deep hypogenic void is intersected by the lowering ground surface. As the base of a solution doline is commonly the lowest point on the surface, a collapse doline may form beneath a solution doline resulting in a compound landform.

a)

b)

Figure 24 - Solution dolines: a) interlocking to form a polygonal karst near Waitomo, New Zealand (photograph by J. Gunn); and b) in Istria (south Slovenia) (photograph by N. Ravbar).

The term *tiankeng* (literally meaning sky hole) is applied to dolines that are over 100 m wide and deep, have a small diameter over depth ratio (generally between 0.5 and 2.0), have a continuous perimeter with vertical or sub-vertical walls, and were formed largely by collapse into an underground void (Figure 25). Where there is active groundwater circulation in limestone that is beneath a non-carbonate caprock, a void may form with a roof that collapses upwards into the overlying rock. Where the void reaches the surface, a caprock doline is formed (Figure 23, Figure 26).

Figure 25 - The Dashiwei tiankeng in Leye county, Guangxi province in south China, is 600 m long, 420 m wide, has a maximum depth of 613 m and a 1,580 m perimeter. The large entrance to the relict Zhongdang Cave is in the middle of the picture and the Dashiwei River Cave is accessible at the lowest point of the tiankeng floor. Around 6,000 m of active cave passage with a large river has been mapped downstream (photograph by J. Gunn).

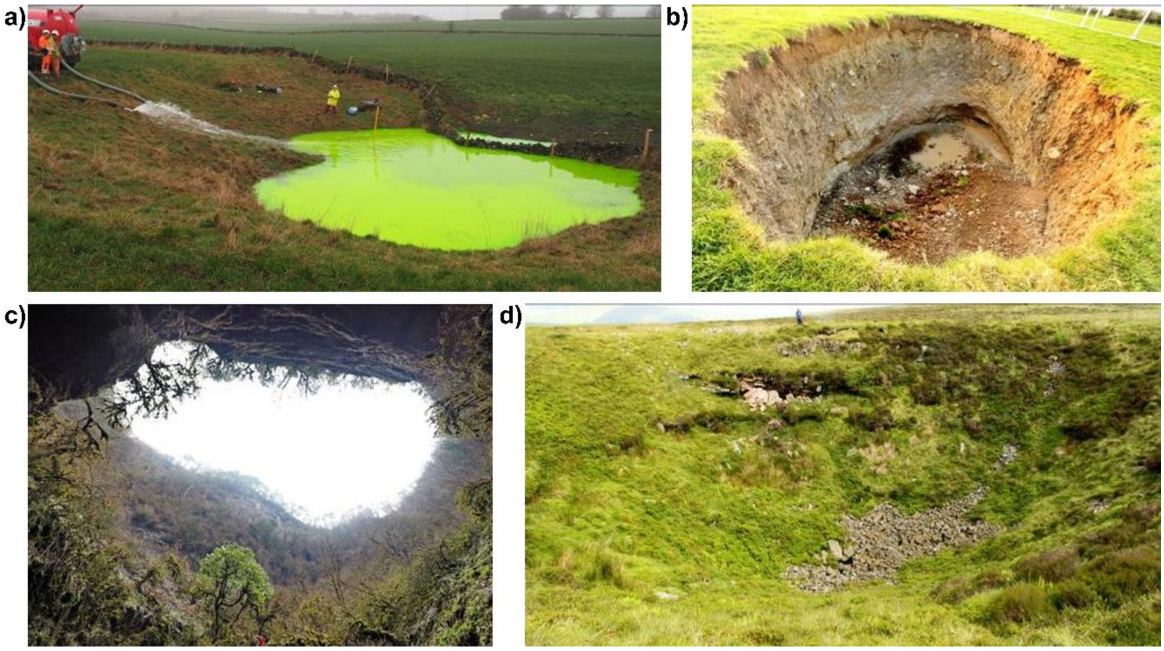

Figure 26 - a) Solution doline in Derbyshire, UK, into which sodium fluorescein dye is being injected to trace the path followed by groundwater; b) Dropout doline in Ireland; c) Boniu Keng tiankeng, a very large collapse doline in China (the caver in red at bottom centre provides scale); and d) Caprock doline in sandstone overlying limestone in south Wales, UK (the person top centre provides scale) (photographs by J. Gunn).

Dropout and *suffosion dolines* are sometimes grouped under the heading *subsidence doline* as in both cases soil and superficial deposits subside into a solutionally enlarged void in the bedrock. They differ in morphology because in non-cohesive soils the deposits are gradually washed into the void forming a conical suffosion doline. In more cohesive materials, a void forms close to the soil-bedrock interface and propagates upwards until the roof becomes unstable and fails, forming a steep-sided dropout doline (Figure 23, Figure 26b). These are particularly hazardous as the void may grow over a period of months to years without any surface manifestation, but the final collapse is instantaneous.

Poljes

Poljes are the largest surface features in karst (Figure 27, Figure 28). The term originated in the Dinaric Karst and there are around 130 poljes in this region (Slovenia, Croatia, Bosnia and Herzegovina, and Montenegro). They are elongated (from one to tens of km long), steep-sided landforms with extensive flat floors that are up to 500 km^2 in area. Most are closed depressions that drain underground but—in some cases—they are drained by a surface watercourse (*open polje*). In the Dinaric Karst, and in most areas with poljes, their long axis is aligned with structural trends. There are many varieties of polje, but most have a thick sequence of sediments on their floor across which perennial or, more commonly, intermittent streams flow, fed by springs. In *closed polje*, these streams drain underground at one or more swallow holes (*ponors*) during those periods when the regional groundwater elevation is less than the elevation of the polje floor. In most closed polje, there are periods when surface water inputs exceed the capacity of the swallow holes and lakes expand across the polje floor. If the regional groundwater level rises above that of the polje floor, the lakes are also fed by groundwater that rises from former swallow holes. These reversing springs are called *estavelles*.

Figure 27 - Popovo polje in east Herzegovina, one of the largest in Dinaric Karst. Before construction of an artificial drainage channel as part of a hydro-electric power system, the polje was flooded for more than 200 days annually by the channelized Trebišnjica River (visible on the right side of the photograph) (photograph by Z. Stevanović).

Figure 28 - The Cerkniško Polje in southwest Slovenia, which can extend over 26 km^2 and contain more than 80 million m^3 of water, is the largest karst polje in the Classical Karst (photograph by N. Ravbar).

2.3.3 Underground karst landforms

A cave is a naturally formed void in an earth material that is large enough for human entry. This definition distinguishes caves from artificial tunnels and other constructed underground voids that are sometimes incorrectly referred to as caves. The minimum void dimension is arbitrary, depending on the size of the human explorer, but a shortest diameter of 0.3 m is a reasonable approximation. Caves are found in many different types of rock, and some are formed in unconsolidated deposits, but globally the majority are formed where groundwater dissolves rocks, primarily carbonate rocks but also evaporites and more rarely silicates. In this book, only karst caves that formed by dissolution of carbonate rocks are discussed. These caves originated in two settings: epigenic and hypogenic (as discussed in Section 2.3).

Epigenic Caves

Caves in epigenic settings are those parts of present or past karst groundwater systems that are accessible to human explorers. They developed alongside the land surface, and they are, or were, fed by tributary conduits that are centimetres in scale. There are four main phases in their development: inception, gestation, growth, and abandonment, followed in some cases by destruction.

Inception. In most carbonates the intergranular porosity is very low and in those carbonate rocks that have a high intergranular porosity (such as chalks), the pores are commonly so small that there is little to no intergranular permeability. Consequently, most carbonate rocks are virtually impermeable at the scale of an individual block prior to the development of dissolutionally enlarged pathways. However, water can move slowly through an interconnected network of small voids including joints, fractures, faults, bedding plane partings, and other discontinuities. Initial flow is distributed along these interconnected fissures, which are then subject to dissolution. This is the inception phase, which represents the change from "rock with no conduits" to "rock with conduits." Some discontinuities may be especially prone to early dissolution by virtue of their physical or geochemical characteristics or, in the case of rocks with a higher matrix permeability, because they promote lateral flow and mixing corrosion which occurs where waters with different chemical properties mix (Ford & Williams, 2007, page 59). These *inception horizons* can be bedding planes, thin shale bands, volcanic ash layers, hardgrounds, or flint/chert bands. Once water flows through the rock, dissolution can commence. When chemically aggressive water enters the rock via fractures, the initial rate of dissolution is rapid. However, the rate of dissolution is not linear and slows markedly as the water approaches saturation with carbonate. This enables slow dissolution to take place along the entire length of a flow pathway from input to outlet such that preferred flow pathways (channels) evolve. Dissolution can be augmented when water of different chemical compositions mix. Following inception, there are three phases in the life of an epigenic cave: gestation, development, and abandonment, the latter phase being followed by destruction.

Gestation is the period when small channels grow to accessible caves. During gestation, some channels attract an increasing percentage of the flow and hence grow larger than those channels with less flow. Gestation ends when two conditions are met: first, the channel penetrates through to an open void, either an existing section of cave passage or the land surface and, second, it grows large enough to permit turbulent flow (around 10 mm). At this point, there is a sudden transition (often termed *breakthrough*) with much more rapid dissolution along the entire flowpath and a commensurate increase in the enlargement rate. Breakthrough marks the point at which a channel becomes a conduit and the start of the development phase. Once a particular flow pathway has achieved breakthrough, it will rapidly enlarge, capturing flow from adjacent fractures and channels. These alternative flow pathways then cease to enlarge or are redirected toward the conduit that has achieved breakthrough. Over time, some of these redirected pathways also develop sufficiently to achieve breakthrough, leading to the self-organization of an integrated conduit network. Given continued flow, these early conduits can continue to enlarge to the point where they become large enough to be accessible to humans. Only then can the conduit be classed as a cave. The time for conduit enlargement after breakthrough is rapid, and caves can reach human size within a few thousand years.

During the *development* phase, the cave is occupied by flowing water and is actively growing. Initially the cave is water-filled, and the roof, floor, and walls enlarge at approximately the same rate forming a phreatic tube (Figure 29a).

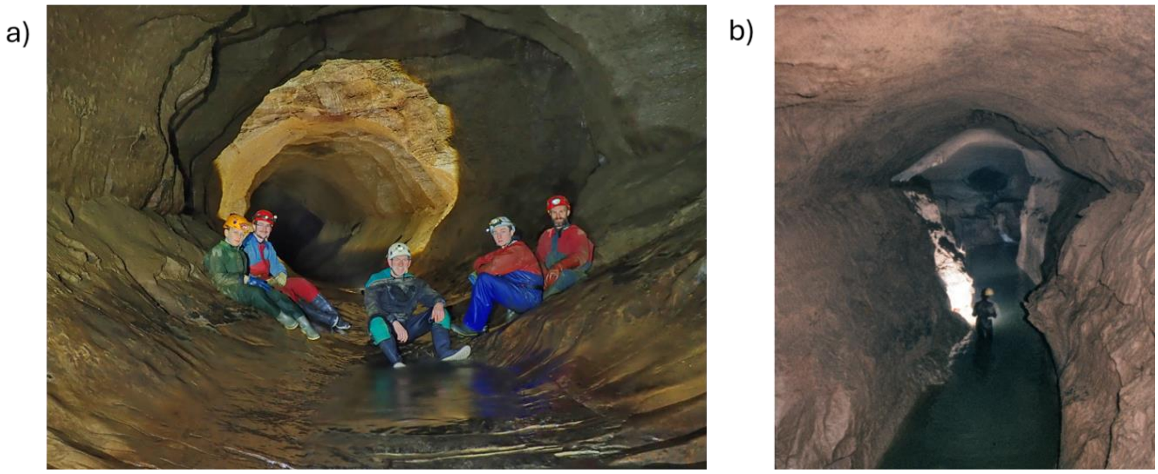

Figure 29 - Examples of epigenic cave passages in Peak Cavern, Castleton, UK: a) is a drained phreatic tube with no incision; b) shows a "keyhole passage" with a vadose canyon below a phreatic tube. Further information is provided in the text of this section (photographs by J. Gunn).

Groundwater flow and epigenic cave development are influenced by glacial–interglacial climatic variations, base level lowering, and valley incision. As the landscape changes over time, particularly in response to glacial–interglacial cycles, the extent of limestone exposed at the land surface may also change, together with the location and number of any stream sinks and springs. Valley incision increases the hydraulic gradient and may result in the floor of a phreatic cave passage becoming incised more rapidly than the roof, forming a keyhole passage in which there is a vadose canyon below the former tube (Figure 29b). As a passage enlarges, it may become too large for the roof to support the weight, leading to collapse and the formation of a more stable arch shape. Where material collapses into an active vadose stream, it is removed in solution or suspension and the passage continues to enlarge. Ultimately, the roof may become sufficiently close to the lowering land surface that collapse occurs forming a collapse doline (Figure 30a).

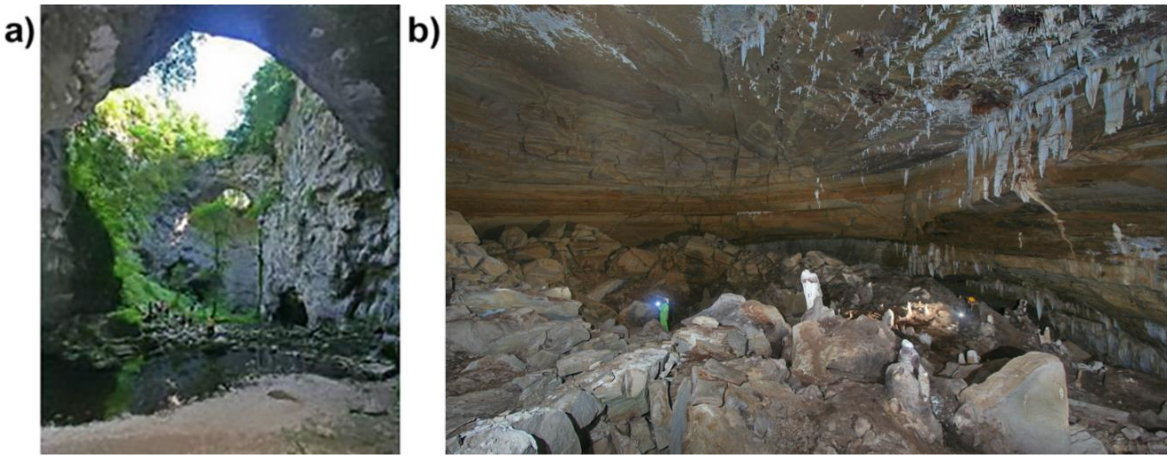

Figure 30 - Collapse processes in epigenic caves. a) Collapse doline and natural arch over an active cave stream, Rakov Škocjan, Slovenia. b) Roof collapse and accumulation of rocks in relict passage, Goda Mea Cave, Ethiopia (the person in green provides scale) (photographs by J. Gunn).

An incising valley may intersect lower elevation inception horizons, conduits, and—in some cases—cave passages, enabling new springs to develop and resulting in *abandonment* of higher-level passages. When a passage has been abandoned by its formative stream, it is relict, although it may still receive groundwater as percolation resulting in the deposition of speleothem (Figure 31). In a relict cave, any material that collapses from the roof or walls will remain in situ **(**Figure 30b). Relict passages may be reactivated if there is a change in groundwater elevation—for example, if lower elevation passages become partially blocked by sediment. As uplift and erosion continue, the higher elevation relict cave passages will eventually become unroofed (Figure 32) and, finally, be destroyed.

Figure 31 - Calcite dripstone speleothem in Waipuna Cave, Waitomo, New Zealand, provide evidence of groundwater inputs to relict cave passage (photographs by J. Gunn).

Figure 32 - Unroofed cave from which sediment fill has been removed on the route of a highway development in Slovenia (photograph by J. Gunn).

Although the inception, gestation, development, and abandonment phases are sequential, they are commonly all present within a single cave system. For example, inception processes may be slowly enlarging channels that are tributary to conduits that discharge into a cave stream. The active stream passages may lie beneath abandoned upper levels that—although relict in the sense that they are no longer enlarging—continue to develop both by growth of speleothem and by breakdown (cave deposits are discussed in the following section).

Hypogenic Caves

These caves and associated voids and conduits, form at depth without any direct genetic linkage with the overlying or immediately adjacent land surface. The fluids that dissolve the rock may originate from distant sources, being confined by less permeable rocks, or from deep (up to several kilometres) sources, in which case they are commonly thermal. As the formative processes are decoupled from the overlying land surface, hypogenic caves can only be entered if they are intercepted in mines or if the lowering land surface intersects the highest parts of the cave. Most known hypogenic caves are relict, but those in limestones that crop out at the surface commonly receive percolating groundwater, as evidenced by extensive speleothem deposits (Figure 33). Fluids rising from depth into carbonate rocks commonly form non-strata bound voids that are vertically extensive: for example, Lechuguilla Cave (> 242 km of explored passage, maximum depth 484 m) and Carlsbad Cavern (> 63 km of explored passage with a maximum depth of 315 m), both of which lie in the Carlsbad Caverns World Heritage Site, New Mexico, USA. Both caves have a single entrance that is markedly smaller than the underground passages and was formed by collapse with no evidence of water entry. Both are relict and both were formed by sulfuric acid speleogenesis. In Carlsbad Cavern, extensive speleothem deposits provide evidence of significant groundwater percolation in the past (Figure 33).

Figure 33 - The Big Room is the largest chamber in Carlsbad Cavern, a hypogenic cave in New Mexico, USA (photograph by J. Gunn).

In contrast to these deep voids, hypogenic maze caves are formed by the slow upward flow of acidic water through a soluble rock that is overlain by, or sandwiched between, less soluble rocks. This is a type of cave development known as *transverse hypogenic speleogenesis*. The Hudgill Burn Mine Caverns cave systems, Cumbria, UK (Figure

34) is a good example of a hypogenic maze cave with over 13 km of mapped passages in an area of only 34,000 m^2. The 17.4 m thick limestone bed is sandwiched between beds of sandstone and shale. The cave is entirely relict with no groundwater and was discovered by lead miners who broke into it in the late 1800s.

Figure 34 - Hudgill Burn Mine Caverns, Cumbria, UK, a hypogenic maze cave (photograph by J. Gunn).

Cave Sediments

There is an extensive literature on the various types of chemical, clastic, and organic sediments found in caves and on the many cave minerals (e.g., Fairchild & Baker, 2012; Hill & Forti, 1997; Springer, 2019). In this book, we only consider the most common types and focus on those that are associated with groundwater. The general term *speleothem* is used to describe mineral deposits that grow within caves. The majority are calcareous, formed largely of calcium carbonate and composed of the minerals calcite and/or aragonite, although many gypsiferous speleothems are also formed, largely of calcium sulphate. Calcareous speleothems form when groundwater entering a cave loses carbon dioxide and becomes saturated with calcium (and sometimes magnesium) carbonate. The two most common types are dripstones and flowstones. Dripstones form when groundwater enters through the cave roof, with stalactites growing down and stalagmites growing up (Figure 31, Figure 33). Flowstones are more continuous deposits that accrete from thin sheets of groundwater on the cave walls and floor (Figure 35).

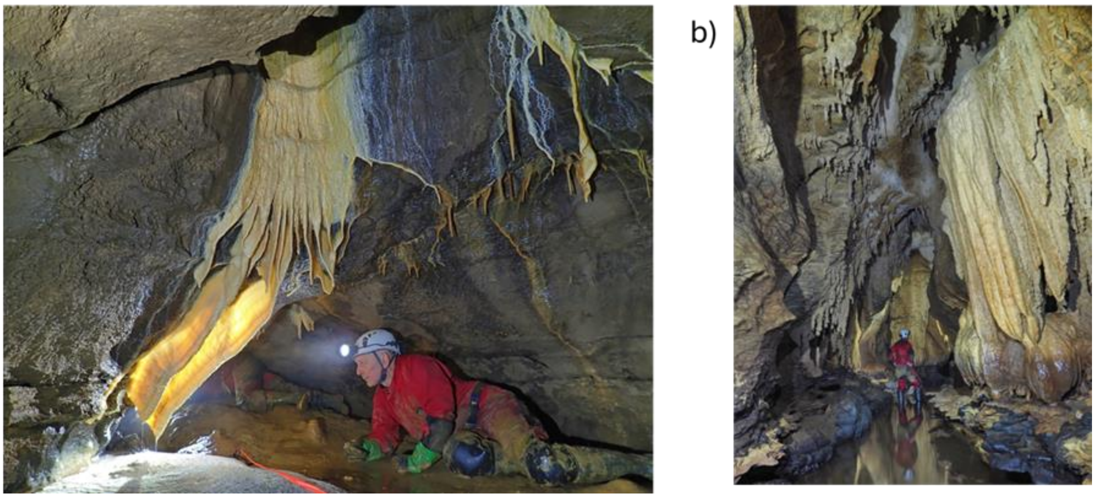

Figure 35 - Calcite flowstone deposits: a) Convenience Cave, Castleton, UK; b) Mangapohue Cave, Waitomo, New Zealand (photographs by J. Gunn).

Clastic sediments in caves range in size from fine clays to boulders several metres long. They may be divided into two groups: autogenic sediments and allogenic sediments. Autogenic sediments are derived within the cave, most commonly by spalling off the passage roof or walls (Figure 30). In most cases, groundwater does not play a significant role, but where the cave air temperature oscillates around the freezing point, rock may be detached by freeze–thaw of percolating groundwater. Allogenic sediments are derived from outside the cave and are transported in by groundwater, most commonly via sinking streams (labelled 1 in Figure 13) but also via shafts below dolines (labelled D in Figure 13) and in much smaller quantities via vadose flows (labelled E in Figure 13). Figure 36 illustrates the range of sediment sizes transported by sinking streams. The finer material is commonly transported through cave systems; springs that are fed by sinking streams are typically turbid, particularly at times of flood (Figure 37; Figure Box 5-1 of Box 5).

Figure 36 - Allogenic clastic sediment deposits. a) Fine silt in Speedwell Cavern, Castleton, UK. The caver is pointing at a mark left by a flood event a few days before the photograph was taken. b) A relict sediment sequence that contains cobbles with a long axis up to 15 cm in Lagangs Cave, Mulu, Malaysia. c) Gravel bar in Gardner's Gut Cave, Waitomo, New Zealand (photographs by J. Gunn).

Figure 37 - Both a) and b) show how, during a flood, the sediment in Speedwell Cavern is mobilized and transported to the pictured spring named Russet Well, Castleton, UK (photographs by J. Gunn).

A wide range of organic materials can be found in caves, some derived from outside and some originating within the cave. Material from outside may be washed in by water (e.g., trees and plant debris), blown in by wind, or may fall into an entrance. Within a cave, excreta from bats and birds are a major source of organic material and guano deposits several metres thick have accumulated. Organic material forms the nutrient base for some of the large range of biofilms that are found in caves, possibly in greater diversity than in surface environments. Other biofilms are associated with inorganic sources of energy, most notably reduced sulfur, iron, or manganese. Biofilms can form in both static groundwater and flowing groundwater, as well as on humid surfaces where there is no running water.

3 Karst Aquifers

In porous media such as sand and gravel, water freely circulates through the pores between sediment grains; in fractured rocks, tectonic voids provide routes for groundwater. Groundwater in carbonate rocks will also occupy, and flow through, intergranular or tectonic voids, but the diagnostic feature of karstic aquifers is that over time these routes are enlarged by dissolution producing a tertiary conduit porosity and permeability. While groundwater may be stored in primary or secondary porosity, in karst systems most groundwater flows through conduits, both vadose conduits (partially air-filled and analogous to *surface streams with a roof*) and phreatic conduits (water-filled). Therefore, a karst aquifer is an atypical groundwater-bearing medium with tertiary porosity, anisotropy, and heterogeneity. Water flows through the intergranular porosity and narrow fractures at low velocities in the laminar regime, commonly referred to as diffuse flow. In contrast, more open fractures and conduits (generally those > 10 mm wide) commonly support larger flow at higher velocity, which can be under either a laminar or a turbulent flow regime. This is commonly referred to as *conduit flow* (Figure 38). Laminar and turbulent flow is discussed in Box 7↴.

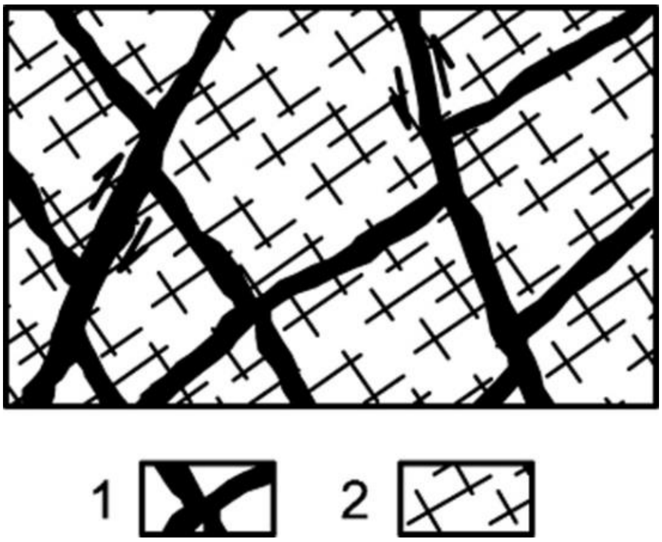

Figure 38 - Karst conduits (1) and the intergranular and fracture porosity (grouped as the matrix) (2) in a segment of karstified rock. The type of porosity dictates the type of flow, which is either conduit (largely turbulent) or diffuse (laminar).

In confined aquifers, the water altitude in a borehole or a piezometer represents the hydraulic head with respect to a common vertical geodetic datum. When there are enough boreholes and piezometers spread spatially within the same confined aquifer and water levels can be measured at all of them within a relatively short period of time, the heads are mapped and contoured to create a *potentiometric surface* for the aquifer for that time. The potentiometric surface represents the altitude at which water would have stood in a tightly cased well at any location within the aquifer at that time. Each potentiometric contour represents a line where the hydraulic head is the same within the aquifer. The change in the potentiometric level relative to distance is called the *hydraulic gradient*. Figure 39 shows a cross section of a karst aquifer where the boreholes have intersected conduits at different levels and distances from the outlet spring within the saturated zone of the karst system. All the conduits meet near the spring outlet and will have the same hydraulic head as the spring altitude closer to the spring and higher heads further from the spring, indicating water moves from higher head to lower head. With typical porous media aquifers, flow directions can be determined by drawing flow lines perpendicular to the potentiometric contours with the arrow pointing from higher head to lower head. For karst systems with conduits, flow is from higher head to lower head, but often the majority of the flow is within conduits that may not be along the flowpaths drawn on the potentiometric contour map (Figure 39, Box 8↴).

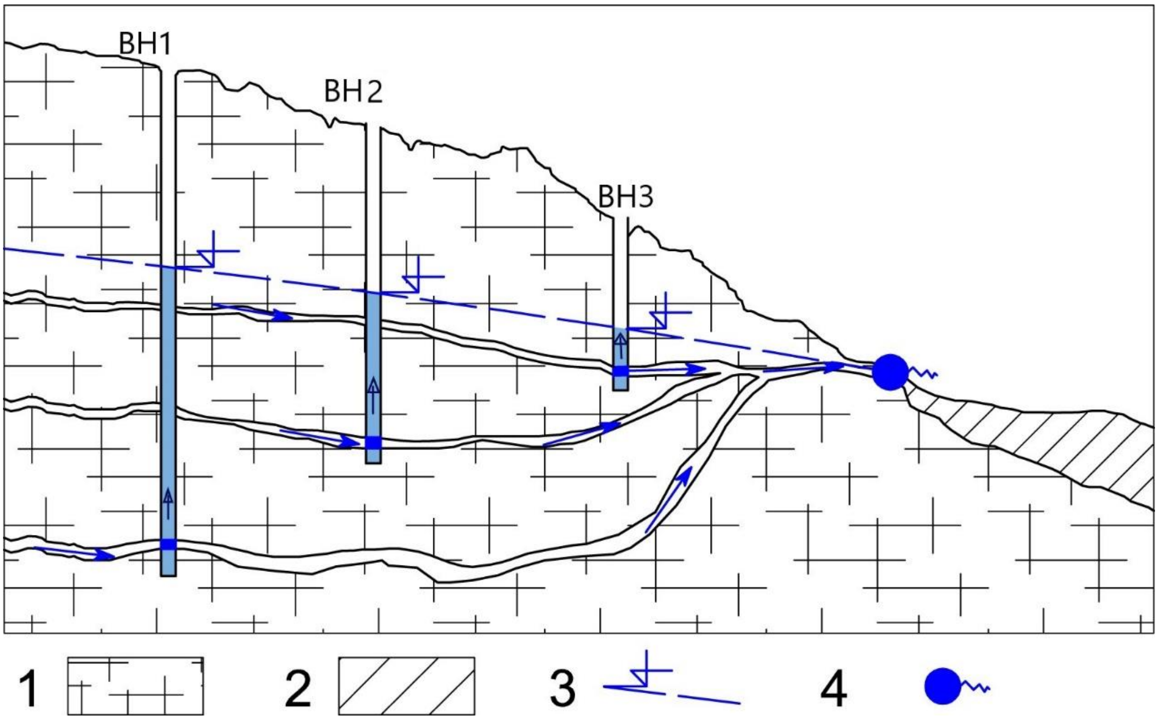

Figure 39 - A complex system of conduits at different elevations in an intergranular/fractured matrix resulting in various groundwater elevations (hydraulic heads) in a single karst aquifer. The potentiometric surface shows the groundwater elevation in drilled boreholes that intersect conduits. Each borehole intersects just one conduit and is isolated from the two others. BH1 captures the deepest conduit and BH3 the shallowest. The potentiometric surface extends as an imaginary line through the rest of the aquifer, including compact blocks that are devoid of water (unsaturated zone). Legend: 1. Limestone, 2. Impervious rocks, 3. Hydraulic head (potentiometric surface), 4. Spring.

Figure 40 shows the elements of a typical karst aquifer (sometimes referred to as a karst groundwater system) as they are commonly understood by modern karst hydrogeologists, where the aquifer is seen as a complete section of soluble carbonate or evaporitic rocks that can store and transmit significant quantities of groundwater. A complete section means that even the unsaturated part called the *vadose zone* is a part of the aquifer including the epikarst (subcutaneous zone), where percolation of infiltrated or temporarily stored water occurs.

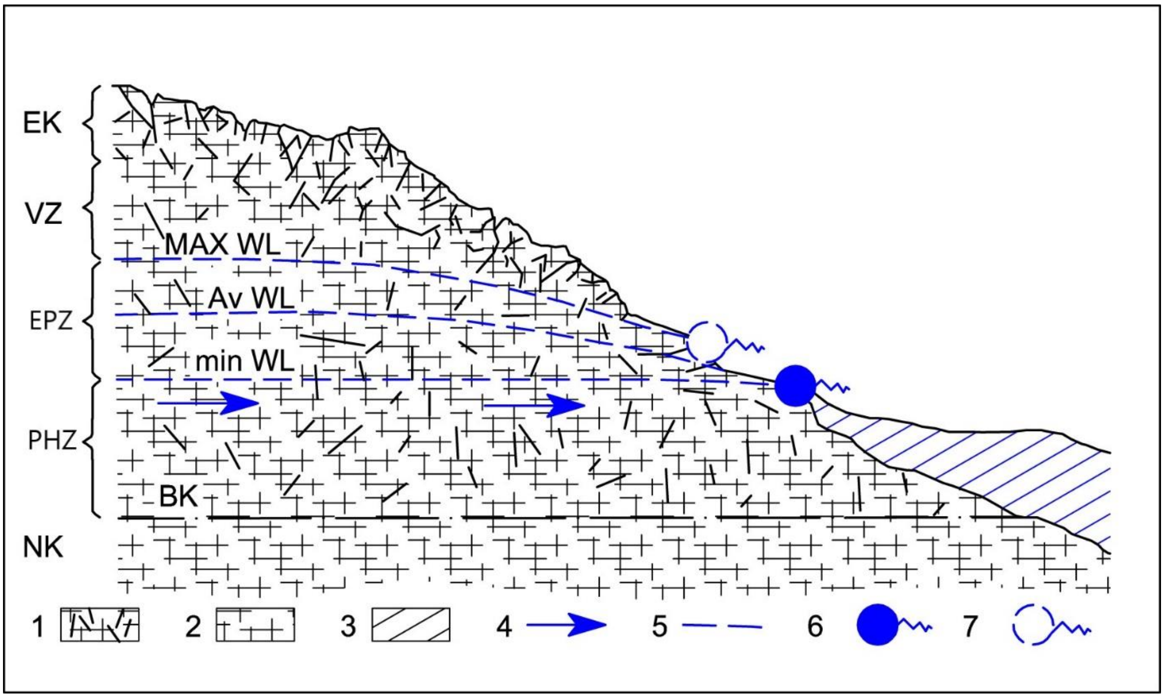

Figure 40 - Cross section of a karst aquifer. Legend: 1=Karstified rocks, 2=Non-karstified rocks in deeper zones (NK), 3=Impervious rocks, 4=Direction of groundwater flow, 5=Groundwater potentiometric surface (groundwater elevation), 6=Permanent spring, 7=Temporary spring, EK=Epikarst, VZ=Vadose zone, EPZ=Epiphreatic zone, PHZ=Phreatic zone, BK=Base of karstification, MAX WL=Maximal water level in high-water season, Av WL=Average water level, min WL=Minimal water level in low water season or during a drought.

Significant quantity (as used in the definition of an aquifer) is a relative term, so some authors suggest the use of terms such as *economical quantity* or *large quantity* (White, 2002). However, it would be better to compare the available water quantity with the potential water supply. For instance, the Water Framework Directive of the European Union (EU, 2000) introduced a category *water body* (similar, but not identical, to an aquifer), which could be delineated and monitored if it serves more than 50 people or provides more than 10 m^3/day.

3.1 Karst Aquifer Distribution and Boundary Conditions

For various practical purposes such as the utilization or protection of groundwater, it is necessary to estimate the boundaries and, hence, the size, of karst aquifers. There are two types of aquifer boundaries: physical and hydrodynamic.

Physical boundaries can be lateral (horizontal) and vertical. The boundary may be a disruption in the lithological continuity or a contact with another rock formation. Contact between rock formations can be stratigraphic or tectonic (e.g., a fault). The base of karstification is commonly at the contact between the karst rock and rocks of lower permeability. In general, porosity and permeability decrease with depth, but air-filled caves have been explored at depths of over 2,000 m below the land surface and boreholes have intercepted conduits with active groundwater circulation at depths of over 3,500 m.

In karst, there is commonly a difference between surface (topographic) and subsurface catchments and there are many examples of how incorrect calculation of the catchment surface area has resulted in erroneous technical estimates—for instance, the volume of water in the system, peak discharge, or volume of water available for exploitation. An example of the difference between a topographical and subsurface divide is illustrated in Figure 41. A further problem in estimating the size of a spring catchment is that divergent drainage—where a sinking stream drains to more than one spring—is common in karst (e.g., Figure 14).

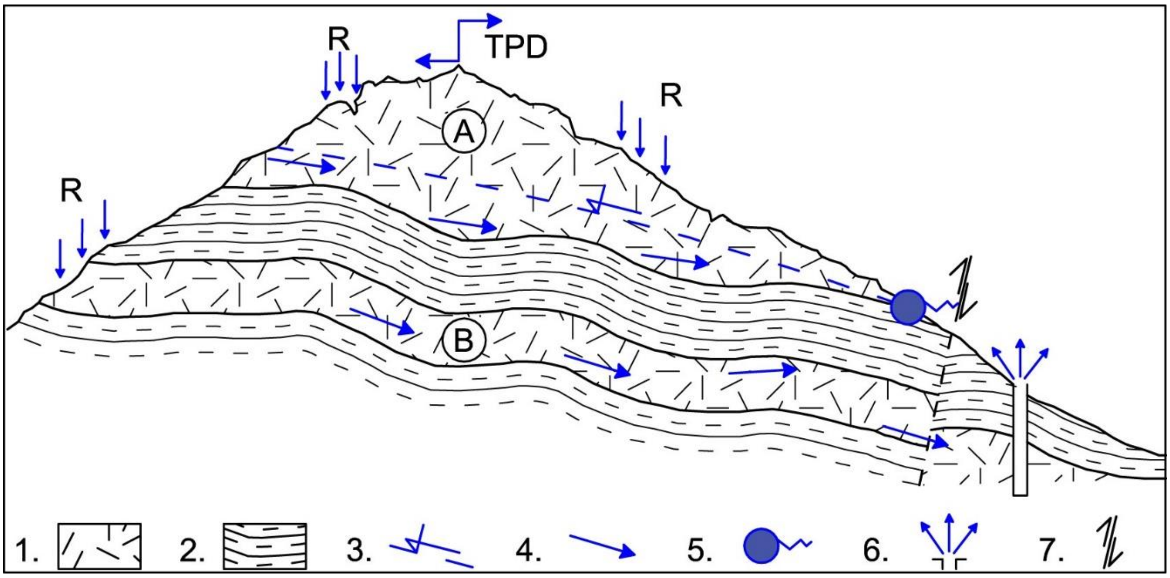

Figure 41 - Cross section of two disconnected karst aquifers: unconfined (A) and semi-confined (B). Both are recharged by rainfall (R). The topographic divide (TPD) and the recharge area of karst aquifers (R) are considerably different, and the latter is much larger. Legend: 1=Karst aquifer, 2=Low permeable marlstone, 3=Potentiometric surface, 4=Direction of groundwater flow, 5=Spring, 6=Artesian well, 7=Fault.

Hydrodynamical boundaries can be permeable, semi-permeable, or impermeable. A boundary is fully impermeable when a karst aquifer is in contact with impervious rocks that form a barrier to groundwater flow, while permeable or semi-permeable barriers are relative so the flow continues but at a slower rate for a semi-permeable barrier. The velocity of karst flow may increase or decrease depending on the permeability of rocks in contact with the aquifer (Figure 42). Box 9➘ provides a few examples of adjacent karst aquifers.

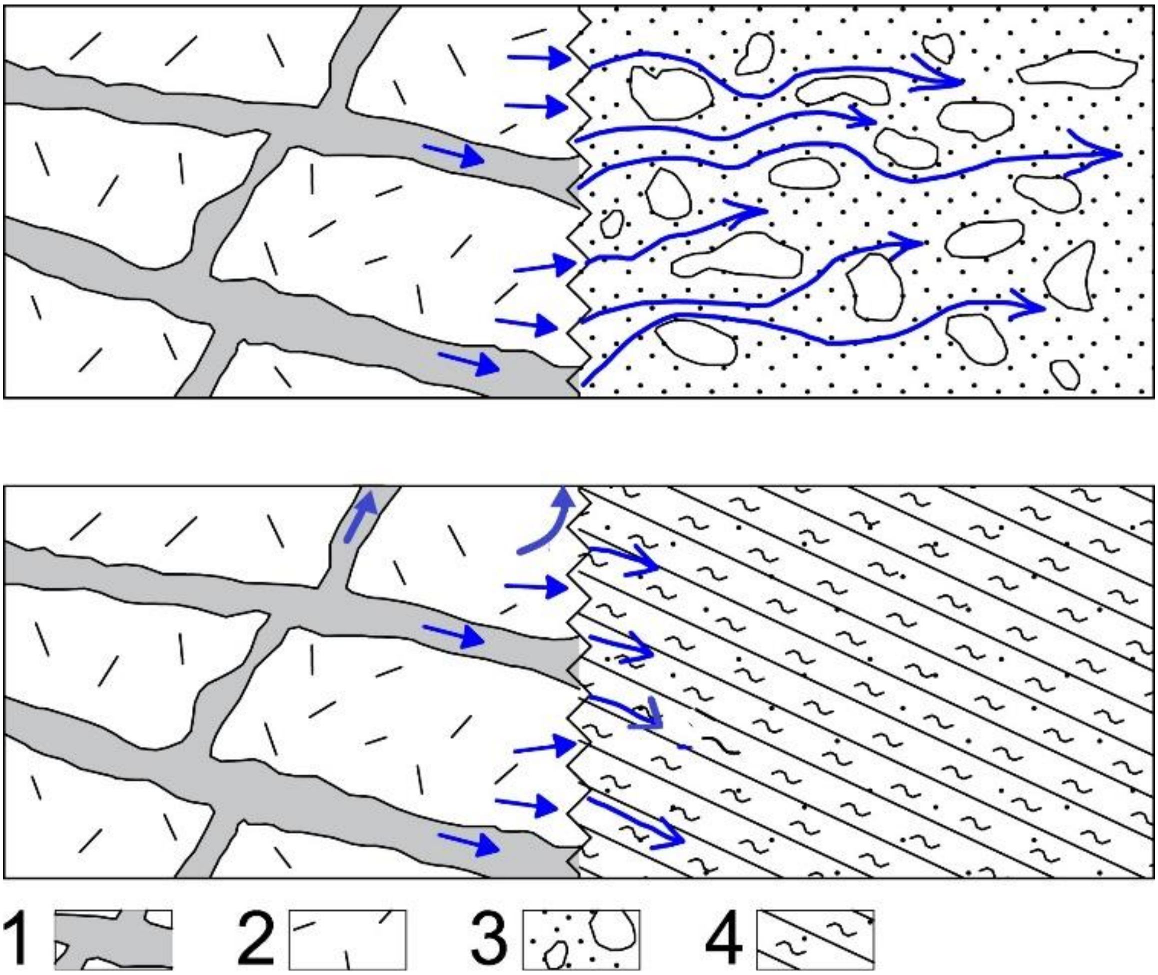

Figure 42 - Lateral permeable boundary between karst and non-karst water-bearing media. More intensive infiltration of karst water and flow velocity occurs in contact with more permeable intergranular aquifer (upper case). Legend: 1=Karst conduits, 2=Karst matrix (diffuse flow), 3=Gravel and sand (intergranular aquifer of high permeability), 4=Sandy clay (intergranular aquifer with lower permeability than the karst).

In common with other aquifers, the hydrodynamic properties—hydraulic conductivity (K), transmissivity (T), and storativity (S)—of karst aquifers can be determined through various field tests (pumping, slug, injection) or laboratory experiments. However, the results obtained should be treated with caution and used for comparison of relative transmissivity or storage in karst aquifers due to their anisotropy and heterogeneity. Especially important among these parameters is the storativity (S), historically called storage coefficient, which indicates the storage capacity of the aquifer and its potential water reserves. An explanation of the limitation of Darcy's Law (1856) in karst is provided by Krešić (2013). He explains the velocity can increase or decrease along the same pipe (conduit) as the cross-sectional area increases or decreases. Flow velocity decreases due to widening of cross-sectional area.

Four broad aquifer types can be identified based on the geological structure and hydrodynamic conditions:

- unconfined karst aquifer,
- confined karst aquifer,
- semi-confined karst aquifer, and
- perched karst aquifer.

Unconfined karst aquifers are characterized by a free water level in karstic voids or groundwater surface in the fissured rock matrix that is equal to the atmospheric pressure. Confined karst aquifers are sandwiched between lower permeability rocks. An example is shown in Box 10↴. If the aquifer is unconfined), the hydraulic head may be sufficient to raise the groundwater level above the base of the overlying bed and/or above the ground surface when it is penetrated by a borehole. However, it is also possible for there to be extensive vadose flow networks in karst rocks that are overlain by thick sequences of lower permeability rocks. Semi-confined karst aquifers contain both confined and unconfined sections. A perched karst aquifer, by definition, is separated from the main aquifer by an unsaturated zone. It typically forms on top of layers or zones of lower permeability or lower degree of karstification; in many cases, the epikarst zone forms a perched aquifer, as it is separated from the main aquifer by an unsaturated zone.

Catchment size can be estimated based on the results obtained from water budget calculations, especially the total amount of discharged groundwater (Goldscheider & Drew, 2007). However, field hydrogeological surveys and tracing tests remain the essential methods for the assessment of karst surface geometry and delineation of catchment boundaries.

Tracing tests are the only reliable method for defining groundwater flow direction and pattern in karst. They were first used in hydrogeological practice near the end of the nineteenth century, when 10 tonnes of $NaCl$ was injected into the upper catchment of the sinking Danube River near to the location shown in Figure 20, followed (also for the first time) by the now widely used dye called Uranine (sodium fluorescein: Knop, 1878; Hötzl, 1992; Figure 43). Tracing is very important in karst as a single input point (e.g., doline, ponor, borehole) may drain to springs that are hundreds or even thousands of metres apart as shown in Figure 14.

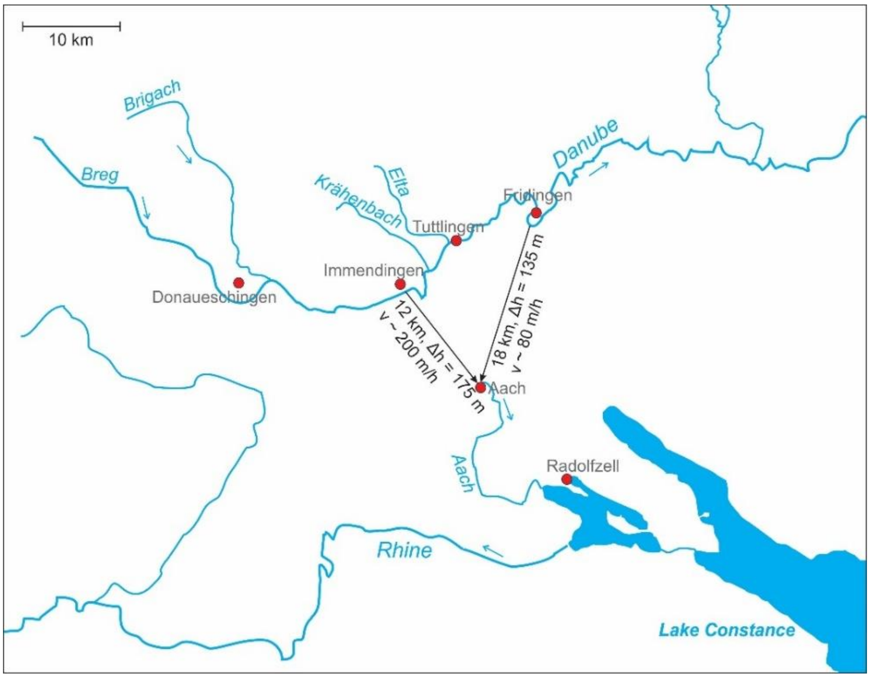

Figure 43 - Sketched map showing the result of a tracing test in the Upper Danube catchment. The tracer injected in ponors in the Danube riverbed near Immendingen and Fridingen appeared at the Aach karst spring in the Rhine basin, demonstrating groundwater piracy between two large European river basins.

Tracers are usually injected into ponors (swallow holes), dolines (Figure 26a) or drilled holes. Box 11↴ provides photographs of dye introduction and flushing. Tracers can also be placed directly on or beneath the soil surface of karstified rocks to: estimate connections with springs or diffuse discharge zones; quantify apparent linear flow velocities; and obtain information on rock–water interaction, contaminant transport, and attenuation capacity of the aquifers (Benischke et al., 2007; Goldscheider et al., 2008; Benischke, 2021). Apparent velocity is the linear distance between the injection and monitoring locations divided by the time required to reach the output. The field velocity is higher because the flow path is longer than the linear distance between the injection and monitoring locations (i.e., the numerator is larger). The most common tracers are fluorescent dyes such as optical brightening agents (OBA), Uranine (sodium fluorescein), Eosin, Rhodamine WT, Sulforhodamine B and Amidorhodamine G. Tracers should be non-toxic, chemically stable, economical, and easily detectable in small concentrations (Käss, 1998). Some particles such as spores and bacteriophages are also used as tracers in hydrogeological practice. It is important that all points where tracer may potentially emerge are monitored and not just the points where it is expected to emerge. Box 12↴ provides additional information on tracer tests with examples from the Dinaric karst. Together with the calculation of apparent velocity, the construction of a breakthrough curve enables quantitative analysis of the hydrodynamical, physicochemical, and biological processes to which the tracer was subjected in the karst as discussed in Box 13↴.

It is good practice to repeat tracing tests under different groundwater elevations to assess the catchment size fluctuations. The phrase "*catchment size fluctuation*" sounds strange, but in karst it is common for catchment boundaries to expand and contract depending on the antecedent effective precipitation (Göppert & Goldscheider, 2008; Stevanović, 2015). During times of high recharge, the discharge of springs is much larger and this may reflect the catchment becoming larger. For example, in Castleton (UK) there are three springs in close proximity, two at the same elevation and known to be hydraulically connected and one at a higher elevation. For most of the year the higher elevation spring is supplied by an autogenic catchment and has a lower flow than the other springs which drain a mixed allogenic-autogenic catchment. However, at times of high recharge the conduits that supply the lower elevation springs are surcharged and water rises to a normally dry conduit and enters the conduit that supplies the higher elevation spring. This greatly increases the catchment area draining to, and the flow from the higher elevation spring. A contrasting situation occurs when the catchment surface area becomes smaller during floods due to an overflow toward an adjacent catchment, which is inactive during the dry season (Ravbar et al., 2011; Figure 44). Such hydraulic conditions can be discovered using tracing tests.

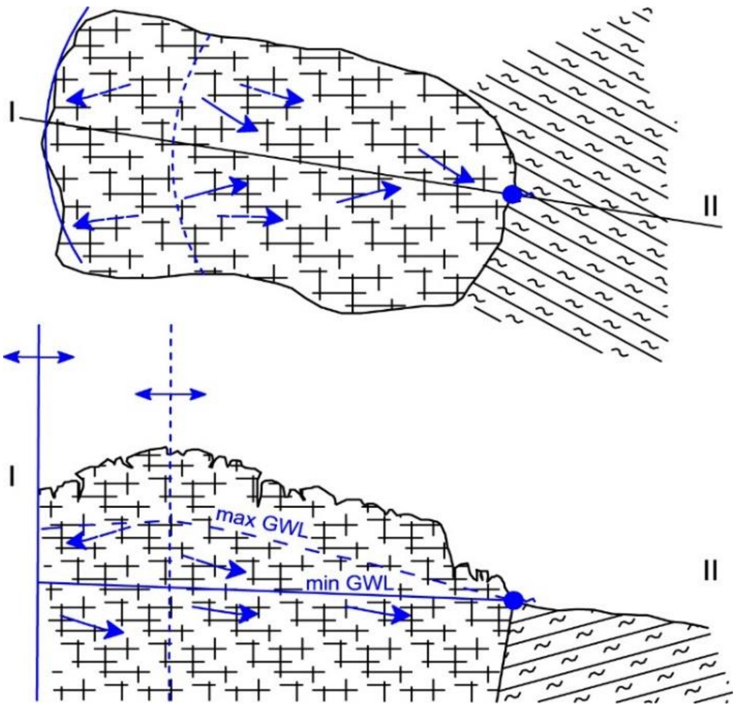

Figure 44 - Changeable surface area of a karst aquifer. At maximal groundwater level (max GWL shown by the dashed blue line), infiltrated water flows in two directions and the main catchment on the right with an active spring is smaller. The area is shown to the right of the divide in the plan view. At minimal water level (min GWL shown by the solid blue line), the groundwater flow is exclusively oriented toward the main spring orifice with the entire karst area shown in the plan view contributing to the spring. The catchment is larger in size despite the smaller amount of water being discharged (modified from Stevanović, 2015).

3.2 Recharge in Karst

Infiltration is the process by which water enters the soil through the soil surface. Part of the infiltrating water can be retained and increases the soil moisture, and another part moves down through the soil and subsoil and continues down through the underlying rock (a process commonly called *percolation*), eventually arriving in the saturated zone. Precipitation that reaches the saturated zone is called *recharge* because it replenishes the groundwater store. These principles, well established in soil-covered permeable rocks, cannot be simply applied to karst groundwater systems. For example, bare rock at the surface is more common in karst than in most other systems and in these areas, water enters the ground directly without *infiltrating* in the sense that the word is commonly used. In addition, groundwater is commonly stored in the epikarst and the vadose zone (which can be hundreds of metres thick) as well as in the phreatic zone, and it is possible for precipitation to enter the ground, flow through the rock, and emerge at a spring without ever entering the phreatic zone (Figure 45). For this reason, in karst the term *recharge* has a volumetric meaning (the amount of recharge) and can also be used to describe the process by which water enters and moves through the karst rock to an output point, which may be a natural spring or a borehole. In common with other aquifers, recharge to karst may be natural or artificial.

Figure 45 - Spring at the exit of Mangapohue Cave, Waitomo, New Zealand. The cave can be followed from the ponor (sink) to the spring for over 1,100 m entirely in the vadose zone. The stream receives both allogenic recharge from a sinking stream and autogenic recharge from an area of polygonal karst (photograph by J. Gunn; taken during a period of exceptionally low flow).

Natural recharge is divided into *autogenic recharge* and *allogenic recharge*. Autogenic recharge is precipitation that has only been in contact with karst rocks whereas allogenic recharge enters karst rocks having previously flowed over or through non-karst rocks. Both types may be subdivided into *dispersed* (diffuse) and *concentrated* types. Dispersed autogenic recharge is supplied by precipitation that enters the karst rocks through a soil cover (if present) or directly into the bare bedrock. Autogenic recharge may be concentrated in dolines and in the epikarst which is described in Section 2, *Karst Environment*, and Figure 13. Allogenic recharge may be supplied by surface water (e.g., where streams and rivers flow from non-karst rocks onto karst and sink) or by groundwater where karst rocks are overlain by, or are in lateral contact with, permeable non-karst rocks. Recharge of allogenic surface water may be focused on a single point such as a ponor or stream-sink (Figure 13; Figure 21a, b; Figure 46; Figure 47) or the stream or river may lose flow over a reach (Figure 20; Section 2 *Karst Environment*).

Figure 46 - Ponors: a) the large Ponor Pandiralo, at the end of a blind valley (Timok basin, Carpathian karst of eastern Serbia) and b) a river disappearing into a large ponor (Xiangqiao Geopark, Guanxi, China). (photographs by Z. Stevanović). c) The Tržiščica River, southeast Slovenia, flowing from a non-karst area and sinking on the contact with karst (photograph by N. Ravbar). d) Meltwater sinking into a small swallow hole, Tsanfleuron-Sanetsch, Switzerland (photograph by N. Goldscheider).

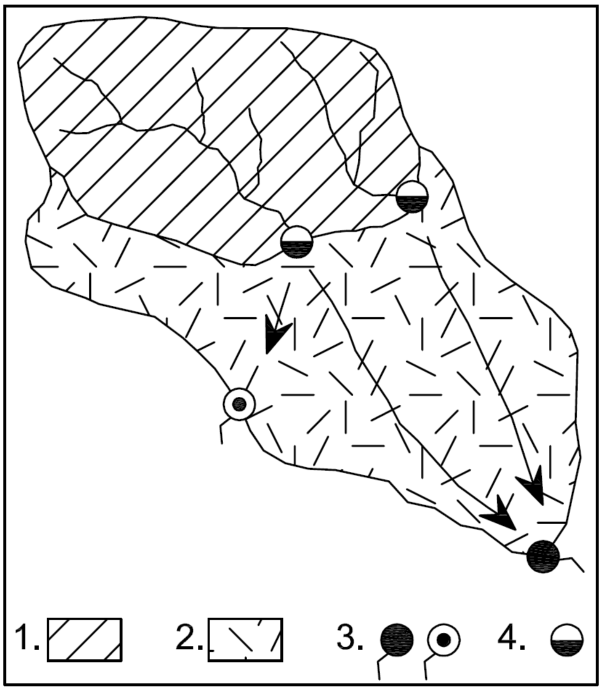

Figure 47 - A mixed allogenic-autogenic karst system. Perennial streams flow from the non-karst (allogenic) catchment and lose water via ponors located at the contact with karst. Some water from both ponors flows to one spring (convergent flow), but some of the west ponor's water flows to a different spring (divergent flow) (modified from Stevanović, 2015). Legend: 1. Non-karst terrain, 2. Karst aquifer, 3. Springs, 4. Ponor.

The primary factors that influence the portion of precipitation that becomes recharge are geology, soil, and vegetation. Box 14 provides estimates of the portion of precipitation that recharges in a few areas of Africa, Europe, and the Middle East. In areas with bare karst, topography is also important because where beds are sub-horizontal some precipitation may be stored on the surface, forming solution hollows (*kamenitza*; Figure 17) from which some water is lost as evaporation, whereas on steeper slopes water runs off more quickly. In both cases, the porosity/permeability of the rock and the extent of fracturing influence entry of water into the ground (Figure 48). Where the karst is covered by soil, the well-established principles of surface water hydrology apply. The maximum rate at which water can enter the soil is the *infiltration capacity* (IC) and if rainfall intensity (RI) is greater than IC, then *infiltration-excess overland flow* (IOF) is generated. Precipitation infiltrating into the soil contributes to the soil moisture storage and is either transferred laterally as *throughflow* (also called *interflow*) or moves downwards to enter the epikarst and vadose zone. Topography influences throughflow as steeper slopes are likely to have greater amounts of throughflow. If the entry of water is faster than the rate of lateral and vertical transfer, then the soil moisture store increases and the soil may become saturated. This reduces the IC and the excess water runs off as *saturation-excess overland flow* (SOF). Both IOF and SOF can be generated on the slopes of dolines and valleys in karst. In the case of dolines, there is no reduction in recharge because the overland flow enters the karst at the base of the doline (Figure 13), but if overland flow enters a surface stream that flows out of the karst area, then there is a loss of recharge. After a rainfall event the soil drains slowly under gravity until the *field capacity* is reached and after this point there is no gravity drainage, but *capillary water* can be removed by plants. During drought periods, all capillary water may be withdrawn, a condition referred to as the *permanent wilting point* (PWP). Rain falling after a drought must increase the soil moisture storage to above field capacity before recharge to groundwater can occur. Hence, a given amount of rain falling on a saturated soil will generate both SOF and recharge; the same amount of rain falling on a soil at PWP may generate neither recharge nor overland flow but may simply increase soil moisture storage.

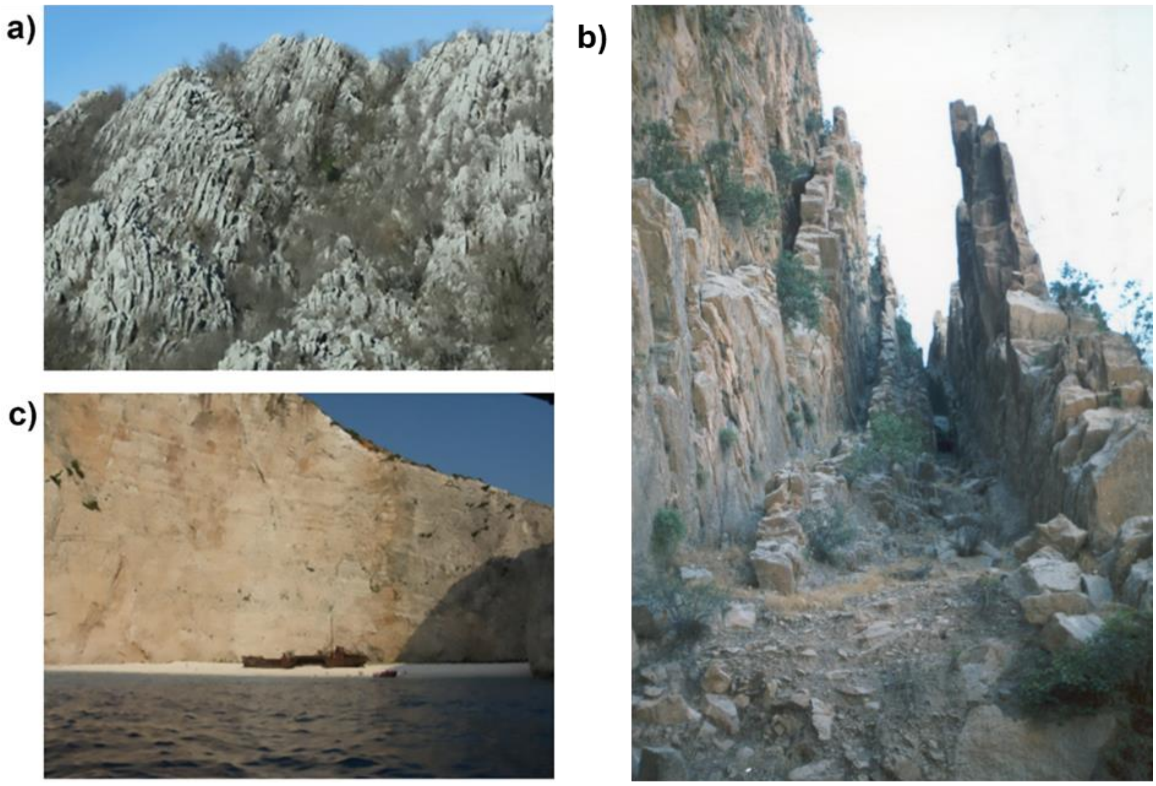

Figure 48 - Influence of geology on recharge: a) steeply dipping Cretaceous limestone in the Stone Sea above Risan, Montenegro; b) eroded vertical Miocene limestone with the highest recharge capacity in the Sulaimani area, northern Iraq near the border with Iran; and c) sub-horizontal Turonian limestone with long faults as preferred flowpaths at the famous Shipwreck Beach on the western shoreline of Zakynthos Island, Greece (photographs by Z. Stevanović).

Vegetation influences recharge to karst through evapotranspiration, the process by which plants return water to the atmosphere. Precipitation is intercepted by trees, shrubs and herbs/grasses and part of this intercepted water is returned directly to the atmosphere as evaporation. The remainder reaches the ground either as drippage or stemflow. As discussed above, the roots of plants (which may extend down into the epikarst and the vadose zone or even draw water from karst conduits) remove water from the soil and bedrock. Some of this water is used in growth and some is transpired. Thus, changes in land use have the potential to influence the amount and speed of recharge. For example, it is well established that trees use more water than grasses and hence conversion of forest to grassland is likely to increase recharge. The soil carbon dioxide concentration under grassland is commonly lower than under a tree cover so conversion of forest to grassland is also likely to reduce the rate of carbonate dissolution.

Artificial or managed aquifer recharge (MAR) is more common in water management of alluvial aquifers than in karst. MAR involves inducing inflow, with or without pressure, into an aquifer. Rather than MAR, artificial control or regulation is more common in karst aquifer regimes. It aims to stabilize or increase the lowest spring discharges, and is discussed in Section 4.4.2 *Engineering Control of Surface and Groundwater in Karst Terrain*.

Artificial recharge also occurs unintentionally. Water used for irrigation of agriculture or parks can lead to substantial increases in recharge (Younger, 2006). This may be the indirect result of soil watering or due to leakage from channels that convey the irrigation water. Such recharge is commonly termed *irrigation return flow*. Finally, urbanized areas on karst provide significant recharge to aquifers. Losses from water-conveying pipes range from around 10 percent to as much as 60 to 70 percent (in some undeveloped cities) and the large quantities of water lost this way can re-infiltrate the aquifer (Sharp & Garcia-Fresca, 2004).

Exercise 2↴ examines assessment of average effective recharge for a karst system.

3.3 Aquifer Discharge and Regime

Drainage from karst can be natural or artificial, the latter being via wells, galleries, or similar water intake structures.

There are three broad types of natural discharge from karst: point, linear, and dispersed. *Point discharge* from springs is more common in karst—and spring discharge is typically greater than in other rocks because conduit drainage is commonly convergent. Springs may emerge at the surface or from beneath a water body (river, lake, or the sea). The term *rising* is used as a synonym for a spring. A location where water known to be fed by allogenic sinking streams discharges from a spring is commonly called a *resurgence*. *Linear drainage* is less common from karst than from other lithologies and is manifest as a gradual downstream increase in discharge during periods with no precipitation in the absence of any point inputs. These linear drainages are called *gaining streams*. *Dispersed discharge* takes place through a cover of soil or sediment and is manifest as a large area of wet ground commonly with groundwater-dependent terrestrial vegetation. The following sections focus on springs, which are the most prominent discharge features in most karst systems.

3.3.1 Karst springs

A spring is a location on the land surface where groundwater discharges from the aquifer, creating a visible flow (Krešić, 2010). Groundwater may be discharged from a single orifice, from several distinct orifices that may be tens of metres apart (sometimes referred to as a spring-group), or there may be an area of seepage with no distinct orifice. The volume and velocity of groundwater flow toward the discharge point(s) are a function of the conduit cross-sectional area and the hydraulic gradient. The greater the inclination of the potentiometric surface and the larger the hydraulic head, the greater the energy that will push stored water to flow out from the aquifer (Fiorillo, 2011).

Major springs are commonly located at or near the base level of erosion which is the lowest level of the terrain where erosion by water is still possible. These are commonly riverbeds, bottoms of valleys, karstic poljes, major lakes, and the sea. These low points in the local topography are the principal controlling factors in the development of karst landforms (Ford & Williams, 2007). However, many small springs and overflow springs are located at higher elevation. The erosional base changes over geological time, and the evolution of the karstic process adapts to that descending level. Many presently relict karstic caves on the slopes of deep canyons previously functioned as springs (Figure 49).

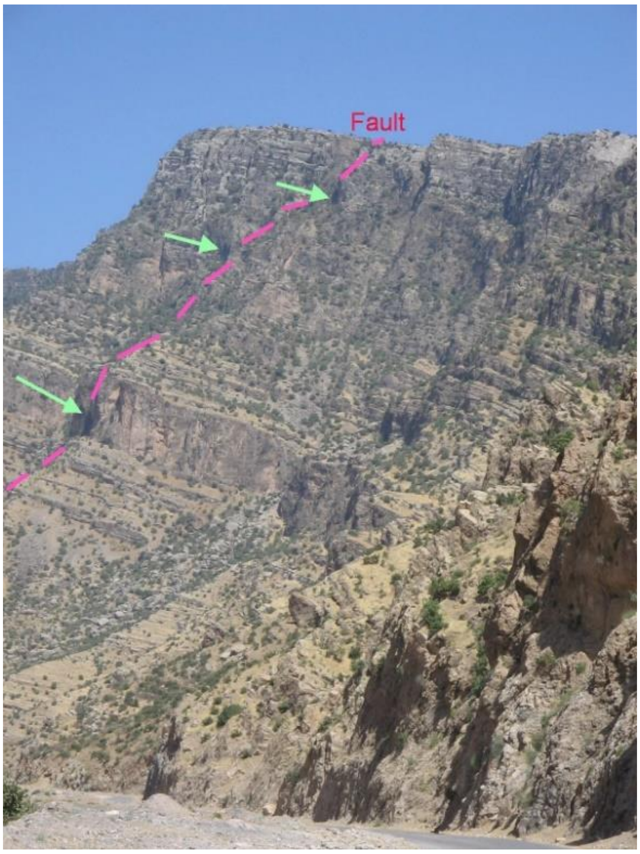

Figure 49 - Several relict spring orifices along a fault line in the Bekhme Formation, a well bedded limestone in the Qandil Mountains (Great Zab gorge, Iraq) (photograph by Z. Stevanović).

Besides their appearance at erosional bases, many springs are located at the contact points of karst and lower permeability or nearly impervious rocks, which are lithological barriers that prevent further underground flows as discussed in Section 3.1 *Karst Aquifer Distribution and Boundary Conditions*.

Depending on the type of flow and hydraulic head, springs can be *descending (gravity)* or *ascending (artesian)* (Figure 50a, b). A distinction can be made between a *contact spring*, where the barrier is lithological, and a *fault spring*, where water is upwelling via a tectonic path (Figure 50). Depending on the discharge point feature, there are *cave springs*, *lake (pond) springs*, and *siphonal springs*. The last two are often combined; the lake bottom extends into a siphon, and such a spring is also called *vauclusian* after the famous La source de Vaucluse in southern France. Many karst springs have several orifices, and it is common for the lowest elevation orifice to have perennial flow while higher elevation orifices (overflow springs) operate during periods with greater flow (Box 15↴). *Perched springs* emerge where there is a lower permeability layer in the limestone or other karstic rocks' sequence. The water from such springs emerges, flows on the surface, and may often sink back into the limestone downstream of the less permeable layer.

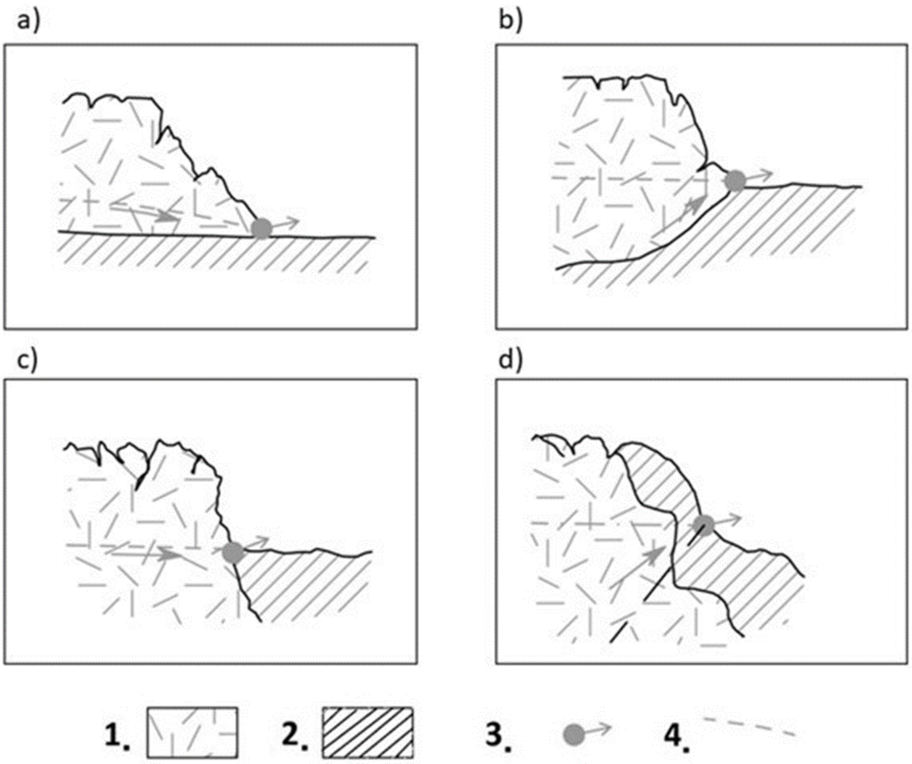

Figure 50 - Types of karst springs: a) a descending, also called gravity, spring occurs at the terminus of a karst aquifer that sub-horizontally overlies lower permeability rocks, b) an ascending spring occurs where the karst aquifer thins and terminates against lower permeability rocks forcing flow upward to discharge, c) a contact spring occurs where the karst aquifer abuts lower permeability rocks forcing lateral flow in the karst to discharge at the contact, and d) a fault spring occurs where a fault carries water from the karst aquifer up through lower permeability rocks to the surface. Legend: 1. Karst aquifer, 2. Non-karst, 3. Spring, 4. Groundwater level.

An important factor for classifying springs is the duration of their discharge. *Perennial* springs flow throughout the year; *intermittent* springs flow for more than half the year; and *episodic* springs flow for less than half the year, mainly after periods of high recharge. Some springs exhibit short duration changes in flow that are not related to recharge, and these are referred to as *rhythmic* or as *ebbing and flowing* springs. An *estavelle* is an orifice that may either function as a sink (ponor) or as a spring depending on the groundwater elevation. Meinzer (1923) classified springs into eight categories based on their mean discharge (Table 2).

Table 2 - Classification of springs based on Meinzer criteria (Meinzer, 1923).

Category	Main Discharge (L/s)
1	> 10,000 L/s
2	1,000–10,000 L/s
3	100–1,000 L/s
4	10–100 L/s
5	1–10 L/s
6	0.1–1 L/s
7	0.01–0.1 L/s
8	< 0.01 L/s

The discharge variation over the hydrological year (Q) allows us to categorize springs into three main groups:

1. extremely variable ($Q_{min} : Q_{max}$ over 1:100),
2. variable ($Q_{min} : Q_{max}$ between 1:10 and 1:100), and
3. stable ($Q_{min} : Q_{max}$ under 1:10).

The largest springs in the world are described in Box 16↴. Most karst springs issue fresh and slightly mineralized water, but there are also many with thermal and mineral water (Goldscheider et al., 2010). These thermal and mineral springs are not the focus of this book and will not be discussed in detail here.

3.3.2 Discharge regime of karst aquifers

The potentiometric surface variations between recharge and discharge points in an aquifer system—depend on many factors such as the distribution, amount, and intensity of recharge as well as size, geometry, permeability, and saturation of the aquifer system. A spring's hydrograph (Figure 51) is the result of processes that take place on the land surface or inside the aquifer system. The type of spring and the aquifer drainage regime are closely related: ascending springs have a more stable regime, while gravity springs are characterized by a greater variation of discharge. The project World Karst Springs (WoKaS↗) and its database contain many springs of both types and their discharge regimes (Olarinoye et al., 2020).

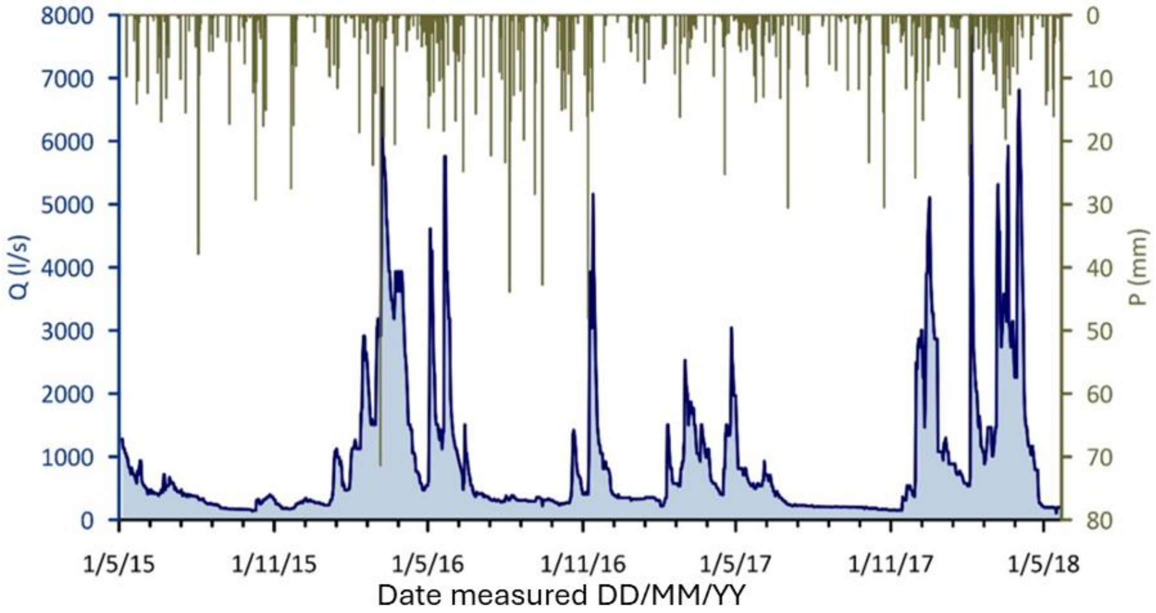

Figure 51 - Correlative diagram of average daily karst spring discharge (Q) and daily total precipitation measured at the nearest meteorological station (P).

When recharge is primarily dispersed autogenic, the difference between the maximal rainfall peak and the maximal spring discharge peak represents the *residence* or *travel time,* which makes it possible to estimate the character of the aquifer. When the recharge is primarily allogenic or there is substantial concentrated autogenic recharge, spring and surface stream hydrographs can have a similar shape. The analysis of spring hydrographs and the correlative rainfall/spring flow diagram is essential for understanding the behaviour of a karst aquifer (Figure 51). The methods of spectral analysis and time series analysis (autocorrelation and cross correlation) have been applied to karst groundwater systems since the 1970s both to characterize recharge to caves (Gunn, 1974, 1981) and to karst aquifers (Mangin, 1984; Bonacci, 1993; Fiorillo & Doglioni, 2010; Krešić, 2013). Recharge pulses can pass quickly through a system or can accumulate if the deficit in stored reserves is large (after a prolonged drought). In most cases the hydrograph is a result of super-position of single hydrographs that correspond with episodic rainfall within a storm or from multiple storms. These are called complex hydrographs.

Direct application of classic statistical methods in the investigation of rainfall-discharge relationships can lead to inconsistent results in the case of karst springs. Although discharge peaks show a reasonable correlation with daily rainfall data, spring baseflow is not well correlated with rainfall. This is a direct consequence of the dual (matrix–conduit) hydraulic behaviour of karst. While spring hydrograph peaks originate from rapid flow of recharge through the aquifer, baseflow originates from the release of water infiltrated into and stored in low permeability matrix blocks, including epikarst. Baseflow is thus temporally delayed (known as a *memory effect*) compared to rainfall and spring discharge peaks (Figure 52). While flood discharges can be approximated by applying regression functions between rainfall and discharge, the description of baseflow discharge requires the application of physics-based analytical functions (Kovács 2003; Kovács et al., 2005). The latter can sometimes be replaced by complex machine learning techniques if enough data are available to train the model.

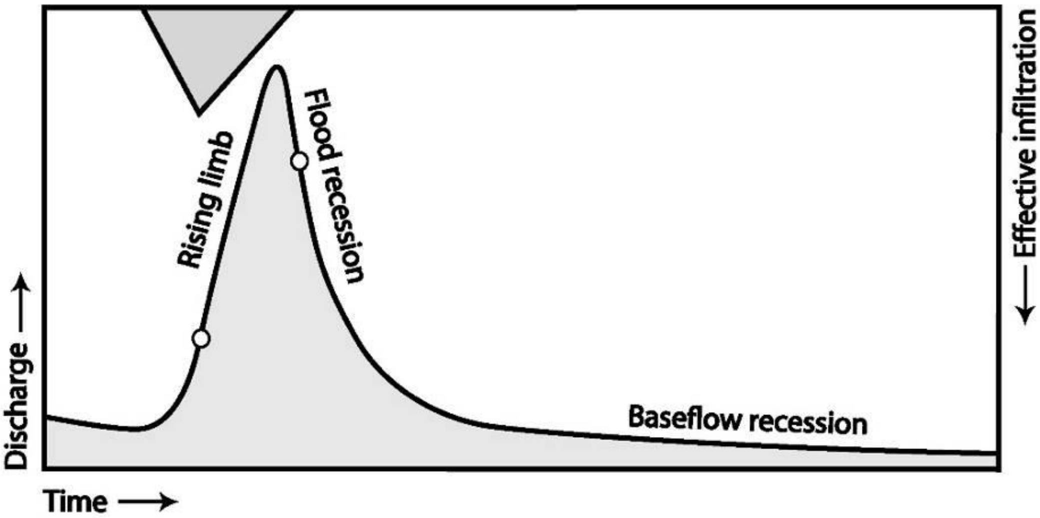

Figure 52 - Typical shape of an individual hydrograph peak. White dots indicate inflection points, which belong to the maximum infiltration state and to the end of the infiltration, respectively (Kovács, 2003).

In the practice of karst hydrogeology, *recession curve analysis* is widely used for assessing groundwater reserves accumulated in a karst aquifer and potential for its utilization. The classical expression characterizing the baseflow was provided by Maillet (1905). This model is based on emptying a reservoir and assumes that spring discharge is a function of the volume of water held in storage. This behaviour is described by an exponential equation as shown in Equation (3).

$$Q_{(t)} = Q_0 e^{-\alpha t} \tag{3}$$

where (parameter dimensions are dark green font with mass as M, length as L, time as T):

$Q_{(t)}$	=	discharge at the end of recession episode (L^3T^{-1}) often expressed in m^3/s
Q_0	=	discharge at the beginning of recession (period without recharge, or with significantly reduced recharge) (L^3T^{-1}) often expressed in m^3/s
α	=	recession coefficient (T^{-1}) often expressed in $days^{-1}$
t	=	duration of recession (T) often expressed in days

If this function is plotted on a semi-logarithmic graph, it forms a sloping straight line.

The recession coefficient, α, can be calculated using the formula shown in Equation (4). The factor 0.4343 in the denominator adjusts for the conversion of natural logarithm to logarithm base 10.

$$\alpha = \frac{logQ_0 - logQ_t}{0.4343\ (t - t_0)} \tag{4}$$

This Maillet equation is usually adequate for describing karst systems at low water stages with dominant laminar flow. Forkasiewicz and Paloc (1967) assumed that different segments of a spring hydrograph represent micro regimes of different aquifer sections, all contributing to the discharge of the spring. Thus, a decreasing hydrograph limb with peaks can be separated into several exponential segments (Figure 53). In such a case, spring discharge can be described using the formula shown in Equation (5).

$$Q_{(t)} = Q_1 e^{-\alpha_1 t_1} + Q_2 e^{-\alpha_2 t_2} + Q_3 e^{-\alpha_3 t_3} \tag{5}$$

where:

Q_i, α_i, t_i are as in Equation (4) but represent separate sections of the recession

The recession coefficient, α, and the volume of stored gravitational groundwater are inversely proportional as shown in Equation (6).

$$\alpha = \frac{Q_{(t)}}{V_{(t)}} \tag{6}$$

where:

$V_{(t)}$ = volume of stored gravitational groundwater (L^3) often expressed in m^3

Thus, it is possible to calculate the ratio of discharged to stored water for each segment (Figure 53), and to estimate the theoretical time that will be required for a spring to almost dry up without any new recharge as shown in Box 17.

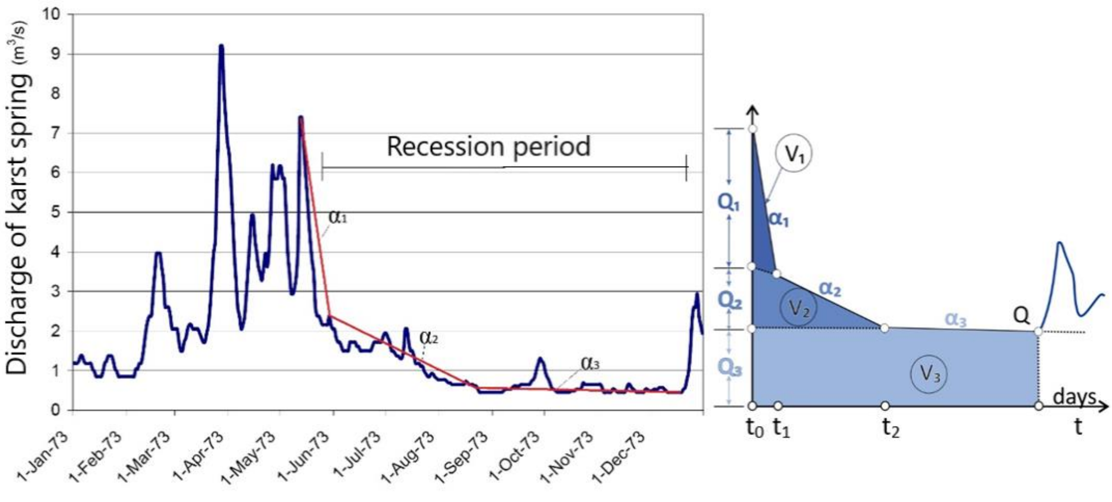

Figure 53 - Karst spring hydrograph with three micro regimes ($\alpha_{1,2,3}$) related to three volumes ($V_{1,2,3}$) of discharged water. As $\alpha = Q_{(t)}/V_{(t)}$, then, $\sum V = (V_1 + V_2 + V_3) = (Q_1/\alpha_1 + Q_2/\alpha_2 + Q_3/\alpha_3)$.

It is common for flow to be turbulent during the first recession period, requiring a linear—not exponential—expression. More on this topic can be found in the literature (Drogue, 1972; Fiorillo, 2011; Malik, 2015).

Although recession curve analysis is widely used in karst, less attention has been given to storm hydrograph analysis. Studies of small drainage basins on the surface have shown that the size and shape of storm hydrographs are a function of precipitation characteristics and runoff generation mechanisms (e.g., Hewlett & Helvey, 1970). Gunn and Turnpenny (1986) applied the time-based hydrograph separation technique, which is the basis of this type of analysis, to analyse the characteristics of two springs that discharge from caves and of a subterranean stream in New Zealand. In each case, flow was entirely in the vadose zone. They concluded there were broad similarities between the hydrograph characteristics of the small karst drainage systems and those of drainage basins on non-karst rocks in New Zealand. Based on this work, it is important to recognize that a broad spectrum of flow routes may be present in karst with what may be termed "surface streams with a roof" at one extreme and deep phreatic systems that respond very slowly to recharge at the other.

The information provided in Box 17 can be used to undertake Exercise 3↴ which provides an opportunity to practice calculating the recession coefficient and water availability in a karst aquifer.

3.3.3 Subsurface drainage

The invisible drainage of karst aquifers is difficult to measure and, in many cases, even to estimate. In the case of a lateral contact between a karst aquifer and non-karst permeable rocks, groundwater extraction from the adjacent permeable (porous) aquifer and steady state capacity (stabilized drawdown and discharge of pumping wells) could provide an estimate of the rate of the subsurface flux. If subsurface drainage is discharged through the bed of a river, it is possible to undertake simultaneous measurement of the river flow in successive sections of the river to obtain the discharge rate by subtraction (Figure 54). Separation of the river hydrograph is another commonly practiced method for assessing the baseflow (Figure 55), that is, contribution of groundwater discharge to the total flow (Bonacci, 1987; Krešić, 2007). Computer programs have been developed for this purpose (Sloto & Krause, 1996; Rutledge, 1998; Barlow et al., 2014). However, baseflow includes subsurface drainage as well as visible, easily-measurable drainage via springs, thus requiring additional separation of these two components.

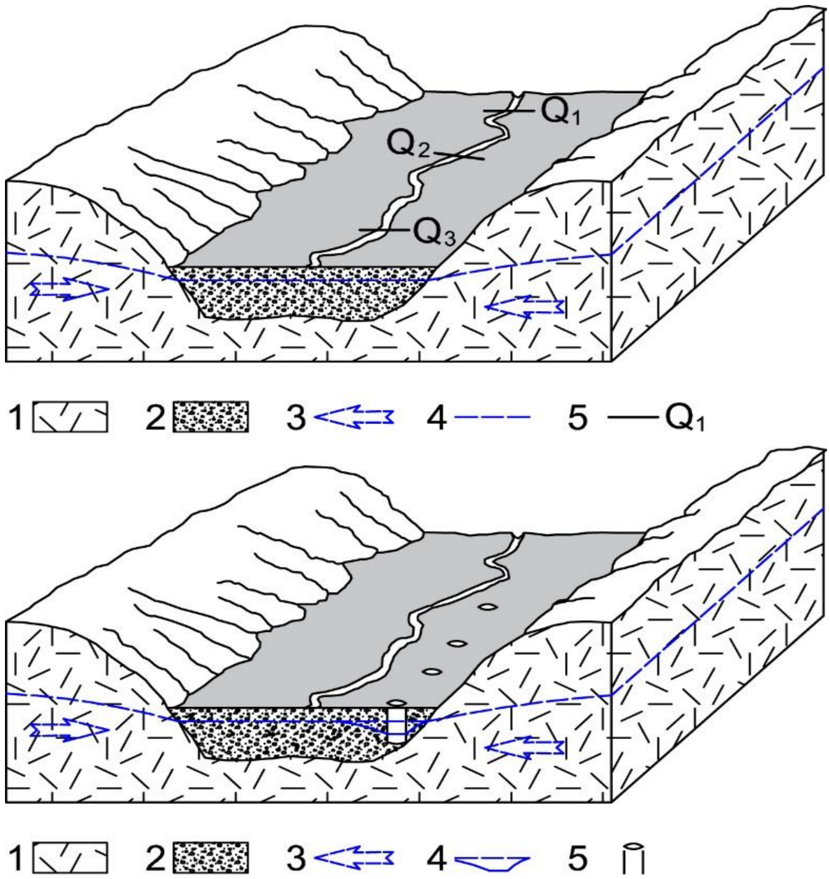

Figure 54 - Two ways of estimating subsurface flows from karst aquifers. Top sketch: Hydrometric sections along a riverbed. A downstream increase in discharge ($Q_3 > Q_2 > Q_1$) along a reach without any tributaries is a clear sign of discharge from the aquifer to the stream. Bottom sketch: Battery of pumping wells located in the alluvium with negligible stream loss indicates the recharge is dominantly due to flow from the lateral karst aquifer. Legend: 1. Karst, 2. Alluvium, 3. Direction of groundwater flow, 4. Potentiometric surface in the top sketch; Drawdown cone in the bottom sketch, 5. Location of discharge measurement in the top sketch, Pumping well in the bottom sketch.

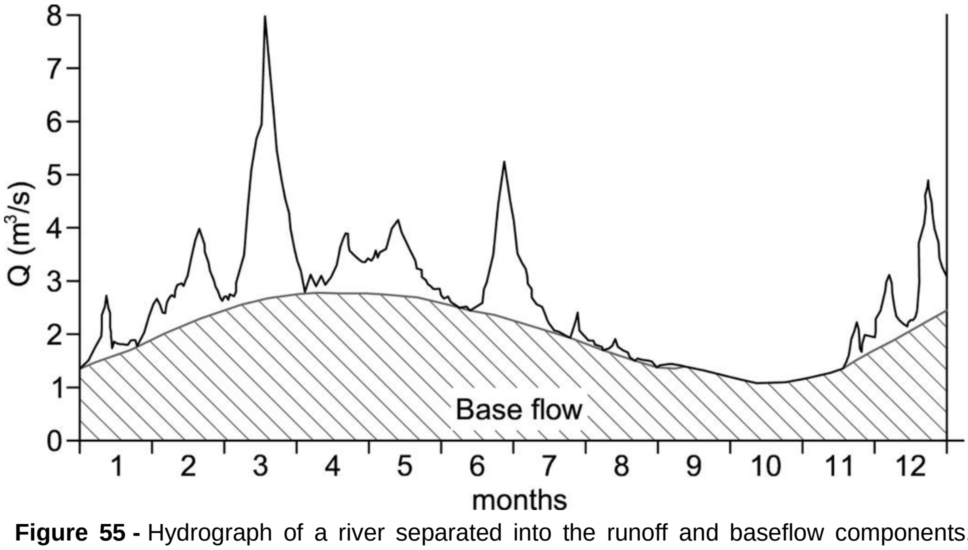

Figure 55 - Hydrograph of a river separated into the runoff and baseflow components. During a recession period, almost the entire river flow is groundwater discharge.

In the absence of all other options, a rough estimation of the subsurface flow component can be made by assessing all other known parameters in a water budget prepared for the system.

3.3.4 Capturing karst springs and tapping karst aquifers

Due to the non-homogenous and anisotropic character of karst groundwater systems, the exploitation of groundwater is more complicated than is the case in media that are dominated by primary porosity and permeability. Adjacent springs may be fed by different conduit systems. Boreholes that are only a few metres apart may tap different parts of the permeability such that one is productive while a near neighbour is not. Hence, detailed hydrogeological research is required to obtain and utilize as much available water as possible. Even then, successful results are not guaranteed.

The two main ways of exploiting groundwater in karst are:

1. capturing karst groundwater at a spring site using an intake structure; and,
2. tapping the karst groundwater flow using wells (boreholes), galleries (adits), or similar structures.

Capturing spring water is an ancient art, as old as the earliest civilizations. Many remnants of intake structures around large springs are found in the lands of ancient Rome, Persia, and Babylon. Many intake structures worldwide were constructed by local inhabitants or semi-skilled workers. The main elements of a simple spring capture are the collection chamber (spring box), pipes (delivery and evacuation/outflow), and taps (at usage points). The following elements may also be included: a storage box (reservoir), a maintenance room (with a chlorinator and monitoring equipment), pumps (if gravity use and distribution is not possible), cut-off and retention walls (to collect and channel groundwater, but also to protect it from debris and landslides), ventilation, and fencing (Stevanović, 2010; Box 18↴).

Tapping karst groundwater using wells, galleries (Figure 56), or similar structures requires the application of different technology. Galleries driven horizontally into the karst groundwater system from a point below the average groundwater elevation are expensive but have a high probability of success as they will intercept elements of the tertiary (conduit) porosity in addition to the secondary (fracture) porosity and the primary (intergranular) porosity. Vertical tube wells are commonly used because drilling rigs are available everywhere and the technology is well known. They can yield exploitable volumes of groundwater, but there are also many examples of boreholes in karst that are dry or have a very low yield.

Figure 56 - Karst water drainage gallery in the Areuse gorges for the drinking water supply for the city of La-Chaux-de-Fonds in the Swiss Jura Mountains (photograph by N. Goldscheider).

Assessing which site is appropriate for drilling and tapping karst water requires complex geological and hydrogeological surveys. These include remote sensing, geological prospecting, geophysical surveys, water feature survey, speleological investigation, simultaneous hydrometry, tracing tests, and finally, exploratory drilling and testing (Milanović, 2004; Goldscheider & Drew, 2007; Stevanović, 2015).

Design of a well includes several elements: drilling technique, depth, drilling diameter, casing, screen, isolation from surface contamination and undesired ground water, gravel pack, and protection cover.

The two most frequently applied drilling techniques in karst aquifers are:

1. rotary drilling and,
2. down-the-hole hammer.

In *direct rotary drilling*, the drilling fluid is pumped down the drill rod and through the bit attached to its end. The role of the fluid is to

- cool and lubricate the bit;
- stabilize the borehole wall to prevent collapsing;
- seal the wall, to prevent fluid loss and inflow of drilled formation fluids; and
- remove cuttings.

The reverse circulation method is more efficient than any other for removing drill cuttings, but it is rarely applied in karst. When choosing fluid for drilling, care should be taken not to use one that is too dense, such as barite or bentonite, which are both extremely surface-active and form clay/organic complexes that fill the voids and openings of the original rock (Aller et al., 1989). To ensure the stability of the walls, it is better to drill using water or muddy water.

Drilling with a hammer and using only air for cooling and removing particles is a method that is often recommended in karst because of

- drilling efficiency,
- proper identification of groundwater level position, and
- absence of mud or liquid that could disrupt normal groundwater circulation.

The *combined method*—hammer drilling with small rotation and the use of compressed air or foam—produces the best results when drilling limestone, achieving drilling penetration rates of 100 m/day or even faster (Stevanović & Iurkiewicz, 2004; Figure 57). Foam effectively extracts the cuttings and cools the bit but should be completely removed during the well development to prevent its reaction with local groundwater.

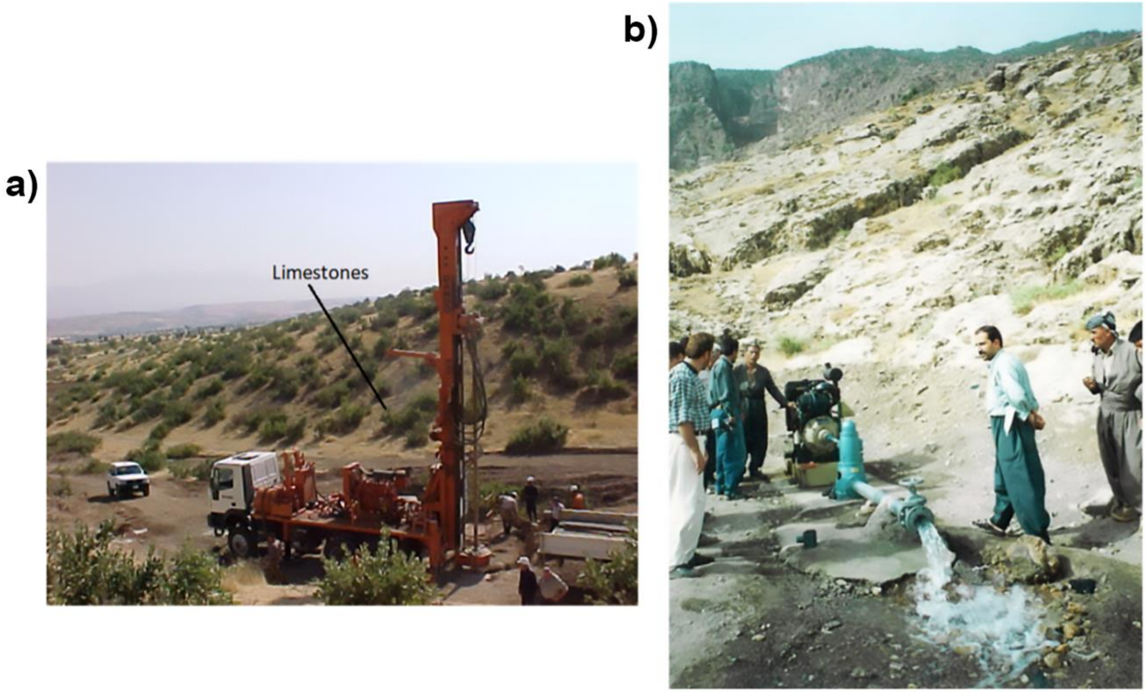

Figure 57 - Drill operations: a) drilling limestone in the foothill zone, and b) pumping of the completed well used for irrigation of orchards in the Shaqlawa Plain, northern Iraq (photographs by Z. Stevanović).

In drilling practice, fully penetrated wells have some advantages over those that do not fully penetrate, such as a larger inflow capacity and possible larger drawdown (Driscoll, 1986). Similarly, the larger the hole and screen diameters, the larger the pump that can be installed and larger well capacity can be obtained. This is of great importance in a karst aquifer of high productivity. Driscoll (1986) suggests that the diameter of the casing should be twice the largest diameter of the pump, but modern technology provides pumps that are efficient even with small diameters.

To protect groundwater from surficial pollution, an entry-level casing column should be inserted into the hole, and the annular space between the casing and the wall should be cemented (i.e., grouted) or sealed with clay. In a highly fissured or karstified subsurficial zone (epikarst), proper sealing is of great importance. For wells in most aquifer types, it is common to install a gravel pack in the annular space between the casing pipes/screen and the walls of the hole that provide groundwater. The aim of the gravel pack is to prevent large formation materials from entering the well but also to work in conjunction with the well screen to filter out very fine materials often deposited in captured conduits. However, if the walls of the drilled hole are stable, the installation of casing pipes is not necessary. The open hole system produces a much bigger yield, simply because there is no resistance from a screen when water enters the well and is common for many karst aquifers when the limestone or dolostone is competent (Figure 58).

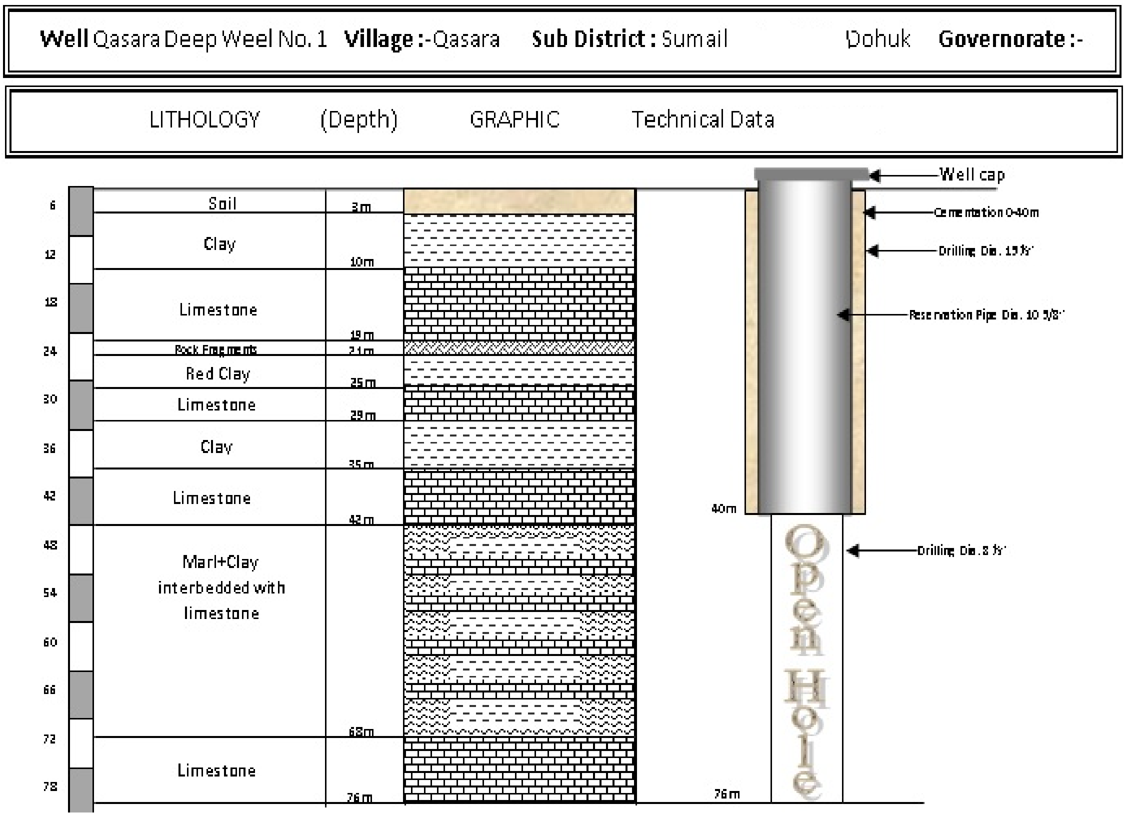

Figure 58 - An example of a geological and technical profile for an open hole well (yield of 30 L/s), Qasara village, Dohuk, Iraq (from Stevanović & Iurkiewicz, 2004).

The protective casing pipes and the screen can be made of metal (stainless steel, galvanized steel, low-carbon steel) or plastic/polymer materials (PVC, PTFE, or similar). To avoid deformation of the pipes, a more solid material must be chosen as the well becomes deeper. Corrosion, which is a frequent problem in well exploitation, can be avoided by using resistant plastic materials or stainless steel.

Driscoll (1986) emphasizes the following desirable features of a well screen (Figure 59):

- openings in the form of slots and uninterrupted around the circumference of the screen,
- close spacing of slot openings to provide maximum percent of open area,
- V-shape slot openings that widen inwardly,
- adaptability to different conditions by use of various materials,
- maximum open area consistent with adequate strength, and
- a full series of accessories and end fittings to facilitate screen installation and well completion operations.

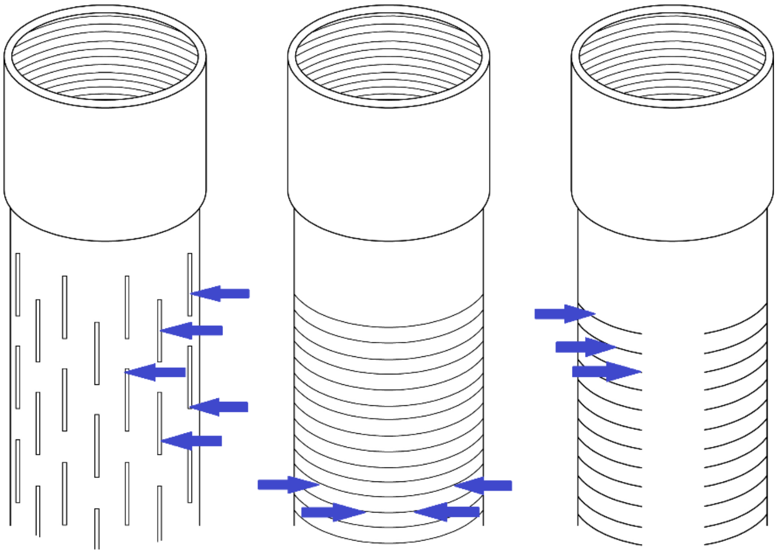

Figure 59 - Several types of screens with threaded joints (from left to right: slotted screen, continuous slot wire-wound screen, and screen with plain surfaces).

Once the drilling process is completed, the stage that follows is *well development*. Although more applied for stimulation of intergranular media, long development of a well is necessary in karst if captured cavities and joints are filled with fine particles.

Conventional development of a well includes washing and air lifting. Initial washing (backwashing) can be done by using the rig's pump and circulating clean water. Use of compressed air is a very efficient method of well development. When only a small diameter exploratory borehole is drilled for monitoring purposes, air lifting is the sole method for developing and testing and estimate the aquifer's productivity prior to deciding whether to expand the diameter or drill a new well nearby.

The duration and intensity of well development depends on many factors; in karst, it can take weeks, even months. This is because cavities and joints may be filled with thick secondary silty, clayey, and sandy materials transported by groundwater, which it is best to completely remove before using the well for clean water supply.

Pumping the well is best way to

- complete the well development;
- estimate the quality and efficiency of the well;
- test the aquifer's productivity;
- assess the aquifer's permeability; and
- create a base for the completion of the well, setting up of the permanent pump, and equipment installation (Stevanović, 2015).

There are *short-term control pumping tests* (*step drawdown tests*), whose aim is to estimate the quality of the constructed well and its elements (e.g., hydraulic head loss through well screen), and *long-term pumping tests*, which simulate long-term exploitation and provide a base for defining the optimal capacity of the well, as well as the type and depth of the pump that needs to be installed for permanent groundwater extraction (Box 19↴).

Many of the references that deal with groundwater hydraulics can be applied for testing of karst aquifers, albeit with due caution because of the previously discussed limits of Darcy's Law (1856). Formulas for steady-state flow are based on Darcy's Law and were reformulated by authors such as Dupuit (1863) and Forchheimer (1901) and Thiem (1906). The calculation of hydraulic parameters and well losses (resistance of well intake) is based on the observation of drawdown or recovery values per time and, in the case of non-steady-state flow, the formulas of Theis, Jacob, Hantush, Cooper, or others (Theis, 1935; Jacob, 1940; Todd, 1959; Ferris et al., 1962; Castany, 1967; Freeze & Cherry, 1979) are commonly used. A freely available resource for understanding aquifer pumping tests is *Analysis and Evaluation of Pumping Test Data* by Kruseman and deRidder (2000).

Without going into an extensive discussion on hydraulics and aquifer parametrization, we provide some recommendations for the pumping test procedure.

- It is necessary to ensure the presence of qualified mechanics and spare parts to reduce the possible risk of operation breaks or damages.
- The pump and its capacities should be determined based on the assessed aquifer potential (drill logs, drilled core logs, geophysical logs, well development data).
- In the case of unconfined karst, pumped water should be evacuated as far as possible from the tested well to prevent return flow.
- It is recommended that drawdown does not exceed 1/3 of the total aquifer thickness.
- If the water level is more-or-less stable for a certain yield, more intensive pumping can be allowed during the following test stages. In contrast, significant drawdown requires a reduction of further pump capacities.

- Pumping rates during testing should be greater than the anticipated exploitation rate.
- The construction of a curve showing drawdown and recovery versus time [d = ƒ (log t)] is essential for the calculation of parameters in non-steady-state flow conditions (Figure 60).
- The groundwater level should be observed automatically by installed pressure transducer with a data logger or manually with dip meters using frequent measurements—especially at the beginning of pumping and at the start of recovery (after the pump is turned off).

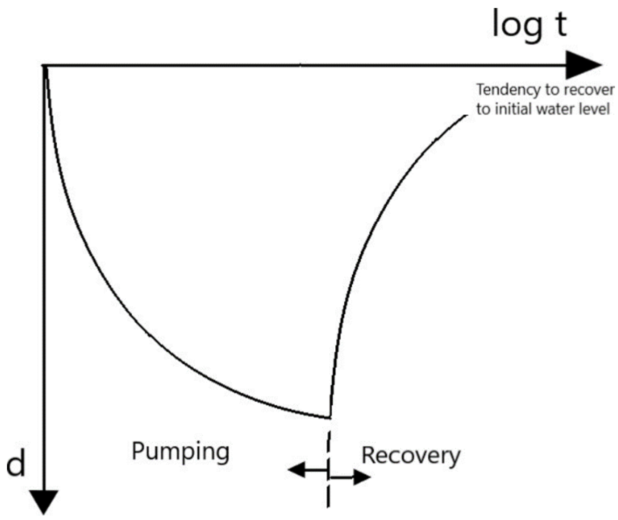

Figure 60 - Diagram of pumping test drawdown versus time [d = ƒ (log t)] and groundwater recovery.

The construction of galleries, shafts (large diameter holes), canals, and similar tapping structures is not as frequent in water supply practice as that of drilled wells. However, slightly inclined or sub-horizontal galleries can be a successful solution, especially in the case of contact springs, and for secondary springs where the original drainage site is masked by debris or other permeable rocks. The idea is to reach the aquifer layer below the discharge points by drilling horizontally, or by excavating a hole, thereby enabling gravity flow from the aquifer. Full control over the flow can be achieved by piping and installing a valve on the gallery.

3.4 Groundwater Chemistry and Quality

3.4.1 Intrinsic hydrochemical composition of karst groundwater

The natural hydrochemical composition of karst groundwater is essentially determined by water–rock interaction, particularly the process of carbonate and/or sulphate rock dissolution, but also by processes in the soil zone, mixing with other water types, and various other processes. This section focuses on the natural or intrinsic karst groundwater chemistry resulting from such processes. The vulnerability of karst aquifers to contamination and the occurrence and behavior of contaminants in groundwater is discussed in Section 4.3 *Karst Water Under Threat*. The key processes of rock dissolution are outlined in Section 2.2 *Karstification and Karst Distribution.* The intrinsic hydrochemical composition of karst groundwater is relevant from at least three perspectives.

1. *Drinking water quality*. In most carbonate rock aquifers, the natural water quality is excellent, and high levels of bicarbonate, calcium, and magnesium are generally considered favourable for human health. However, in karst aquifer systems containing gypsum or anhydrite, sulphate concentration may exceed legal limits for drinking water.
2. *Groundwater and ecosystems*. Biocenoses as associations of different organisms inside the aquifer and groundwater-dependent ecosystems at the land surface also depend on the composition and quality of the water. For example, salt concentrations determine the composition of species, and contaminants can harm or kill vulnerable species as discussed in Section 4.4.5, *Karst Groundwater-Dependent Ecosystems*.
3. *Scientific interest as natural tracers.* From a scientific point of view, the chemical and physical water composition and their temporal variations can be used to interpret processes in the aquifer system such as water–rock interaction, transit times, and conduit–matrix interactions.

3.4.2 Overview of parameters and processes

According to Hunkeler and Mudry (2007), the chemical composition of karst groundwater depends on several factors such as recharge sources (allogenic or autogenic), recharge processes (dispersed or concentrated), land use in the catchment, climatic conditions (temperature, as well as spatial and temporal distribution of precipitation), lithology (carbonates or evaporates), and type of flowpaths (conduit, fracture, matrix).

Key parameters of natural karst groundwater quality, along with major processes acting as sources and sinks for these parameters are summarized in Table 3. Parameters can be grouped into those related to

- atmosphere, soil, and vegetation,
- carbonate mineral/carbonate rock dissolution, and
- weathering of any other rock types in the catchment.

Table 3 - Key parameters of natural karst groundwater quality and major processes acting as sources and sinks (generalized and modified after Hunkeler & Mudry, 2007).

Group	Parameter(s)	Sources	Sinks
Parameters related to soil and atmosphere	O_2	The atmosphere.	Aerobic biodegradation of organic matter.
	CO_2	The atmosphere and soil where present. The soil commonly has concentrations tens or hundreds of times higher than the atmosphere. Also produced by degradation of organic matter washed into the karst.	Degassing to the atmosphere and mineral dissolution.
	Na^+, Cl^- and other ions	Salt particles (aerosols) in the atmosphere, rainfall.	No efficient sinks, stable and mobile compounds.
	Organic carbon (TOC, DOC)	Incomplete decomposition of organic matter.	Biodegradation to CO_2
	Nitrate (NO_3^-) and other nutrients	Faecal and organic matter, anthropogenic (primarily fertilizer).	Plant uptake, denitrification under anaerobic conditions.
	K^+ and other metal cations	Dissolution of silicate minerals and anthropogenic (primarily fertilizer).	Ion-exchange, adsorption to clay minerals.
	Turbidity	Mobilization of particles at times of high discharge.	Filtration and sedimentation.
	Bacteria	Natural soil bacteria and faecal contamination.	Filtration, inactivation, die-off.
Parameters related to carbonate mineral/rock dissolution	Ca^{2+}	Dissolution of limestone (≈ 100 percent Ca^{2+}) or dolomite (≈ 50 percent Ca^{2+}).	Re-precipitation of carbonate minerals, ion-exchange.
	Mg^{2+}	Dissolution of dolomite or calcite containing traces of magnesium.	Re-precipitation of carbonate minerals, ion-exchange.
	Sr^{2+} and other trace metals	Mobilization during carbonate mineral dissolution.	Re-precipitation of carbonate minerals, ion-exchange.
	HCO_3^-	Dissolution of carbonate minerals (dominant at 6.5 < pH < 10.5).	Precipitation of carbonate minerals.
	CO_3^{2-}	From HCO_3^- at high pH (dominant species at pH > 10.5).	Precipitation of carbonate minerals.
	Turbidity	Insoluble residuals from carbonate rock dissolution, mobilization by turbulent flow.	Sedimentation in low velocity flow zones.
Parameters related to other mineral/rock types	SO_4^{2-}	Dissolution of gypsum and anhydrite in evaporite rocks; oxidation of pyrite and other metal sulphides.	Typically, conservative (no relevant sink).
	Ca^{2+}, Mg^{2+}, K^+ and other cations	Dissolution of silicate minerals in adjacent non-karst.	Ion-exchange, adsorption, mineral precipitation.
	Cl^- and Na^+	Dissolution of rock salt, seawater intrusion, mixing with mineral water from deep flow systems.	Typically, conservative (no relevant sinks).

Parameters and processes related to atmosphere and soil

The most obvious parameter related to the atmosphere is dissolved oxygen (O_2). The atmospheric oxygen content is 20.9 percent, and the solubility of oxygen in water is inversely related to temperature (the higher the temperature, the lower the solubility). At normal atmospheric pressure at sea level, the solubility of oxygen in water is 14.6 mg/L at 0 C, 11.3 mg/L at 10 C and 9.1 mg/L at 20 C (Appelo & Postma, 2005). In pristine, near-surface karst groundwater, the oxygen saturation is often around 100 percent—for example, in water from alpine karst springs. The aerobic degradation of organic matter—including plant remains, organic fertilizers, and organic contaminants in the soil or groundwater—consumes oxygen and generates CO_2 as illustrated by the strongly simplified chemical Equation (7).

$$CH_2O + O_2 = CO_2 + H_2O \tag{7}$$

In Equation (7), CH_2O does not represent a distinct compound. Rather, it represents the generalized average composition of natural organic matter in plant material. This process causes declining oxygen levels in the soil or water and can ultimately lead to anoxic reducing conditions, which involve the mobilization of toxic metals. Oxygen is also highly relevant for species living in the aquifer and associated groundwater-dependent ecosystems (Mahler & Bourgeai, 2013). For all these reasons, oxygen is an important parameter of karst groundwater quality that can be measured easily and continuously in situ.

Carbon dioxide (CO_2) is also originally derived from the atmosphere, where its concentration has increased from 280 ppm in preindustrial time (1850 CE) to around 414 ppm (average value in 2020). However, in terms of groundwater quality and karst processes, CO_2 from the soil zone is generally more important. Biodegradation of organic matter in the soil by the respiration of soil organisms consumes oxygen but generates carbon dioxide as shown in Equation (7). Therefore, CO_2 partial pressures in the soil gas are much higher than in the atmosphere, often by a factor of 10 to 100. During recharge through biologically active soil, water encounters these high CO_2 partial pressures, which subsequently cause more intense carbonate rock dissolution and, thus, higher concentrations of $Ca^{2+}$and HCO_3^- in the groundwater.

Organic carbon (OC) is another important water-quality parameter related to processes in the soil. In pristine environments, OC in groundwater originates from the incomplete degradation of plant remains in the soil. OC in groundwater can be classified into dissolved (DOC) and particulate (POC), the sum of which is referred to as total organic carbon ($DOC + POC = TOC$). DOC commonly contributes about 90 percent to TOC, and TOC is the most common monitoring parameter. TOC is a very important water-quality parameter in karst systems, for several reasons.

1. The biodegradation of TOC in karst groundwater under oxic conditions generates CO_2 (Equation (1)) inside the aquifer, which can contribute to karstification even when the original atmospheric CO_2 has already been consumed by carbonate dissolution (Gabrovšek et al., 2000).
1. Due to the relatively rapid degradability and short lifetime of OC, TOC can be used as a time tracer in karst systems, indicating fast transport and short transit times (Celle-Jeanton et al., 2003).
2. The sources and mobilization processes of TOC are similar to those of faecal bacteria. Therefore, TOC is a useful monitoring parameter to indicate faecal contamination in karst water and can be used for early-warning systems (Pronk et al., 2006).

Nitrate (NO_3^-) and other nutrients also originate from the soil and atmosphere, either from natural processes such as nitrogen fixation by legumes and subsequent biodegradation in the soil, or by human land use activities such as animal husbandry and application of fertilizers (Huebsch et al., 2014). Nitrate is a major contaminant in many groundwater bodies and is discussed in greater detail in Section 4.3 *Karst Water Under Threat*.

Potassium (K^+) and various other inorganic compounds can also originate from the soil zone and are released by chemical weathering of silicate minerals.

Intense rainfall commonly causes mobilization of mineral particles from the soil, and these may reach the karst aquifer via two different pathways, corresponding to the two principal recharge processes: allogenic and autogenic recharge. Most sediment enters the karst via surface streams from adjacent non-karst areas sinking into swallow holes (allogenic recharge) and often coincides with the mobilization of organic carbon and faecal bacteria from the soil zone. Therefore, turbidity is another important monitoring parameter for water quality and ideally is combined with TOC (Pronk et al., 2006). Concentrated autogenic recharge via dolines can transport significant amounts of sediment while vadose flows fed from the epikarst mobilize smaller amounts of sediment (Hardwick & Gunn, 1990).

Parameters and processes related to carbonate rock dissolution

These processes were introduced in Section 2.2 in the context of karstification and speleogenesis. In terms of groundwater chemistry, carbonate equilibrium is the key process. It consists of several chemical equilibria and processes involving carbon dioxide (CO_2), bicarbonate (commonly termed hydrogen carbonate: HCO_3^-), carbonate (CO_3^{2-}), and calcite ($CaCO_3$) (Dreybrodt, 2000; Appelo & Postma, 2005; White, 2010) or dolomite.

The equilibrium between carbon dioxide, bicarbonate, and carbonate can be described by a set of three equations. First, the solution of carbon dioxide in water to form carbonic acid is described by Equation (8).

$$CO_2 + H_2O = H_2CO_3 \tag{8}$$

Only a small proportion of the CO_2 reacts chemically with water to form carbonic acid. The largest proportion is physically dissolved as CO_2 gas.

Second, the dissolution of carbonic acid to form bicarbonate is shown as Equation (9).

$$H_2CO_3 + H_2O = H_3O^+ + HCO_3^- \tag{9}$$

Third, the dissolution of bicarbonate in water to form carbonate is described by Equation (10).

$$HCO_3^- + H_2O = H_3O^+ + CO_3^- \tag{10}$$

These equilibria are pH dependent. In acid water, at pH < 6.5, dissolved CO_2 and carbonic acid are the dominant species. At pH = 6.5, there is equilibrium (50:50) between carbonic acid and bicarbonate. Under neutral to moderately basic conditions, at pH values between 6.5 and 10.5, bicarbonate is the dominant inorganic carbon species in water. This is the case in the great majority of karst groundwater systems. Only under extremely basic conditions, at pH > 10.5, is carbonate the dominant species. Such conditions only occur in exceptional climatic and geochemical environments.

The dissolution of calcite can be described by the equilibrium shown in Equation (11).

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + HCO_3^- + HCO_3^- \tag{11}$$

This formulation and the green and red colour coding of Equation (11) indicate that, theoretically, half of the bicarbonate in karst groundwater originates from the carbonate rock and half originates from the atmosphere. Although the two bicarbonate anions are chemically identical, they generally have different isotopic composition. This finding is also relevant in terms of quantifying the role of karst processes as an atmospheric CO_2 sink, which can be estimated by measuring bicarbonate fluxes at springs while considering that only half of the bicarbonate comes from atmospheric CO_2 (Liu & Zhao, 2000).

The dissolution of dolomite ($CaMg(CO_3)_2$) is similar to the dissolution of calcite but also involves the release of a magnesium ion (Mg^{2+}). Calcite often also includes traces of magnesium, generally a few percent.

Therefore, the dominating compounds of natural karst groundwater are bicarbonate—often representing > 90 percent of all negatively charged ions (anions)—and calcium and magnesium cations, which together often contribute > 90 percent of all positively charged ions (cations). The relative contributions of Ca^{2+} and Mg^{2+} range between nearly 100 percent Ca^{2+} in pure limestone karst aquifers and 50 percent Ca^{2+} along with 50 percent Mg^{2+} in pure dolomite aquifers. Intermediate mixtures either result from traces of Mg^{2+} in calcite or complex aquifer systems involving different types of limestone and dolomite. As the dissolution process of dolomite is slower than the one for calcite, magnesium can also be used as a time tracer (Celle-Jeanton et al., 2003) in karst groundwater systems. Higher magnesium concentrations indicate longer transit times and more intense water–rock interaction, although there is no simple, straightforward relationship.

Strontium (Sr^{2+}) and several other trace elements occur in carbonate rocks and are also released during the dissolution process but are not discussed in detail here.

All carbonate rocks include traces of non-soluble minerals, often in the form of clay, silt, or sand. During carbonate rock dissolution, insoluble minerals are released as residual intra-karstic sediments. Unless these are removed while in suspension, they can build up and inhibit further karstification. It is sometimes said that carbonate rocks are only karstifiable when these non-soluble compounds do not exceed 25 percent but under conditions of high recharge, and hence rapid groundwater flow, karstic groundwater circulation is possible at lower purities. For example, at Port Waikato in New Zealand there are well-developed caves in calcareous sandstones (Gunn & Turnpenny, 1986).

In addition to sediments transported from the land, soil zone, and sinking streams (discussed earlier), residual sediments from inside the karst aquifer are a second, major source of turbidity at karst springs. This autochthonous turbidity can be mobilized by high flow velocities in the karst conduit system during high-flow events. Unlike the allochthonous turbidity from the land surface, the autochthonous turbidity is generally not related to increased levels of organic carbon and faecal bacteria (Goldscheider et al., 2010).

Parameters related to other mineral rock types

In addition to carbonate rocks, sulphate rocks and minerals, such as gypsum and anhydrite, are also karstifiable. There are examples of karst aquifers and cave systems that are entirely developed in sulphate rocks—for example, the giant gypsum caves of Podolia in Ukraine (Klimchouk, 2004). Sulphate rocks are also commonly associated with carbonate rocks as underlying, overlying, or intermediate sedimentary formations. Sulphate minerals have a higher solubility in water than carbonate minerals, and their dissolution does not depend on CO_2 concentration or pH value (Appelo & Postma, 2005). The dissolution of gypsum can be described as shown by Equation (12).

$$CaSO_4 + 2H_2O = Ca^{2+} + SO_4^2 + 2H_2O \tag{12}$$

This process adds calcium and sulphate to the water. The legal limit for sulphate in drinking water is 250 mg/L (according to most European water quality standards). Water from sulphate aquifers is less favourable for drinking water supply than water from carbonate aquifers (Krawczyk & Ford, 2007).

The oxidation of pyrite (FeS_2) and other sulfides, which are relatively abundant in some carbonate rocks, is another source of sulphate in karst groundwater. It also releases iron and associated metals, which are often subsequently precipitated as metal hydroxides in oxygen-rich groundwater.

The dissolution of halite ($NaCl$) and other salts is a source of sodium (Na^+) and chloride (Cl^-) in karst groundwater. Upwelling of thermal and mineral water from depth, coastal seawater intrusions related to aquifer over-pumping or inappropriate irrigation techniques are other important causes of salinization, which can make freshwater resources undrinkable (Escolero et al., 2007; Mijatović, 2007).

Many karst aquifers also receive inflow from non-karstic lithologies. Most common are inputs from laterally bordering, allogenic non-karst areas that drain into the karst aquifer via sinking streams and swallow holes. Less common are inputs from overlying, underlying, or intermediate geologic formations (i.e., cross-formational groundwater flow). Depending on the mineralogical composition of these other lithologies, the operating geochemical processes, and the hydraulic interactions of the karst and non-karst formations, inflow from non-karstic lithologies can result in many different types of groundwater chemistry. Chemical weathering of silicate minerals and rocks is probably the most important group of relevant processes in this context and leads to input of several types of metal cations such as $Ca^{2+}, Mg^{2+}, K^+, Na^+$, and silicic acid. Under reducing conditions, iron and manganese are also mobile as bivalent Fe^{2+} and Mn^{2+} cations (Appelo & Postma, 2005).

4 Karst Management

4.1 Importance of Karst Aquifers

Karst is a global phenomenon (Figure 11) and is present in 75 percent of the 195 UN member states (Stevanović, 2019). Some countries can be purely karstic and their citizens' lives are heavily dependent on karst water and other natural karst terrain resources. Cuba, Jamaica, and Montenegro, as well as islands such as Malta, the Bahamas, or Barbados, have soluble karstified rocks covering more than 80 percent of their territories. Karst aquifers largely contribute to the water supply in regions where they are extensive—for example, in the southern part of the USA and the Caribbean basin, central and southeastern Europe (Alps and Carpathian Mountains), the Mediterranean basin, the Near and Middle East, southeast Asia, and northeast Africa (Goldscheider et al., 2020).

Due to their generally high permeability, karst aquifers located in humid and temperate climate zones are often rich in groundwater reserves. However, even in karst areas with sufficient rainfall and adequate replenishment of aquifers, there are large zones with limited access to water resources. This is the case with the elevated parts of karst plateaus and mountainous areas that function as regional recharge zones. In these areas, the accessibility of freshwater is often limited, as the groundwater might be several hundreds of meters below ground, and springs are far away and deep down in the valleys as illustrated in Box 20↴.

As in other geological formations, the four main uses of water in karst are:

1. drinking water supply,
2. agriculture (irrigation and drinking water for animals),
3. mining and industry, and
4. hydropower generation.

According to Zektser and Everett (2004), the majority of the world's groundwater—almost 70 percent—is used for irrigation. Municipal water supply consumes 21 percent, while the remaining 9 percent is abstracted for industrial and mining purposes. The calculation provided by Margat and van der Gun (2013) is quite similar, and the share of karst water utilization is probably not much different. Many cities that were intentionally built in the vicinity of large springs still use this type of water.

The largest cities in Europe and North America that exclusively use karst groundwater are Vienna, Austria (Box 21↴) and San Antonio, Texas, USA, respectively. Both have more than 1.5 million inhabitants. Citizens of San Antonio in Texas, USA, consume water from the large karst platform of the Edwards aquifer, which is tapped at numerous springs and by pumped wells. Rome, the capital of Italy, is a city in which an even greater number of citizens consume karst groundwater. The Peschiera spring supplies about 60 percent of the water required by its 4 million citizens, maintaining the historical continuity of Rome as a world leader in karst water use. The case of Naples (Italy) is similar, as the 3 million inhabitants of the metropolitan area traditionally obtain water from numerous karst springs, as well as from rivers and alluviums formed from these springs. Four capitals in the Dinaric karst of southeastern Europe (Sarajevo, Skopje, Podgorica, Tirana) utilize water from karst springs for drinking purpose (Stevanović et al. 2016). Two capitals and large cities in the Near East—Beirut (Lebanon) and Damascus (Syria), with about 2.4 million inhabitants each—also depend predominantly on karst spring water. Out of an estimated 150 million consumers of karst water for drinking purpose in China (Stevanović, 2019), at least one-half live in urban areas. However, some megalopolises were forced to reduce their use of traditional karst water sources because of their enormous expansion and population increase. For example, Paris (France) uses many sources, including treated surface water, having substituted surface water for some of the water from springs located 100 to 150 km from the city that were captured between the 1860s and the 1890s.

Intakes of springs are the most common structures in karst environments for both potable water supply and irrigation. Channelling gravity springs and diverting water over long distances was a simpler solution than drilling numerous wells (Figure 61). However, in the cases of less productive aquifers or those located in arid zones with potentiometric surfaces at greater depths, drilling was inevitable. Due to unstable groundwater regimes and reduced discharge of karst springs in recession periods, many sources require a combined system: delivery of water from a gravity spring during high-water periods and pumping of water in times of drought (Stevanović, 2018).

Figure 61 - Hayasi karst spring and diverting channels used for irrigation, Bazian area, northern Iraq (photograph by Z. Stevanović).

Some countries with large karst areas use much of their groundwater for irrigation. For instance, Libya and Saudi Arabia use more than 90 percent of their pumped groundwater for such purposes, while Algeria and Jordan use more than 65 percent (Margat & van der Gun, 2013). Spain is another large karst water user; in the 1980s, 40 percent of all water that was pumped for irrigation came from karst aquifers.

Hydropower generation is another way to use water in karst. It mostly involves accumulation of river water in reservoirs but also includes direct use of hydraulic head of groundwater at spring sites. There are many examples of small hydropower facilities all over the world, although this engineering art has the longest tradition in Europe in countries such as France, Switzerland, and Austria. Important examples can also be found in China.

4.2 Water resources development

4.2.1 Karst aquifer's water budget and resources assessment

The concept of water budgets or balance is simple but starts with the understanding of the hydrologic water cycle. The water cycle involves the continuous circulation of water from the upper layers of the earth's soil, rocks, and water bodies as shown by Equation (13).

$$\text{Input} = \text{Output} + \Delta\text{Storage} \tag{13}$$

When the system is in equilibrium over the period specified, then input equals output and there is no change in storage. Differences in the budgeting period result in surplus or deficit of stored water (change in storage). The change in storage is positive when there is a surplus and negative for a deficit. The chosen budgeting periods can vary from relatively short—for example, single events such as a flood or drought—through monthly, seasonal, or annual; to medium- (multi-annual) and long-term (historical). Since variation of the input and output components and variation in stored water reserves is quite normal during short observation periods, a water budget period is better established over a long period, most commonly the hydrometric year. For example, in the UK, the hydrometric year runs from 01 October to 30 September. In the United States, the US Geological Survey calls this same period the water year. However, even on a multi-annual time scale, significant changes in storage can occur such as in the case of long-term groundwater depletion from pumping, drought, or retreating glaciers.

The budget equation for a surface drainage basin or an aquifer system is shown as Equation (14) and illustrated in Figure 62. The change in storage is with respect to the period of the water budget, combining all zones of storage across the drainage basin.

$$\text{Recharge} = \text{Discharge} + \Delta\text{Storage (i.e., Groundwater Reserves)} \tag{14}$$

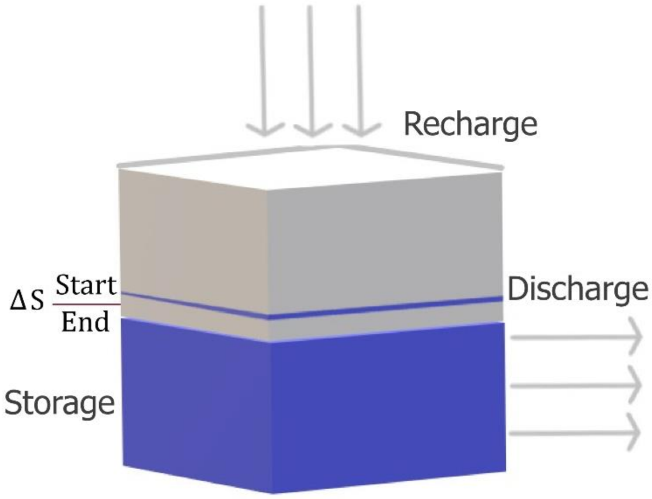

Figure 62 - Scheme of a *black box* system with recharge–discharge components over a long period. ΔS is the change of storage (groundwater reserves) between the start and end of the chosen water budget period. In this case the change in storage is negative because the water level is lower at the end of the period.

In the case of an entirely autogenic karst system with absence of surface flows (runoff), the budget for a spring or a well can be expressed as shown in Equation (15).

$$(P - ET)\,A = V + \Delta S \tag{15}$$

where (parameter dimensions are dark green font with mass as M, length as L, time as T):

P = precipitation (L) herein m

ET = evapotranspiration (L) herein m

A = area supplying recharge and experiencing evapotranspiration (L^2) herein m^2

V = volume discharged by the spring or abstracted from the well (L^3) herein m^3

ΔS = change in storage (L^3) herein m^3

Precipitation, evapotranspiration, and discharge are relatively easy to measure as discussed in Box 22↴, and change in storage can be estimated from the spring recession curve. However, it is commonly very difficult to determine the area draining to a spring or the area that provides recharge to a well. If this is the case, then if a period of measurement is selected during which ΔS can be assumed to be zero, the equation may be rearranged as shown in Equation (16) to estimate the catchment area.

$$A = \frac{V}{P - ET} \tag{16}$$

Where there is both autogenic recharge and concentrated allogenic recharge from an area that is small in relation to the autogenic catchment, and where there are several allogenic streams that sink close to the boundary of the karst, then Equations (15) and (16) can still be applied. However, in this case A is the total area of the allogenic and autogenic catchments and P and ET are measured over the whole area. Alternatively, if there is a single large stream bringing allogenic water onto the karst and the water all sinks at a single point it may be better to measure the flow of the stream before it sinks and to express the equation as shown in Equation (17).

$$(P - ET)\,A = V_{tot} + V_{al} + \Delta S \tag{17}$$

where:

$P, ET,$ and A = relate only to the autogenic catchment – P and ET (L) herein m, A (L^2) m^2

V_{tot} = total volume of discharge and abstraction (L^3) herein m^3

V_{al} = volume of water entering from the allogenic catchment (L^3) herein m^3

Further complications can be envisioned, particularly if an allogenic river flows through the karst area, losing flow to the karst but not sinking entirely. The main budget components for a complex system are shown in Figure 63 and by Equation (18).

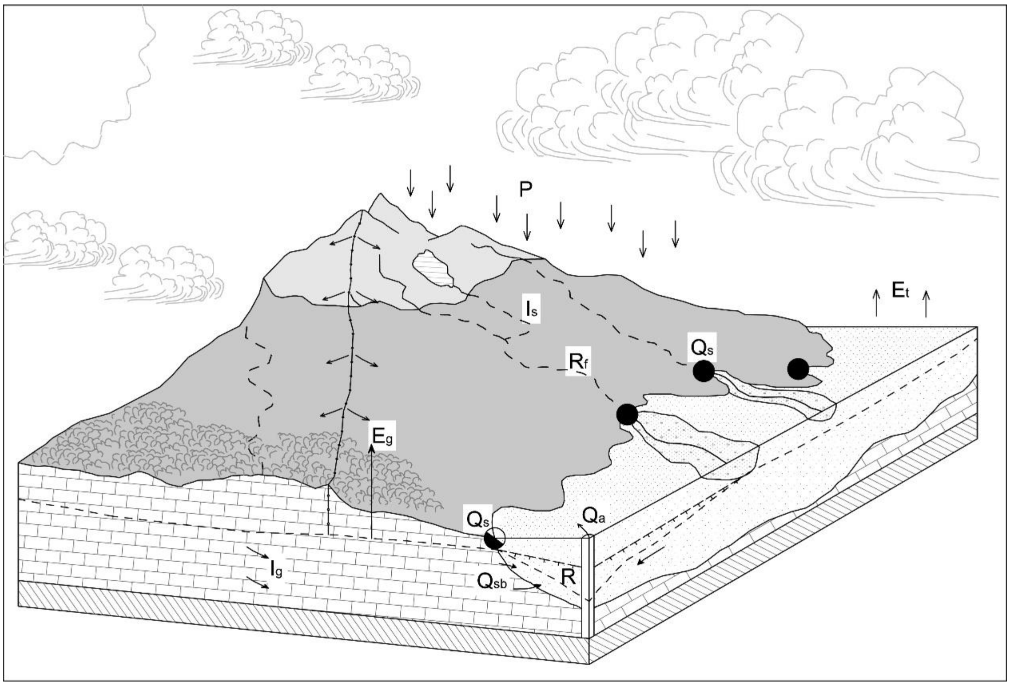

Figure 63 - Water budget elements in an open (unconfined) karst aquifer (modified from Stevanović, 2015). Legend: dark grey = karst; light grey = non-karst; circles = karst springs (solid = perennial; half-white = intermittent); dashed lines on the surface = sinking streams; line with arrows directed away on both sides = surface watershed; diagonal lines = impermeable basement; dashed lines in the subsurface are potentiometric surfaces, R = zone of depression due to pumping from borehole. Labels are explained in Equation (18).

$$P + I_s + I_g = R_f + E_t + E_g + Q_s + Q_{sb} + Q_a + \Delta S + E \tag{18}$$

where:

All terms represent a volume for the budget period (L^3) herein expressed in m^3

P = volume of precipitation on autogenic part of catchment

I_s = volume of surface inflow via streams with their headwater in allogenic part of catchment

I_g = volume of groundwater inflow from adjacent catchments including allogenic water from sinking streams and hypogenic inflow

R_f = volume of runoff generated in autogenic part of catchment

E_t = volume of evapotranspiration

E_g = volume of groundwater evaporation where groundwater body is open to the surface

Q_s = volume of spring discharge

Q_{sb} = volume of groundwater discharge to adjacent catchments

Q_a = volume of artificial withdrawal such as well extraction

ΔS = change in groundwater storage

E = error, a positive value indicates inflows exceed outflows

Some budget elements are relatively easy to measure or quantify (e.g., precipitation, spring discharge, and artificial withdrawal) while others (such as subsurface inflow or drainage) are very difficult, sometimes even impossible, to determine (Box 22↴). Although not directly involved in the budget equation, various climatic factors significantly alter recharge/discharge parameters. For instance, air temperature, humidity, wind, solar radiation, and latitude directly influence the rate of evapotranspiration. In addition to these factors, bifurcation of underground flow routes or artificial interventions can also influence the water budget. For instance, leakage from reservoirs, leakage from underground pipes, irrigation return flow, and managed aquifer recharge can represent important recharge constituents.

Any one budget parameter can be calculated from the general budget Equation (18) if all other parameters are known. Therefore, the change in groundwater storage could be theoretically determined if all other parameters are properly estimated. However, the many uncertainties may preclude such a calculation.

Effective recharge (I_{ef}) is the discharged amount of water leaving the aquifer expressed as a fraction of the precipitation that reaches the groundwater zone as shown in Equation (19).

$$I_{ef} = \frac{Q_s + Q_{sb} + Q_a}{P} \tag{19}$$

Dynamic groundwater reserves (Q_{dyn}) correspond to the sum of the average annual discharge from all registered springs in a studied karst basin (the quotient of Q_s for an annual budget and the length a year). Dynamic reserves issue from the zone between the maximal and minimal water table (ΔH) in an annual hydrology cycle (Figure 64). The spring flows can vary greatly throughout the year and are expressed in m^3/s.

Static (non-renewable) groundwater reserves (Q_{st}) occur beneath the minimal groundwater level (Figure 64). They depend on the aquifer's pore volume: which is the product of its surface area (A_{aq}), saturated thickness below the minimal groundwater level (H_{st}), and storativity (S) of the aquifer below H_{st}, as shown in Equation (20).

$$Q_{st} = A_{aq} \; H_{st} \, S \tag{20}$$

where:

Q_{st}	=	volume of static groundwater reserve (L^3) herein expressed in m^3
A_{aq}	=	aquifer surface area (L^2) herein expressed in m^2
H_{st}	=	saturated thickness below minimal groundwater level (L) herein expressed in m
S	=	storativity (dimensionless)

Static reserves are often referred to as being non-renewable or geological (Castany, 1967), but this is not always the case. If there is subsurface drainage (Q_{sb}) or forced artificial drainage—extraction (Q_a) with a decline of the potentiometric surface—water from the upper section with dynamic flow percolates downward to the zone of static reserves to refill the depleted water, maintain the stored volume (Q_{st}), and maintain the deep groundwater discharge (Q_{sb}).

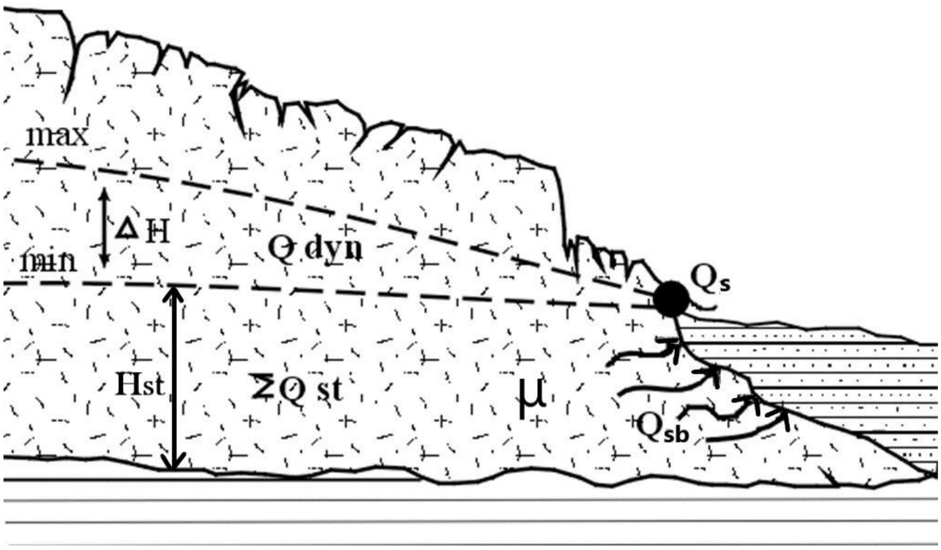

Figure 64 - Scheme of groundwater reserves: volume of dynamic (Q_{dyn}) and static (Q_{st}). The latter is only conditionally "static" because some renewal of reserves is possible due to the existence of subsurface drainage (Q_{sb}) to the adjacent aquifer and percolation from the overlying zone (Q_{dyn}), which compensate this water loss. This scheme explains why in water practice the often-used term "non-renewable reserves" is inappropriate as a synonym for "static reserves."

Available (exploitable) reserves (Q_{expl}) can be expressed as dynamic reserves (Q_{dyn}) minus water that is required for water dependent ecosystems (Q_{eco}) as shown in Equation (21).

$$Q_{expl} = Q_{dyn} - Q_{eco} \tag{21}$$

where:

Q_{expl} = exploitable reserve expressed as annual discharge rate (L^3T^{-1}) herein m^3/s

Q_{dyn} = dynamic reserve expressed as annual discharge rate (L^3T^{-1}) herein m^3/s

Q_{eco} = discharge required to maintain water dependent ecosystems (L^3T^{-1}) herein m^3/s

Water needed for the dependent eco-system is commonly defined as equal to the minimum natural discharge of springs (average minimal values), however in practice it is typically specified as 70 to 80 percent of the average minimum values.

The exploitable reserves can also be manipulated by engineering works and this is discussed in Section 4.4 *Toward Sustainability*.

4.2.2 Karst water resources availability and utilization

The USA provides an example of a country in which there was initially extensive use of karst groundwater in smaller settlements and sparsely populated areas, but during the twentieth century- fast-growing large urban settlements and industrialization resulted in an increased reliance on surface water. Nevertheless, it has been estimated that approximately 50 million people in the United States currently depend on karst water. The Edwards aquifer in Texas and the Floridan Aquifer system in Florida and parts of Alabama, Georgia, and South Carolina are some of the largest karst systems in the USA, with many natural springs and well fields that utilize its water (Figure 65). Lovelace and others (2020) estimated that around 100 m^3/s is an average total withdrawal from carbonate aquifers for potable water supply. Out of this amount of water, around half is utilized from the Floridan aquifer. The world's largest artesian well, issuing more than 2.5 m^3/s, has been drilled in Texas. Apart from the Edwards aquifer, the eastern states—Alabama, Florida, Georgia, Kentucky, South Carolina, Tennessee, and West Virginia—are also rich in karst aquifers, and many municipal water utilities distribute their water.

Figure 65 - Comal Spring, the largest spring issuing from the Edwards Aquifer. Its maximum yield of 18.5 m^3/s was recorded in April 1977 (photo by Z. Stevanović).

The greatest number of consumers of karst water in Central America can be found in Mexico on the Yucatan Peninsula, where the Cenozoic-age limestone platform is pitted by water-filled depressions (cenotes), many of which connect to caves. Nine of the ten longest underwater caves in the world are in Mexico, ranging in length from 25 km to 370 km. The expansion of the tourist industry in the northern and north-eastern coastal area, coupled with intensive pumping (Merida, Cancun), has resulted in saltwater intrusion deep inland.

In Jamaica, where the White Limestone is the dominant karst formation, groundwater accounts for about 84 percent of all available water (Karanjac, 2005). The largest portion thereof is used for irrigation (75 percent of the total water production). The Dominican Republic is also rich in karst aquifers, but both these countries are suffering from saltwater intrusion and contamination of groundwater by untreated industrial water, poor sewage management, and tourism (Karanjac, 2005). Cuba is another island with many karstic rocks and intensive use of karst water. There are also several other Caribbean islands that have no water sources other than karst groundwater (Robins, 2013).

If we consider the number of citizens dependent on karst water, China is the major karst water consumer. About one third of the estimated 150 million Chinese that use potable water from karst aquifers live in the northern and north-eastern parts of China, including a portion of the city of Beijing. Yuan (1994) has listed 60 springs issuing from Ordovician–Devonian carbonate rocks, with a discharge of more than 1 m^3/s. According to Wu and others (2010), these springs are widely used for water supply, especially in the provinces Shanxi, Hebei, and Shandong (Figure 66). In the south of China, where karst outcrops to a larger extent than in the north, there are roughly 100 million consumers (Stevanović, 2019). For example, approximately 2,680 municipalities in Guizhou province use karst springs for potable water supply (Wu et al., 2010).

a) b)

Figure 66 - Karst water supply in China. a) One of the wells drilled under a campaign for rural water supply in south China. The International Research Centre on Karst (IRCK), Guilin, China, stated that 2,348 wells were drilled up to 2013 providing a water supply to some 5.2 million inhabitants in rural and semi-rural areas. b) Black tiger spring in Jinan city, Shandong province (both photographs courtesy of IRCK.

Karst water is extensively used in parts of Vietnam, Laos, Malaysia, and northern and southern Thailand. Java in Indonesia and the Palawan Province in the Philippines are just some of many islands that depend heavily on karst water sources. The main karst aquifers in Iran are in the southern part of the country and provide the water supply for Shiraz, Kazeroon, Bushar, and many other cities (Raeisi & Stevanović, 2010). In Iraq, the use of karst water is dominant in the northern part of the country, in the province of Kurdistan (Stevanović & Iurkiewicz, 2004).

Jordan, Syria, Israel, and Lebanon are also countries with large extensions of karst aquifers from Jurassic to Tertiary age. Many cities, including the capital cities Damascus and Beirut, have developed karst sources to serve their populations.

Turkey is one of the large karst countries. Karst is extensive over its southern part, providing the water supply for most tourist cities along the Mediterranean coast. Many reservoirs built across Turkey over the last 50 years have captured karst water. For example, one of the world's largest karst springs—Dumanli—was submerged beneath the Oymapinar reservoir in 1984.

Egypt, Libya, Algeria, Somalia, and Ethiopia are the African countries with the largest extensions of karst and utilization of karst water. The majority of the aquifer systems are of Upper Cretaceous to Eocene age.

In France, about 60 percent of the population is supplied from groundwater and the rough estimate is that karst aquifers provide about 50 percent the groundwater supply. Major cities in the south, such as Montpellier and Marseille (Figure 67), are exclusively karst-water oriented (Margat et al., 2013; Bakalowicz, 2015). In Italy, some 290 major springs in the central-southern Apennines have a total mean discharge of 320 m^3/s (Boni, 1992) and karst water is also widely utilized in the south (Puglia, Sicily), as well as in the north, in the foothills of the Alpine mountains. Greece and Spain are two other Mediterranean countries that use karst water extensively, especially on islands.

Figure 67 - Two springs, Bestouan and Port Miou, supply water to the city of Marseille. This water is fresh or brackish, depending on the pressure in the littoral karst aquifer (courtesy of Potié, modified).

Karst water is used to a considerable extent in south-east Europe as well. The leader is Montenegro, where almost 90 percent of the population depends on karst water supply. More than half the citizens of Albania, Austria, Bosnia and Herzegovina, and Slovenia also drink karst water (Figure 68). In Austria, total renewable water resources per capita are higher than 9,000 m^3/year, but the utilization rate is only 4.7 percent (FAO, the Food and Agriculture Organisation of the UN, 2016). According to the same source, Albania has even greater water availability. In that country, each citizen has about 13,000 m^3 of water available per year—35 m^3/day.

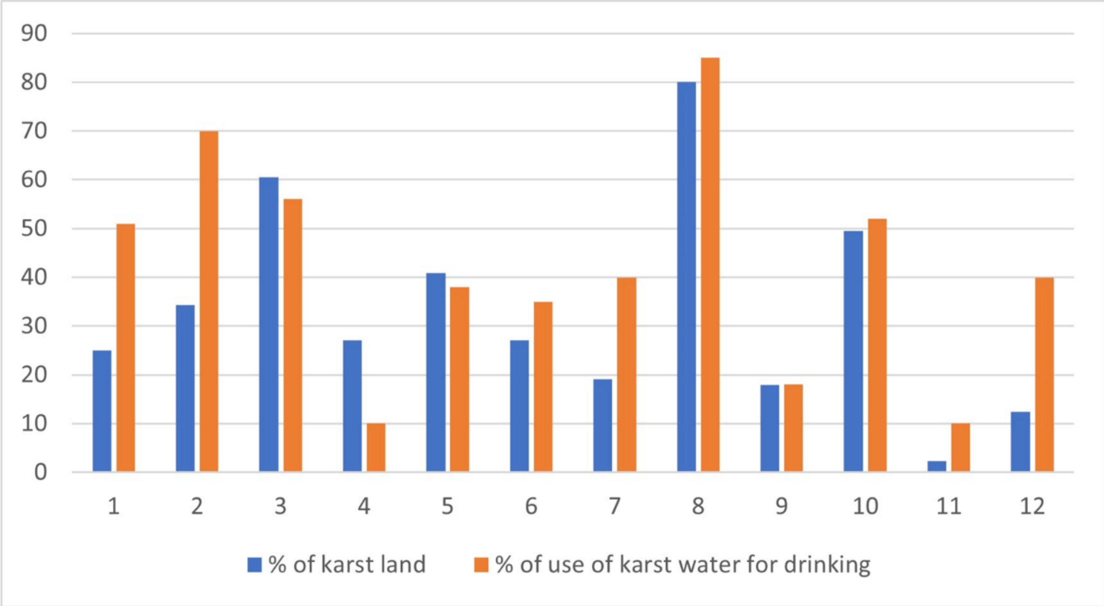

Figure 68 - Karst distribution and karst water use: Relationship between the percentage of area covered by karst and the percentage of population using karst water for water supply in the countries of southeast Europe. Legend: 1 - Austria, 2 - Albania, 3 - Bosnia and Herzegovina, 4 - Bulgaria, 5 - Croatia, 6 - Greece, 7 - Italy, 8 - Montenegro, 9 - Serbia, 10 - Slovenia, 11 - Romania, 12 - North Macedonia (from Stevanović, 2021).

The karst spring that supplies the capital of North Macedonia is pictured in Figure 69 (Stevanović, 2021). 40 percent of North Macedonia citizens depend on karst water supply, while 35 percent rely on karst water in Croatia, and 20 percent in Serbia. The main aquifers are of Mesozoic age, ranging from Triassic to Lower Cretaceous units.

Figure 69 - The intake of karst spring Rašče, which supplies drinking water to Skopje, the capital of North Macedonia. The karst aquifer is formed in Paleozoic marbles and metamorphized limestones and is partly fed by water from the Vardar River and adjacent alluvial fan (photograph by Z. Stevanović).

Karst aquifers have large extensions in the southern parts of Russia, Ukraine, and Moldavia where large cities and industrial centres are located. For instance, it can be roughly assessed that some 8 million Ukrainian citizens are consuming potable water from karst aquifers consisting mainly of Tertiary (Miocene) stratified limestone.

About half of the island of Ireland is underlain by limestones and karst groundwater forms an important part of the potable water supply, particularly in rural areas, as well as being used by agriculture. In England and Wales, water from the Carboniferous-age limestones is largely exploited at springs but adits (galleries)—driven to dewater lead mines in the eighteenth and nineteenth centuries—are also used for potable supply in some areas. However, the most important karst aquifer in the UK is the Cretaceous Chalk, which crops out in southeast England and is confined in the London basin syncline. Despite this relatively small geographic area, the chalk accounts for about 60 percent of groundwater use and 20 percent of total water use in the whole of England and Wales.

An assessment of global karst groundwater rate of utilization is provided in Box 23↓. Exercise 2↓ examines assessment of average effective recharge for a karst system. Exercise 4↓ provides an opportunity to practice calculating water budget components. Exercise 5↓ concerns assessment of available exploitable groundwater resources of a karst aquifer while ensuring ecological flow for dependent ecosystems.

4.3 Karst Water Under Threat

As a result of karst heterogeneity and its unstable regimes, the phrase "expect the unexpected" is commonly used by many engineers and managers dealing with karst and its properties. Through their regular activities, these engineers and managers are trying to combat or mitigate negative consequences of major threats on karst aquifers and terrains, for example:

1. over-extraction of groundwater,
2. contamination of groundwater and soil,
3. climate change impact, and
4. natural hazards.

4.3.1 Over-extraction

Many countries or regions with widely distributed karst are facing water shortages and significant depletion of water reserves (for example, parts of the USA, China, the Arabian Peninsula, northern Africa, and southern Spain). Such a situation is likely to continue. Forecasts are even worse concerning the arid part of our planet, where insufficient recharge is the consequence of rare or erratic rainfalls and increased water demands cannot be met.

High demographic growth, especially in the developing world, and the expansion of large urban settlements mean there is an ever-increasing demand for water. Poor economic and sanitary conditions in many countries of the arid part of the world, coupled with unstable political situations, are causing migrations the extent of which has not been encountered in modern history. At the beginning of 2022, the global population reached around 7.9 billion (Worldometer↗), while in the next 50 years there could be an additional two billion people on the planet. More than half of the world's population already lives in urban settlements. By 2030, it is projected that 662 cities will have at least one million residents, while the number of *megacities* with more than 10 million inhabitants will reach 41 (United Nations Department of Economic and Social Affairs, Population Division, 2016). Different water sources will be required to satisfy their water demands, but karst aquifers will not be in the priority group. While in ancient times towns were built near major springs, modern urbanization does not take such factors into account. Nowadays, major karst springs and their locations—except for some cities in southern and southeast Asia—rarely correspond with the locations of megacities and are not even within a radius of 100 to 200 km (Stevanović, 2019; Goldscheider et al., 2020). However, potable water supply from karst water sources will still be possible for settlements with populations of up to two million.

Based on the experiences of several arid countries, the 1:3.5 approximate proportion (globalagriculture.org↗) of potable versus irrigation water can be even higher, so with increased demand for drinking water less water will be available for growing food. Although it is now widely accepted that certain regions will face severe water shortages, not everyone realizes that future water shortages will also mean a future of food shortage. Currently, 40 percent of global food products arrive from irrigated agriculture, while the rest comes from rain-fed agriculture. In China, which is now the global leader in food consumption, 80 percent of the grain harvest comes from irrigated land. Brown (2012) noted that 18 countries, with a combined population of 3.6 billion, are over-pumping their aquifers and based on WOKAM, in 14 of those countries more than 20 percent of the land is karst.

Maupin and Barber (2005) stated that total groundwater withdrawal in USA averages a flux of 3,350 m^3/s, of which around 8 percent—or a flux equivalent of 268 m^3/s—originates from carbonate aquifers. Although many non-karstic aquifers are over-exploited (e.g., Ogallala in the Great Plains, California's Central Valley, in the USA), in regions with rich karst aquifers (Texas, Florida) there is still no evidence of significant groundwater depletion. The exception is karst aquifers whose water is pumped for local irrigated agriculture.

Mexican food production also heavily depends on irrigation, but 58 percent of all the water extracted in the country comes from aquifers that are currently over-exploited

(Brown, 2012). Jamaican aquifers are also over-exploited, and their water availability is 1,500 m^3/year/capita, which classifies country as "water stressed" (Karanjac, 2005).

Lu (2005) estimated that almost 80 percent of the large available karst groundwater flux in northern China (circa $12.5x10^9$ m^3/year) had already been exploited, in contrast to about 15 percent of karst aquifers developed in southern China. In the North China Plain, the average drop of the groundwater surface elevation is about 3 m/year. According to the World Bank (2002), drilling in the area of Beijing now has to go five times deeper than 20 years ago to reach the required well discharge. If no other options or alternatives are found, the report envisages catastrophic consequences for future generations.

Wu and others (2010) noted a decline of discharge in several groups of springs in China. This is the case with 20 of the 29 large karst springs in Shandong province, while a similar situation has been recorded regarding the springs in Shanxi, Hebei, and Henan provinces. The discharge of the large Jinan springs has also been declining since the 1980s due to over-exploitation for irrigation purposes. Similarly, the group of large Niangziguan springs (Mianhe River, Shanxi province, northern China, Figure 70) suffers from over-exploitation, which has intensified since the mid-1950s, and from pollution by local industries and mines (Wu et al., 2010).

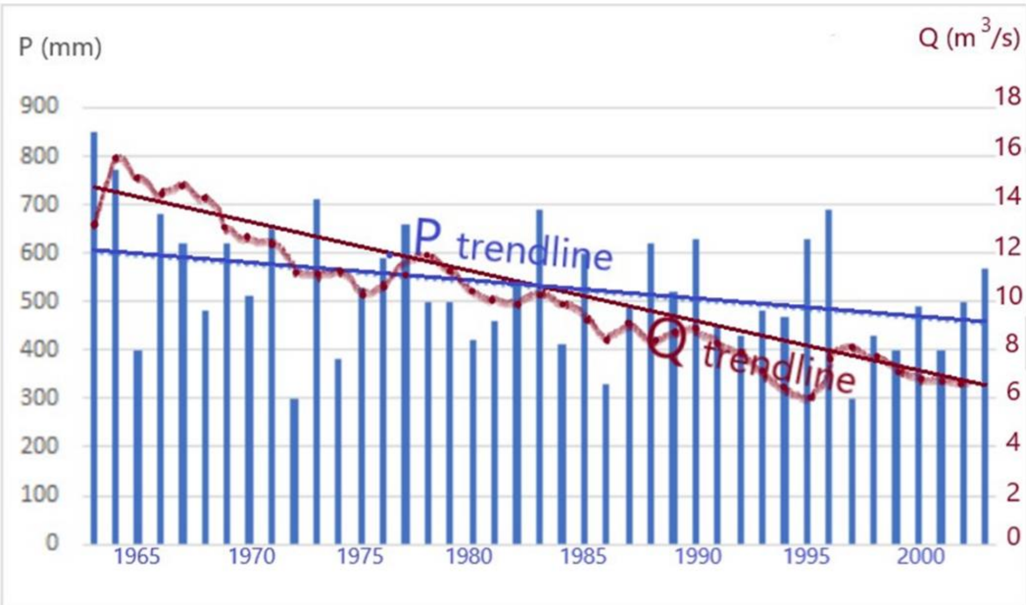

Figure 70 - Precipitation and springs discharge trends: Trendlines of precipitation (P - blue) and discharge (Q - red) of Niangziguan group of springs for the period 1963 to 2003 (adapted from Wu et al., 2010). The considerable decline of spring discharge (i.e., a decrease of 57 percent over a 40-year period) cannot be solely the result of lower precipitation which declined only 20 percent.

In the developing world, it is very difficult—sometimes even impossible—to meet increased demands and provide sufficient water to the population. A typical example of such a situation is the city of Sulaimani in northern Iraq (Iraqi Kurdistan province), discussed by Stevanović (2018). In 60 years, this city expanded from less than 50,000 to

2 million inhabitants. The local karst source, Sarchinar (discharge 0.6 to 7 m^3/s; Figure 71), is simply not able to accommodate such an increase in population. In addition to the spring, the city now obtains water from the Dokan reservoir and from several thousand wells that have been drilled in the karst aquifer, mostly illegally. Utilization of water from these wells without sanitary control and treatment has caused hydric epidemics of gastrointestinal diseases and even numerous cases of cholera (Salahaddin S. Ali, Komar University, Sulaimani, Iraq, personal communication, 14 December 2010).

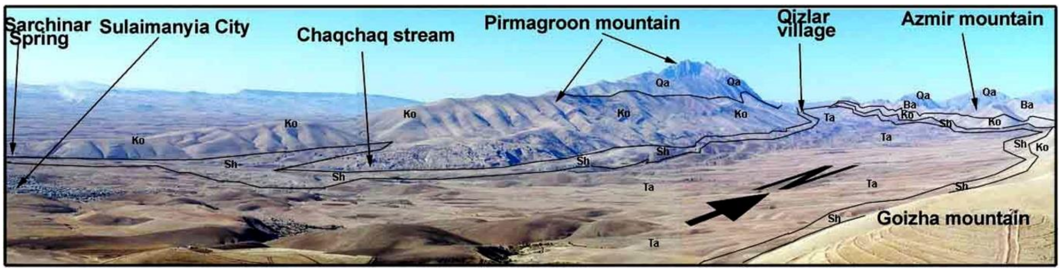

Figure 71 - Pirmagroon Mountain: Catchment area of the Sarchinar spring used for drinking water supply of Sulaimani city in northern Iraq (image after Ali, 2007). Geological formations Ko (Kometan) and Qa (Qamchuga) are purely karstic. Groundwater pollution takes place exclusively in urban area.

Some countries that have large karst aquifers still experience a great shortage of water. This is mostly the consequence of rare or erratic rainfalls and insufficient recharge, but sometimes also due to uncontrolled extraction. In Saudi Arabia, pumping is quickly depleting the country's major aquifers. After the Arab oil-export embargo in the 1970s, this country's leaders realized that since they were heavily dependent on imported grain, they should start to tap their own deep aquifers to produce irrigated wheat. However, after more than 20 years of wheat self-sufficiency, in January 2008 their aquifers were largely depleted, causing the national wheat production to almost stop. FAO AQUASTAT (FAO, 2016) data show that Saudi Arabia uses eight times more water than is provided by its internal renewable water resources.

Some large karst sources and their catchments are exposed to intensive over-extraction. For instance, the largest Syrian spring and one of the largest in the Mediterranean karst, Ras el Ain, dries out each summer due to forced pumping to irrigate cotton fields in the border area between Syria and Turkey.

We live in a world where more than half the people live in countries with food bubbles—inflated production of food through unsustainable use of water and land—based on over-extraction of groundwater. The question for each of these countries is not whether its bubble will burst, but when that will happen (Brown, 2012).

It is suggested that the global response to such pressure on karst aquifer systems be to, wherever possible, use karst water resources only to satisfy demands for drinking water. Since 1,000 m^3 of water are needed to produce one ton of grain, it makes more sense to import grain than to import water.

4.3.2 Vulnerability to pollution and contamination of karst

Self-purification capacity of karst aquifers

As discussed earlier in this book, water infiltration into, and flow through, karst aquifers differ from that in most other aquifer types. In particular, pollutants spread differently and more rapidly in karst than in most fractured and porous aquifer systems (Figure 72). Globally, non-karst aquifers are more commonly covered by thicker soil and sediment layers than is the case in karst areas. These materials provide a greater protective layer by preventing the immediate entry of substances into the subsurface. Once substances reach the aquifer, they migrate more slowly (a few metres per day) through non-karst and disperse through the pores between the grains, causing some contaminants to sorb, filter, decay, and/or decompose before reaching a location where the groundwater is accessed by people or used by ecosystems.

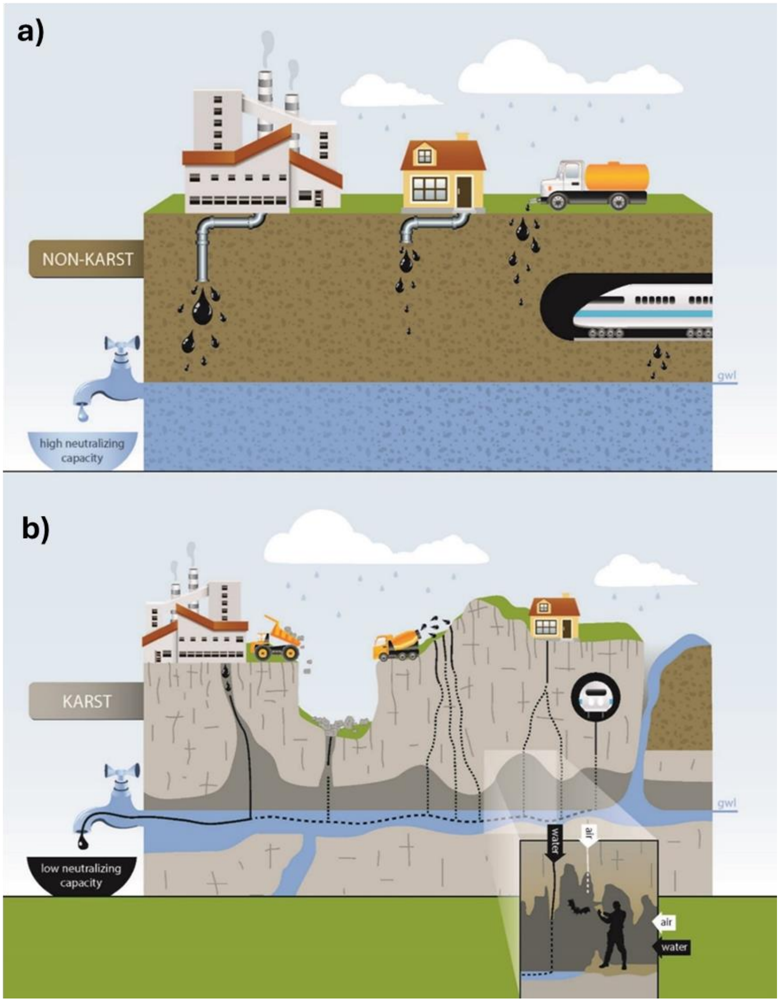

Figure 72 - The self-purification capacities of a) non-karst aquifers are significantly higher than those of b) karst due to specific characteristics of water infiltration and flow in the subsurface (from Ravbar & Šebela, 2015).

Where the karst surface is bare or covered with a thin layer of soil and vegetation, immediate infiltration of rainwater into the interior of the aquifer is possible through cracks and voids in the bedrock. Even in covered karst, rapid infiltration is facilitated by areas of point recharge (e.g., dolines). Surface streams that collect water on the non-karst surface may also sink into the karst at their contact through ponors (swallow holes). When water enters the aquifer, it flows mainly along channels and conduits, partly also through fissures, tending to concentrate on the way to the springs. However, due to the high heterogeneity and anisotropy of underground pathways, they are often complex, mostly unknown, and may vary due to specific hydrological conditions.

In general, water flows rapidly along conduits, reaching high velocities of up to several hundred metres per hour. High flow rates limit the capacity for contaminant degradation and for microorganisms to die off. In karst conduits, the flow is predominantly turbulent during storm events, mobilizing water-insoluble pollutants and preventing their stagnation. As a result, pollutants can reach springs very quickly (via conduits), poorly diluted, and in high concentrations, but they can also be stored (in the matrix) and slowly percolate toward groundwater and springs, leading to long-term pollution. In cases of anaerobic conditions, the possibility of biodegradation is reduced. Flow is commonly slower in confined conditions and anaerobic conditions may prevail reducing the possibility of biodegradation. Groundwater also flows more slowly and is mostly laminar in the less permeable volumes of the rock matrix.

Large karst springs usually have a large catchment area, but high flow rates cannot ensure sufficient pollutant removal or degradation. Therefore, even a greater distance from the water source does not necessarily mean greater safety from contamination. Consequently, the self-purification capacity of groundwater in karst is typically very low and occurs only to a limited extent. Therefore, karst aquifers are extremely vulnerable to contamination when compared with other aquifer types.

Contamination may originate from point hazards (septic tanks, accidents), linear hazards (roads and railway lines), or areal hazards (manure spreading). Contamination can be a one-time incident or a long-term activity. The most endangered karst water is that recharged in densely populated areas with developed industry, and tourism, as many settlements and economic activities have no regulated wastewater drainage. These often flow untreated or only partially treated into sinking rivers, which then recharge the karst. The major polluters of karst water are domestic, industrial, and municipal wastewater, leachate from roads and parking lots, illegal surface and subsurface dumping, and improperly constructed landfills (Figure 73, Figure 74, Figure 75, Figure 76, Figure 77; Box 24⤵).

Figure 73 - Discharging wastewater into dolines is inappropriate, as they provide a concentrated inflow of water to the subsurface and pollutants can rapidly reach groundwater (photograph by N. Ravbar).

Figure 74 - Caves are often places of illegal dumping, even where waste collection is regulated, because garbage does not pile up and is not visible. However, such waste disposal is inappropriate, as underground pollution is difficult to remove and can quickly reach groundwater (photograph courtesy of J. Tičar).

Figure 75 - During construction, the protective layer of the aquifer is usually removed, increasing its vulnerability (photograph by N. Ravbar).

Figure 76 - Piles of coal combustion waste from the Gacko thermoelectric power plant in an excavated coal open pit mine area at the Gatačko Polje, Bosnia, and Herzegovina (photograph by N. Ravbar).

Figure 77 - In the period from 1950 to 1990, 250,000 m^3 of tar, acetylene sludge, and various other refinery and industrial wastes were disposed of from the port of Rijeka, completely filling the Sovjak collapse doline near Viškovo, Croatia (photograph courtesy of F. Drole).

Karst water quality is also threatened by agriculture, where excessive and improper fertilizer and pesticide use, and poorly regulated manure and septic tanks, are common. The vulnerability of karst aquifers is also increased by construction activities, which often remove virtually the only protective layer of the aquifer. Spills of large quantities of hazardous and toxic substances during accidents also pose a major threat to karst aquifers.

The transfer of contaminants depends on their properties. They often behave differently from water and react in different ways with the protective soil, sediment, or vegetation layers (if present) and with the rock through which they move. The transfer of liquid contaminants is also affected by whether the substance is lighter or heavier than water and whether it is soluble in water.

Different types of contaminants relevant in karst systems

Contaminant hydrogeology is an extremely large topic, which is discussed in detail in many textbooks (e.g., Appelo & Postma, 2005; Fetter, 1999) as well as in several online books of this GW-Project series↗. Therefore, this section presents a very brief overview of relevant groups of contaminants and their specific properties with respect to karst aquifers, that are summarized in Table 4. The huge number of groundwater contaminants can be grouped according to different criteria.

Table 4 - Overview of selected groups of contaminants, their general properties and sources, and their specific relevance in karst groundwater systems.

Type or group of contaminants	General description and major sources	Specific relevance for karst aquifers
Faecal bacteria and pathogenic microorganisms	Include viruses, bacteria, and protozoa, mainly from wastewater and agriculture	Frequent problem in karst aquifers because of short transit times and limited filtration capacity
Turbidity and organic carbon	Not contaminants but undesirable in drinking water	Frequent in karst, often together with bacteria; can be used as early warning parameters for microbial contamination
Nitrate and other nutrients	Widespread problem in agricultural areas from organic and inorganic fertilizers	Mostly stable in oxygen-rich karst aquifers (no denitrification)
Pesticides	Widespread problem in agricultural areas	Thin and highly permeable soils on karst facilitate leaching to groundwater
Arsenic, cadmium, and other toxic metals	Partly geogenic, partly from mining or industry	Often immobile in oxygen-rich karst groundwater but possible transport attached to sediment particles
Uranium, radon, and other radioisotopes	Generally, geogenic but sometimes from mining or other sources	Specific geochemical conditions and mixing can cause high levels of radioactivity
Chloride	From seawater intrusion related to over-pumping, road salt, inappropriate irrigation, or geogenic	Particularly complex seawater–freshwater interactions in coastal karst aquifers
Sulphate	Geogenic from the dissolution of sulphate rocks; anthropogenic from burning of coal ("acid rain")	High levels occur in gypsum or mixed karst aquifer systems
Light non-aqueous phase liquids (LNAPL)	Float on groundwater surface, toxic, e.g., benzene and petroleum chemicals	Transient trapping and accumulation at the water surface of siphons (water-filled cave passages)
Dense non-aqueous phase liquids (DNAPL)	Sink to the bottom of the aquifer, toxic, chlorinated solvents from industrial applications	Accumulation at the bottom of siphons and in cave sediments; mobilization during high-flow events

Based on the general type of contaminants, it is possible to differentiate inorganic compounds (e.g., nitrate, heavy metals), organic compounds (e.g., petroleum chemicals, chlorinated solvents), and pathogenic microorganisms including viruses, bacteria, and protozoa. All types of contaminants can occur in karst groundwater, but pathogenic microorganisms are particularly relevant because of the high flow velocities, short transit times, and limited filtration capacity in karst aquifers.

In terms of their origin, the main sources of contaminants include the following:

1. industry, mining (Figure 78), contaminated sites and landfills (Figure 79a),
2. agriculture,
3. buildings and settlements, including tourist infrastructure (Figure 79b); and
4. the often-forgotten geogenic—that is, naturally occurring—contaminants.

Figure 78 - Acid mine drainage in a Chinese karst area. During this process, metal sulphides are oxidized and dissolved, generating sulphuric acid and mobile toxic metals (photograph by N. Goldscheider).

Figure 79 - Contamination threats to karst. a) Unmanaged waste disposal site in a Chinese karst area. b) Concrete shaft for the injection of wastewater from a skiing station in the Austrian Alps. After this photograph was taken a proper treatment and disposal system was installed (photographs by N. Goldscheider).

Globally, arsenic is the most important geogenic contaminant in groundwater (Nickson et al., 1998) but it is mostly present in fine-grained sedimentary aquifers with reducing conditions and is not commonly found in karst. In karst aquifers, relevant geogenic contaminants include sulphate (SO_4^{2-}), which results from mineral dissolution in pure gypsum or mixed carbonate–sulphate karst systems. Mineral ores in carbonate rocks can also cause increased geogenic levels of lead (Pb) or other heavy metals.

Contaminants can also be grouped based on their solubility. Some contaminants are highly soluble such as nitrate, sulphate, and chloride. Others have a much lower solubility such as many heavy metals that often occur in the form of nearly insoluble minerals (carbonates, sulphides, and sulphates). However, insoluble metal sulphides can be oxidized and mobilized in contact with oxygen-rich (karst) groundwater, processes that occur during acid mine drainage (Figure 78). Organic contaminants with very low solubility are a special case as they form a separate liquid phase that does not mix with groundwater. These non-aqueous phase liquids (NAPL) are further differentiated according to their density:

- Light non-aqueous phase liquids (LNAPL) are less dense than water and float on the groundwater surface, analogous to an oil slick on the sea. LNAPL include benzene and different types of petroleum chemicals.

- Dense non-aqueous phase liquids (DNAPL) are denser than water and sink to the bottom of the aquifer or even lower, as they can also traverse aquitards. DNAPL include various chlorinated solvents such trichloroethylene (TCE).

LNAPL and DNAPL are highly problematic contaminants and there is plenty of practical experience and scientific research regarding the behavior and treatment of these substances in porous aquifers. Their behavior in karst is more complex, and the remediation of contaminated sites in karst is particularly challenging. A general conceptual model for the behavior of LNAPL and DNAPL in karst has been proposed by Loop and White (2001). In karst aquifers, LNAPL tend to accumulate at the water surface upstream from siphons (and are sometimes released during low-flow conditions, when the water level is lower than the ceiling of the siphon), whereas DNAPL accumulate at the bottom of siphons and in conduit sediments, and are mobilized during extreme high-flow events, along with the erosion and transport of these sediments.

In addition to the presence of NAPLs and DNAPLs as pools of free product (i.e., in a separate organic phase), some of the free product dissolves in the groundwater causing plumes of dissolved constituents that emanate from the floating or sinking pools. These behave and are treated with techniques applied to other dissolved plumes, but the presence of many pools at locations throughout the karst makes remediation difficult.

In terms of relevance for human health, contaminants can be grouped based on their toxicity. Some contaminants, for example nitrate, chloride, and sulphate, are not toxic but are undesirable at high concentrations. The legal limits for these contaminants are often in the range of several tens to hundreds of milligrams per litre (e.g., nitrate: 50 mg/L). Other substances, including both organic contaminants and heavy metals, are much more toxic and have legal limits in the μg/L-range (e.g., arsenic: 10 μg/L). The harmfulness of microbial pathogens is described by means of their virulence.

Contaminants also differ with respect to their mobility in groundwater, which depends on their tendency to adsorb to mineral surfaces. Some contaminants such as nitrate and chloride—but also volatile chlorinated hydrocarbons—are highly mobile and are transported at the same velocity as flowing groundwater. Many toxic metals that occur in the form of bivalent cations such as lead (Pb^{2+}), cadmium (Cd^{2+}) and several radioisotopes are generally immobile as they strongly adsorb to clay minerals in the soil or in conduit sediments (Vesper & White, 2004). However, in karst systems, sediment particles in soils and conduits are easily mobilized during high-flow events (Herman et al., 2008). Such particle-bound contaminant transport is important in karst systems and can lead to a rapid and efficient transport of all types of contaminants that are otherwise expected to be immobile.

Last but not least, contaminants can be classified according to their lifespan, stability, and degradability. Toxic metals such as chromium, cadmium, and arsenic have an unlimited lifespan, but geochemical processes can change their toxicity and mobility (e.g., chromium-VI is much more toxic and mobile than chromium-III). Organic contaminants range from recalcitrant compounds such as volatile chlorinated hydrocarbons to readily degradable compounds such as benzene, toluene, and ethylbenzene. The lifespan of pathogenic microorganisms in groundwater varies from absent/zero (e.g., the AIDS virus) to several months or years (e.g., the cysts of *Cryptosporidium parvum*). Due to the fast flow velocities and short transit times in karst aquifers, along with the limited filtration capacity, the lifespans of microbial pathogens are highly relevant for groundwater protection in karst areas (Pronk et al., 2009).

4.3.3 Climate changes impacts

A series of reports issued by the Intergovernmental Panel on Climate Change (IPCC) have concluded that the climate of our planet is changing. This change will have an impact on land use activities, which in turn will exert pressure on water resources and dependent eco-systems. Some of the greenhouse gas emission scenarios developed by the IPCC (2007) make climate projections by manipulating General Circulation Models/Global Climate Models (GCM), as was done in projects such as PRUDENCE (Christensen et al., 2007), ENSEMBLES (van der Linden & Mitchel, 2009), and CORDEX (Giorgi et al., 2009).

The fourth IPCC report (2007) estimated that a global pattern of contrasting changes in rainfall is expected to occur between the present and the end of the twenty-first century, with a decrease in rainfall compared to 1980 to 2000 averages that could exceed 20 percent in arid and semi-arid zones, which are already vulnerable to reduced recharge of water resources. Negative impacts will include increased risk of inland flash floods and increased erosion. Mountainous areas will face glacier retreat, reduced snow cover and winter tourism, and extensive loss of species. There is overwhelming evidence that almost all natural, biological, and physical processes are reacting to climatic changes worldwide. Although forecasts show that in the next 50 years recharge of aquifers in the Northern Hemisphere could be stable or will slightly increase, in the Southern Hemisphere recharge may decrease by 30 percent, even up to 70 percent. The predicted changed climate elements include intensive rainfall in winter and extended droughts in summer–autumn months. This will primarily influence those karst aquifers with smaller storage capacities and already unstable discharge regimes. In contrast, karst aquifers with high permeability and large storage capacity may function as buffers to peak floods and could ensure water supply during prolonged droughts (Stevanović et al., 2015).

Hartmann and others (2014b) reviewed different modeling tools that can be used to better predict climate change impacts on karst water resources in a changing world, including an appropriate consideration of major uncertainties at all levels. The Mediterranean region is identified as a prominent example where large-scale climate-change impacts on karst water resources are expected. For example, Fiorillo and others (2021) analysed long-term (over 100 years) karst spring discharge series from two karst aquifers in southern Italy to determine trends, fluctuations, and relationship to climate. The analyses revealed a general decrease of spring discharge over the past decades—not only related to precipitation change but also and mainly due to increasing temperature and, thus, evapotranspiration.

In the case of a Mediterranean karst spring in southwest Slovenia, which is the only source of drinking water for the entire region of the Slovenian coast, Ravbar and others (2018) found an increase in mean annual air temperatures, a decrease in annual precipitation, and an increase in actual evapotranspiration (especially in spring and summer). As a result, the mean annual discharge of the spring, which was 3.5 m^3/s from 1989 to 2018 (Republic of Slovenia Ministry of Environment, Climate and Energy, 2019), is expected to decrease by about 0.5 m^3/s per decade, with prolonged dry periods in summer when water demand is highest. Detailed monitoring of physical, chemical, and microbiological parameters has shown that if water conservation practices remain unchanged, pulses caused by precipitation events following a long dry period could lead to a significant deterioration of water quality.

A special situation occurs in glaciated alpine karst systems where rapid glacier retreat leads to high-flow conditions in the warm season. However, when the glaciers eventually disappear, decreased recharge and reduced karst spring discharge is expected, mainly in summer and autumn periods (Gremaud et al., 2009).

In addition, changes in weather patterns—especially extreme events, increased CO_2 emissions to the atmosphere, and the effects of direct anthropogenic activities such as rapid urbanization and industrialization—can lead to abrupt changes in vegetation cover. Changes in vegetation cover, which include, for example, afforestation or natural overgrowth; deforestation; and large-scale forest disturbance due to drought, ice breakage, natural fires, windthrow, and bark beetle infestations, can significantly affect the water balance by altering evapotranspiration and filtration, thereby affecting the quantity and quality of water resources and underground habitats (Kovačič et al., 2020).

Several other projects conducted in the past two decades aimed to forecast the magnitude and effects of climate changes on groundwater; and some specifically targeted karst aquifers (Treidel et al., 2012; Stevanović et al., 2012). By correlating GCM downscaled climate data to the basin scale of a specific grid and coupling them with observed historical data of a spring's discharge or potentiometric surface fluctuations, it is possible to establish a correlation or cross-correlation between climate elements and the groundwater regime. A modified spring hydrograph can be obtained by transferring the relationship to a regional climate model. Stochastic modeling of climate elements and aquifer properties is thus a habitual procedure that allows for a rough assessment of changes in groundwater resources (Bonacci, 1993; Kovács et al., 2005; Kumar, 2012). The outputs of these coupled models are numerical and include the aquifer's response to predicted climate conditions (Box 25↴).

Although the numerical response (discharge or potentiometric surface data) makes it possible to estimate the reactions of aquifers to various recharge scenarios, few projects are dealing with the assessment of aquifers' behavior and their intrinsic resilience to variable climate elements and rainfall as the main recharge component. The intensity of rainfall or snow melting influences recharge and aquifer replenishment. Drainage of a karst aquifer can be very fast when an aquifer is full, or slow when an aquifer has considerable storage capacity.

Climate change will modify water demands and water use in the future, which in turn will further affect aquifer systems and their exploitation. Nevertheless, it is expected that in many increasingly water-scarce areas around the world, dependence on groundwater—including karst water—will increase, since storage of groundwater provides a buffer and is more resilient than further diminishing surface water resources (Margat & van der Gun, 2013).

4.3.4 Natural and anthropogenic hazards

The peculiarities of karst environments make them highly vulnerable to geohazards such as collapse and dropout dolines (sinkholes), slope movements, and floods (Waltham et al., 2005; De Waele et al., 2011; Kuniansky et al., 2015). To these we must add anthropogenic hazards such as pollution events, land use changes resulting in the loss of karst landscape, and destruction of karst landforms (Parise, 2015). There are also many problems that relate to relict karst in the vadose zone. Karst creates voids in carbonate and evaporitic rocks, leading to underground collapses whose upward propagation can lead to ground subsidence that can severely affect agricultural land (Figure 80) and engineering structures (Parise & Gunn, 2007). Collapse of buildings, roads, and railways constructed over sinkholes (dolines) filled by unconsolidated sediments is also common in karst environments (Figure 81).

Figure 80 - Dropout doline (sinkhole) in Guizhou Province, China. A void formed in the soil due to material being washed into a karst conduit or conduits. When the top of the void approached the ground surface, there was a rapid collapse (photograph by J. Gunn).

Figure 81 - Dropout doline (sinkhole) that formed beneath a highway in Guilin, China (photograph courtesy of the Geological Museum of the IRCK, Guilin).

In Russia, the incidence of collapse and related problems led to the development of specific methodologies for karst risk assessment and special construction standards in designated problematic areas (Tolmachev, 2005). About 30 percent of the cities and towns in Russia experience a considerable negative influence of karst processes. Nizhny Novgorod, Tula, and Perm are among the most hazardous regions in Russia, as are the Republics of Bashkortostan and Tatarstan. Consequently, a special Antikarst and Shore Protection Institute was established in the Russian city of Dzerzhinsk.

Excavations have several effects when it comes to lowering the ground surface. They create topographic depressions for runoff concentration and enhanced infiltration, often modifying the groundwater flowpaths and rates (White, 2002). Further in addition to dewatering by pumping, tunnels and mine galleries can cause dramatic changes in the local hydrogeology (Milanović, 2002), directly leading to the formation of sinkholes or intercepting karst conduits, and causing dangerous inrushes of water under pressure. Knowledge of the precise position of existing or artificially created voids and their stability is thus fundamental for avoiding possible damage to objects and infrastructure, even the loss of human lives.

Milanović (2014) has listed the common destructive processes in karst that result from various factors:

- massive turbulent flows;
- fast erosion of unconsolidated deposits in caverns and joints;
- great kinetic energy of underground flows;
- propagation of hydraulic pressure at large distances (piston effect); and
- enormous hydraulic pressures created in periods of full aquifer saturation, including water-hammer and air-hammer effects caused by rapid fluctuation of the water levels.

To assess the effects of different types of human activities on karst environment, van Beynen and Townsend (2005) introduced the Karst Disturbance Index (KDI) based on the assessment of 31 environmental indicators grouped into five main categories

Exercise 6↴ provides an opportunity to estimate how long a contaminant would take to travel from the point of pollution to a spring.

4.4 Toward Sustainability

Groundwater scarcity is increasingly recognized as a global concern. In view of the predicted climate changes, whatever the scenarios may be, more attention must be paid to its sustainable use and protection from pollution. What are the solutions to control karst groundwater use while at the same time meeting basic human and environmental needs, preventing over-extraction, and mitigating the negative consequences of climate changes? The answer lies in sustainable use, monitoring, engineering regulation measures, and preventive protection.

4.4.1 Sustainable water uses and monitoring

According to Gleeson and others (2010), groundwater extraction has facilitated significant social development and economic growth, enhanced food security, and alleviated drought in many farming regions. However, it also has many negative implications: groundwater depletion, degraded ecosystems, and deterioration of groundwater quality. In addition, it can lead to conflict among the water users.

In contrast to the first half of the twentieth century when the prevailing attitude was that humans changed nature to suit their needs, today it is more appropriate to say that humans adapt their technical solutions to environmental requirements. This great change resulted from the concept of *sustainable development,* which was widely introduced into social and political life after the UN conference in Rio de Janeiro in 1992. Since then, many conventions, protocols, and agreements at the international and local level have been signed with the aim of regulating water management issues, considering mostly rational and balanced utilization of surface and groundwater resources and their protection from pollution. Among them, the Water Framework Directive (WFD) was adopted by the European Union (EU) in 2000 with the aim of preserving, protecting, and improving the environment and the quality of water by also promoting reasonable and rational use of natural resources. WFD is a framework that describes several steps that need to be taken to achieve a good qualitative and quantitative status for all water bodies to protect and restore aquatic ecosystems as a basis for ensuring long-term sustainable use of water for people, businesses, and nature (European Commission (EC), 2012).

Sustainable karst aquifer development and water use cannot be easily applied everywhere. In many arid regions, karst groundwater is essential for the environment, health, agriculture, and economic development. It is also a key resource for the alleviation of poverty and the improvement of conditions in both urban and rural areas. Groundwater is often the sole available resource in many arid countries, and pressure placed thereupon will further increase with population growth, urbanization, and industrialization. Humanitarian demands for drinking water and water for crop irrigation used for food production must be viewed as a priority (Figure 82).

Figure 82 - One of the *humanitarian* wells drilled during a drought in a confined karst aquifer near Said Sadiq (Iraq), with a dual purpose-potable water supply and irrigation (photograph courtesy of S. Ali, 2007).

Without water and food security for future generations in the arid world, sustainable development will be nothing but a motto (Stevanović, 2018). Groundwater in arid regions is potentially of vital importance to human wellbeing and ecosystems. However, the groundwater may be fully fossil such that it was supplied by recharge during past pluvial conditions and is not being replenished under present climates. Hence, it is very important to assess the extent of the karst groundwater reserve and to limit abstraction from *humanitarian* wells in arid karst regions to ensure the wells do not dry up after a few years (Figure 83).

Figure 83 - This borehole in the arid Nullarbor Plain, Australia, intersected a large body of fossil groundwater. It was initially productive, but once all the water had been pumped out, it was abandoned (photograph by J. Gunn).

The development of groundwater resources should always consider both technical solutions and local policy/water practice. Cooperation with the local population requires explanation of the tasks for and benefits to the local people. Raising the awareness of the importance of rational use of water at the local level is an important managerial step (Stevanović, 2018).

As discussed in previous chapters, out of all the aquifer systems, karst aquifers are characterized by the most dynamic regime: the potentiometric surface fluctuates, and the discharge of springs or their water chemistry can vary from one day or hour to the next. Therefore, the effects of groundwater extraction and the quality of water must be continually monitored whenever possible. If subjected to uncontrolled pumping, groundwater in aquifers may take many years to recover to the levels that enable economic extraction.

In the WFD, the groundwater level is the main parameter that defines the quantitative status, whether good or bad. Box 26 illustrates information gained/lost given different frequencies of water level measurement. There is no exact limit to minimum acceptable water levels, but the selected limit needs to ensure that long-term use will not threaten the available groundwater resource, that the environmental objectives of associated surface water bodies will be achieved, and that there will be no threat to terrestrial ecosystems.

In terms of quantitative assessment, the distribution of monitoring points must ensure that spatial and temporal variability of the groundwater surface can be sufficiently well recorded within a studied karst aquifer. In the practice of systematically organized monitoring, four categories of monitoring of the water level or discharge of karst springs can be distinguished (Stevanović & Maran Stevanović, 2021):

1. manual (spot measurements are made by an observer; Figure 84);
2. semi-automatic (an instrument is used to collect and store data, but it must be downloaded by an observer; Figure 85);
3. fully automated (the data logger can be interrogated remotely by mobile phone or satellite (Figure 86), removing the need for an observer to visit the site); and
4. remote sensing using satellite imagery.

Figure 84 - Weir on the karst spring Bolje Sestre (Skadar Lake, Montenegro). The velocities at 24 verticals with known depths are measured by an observer and the discharge is calculated using the velocity-area method. A staff gauge, installed for control readings of water level in the intake, can be seen in the right corner (photograph by Z. Stevanović)

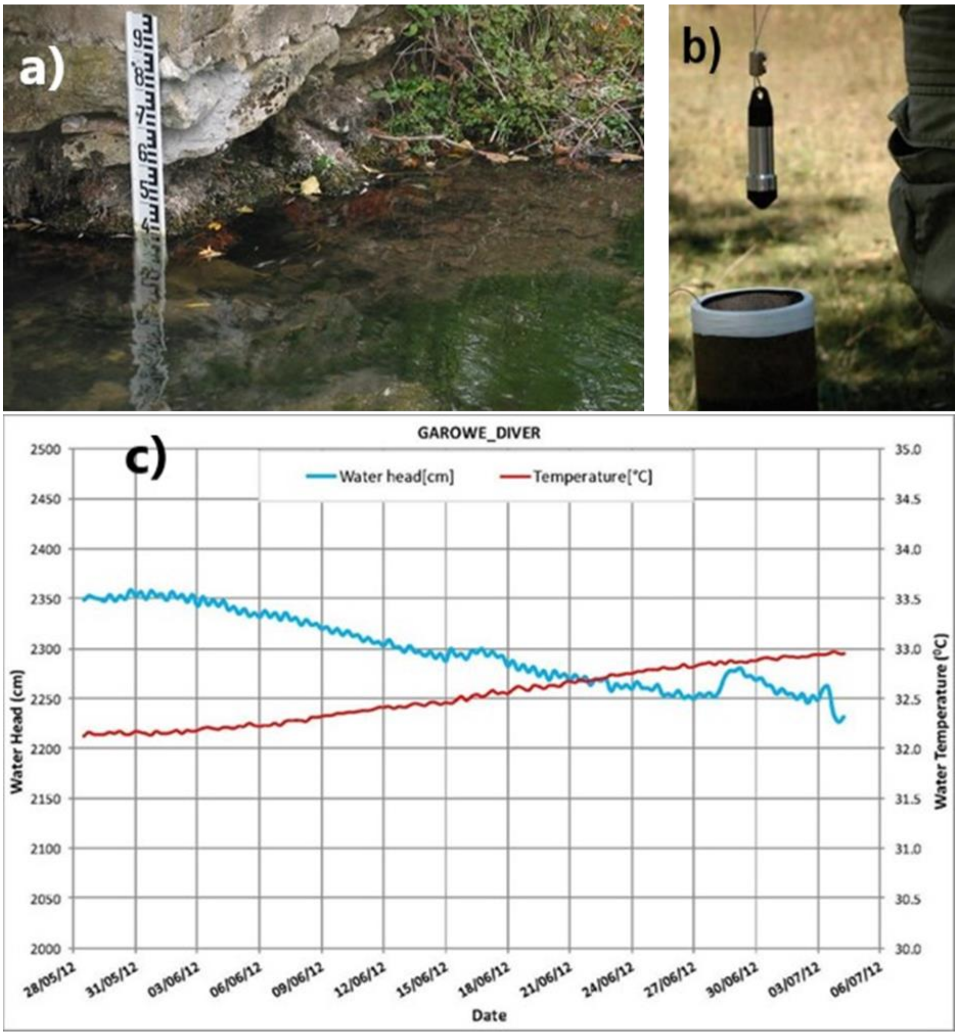

Figure 85 - Water level monitoring. a) Classic staff gauge and b) water level/temperature recorder with data logger. c) A graph showing two months of data on water level and temperature, digitally recorded in one borehole in the karst of Somalia.

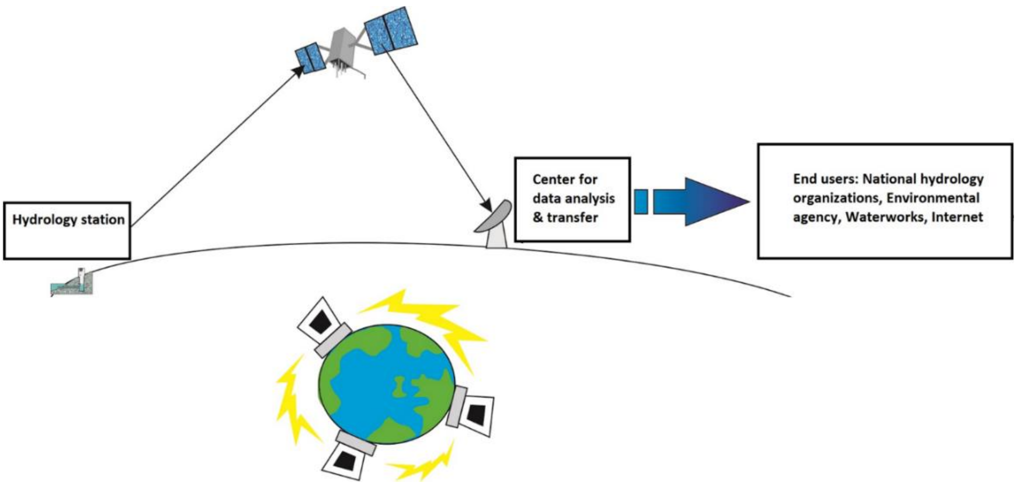

Figure 86 - Data transmission from a hydrology station via satellite.

Monitoring the parameters of water quality is similar. Data loggers are commonly used to continuously record depth, electric conductivity (*EC*), and water temperature (*T*).

There are also instruments to record pH values and specific ions, but field collection of water (Figure 87) for analysis in a laboratory is still necessary for determination of most major ions and micro-constituents. Monitoring of an injected tracer requires covering of numerous potential discharge sites and—whenever possible—continual observation (Figure 88).

Figure 87 - Water sampling using a small submersible pump (photographs courtesy of S. Milanović).

Figure 88 - Installation of field fluorimeter (Blue Cave, Swabian Alb, Germany) for an in-cave dye-tracer test (photograph courtesy of A. Kücha).

Remote monitoring by means of satellite data interpretation is not as reliable as in situ measuring, but satellite-based GRACE measurement (of the Earth's gravity) over large regions has become an alternative approach to water monitoring in recent years. GRACE observations have the potential to extend estimates of groundwater storage over time, although only as far back as 2002 when GRACE satellites were launched (Tapley et al., 2004). Further application of satellite observations for the estimation of the recharge component via soil-moisture dynamics has been discussed by Hartmann and others (2021).

In the last decade, there have been several projects aimed at developing the so-called Early Warning System (EWS), which would indicate the arrival of poor-quality water (especially during and after flooding events), prevent further deterioration, and cancel water distribution to consumers until appropriate treatment measures have been taken or pollution has gone. Systematic observation of karst spring water in remote mountain areas may provide an insight into the natural water quality or presence of bacteria and other pathogens originating from decayed vegetation, livestock manure, farming, and rare cottages. The EWS indicators such as turbidity, particle size distribution, or total organic content can be observed separately or together, depending on available instruments.

Exercise 7↴ examines the planning of karst water quality monitoring.

4.4.2 Engineering control of surface and groundwater in karst terrain

The two main aspects of engineering control of water in karst terrain are:

1. engineering works to protect structures from floods and generate hydropower, and
2. management of aquifer discharge to withdraw more water in critical drought periods.

Engineering activities in karst terrain are made difficult by both fast movement of water through underground dissolution features and sinking streams.

Erecting large structures such dams or tunnels always requires exploration and may involve grouting combined with drainage structures to minimize leakage or control leakage and drain it off safely. According to Milanović (2002), construction risks can never be completely eliminated, not even with complex research and the use of best engineering practices. In the twentieth century, many reservoirs were built with the aim of maintaining or storing river flows in karst terrain to help control flooding, maintain base flows, or for hydroelectric power. However, many dams were built at inappropriate sites or without proper research and feasibility studies, which resulted in significant water leakage and sometimes even complete abandonment (Milanović, 2002, 2014; Parise et al., 2015). Milanović (2015) compiled a list of dams and reservoirs that are suffering from unacceptable leakage despite frequent remedial measures. Some never filled up with water, while in others water loss reached 50 m^3/s. In some instances, remedial measures such as grout curtains, sealing of ponors, and impervious blankets has helped reduce water loss albeit with high costs and/or environmental impacts. Despite the problems, many projects in karst have been completed successfully, enabling the maintenance of seasonal (base) flow, generation of hydropower, and, in many cases, provision of potable water to local citizens. One of the largest successful projects is described in Box 27↴.

Subsurface (underground) reservoirs are designed to increase the volume of stored water inside the aquifer by increasing the water level at the discharge point (Milanović, 2004). Such an increase is possible if the discharge point is fully or mostly blocked and artificially controlled. However, care is needed because restricting the output of a spring and increasing the upstream head may simply result in water being discharged by another spring. There is also a danger that the increased head will result in sediment being washed out of paleokarst voids, by-passing the control structure. According to Yuan (1990), 16 underground dams have been constructed in karstified rocks in the Guizhou province of China alone. One of the largest underground reservoirs was created by constructing a 15 m high dam on the Linlangdong underground river.

During periods of minimal flow followed by increased demand—which can go on for months, especially in arid parts of the world—water deficit for the population and dependent ecosystems is the rule rather than the exception. The main challenge for many waterworks is, thus, to ensure water supply and avoid restrictions or total interruptions in water provision during these critical periods.

If an aquifer is well karstified and has adequate storage in its deeper parts, it is often possible to regulate and manage minimal flow by various engineering interventions (Stevanović & Milanović, 2015). There are two main groups of engineering regulations for controlling karst groundwater:

1. regulation of the discharge zone and
2. regulations in the wider catchment area.

Engineering interventions for regulating karst groundwater flow are categorized as follows (Stevanović, 2015):

1. over-pumping the spring,
2. drilling wells or other supplementary intakes,
3. constructing a subsurface (underground) reservoir, and
4. artificial recharge.

However, regulation of aquifers is not possible everywhere, therefore knowledge of aquifer characteristics (the discharge regime and the position of the hydraulic head in the aquifer), the thickness of the saturated zone, and the aquifer storage capacity are of key importance.

Over-pumping a spring implies temporary utilization (*loan*) of water from the deeper parts of the aquifer. In the case of deep ascending (vauclusian) springs, it is possible to install pumps in siphon channels and pump the required amount of water that should be compensated during later periods of flood. An example of a project that balanced water demand and ecological needs is presented in Box 28.

Due to much deeper potentiometric surface depletion, wells or other supplementary intakes such as shafts or galleries (Figure 56) provide more opportunities for loans (Figure 89). Several such engineering regulation projects have been successfully completed in the Carpathian karst of eastern Serbia (Stevanović, 2010). The Wala Dam and Reservoir in Jordan is a rare—but very prominent—example of successfully managed recharge into a karst aquifer (Xanke et al., 2016). Edwards (1984) presents another example of artificial recharge in the Floridan platform karst (Florida, USA), where recharge-connector wells are being used to convey water from the shallow to the underlying Floridan karst aquifer.

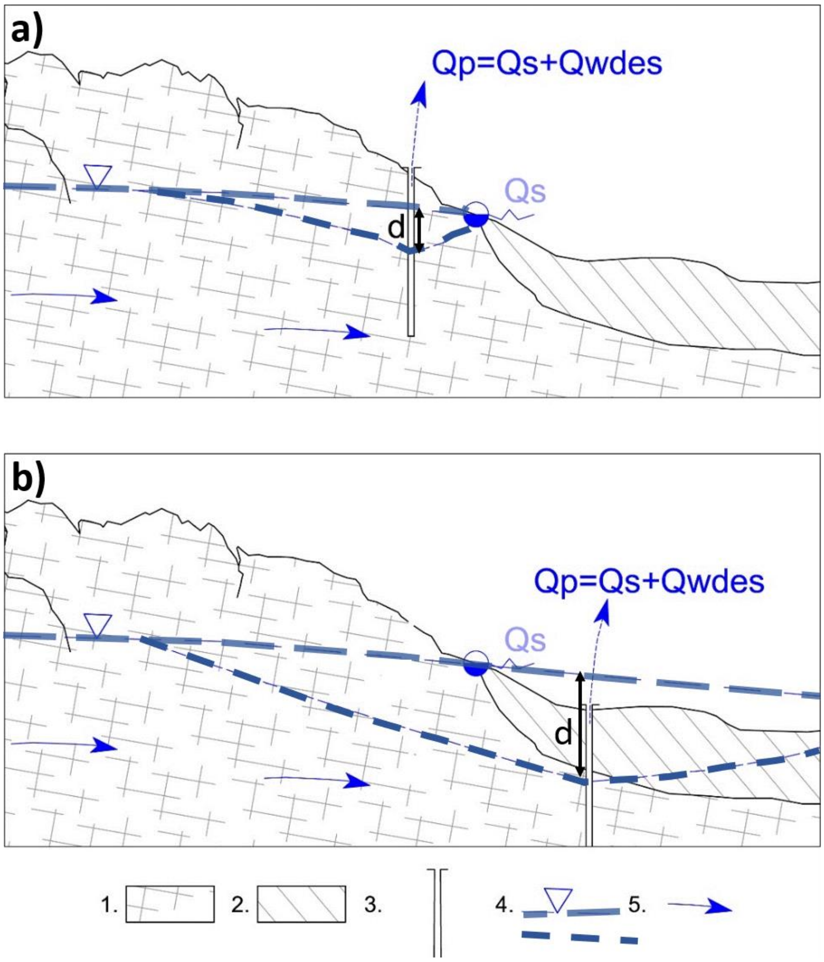

Figure 89 - Deep wells can provide more loans. Both diagrams have the same initial condition with a water table in karst (long-dashed line) discharging as a spring (faded Qs) at a contact with non-karst rocks. a) Water pumped from a well (Qp) located directly in karst, behind a natural spring can reduce or eliminate the natural spring flow (Qs); however, more water can be obtained in this way because drawdown of the water table increases the flow such that the well produces both the spring discharge and water supply for a dependent ecosystem (Qwdes). b) Alternatively, a well can be placed in a confined karst aquifer underlying adjacent less-permeable rocks. Legend: 1. karst aquifer, 2. Non-karst, 3. drilled well, 4. groundwater elevations before (static represented by long-dashed line) and during pumping (dynamic represented by short-dashed line), and 5. direction of groundwater flow.

Regulation of karst aquifers by different measures applied in the discharge zone or the entire catchment may secure or facilitate water delivery not only for human needs (e.g., potable water supply, irrigation, industry, hydropower) but to the entire ecosystem as well. This ecological flow (*EF*) or water for dependent ecosystems (WDES) as shown in Figure

89 is the quality, quantity, and timing of surface water and groundwater required to sustain the functions and processes of freshwater ecosystems and the human livelihoods and wellbeing that depend on these ecosystems. The EF rate depends on the type of ecosystem, characteristics of the watercourse and its banks, and water demands. There is no uniformly adopted method for estimation of EF, but in water practice it could be estimated, in the following ways:

1. *EF* as the minimum average monthly discharge with a 95 percent probability of occurrence,
2. *EF* as the average minimum annual discharge defined as an arithmetic mean of the annual absolute minimum discharges recorded in the analysed period, and
3. *EF* as the discharge of 80 percent duration on the average duration curve.

Artificial recharge is a term that is commonly used in water practice to describe a type of intervention aimed at regulating the regime of an aquifer. However, it should be used in the sense of its real meaning: adding some new water to the aquifer (Stevanović & Milanović, 2015). Such an operation is not common in karst due to the limited attenuation capacity and only clean water should be used for direct infiltration. This can significantly increase operational costs.

Finally, all engineering work should be done in line with safe environmental requirements. One of the main tasks is to guarantee EF for the dependent ecosystem. Since their introduction in the 1970s, environmental impact assessments have been required for most large engineering projects.

Exercise 5↴ concerns assessment of available exploitable groundwater resources of a karst aquifer while ensuring EF for dependent ecosystems. Exercise 8↴ examines an intervention to enlarge a karst aquifer's storage capacity.

4.4.3 Preventive protection of karst aquifers

To preserve groundwater quality, protection and management of groundwater resources are generally provided for in national water and riparian use laws. Sources of drinking water supply are usually protected by sanitary protection zones. These include areas that recharge a water source (for example, tapped wells and springs). In most regulatory frameworks, demarcation of protection zones is expected to be in concentric spheres up-gradient from the source although, as discussed below, this approach is not applicable to karst aquifers. Delineation is accomplished through a combination of topographic, geologic, hydrogeologic, and hydrologic characterization with consideration of local regulations, usually based on distance from the water source or flow velocity (Živanović, 2015). Within sanitary protection zones, restrictive measures are implemented at various levels to limit or prohibit activities that could jeopardize the quality of the water source (Figure 90). The nomenclature and number of protection zones depends on national or local legislation and prevailing hydrogeologic conditions in the catchment area. Commonly three zones are defined:

- Zone I (the inner zone around the actual source),
- Zone II (the outer zone), and
- Zone III (the entire catchment of the source).

Figure 90 - In water protection zones, various activities that could endanger the quality of the water source are restricted. This traffic sign indicates the boundary of Protection Zone II for the Dobličica spring in southeast Slovenia. Access is allowed only for authorized persons. Pictograms prohibit entry by vehicles with cargo containing environmentally hazardous substances, explosive or highly flammable substances, and dangerous goods. The passage of livestock and the dumping of waste are also prohibited (photograph by N. Ravbar).

In some cases, protection zones are further subdivided, but generally the higher zone levels have less strict restrictions (Figure 91a).

However, as noted above, this type of approach cannot easily be used to delineate protection areas in karst because it does not consider their extreme vulnerability to contamination and the peculiarities of hydrogeology such as heterogeneity and complexity of recharge and possible changes in flow direction (Kidd et al., 2001; Ravbar et al., 2021). Inadequate protection of karst water sources may be due to a lack of knowledge of the specific characteristics of the heterogeneity of certain aquifers, where groundwater often flows independently of surface topography. Therefore, catchments and the extent of individual water protection zones cannot be delineated based on geomorphological settings alone; subsurface flowpaths and cave networks should also be considered. When protection zones are defined by isochrones (lines of equal travel times), these criteria are inadequate for the protection of karst water sources due to the duality of recharge (i.e., diffuse versus concentrated recharge). Greater distance from the water source does not necessarily mean greater safety from contamination. Therefore, the role of protective layers and the specifics of allogenic recharge need to be considered.

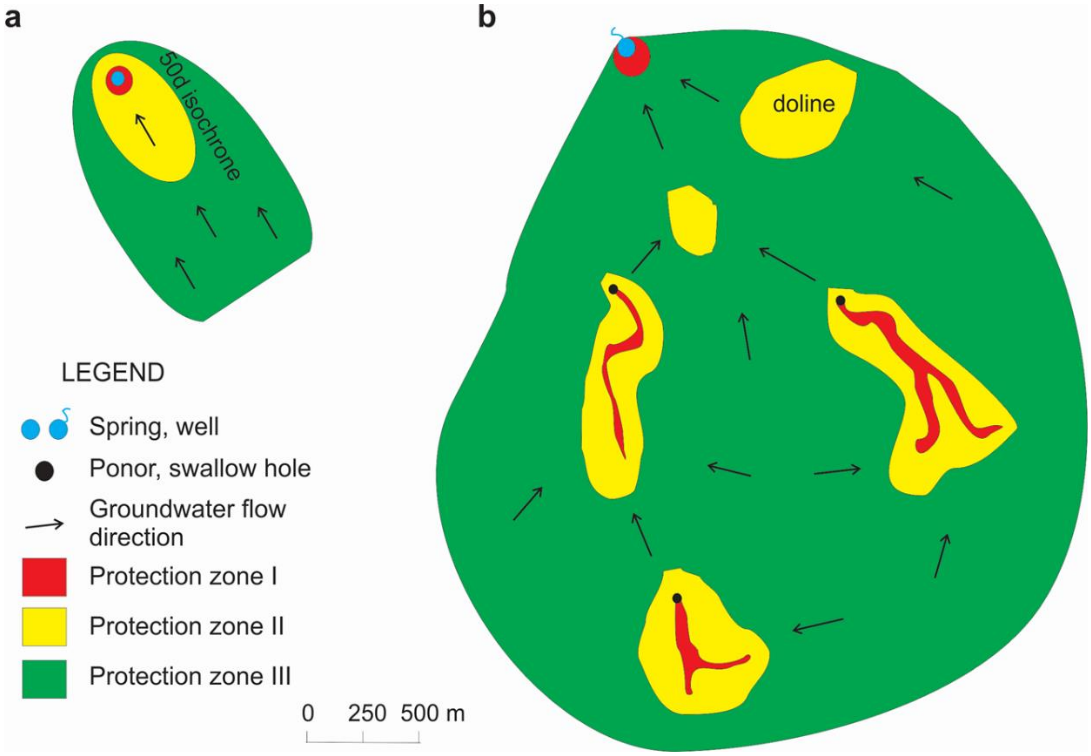

Figure 91 - Schematic representation of a concept of groundwater source protection areas a) based on transit time or distance criteria typically in non-karst aquifers and b) considering special characteristics of water flow in karst aquifers.

In contrast to the generally low groundwater flow rates in non-karst aquifers, where the protection zones extend for only a few hundred metres in diameter, the residence times of water in karst aquifers are commonly short (a few hours to a few days). Therefore, the approach based on transit time or distance to water source criteria results in large zones of high protection regime for karst aquifers and these may lead to conflicts of interest in land use. Another characteristic of karst water is that their flow characteristics vary greatly with hydrologic conditions, which can lead to spatial and temporal changes and consequent shifts in catchment boundaries and groundwater flow direction. Protective measures can therefore be subject to large uncertainties.

Monitoring of the qualitative and quantitative status of water is another important element of water source management. Not all countries have included such monitoring plans in their legal frameworks. Where they do, the frequency of qualitative status monitoring is usually scheduled only a few times per year, and there are no specific requirements for water quality monitoring in karst areas. Because conditions in karst aquifers can change very rapidly, the results of sparse monitoring do not necessarily show representative values of water quality status. Due to the characteristics of groundwater flow, the quality of karst water springs changes significantly under different hydrologic conditions. Often their quality deteriorates very rapidly during periods of more intense precipitation, especially after rainfall following prolonged dry periods, when the most intensive washing and contaminant transfer takes place. Fluctuations in the values of individual parameters are particularly large in those karst springs that have a complex catchment area and are fed not only by diffuse infiltration of precipitation but also by sinking rivers.

Water quantity monitoring must provide a reliable estimate of the quantitative status of groundwater, including an assessment of available groundwater reserves. However, unlike in non-karst areas where piezometer wells provide a relatively good generalization of the spatial distribution of water levels based on point data, this is generally not possible in karst aquifers due to the extreme heterogeneity resulting from their tertiary porosity–permeability architecture. For this reason, monitoring the dynamics of groundwater level fluctuations is uncommon to estimate quantitative status (groundwater budget characterization and quantitative pressure assessment). Most often, the quantitative status is monitored where the groundwater is most accessible and the dynamics are greatest, that is, by monitoring discharge at karst springs.

4.4.4 Land use adaptation and remediation

To address the shortcomings of conventional preventative protection described in Section 4.4.3 and to improve protection zoning in karst, the concept of vulnerability assessment was developed. The term groundwater vulnerability, which was introduced in the late 1960s by Margat (1968), refers to the susceptibility of a hydrological system to contamination or its neutralizing capacities against contamination. At the turn of the 21st century (CE) more precise definitions and a methodological framework specific to carbonate aquifers were developed by COST Action 620 (Daly et al., 2002; Zwahlen, 2004).

The concept of vulnerability is based on what is known as the origin-pathway-target model for environmental management (Daly et al., 2002; Zwahlen, 2004). The term origin is used to describe the location of the release of a pollutant. The term pathway is used to describe the flowpath of a pollutant from the point of release (origin) to the target, which may be a groundwater surface or a drinking water abstraction point—for example, a spring or well. There are two general approaches to target protection: *resource protection* aims to protect the entire aquifer and considers the characteristics of vertical percolation of water from the land surface through the unsaturated zone to the water level, while *source protection* focuses on a specific spring or well and additionally considers the lateral pathway within the saturated zone (Figure 92).

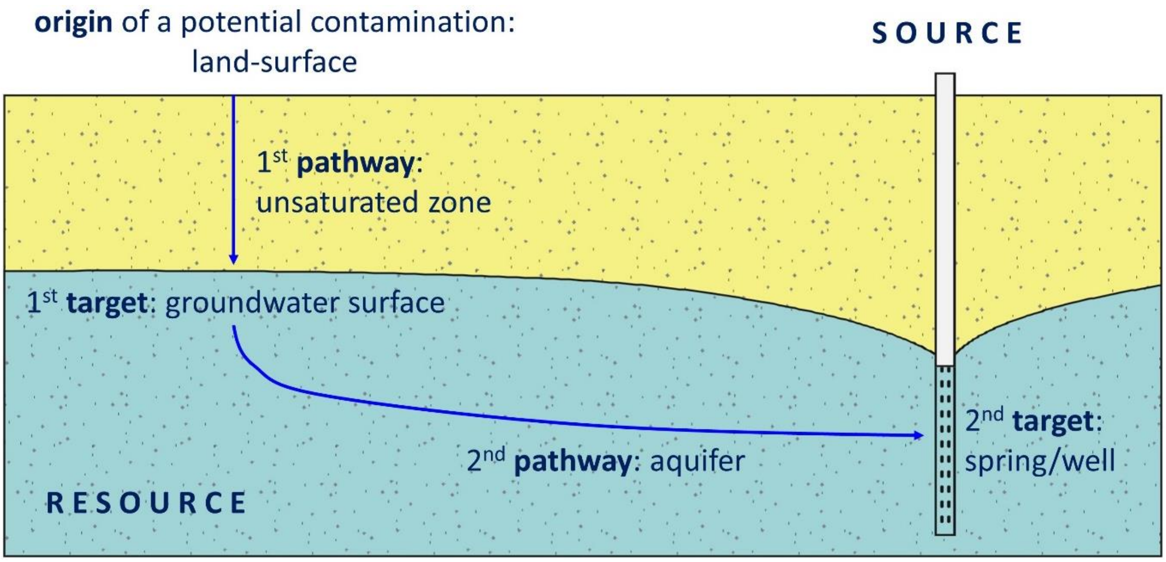

Figure 92 - Illustration of the origin-pathway-target model showing the resource and source (after Goldscheider, 2004).

The assessment of groundwater vulnerability assumes that the natural protection of a hydrological system from contamination varies according to differences in the intrinsic properties of the environment. Consequently, the derived intrinsic vulnerability assessment reflects the degree of natural protection to reduce the adverse effects of contamination and restore the balance of the environment. It distinguishes between areas with varying degrees of natural protection from contamination, while considering the high vulnerability of karst.

The concept of groundwater vulnerability assessment thus provides an approach that synthesizes the available information. Relevant lithological, pedological, hydrogeological, meteorological, geomorphological, speleological, vegetation, residence time, and other information are combined. Because the characteristics that influence the transport properties and flow rates of individual parts of the hydrological system are difficult to predict and/or measure, qualitative considerations and some simplifications of natural conditions are unavoidable.

Vulnerability assessment can be used to optimize land use in the catchment areas of captured water sources and thus minimize groundwater contamination. The concept is suitable as a supplement or alternative solution for adequate water protection.

When the characteristics of the contaminant and its interaction with the hydrological system are considered, the results are presented as the *specific vulnerability*, which determines the susceptibility of groundwater to a particular contaminant or types of contaminants. With respect to potential damage to groundwater, the term *contamination risk* is used to describe the likelihood of a particular adverse consequence occurring. It considers the interaction between the natural characteristics of an aquifer (i.e., the vulnerability of the aquifer) and the infiltrating contaminant load (i.e., the hazard assessment). It also identifies the areas at risk of groundwater contamination at various levels in the case of a hazardous event.

There are several karst-specific vulnerability mapping methods. The first method developed specifically for karst areas was EPIK (Dörfliger & Zwahlen, 1998). Later, COST Action 620 proposed a European approach to mapping vulnerability and risk for the protection of karst aquifers (Daly et al., 2002; Zwahlen, 2004). Within this framework, several intrinsic vulnerability mapping methods were developed such as the PI method (Goldscheider et al., 2000), which served as the basis for the conceptual model of the European approach, and the COP method, a fairly complete implementation of this approach (Vías et al., 2006). In addition, Nguyet and Goldscheider (2006) proposed a simplified vulnerability and risk mapping method for use in data-poor environments while Ravbar and Goldscheider (2007) developed a more detailed method for use in data-rich environments. Subsequently, many other methods have been developed, such as FAVA or PaPRIKa methods (Jonathan et al., 2007; Kavouri et al., 2011). The methods developed range from relatively simple for use in areas where data and economic resources are lacking to more sophisticated for which more data, time, financial, and technical resources are available (Figure 93).

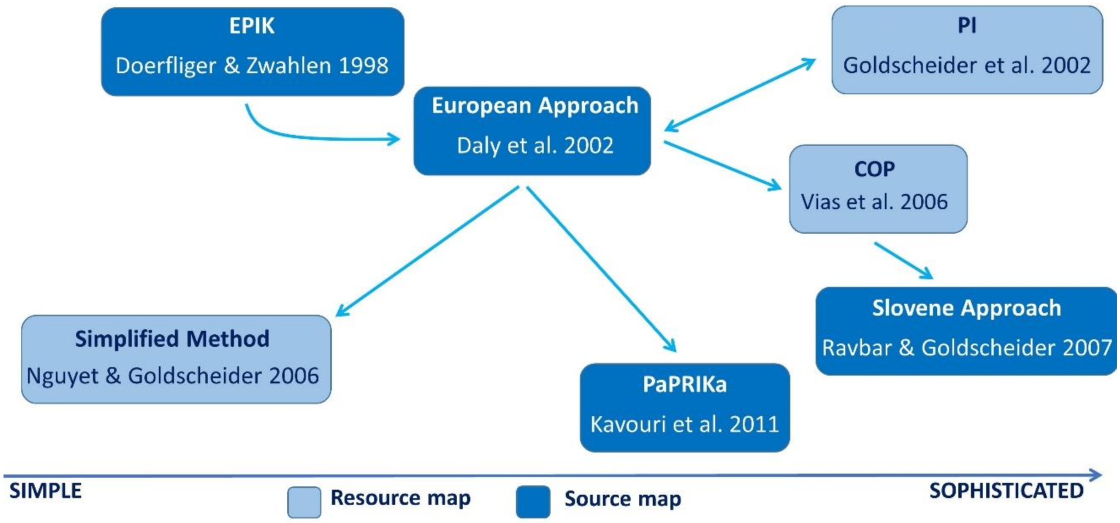

Figure 93 - Historical representation and relations of selected vulnerability mapping methods that account for the specifics of karst aquifer systems, ranging from relatively simple to sophisticated.

The above methods rely on different information about the soil and unsaturated zone, recharge conditions, and aquifer characteristics (Figure 94). This information is classified into different factors. They differ in their nomenclature and require different data sources and different amount of input data, as summarized in Table 5.

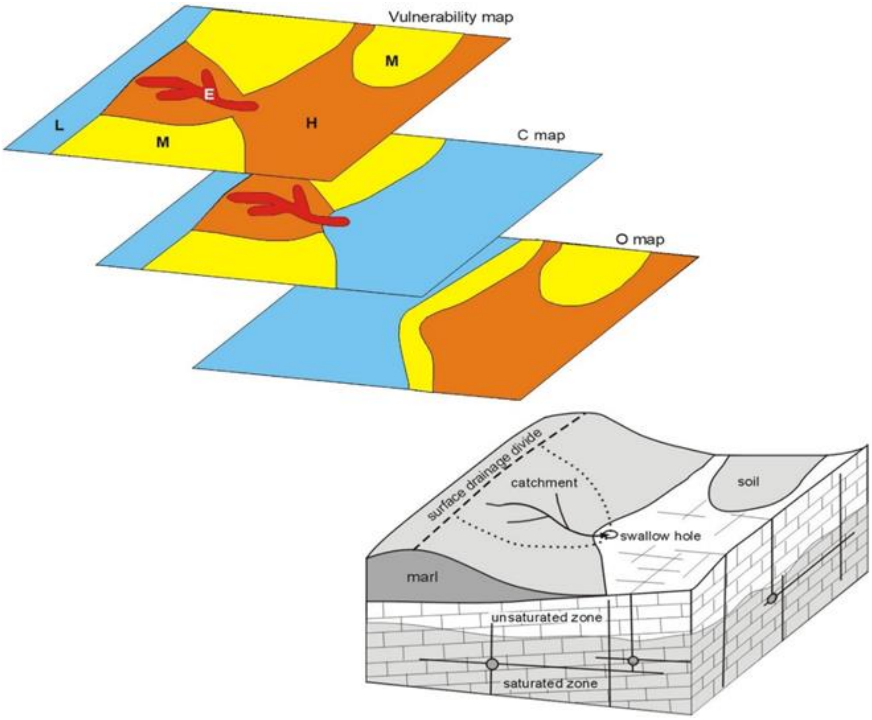

Figure 94 - Most groundwater vulnerability methods are based on different types of spatial information about aquifer properties that are categorized and combined, as shown in this example of the Simplified method. The sketch shows a hypothetical karst catchment that receives allogenic recharge from a sinking stream. A vulnerability map shown at the top is obtained by the combination of two information layers: an O map (protective function of overlying layers) and a C map (concentration of flow). On the vulnerability map, the red colour with the symbol E = extreme vulnerability, the orange with the symbol H = high, the yellow with the symbol M = moderate, and the blue with the symbol L = low vulnerability (from Nguyet & Goldscheider, 2006).

Table 5 - Factors and data required by the four selected methods (from Ravbar & Goldscheider, 2009).

Methods / Factors		**EPIK**	**SM**	**PI**	**SloA**
Karst unsaturated zone	Topsoil thickness	+	+	+	+
	Topsoil texture	-	-	+	+
	Topsoil structure	-	-	+	+
	Subsoil permeability	+	+	+	+
	Subsoil thickness	+	+	+	+
	Depth of the unsaturated zone	-	-	+	+
	Fracturing	-	-	+	+
	Epikarst development/geomorphological features	+	-	+	+
	Confined situation	-	-	+	+
Recharge conditions	Concentration of flow	+	+	+	+
	Slope gradient	+	-	+	+
	Land use/vegetation cover	+	-	+	+
	Autogenic recharge	+	+	+	+
	Allogenic recharge	+	+	+	+
	Temporal variability	-	-	-	+
Karst saturated zone	Presence of active karst network	+	-	-	+
	Hydrological characteristics of a spring	+	-	-	+
	Tracer test interpretation	+	-	-	+
Source vulnerability		+	-	-	+
Resource vulnerability		-	+	+	+

EPIK = EPIK method, SM = Simplified method, PI = PI method, SloA = Slovene approach

The EPIK method (Döerfliger & Zwahlen, 1998) considers four factors:

1. epikarst development (*E*),
2. protective cover (*P*),
3. infiltration conditions (*I*), and
4. karst network development (*K*).

Each factor is assigned a ranking index, and each of the indexed factors is assigned a weighting coefficient according to its degree of protection. EPIK can only be used in karst areas.

The PI method (Goldscheider et al., 2000) considers the protective function of the layers above the saturated zone (*P*) and the infiltration conditions (*I*). The *P* factor is applicable to all types of aquifers, while the *I* factor considers karst-specific recharge and infiltration processes.

The Simplified Method (Nguyet & Goldscheider, 2006) was developed for mapping groundwater vulnerability, hazards, and risk in areas with limited data and economic resources, particularly in Vietnam and other emerging economies. The vulnerability assessment is based on the same two factors as the PI method (although the naming is different): overlying layers (*O*) and concentration of flow (*C*). The amount of data required is reduced and the assessment scheme simplified.

The Slovene approach (Ravbar & Goldscheider, 2007) is the most complete interpretation of the European approach. It can be used for vulnerability mapping and includes an assessment of contamination hazards, an assessment of groundwater importance or value, and various types of risk maps. Groundwater vulnerability mapping is based on the assessment of four factors: overlying layers (*O*), concentration of flow (*C*), precipitation regime (*P*), and karst-saturated zone (*K*). The approach additionally considers temporal hydrological variability of karst.

The various methods have different data requirements and hence at any site the type and accuracy of the data available will influence the choice of method and this in turn will determine the quality and reliability of the results. When selecting a method, care must be taken to ensure that the indices have been validated independently of the assessment process. The discrepancies associated with current approaches to assessing vulnerability are presented in Box 29⤵. As validation has not become a standard practice and there is no universally accepted procedure (Ravbar & Goldscheider, 2009), modern methods and techniques (e.g., numerical modeling, process-based approach) can be used alongside traditional methods (e.g., hydrochemical analyses and artificial tracing).

Because of the peculiarities of infiltration and transport of certain contaminants, the challenges of remediation in karst are even greater than in other hydrogeological environments. The prerequisite is to identify the source and location of the pollution. Treatment of non-point pollution is particularly difficult due to the extent of the pollution source. Treating continuous pollution is equally challenging. Even if the pollution is stopped, it can remain stored in the less permeable volumes of the rock matrix and slowly seep toward springs (Figure 95).

Figure 95 - The Krupa spring in southeast Slovenia, the most important potential source of drinking water in the region, has been contaminated with polychlorinated biphenyls since 1985. The reason for this is the improper disposal of waste condensers in a doline close to the spring (photograph by N. Ravbar).

Most remediation methods in karst are less efficient compared to other aquifer types. Selection of the remediation method for each contamination event requires individual consideration (Figure 96). It is decided based on the fate and transport of the contaminants of concern and accounts for the feasible remediation efficiency, the desired extent of treatment, and the available time and financial resources. Once the contaminant has infiltrated the hydrologic system, the method of reaching and containing the contaminant plume by pumping is unlikely to be feasible because the remediation process usually begins with some delay. Additionally, it is nearly impossible to find all the preferred flowpaths of the dissolved contaminant and hydraulically stop this transport by pumping the contaminant. Instead, some of the in situ remediation methods (thermal or chemical oxidation treatment, bioremediation) might be successful to some extent, especially in treating DNAPL and TCE contamination.

Figure 96 - In case of spillage of toxic substances, removal of the upper layer of thin soil and protection from direct flushing is one possible remediation method (photograph by N. Ravbar).

4.4.5 Karst groundwater-dependent ecosystems

Freshwater in sufficient quantity and quality is not only essential for human use but also for the preservation and supply of ecosystems. Groundwater is part of the global water cycle (Poeter et al., 2020), and the interrelationships between surface water, groundwater, and ecosystems are manifold and complex. Groundwater-dependent ecosystems (GDE) have unique characteristics and include a great variety of different hydrogeological and ecological settings (Klove et al., 2011a). GDE provide manifold ecosystem services and require specific protection and management (Klove et al., 2011b).

The protection of karst ecosystems and groundwater resources requires a holistic approach because healthy ecosystems in the catchment are the best guarantors for good groundwater quality and, in turn, sufficient clean groundwater is critically important for the preservation of all downstream ecosystems (Goldscheider, 2019). This section focuses on aquatic ecosystems that are partly or largely dependent on water from karst aquifers, so-called karst groundwater-dependent ecosystems (KGDE). These include ecosystems in the underground (e.g., caves and aquifers; as described in Box 30⤵) and at the land surface (springs and the associated streams, rivers, lakes, and wetlands). In areas with shallow depth to groundwater, even terrestrial habitats can partly or entirely depend on groundwater if the plant roots reach the saturated zone in the aquifer and if the soil zone does not provide enough water.

Aquifers can be described as "*the ultimate groundwater-dependent ecosystems*" (title of a paper by Humphrey, 2006). Inside the aquifer, there is no primary production by plants, but the entire biocenosis depends on imported organic carbon from the land surface—except for some specific cave environments where microorganisms generate organic matter from CO_2 and generate chemical energy, similar to the activity of biocenoses at mid-ocean ridges. In porous aquifers, groundwater biocenoses mainly consist of microorganisms and very small invertebrates. In karst aquifers, caves and conduits offer much more space. Therefore, much larger animals populate cave environments such as the Mediterranean monk seal that uses underwater sea caves to give birth and care for pups.

Besides such extraordinary examples, species in freshwater caves comprise a great variety of crustaceans and other invertebrates as well as amphibians such as the famous cave salamander *Proteus anguinus* (Figure 97), and cave fish. Such cave and groundwater animals are perfectly adapted to life underground, which is characterized by the complete absence of light, nearly constant water temperatures, and generally low availability of food. Therefore, groundwater animals are often blind (vestigial or absent eyes) and have no skin pigment; their metabolism is slow, but their life expectancy is often very long. Due to their high degree of isolation, cave ecosystems include many rare and endemic species, and it is likely that more will be found. Groundwater contamination could lead to the extinction of such species. This in an ethical argument for groundwater protection independent of human utilization (Goldscheider, 2019).

Figure 97 - The cave salamander *Proteus anguinus* is endemic to the Dinaric Karst region. It is entirely adapted to life in the total darkness of caves. It has no skin pigment and is blind, it can survive with little food, has a slow metabolism, and a long-life expectancy of 70 years or more (photograph courtesy of J. Hajna).

Karst springs and the downstream adjacent streams, rivers, and lakes are the most visible, widespread, and obvious karst groundwater-dependent ecosystems. The typical properties of groundwater-dependent ecosystems are most strongly present at the spring and decrease with downstream flow time and distance. In particular, karst groundwater and spring water that are fed primarily by autogenic recharge are characterized by relatively stable temperatures, generally corresponding to the average local air temperature, and also by the absence of bedload transport and hydro-abrasive erosion, both of which commonly occur in surface rivers and streams during extreme flood events. This has a strong influence on the vegetation and fauna at karst springs, which commonly include much more vulnerable species than typical stream ecosystems (Figure 98).

a) b)

Figure 98 - Comparison of typical stream and spring ecosystems. a) An alpine stream is characterized by extremely variable water temperatures and highly erosive bedload transport during extreme floods. b) An alpine karst spring also has extreme discharge variations, but temperatures are nearly constant and there is no bedload transport, allowing for fragile vegetation (photographs by N. Goldscheider).

Karst spring biocenoses also include many rare and endemic species, some of which are limited to one single karst spring. Famous examples can be found at the large springs draining the Edwards aquifer in Texas, USA (Cox et al., 2009). Comal Springs are the largest springs in this region, and their ecosystem is home to many endemic species including fish, several species of water beetles, and amphipods (Figure 99). The Barton springs in Austin, Texas, issue from the same aquifer and are the natural habitat for the endangered Barton Springs salamander (*Eurycea sorosum*) and another salamander species.

a)

b)

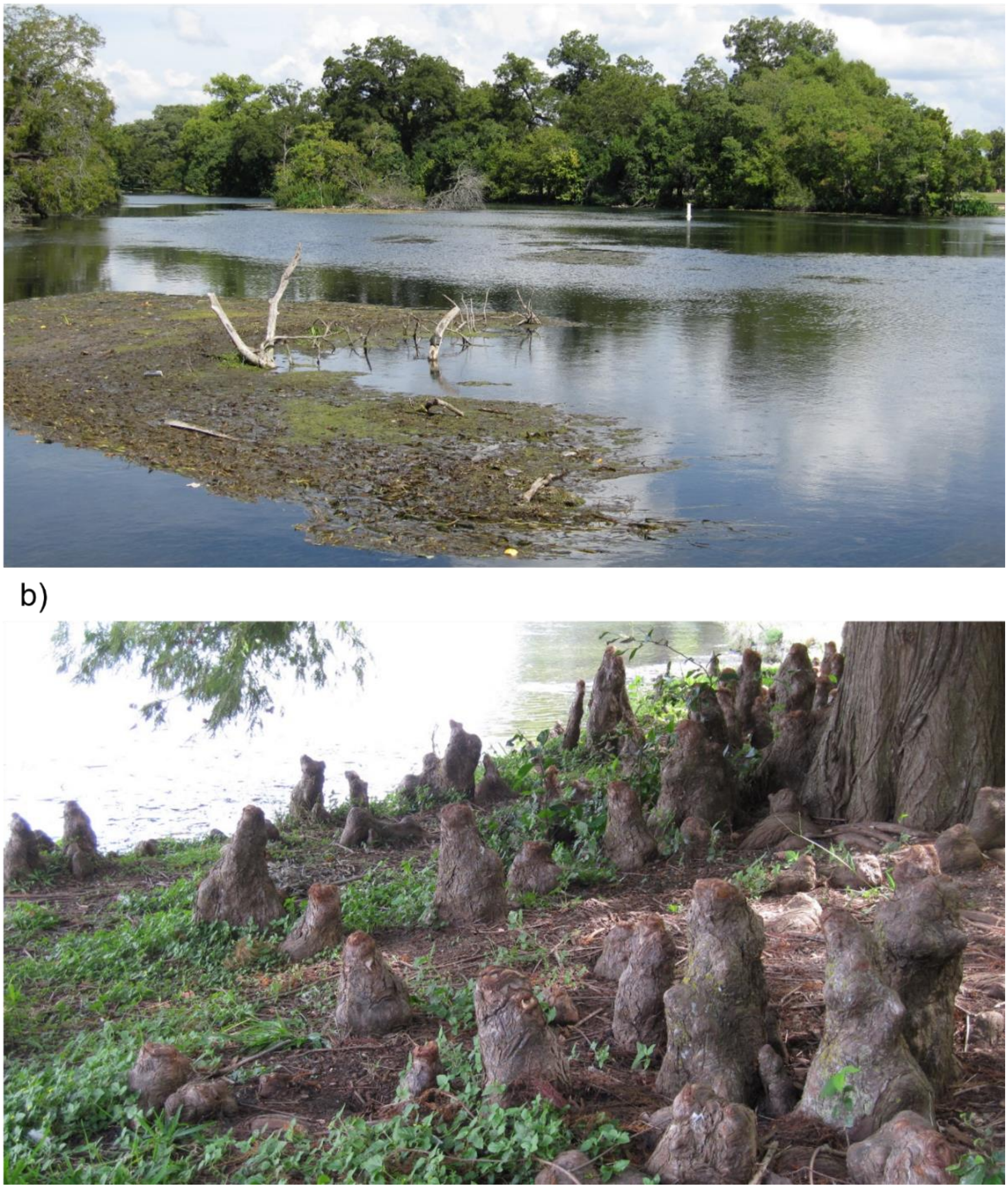

Figure 99 - Impressions from Landa lake formed by Comal springs, the largest karst spring group in Texas, USA. a) The springs are the natural habitat of several endangered and endemic species, including fish, beetles, and crustaceans that only occur in the water of this spring. b) Since tree roots need oxygen to grow, they grow upwards, above the ground surface, at this location near the spring, where the saturated zone begins at a depth of just a few decimetres (photographs by N. Goldscheider).

Mahler and Bourgeai (2013) investigated temporal variation of dissolved oxygen (DO) at this spring and found that, during low-flow periods, concentrations decrease down to levels that adversely affect the salamanders. They concluded that lower discharge at the springs, resulting from increased groundwater withdrawals and reduced recharge along with increasing temperatures due to climate change, could lead to increased salamander mortality. This is another example where a single contamination event in a karst catchment could lead to the extinction of several endangered and endemic species. Not only in karst areas, but also in other hydrogeological environments, springs and their associated ecosystems, are hotspots of biodiversity but are under threat by aquifer over-pumping, contamination in the catchment and, often, mechanical damage; therefore, Cantonati and others (2021) formulated an "*urgent plea for global protection of springs*" (the title of their 2021 paper).

Besides providing habitat for endemic and endangered species, karst springs are also at the origin of a great diversity of landscape forms and associated freshwater ecosystems with great ecological, esthetical, and touristic values. Limestone-precipitating springs and the downstream freshwater systems are especially valuable in this context such as the springs and associated streams, lakes, and waterfalls in the Plitvice National Park in Croatia (Biondić et al., 2010; Stančić et al., 2010) (Figure 100). Further examples are also presented in the following section on karst geoheritage and internationally protected karst areas and features, which often include groundwater-dependent ecosystems.

Figure 100 - Besides the special habitat conditions at the spring orifice, the discharge and hydrochemical characteristics at karst springs can shape entire aquatic and terrestrial landscaped ecosystems such as the Plitvice Lake in Croatia, where calcite precipitation from karst spring water leads to the formation of numerous natural dams, lakes, and waterfalls (photograph by N. Goldscheider).

4.4.6 Karst geoheritage: Nationally and internationally protected karst areas and features

As discussed earlier, most karst springs or boreholes that are used for potable supply, and their catchment areas, receive at least some degree of legal protection through national water and riparian use laws. Karst groundwater may also receive incidental legal protection by being within an area that has been designated because of its aesthetic, biodiversity, or geodiversity interest. The International Union for Conservation of Nature↗ (IUCN) has set out six protected area management categories (one of which is subdivided) to classify protected areas according to their management objectives (Dudley, 2013; IUCN website↗). The categories are recognized by international bodies such as the UN and by many national governments as the global standard for defining and recording protected areas and as such are increasingly being incorporated into government legislation. Legislative protection is always provided at the level of a nation-state, varies markedly from country to country, and, in some cases, within an individual nation-state. Protection in the United Kingdom is described in Box 31↴.

In addition to protection at a national level, a higher level of protection is provided to International Designated Areas (IDA). These are areas that are internationally recognized through one of four designations: Biosphere Reserves (BR), UNESCO Global Geoparks (UGGp), World Heritage Properties (WHP), and Ramsar Sites (RS). BR, UGGp, and WHP are UNESCO designated sites while RS are designated by an International Convention with UNESCO as Custodian. Gunn (2021) used information on the official websites provided in Box 32↴, together with other sources, to undertake an initial assessment of the extent to which carbonate and evaporite karst and groundwater systems are represented in these protected areas. The results are briefly summarized and updated here.

The World Network of Biosphere Reserves (BR) of the Man and Biosphere Programme.

Each BR usually includes a core protected area (or areas) where the focus is primarily conservation, and surrounding zones where sustainable development is encouraged. BR are expected to provide a basis for continuing research, education, and information exchange on the issues around the conservation-development nexus, particularly fostering dialogue for conflict resolution of natural resource use and integrating cultural and biological diversity. Unfortunately, from a karst perspective, the focus is on biological elements and the underlying geological elements have commonly been given relatively little attention. However, in 2019 a CaveMAB network was established (https://cavemab.com/↗) with the aim of improving understanding and protection of caves and karst in BR. The World Network↗ is dynamic, with new BR added each year, but as of 1 January 2022, 151 BR in 62 countries were identified as containing karst formed on soluble rocks. For 149 of these sites, the karst is solely in carbonate rocks. However, in the two others both carbonate and evaporite rocks are mentioned. The three countries with the most BR-containing karst were Spain (15), Mexico (13), and China (9).

The total area of the 151 BR is approximately 490,645 km^2, but the actual area of karst is much lower as although some BR are entirely—or in large part—karst, in others there may only be small areas with karst landforms and groundwater circulation.

Ramsar Sites (RS)

The mission of the Ramsar Convention↗, first agreed in 1971 and amended in 1982 and 1987, is "*the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world*". Before 1996, the importance of groundwater was commonly not recognized but in that year a resolution was adopted for the inclusion of subterranean karst wetlands. A specific category, Zk, was added to the Ramsar Classification System for Wetland Type↗ to denote "*Karst and other subterranean hydrological systems*." The Parties to the Ramsar Convention were urged to assess the significance of karst and cave wetland systems within their territories and to consider their designation as RS. As of 1 April 2020, Gunn (2021) identified 124 RS that contained some karst areas and between 1 April 2020 and 1 July 2022 an additional 2 RS were designated that contain carbonate karst. Hence, as of 1 July 2022 there were 126 RS in 55 individual nation-states that contained some carbonate karst, and their combined area was 48,004 km^2. As with BR, the actual area of karst is less than this figure because many of the RS contain both karst and other rocks. Also, the areas of many of the RS include water bodies.

UNESCO Global Geoparks (UGGp)

In the late twentieth century, several individuals came to the realization that one way of protecting a site's earth science interest was by promoting tourism-led sustainable development with a *geo* focus. The label *geopark* was used to distinguish these areas from the many protected areas with an archaeological or biological focus. In June 2000, four geoparks came together to establish the European Geopark Network (EGN), which expanded rapidly and, independently, geoparks were also established in China. In 2004, members of the EGN and eight Chinese geoparks came together to form a Global Geoparks Network (GGN) and in November 2015, the 195 Member States of UNESCO ratified the creation of a new label, UNESCO Global Geopark (UGGp)↗. While the first geoparks contained earth heritage features considered to be of at least regional or national value, new applicants must demonstrate that their site is of international value. Uniquely among protected areas, the sites in the GGN are subject to a thorough revalidation every four years to examine their functioning and quality. If a site does not fulfil the required criteria, they are given a two-year period to rectify deficiencies; if, at the end of this period, they are judged to be still failing, the geopark loses its status as a UGGp. This should provide a powerful tool to ensure that earth science features, including karst landforms and karst groundwater where present, are managed and protected. As of 1 January 2022, there were 71 UGGp in 27 individual nation-states that contain areas of carbonate or evaporite karst with a combined area of 130,681 km^2, although as in the other protected areas a variable percentage of each UGGp is karst.

World Heritage Properties (WHP)

In 1972, UNESCO adopted a "*Convention concerning the Protection of the World Cultural and Natural Heritage*" (UNESCO website↗). This provides for the identification of sites (now largely referred to as properties) and their inscription upon a register (the World Heritage List↗). It also places responsibility for continuing protection of site integrity and for provision of access by all peoples on the State Party (States Parties are countries which have adhered to the World Heritage Convention; https://whc.unesco.org/en/statesparties/↗), with international support, if necessary, in restoration and protection of sites. States put forward sites for assessment. To be included on the World Heritage List, they must be of outstanding universal value and meet at least one out of ten selection criteria. Each site is also required to meet a series of conditions in respect to integrity, the three most relevant to groundwater in karst being:

1. boundary conditions: to ensure that wherever possible the whole of any one phenomenon is included and that there is an adequate buffer zone around the area of universal value;
2. protection: to ensure adequate long-term legislative, regulatory, or institutional protection; and
3. management: development and implementation of an adequate plan of management.

Williams (2008) undertook a global review and identified 45 WHP with internationally significant karst features of which 27 contained karst considered to be of outstanding universal value and four were on non-carbonate rocks. In addition to these sites, WHP were identified that contain karst of national or regional significance. In 2019, Williams updated the list to include nine WHP inscribed after 2007, all of which contained carbonate karst. Gunn (2021) added further WHP that he thought contained karst groundwater and, following further analysis, he identified 76 WHP that contain areas with karst landforms developed on carbonate or evaporite rocks. They are in 43 individual nation-states and have a total area of 841,422 km^2, although—again—a significant part of this area is likely not karst.

In UGGp, it is to be expected that cave and karst geoheritage will be explicitly recognized and protected and the same applies to those WHP in which the presence of karst was an important part of the designation process. However, some of the WHP that contain caves or karst were designated for reasons unrelated to these features—for example, sites where the Outstanding Universal Value lies in cultural or ecological features. The latter situation is even more the case in BR and RS where protection of biological interest is the primary goal. This problem is addressed by *IUCN Resolution 074 (Geoheritage and Protected*

Areas↗), which was passed at the 2021 World Conservation Congress. In the resolution, IUCN calls on

> *"states, non-governmental organizations, universities, researchers, economic stakeholders and protected area managers to take into account the specific issues linked to underground environments in the definition and implementation of nature conservation policies and* ***to adopt a holistic approach*** *to the management of underground natural environments,* ***considering all relationships between biological and geological elements****."* (emphasis added)

For those who manage protected areas that contain caves or karst, but who do not have specific knowledge of these environments, there are two recent publications that provide useful advice. The *IUCN Guidelines for Geoconservation in Protected and Conserved Areas* (Crofts et al., 2020) provides generic advice that is equally applicable to caves and karst together with three case studies that include caves and karst. Greater detail is provided in the *Guidelines for Cave and Karst Protection*, a joint publication of the International Union of Speleology (UIS) and the IUCN (Gillieson et al., 2022).

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5.1 Web sites

IAH Karst Commission: https://karst.iah.org↗

IUCN: https://www.iucn.org/theme/protected-areas/about/protected-area-categories↗

MIKAS (Most Important Karst Springs): https://mikasproject.org↗

Ramsar Sites Information Service: https://rsis.ramsar.org/↗

UNESCO (Biosphere reserves): https://www.unesco.org/en/mab↗

UNESCO Global Geoparks: https://en.unesco.org/global-geoparks↗

World Heritage List: https://whc.unesco.org/en/list/↗

Worldmeters: https://www.worldometers.info/world-population/↗

Whymap: https://www.whymap.org/whymap/EN/Maps_Data/Wokam/wokam_node_en.html↗

6 Boxes

Box 1 - Karst Terminology

Many terms are karst-specific and some common terms are used somewhat differently by karst scientists when compared to those studying other aquifers. The US Environmental Protection Agency (Field, 1998) has produced a useful *Lexicon of Cave and Karst Terminology* that is free to download:

https://karstwaters.org/wp-content/uploads/2015/04/lexicon-cave-karst.pdf↗.

In our book, we explain most of the key terms and concepts. However, at the outset we provide these brief explanations that we expand on later.

Karst hydrographic zones

In most rocks, two zones, the vadose (unsaturated) and phreatic (saturated) zones are recognized with a water table as the boundary between them. In karst, the situation is more complicated, and three zones are commonly present: epikarst, vadose, and phreatic.

- *Epikarst*. The epikarst (also called the *subcutaneous zone*) is the upper, most weathered layer of bedrock. As the majority of carbonate rock dissolution takes place in the top 5 to 20 m of rock, this zone has a higher porosity and permeability than the rocks below. Water is stored in—and moves both laterally and vertically through—the epikarst, which can form a perched aquifer in some areas.
- *Vadose (unsaturated) zone*. This is the zone in which voids are occupied by air and water. Vertical percolation under gravity dominates. In alpine karst settings, the vadose zone is commonly hundreds of metres thick, and cavers have explored air-filled voids over 2,000 m below the surface. There are commonly phreatic (water-filled) conduits within the vadose zone.
- *Phreatic (saturated) zone.* This is the zone in which all voids are water-filled. The boundary between the vadose and phreatic zones can be difficult to define as a conduit may be water-filled but surrounded by essentially dry rock. This is discussed further later in this book.

In addition to these three main zones, many karst hydrogeologists recognize an *epiphreatic zone*. This is a zone in which the groundwater elevation rises and falls, sometimes by tens or even hundreds of metres. Hence, there are some periods when it is vadose and some when it is phreatic. It may also be possible to recognize both a *shallow phreatic zone* and a *deep phreatic (bathyphreatic) zone.*

Porosity of karst rocks

Most karst rocks have three types of porosity (triple porosity):

- Primary porosity. The bulk rock porosity is commonly called *intergranular porosity*.
- Secondary porosity. This comprises the voids associated with joints, fractures, faults, and bedding discontinuities and is commonly called the *fracture porosity*.
- Tertiary porosity. This porosity is due to rock dissolution by water circulating through the intergranular porosity or the fracture porosity. The smallest elements are channels, in which flow is commonly laminar. Over time, these may grow into conduits (> 10 mm diameter) in which flow is commonly turbulent. Some conduits grow to a size where they can be explored by humans and are then called caves.

In the literature—mainly related to conceptual and numerical models of karst aquifers—primary and secondary porosity are often grouped and summarized as *matrix*; that is, the karst aquifer can be described as a system of hydraulically connected conduits draining the surrounding fissured rock matrix (*dual porosity*). This is discussed further later in the book.

Permeability of karst rocks

The three types of porosity provide three types of permeability, commonly termed intergranular, fracture, and conduit. However, for karst modeling purposes, intergranular and fracture may be lumped together.

Groundwater elevation in karst: The potentiometric surface and water table

In unconfined settings consisting of sand and gravel, infiltrating water descends freely under gravity through the vadose zone to the saturated zone and a clear line can be drawn separating the two zones. This is referred to as the *water table* or, more precisely, the groundwater surface exposed to atmospheric pressure. Where a permeable rock (aquifer) is confined by less permeable rocks, the water level in boreholes that tap the permeable rock will rise to a level called the *potentiometric surface*. This differs from a water table because it is drawn through rocks that contain little or no groundwater and because it can extend above the ground surface. Unconfined karst groundwater systems commonly have more similarities to the confined settings because the groundwater elevation in boreholes that tap conduits commonly differs from that in boreholes that only tap the matrix or fracture permeability. Therefore, instead of using the terms potentiometric surface and water table, it is also useful to refer simply to *groundwater elevation*.

Return to where text linked to Box 1↥

Box 2 - The Origin and Meaning of the Word *Karst*

The term karst originated from the pre-Indo-European word *kars*, *kar(r)a*, or *gar(r)a*, which means rock. Due to the prevailing dry rocky surface, the region on the border between Italy and Slovenia was named Carso (Italian) or Kras (Slovenian). During the rule of the Austro-Hungarian Empire, these names were germanised into karst.

The Slovenian scholar, polymath, and nobleman Janez Vajkard Valvasor (1641 to 1693 CE) wrote the first popular description of karst and karst phenomena in his book *Die Ehre dess Hertzogthums Crain* [The Glory of the Duchy of Carniola; today, Slovenia]. After that, the French physician and naturalist Balthasar Hacquet (1735 to 1815 CE), who worked in Carniola, wrote many books in which he described the geology and geomorphology of karst and used the term. Since he largely contributed to the use of the regional name *Karst* as a term, he is rightly called the pioneer of modern karstology.

The name and other local karstological terms became internationally recognized after the doctoral dissertation of the Serbian geomorphologist and geologist Jovan Cvijić (1865 to 1927): *Das Karstphänomen* [The Karst Phenomenon] (1893). As a student of the Viennese geographer A. Penck, he defended the thesis in Vienna in 1892, following which his work was published and distributed throughout Europe. Furthermore, Slovenian and Serbo-Croatian terms that Cvijić used in the dissertation have since become used internationally for certain karst-related phenomena. For example, doline, polje, uvala, and ponor are now widely used by experts and scientists engaged in karst research.

Due to railroad construction, flood protection, and the search for drinking water, some of the earliest scientific speleological and hydrological studies were carried out in the area between the Ljubljana Marsh and the Trieste Bay. This area is also known as a global hotspot of underground biodiversity and has the oldest European tourist cave, Vilenica. Therefore, the area between Ljubljana (Slovenia), Trieste (Italy), and Rijeka (Croatia) is commonly referred to as the Classical Karst and the cradle of karstology (Gams, 2004; Figure Box 2-1).

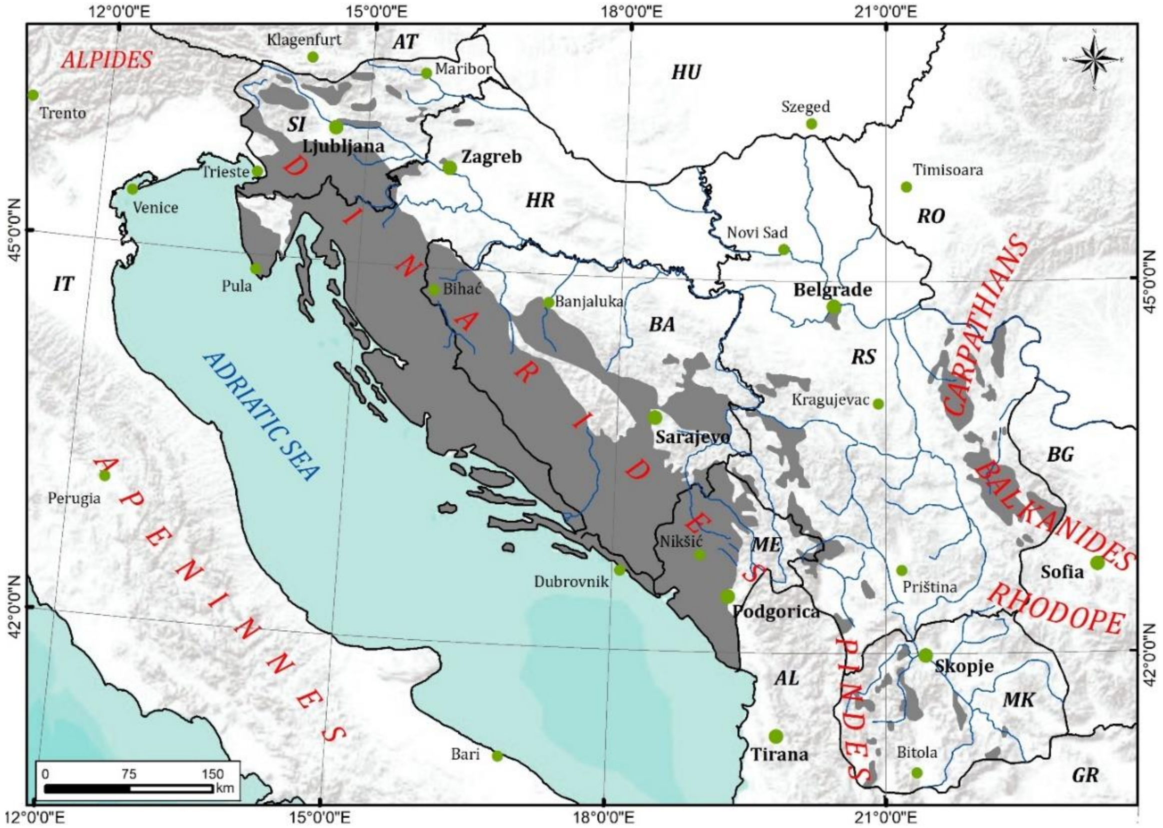

Figure Box 2-1 - Karst terrains in the former Yugoslavia are shaded in gray. The large western area is the Dinaric Karst (Dinarides on the map). The Classical Karst is in the northwest between Ljubljana and Trieste. The Carso/Kras region stretches east of the Trieste Bay. To the north of the Classical Karst is an area that borders Austria (AT) and this is part of the Alpides. To the east of the Dinaric Karst are smaller karst areas in the Carpathians, Balkanides, and Pindes.

Return to where text linked to Box 2↥

Box 3 - Earth's Largest Karst System in an Orogenic Belt

As one of the largest tectonic mega-systems, the Alpine-Himalayan orogenic belt is another home of karst. Most of it was formed during the Cenozoic following the closure of the Tethys Ocean and the collision of the Eurasian tectonic plate with three others—the Indian, Arabian, and African plates—that had moved northward. This belt is more than 15,000 km long and consists of many branches such as the Atlas Mountains in north Africa and Turkey, the Alps and Carpathian–Balkanides in central and east Europe, and Caucasus, Hindu Kush, Java, and Sumatra in south-east Asia. The central part of this large orogenic belt extends from the Alpine Mountains to the Zagros Mountain Range (Figure Box 3-1) where the presence of karst aquifers is much greater than in the Indian sub-continent. Furthermore, the Alpine-Zagros section is characterized by a higher degree of karstification and aquifer utilization than the south-easternmost section of the Himalayas, which is also older in age.

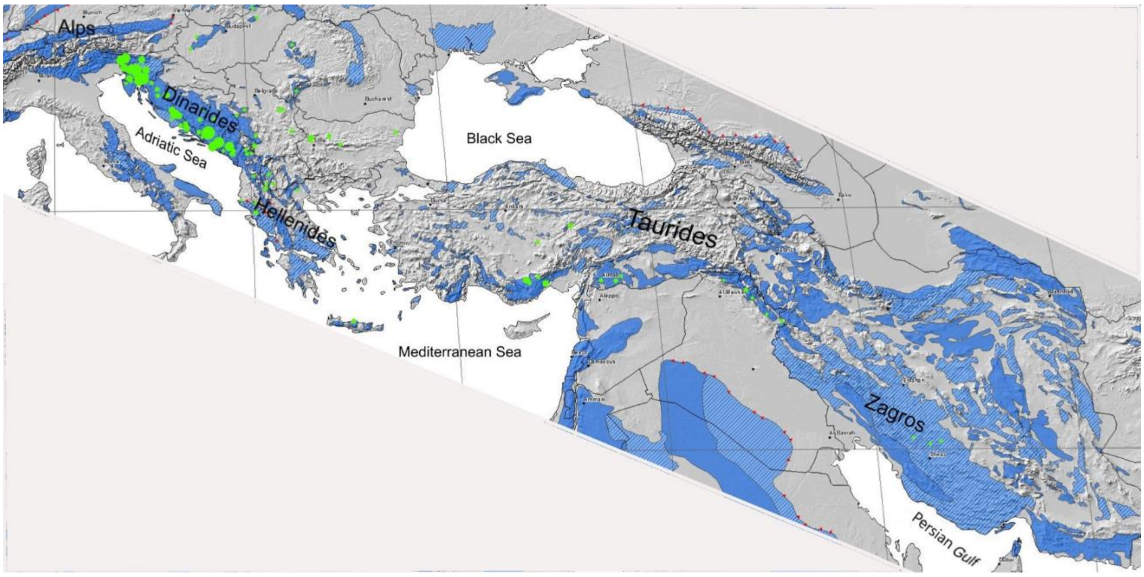

Figure Box 3-1 - Distribution of karst aquifers (blue colour) and large springs (green dots) in the Alpine-Zagros section of the Alpine-Himalayan orogenic belt (extracted from one of the working maps of the WOKAM project; Chen et al., 2017).

Return to where text linked to Box 3

Box 4 - Examples of Different Karst Settings

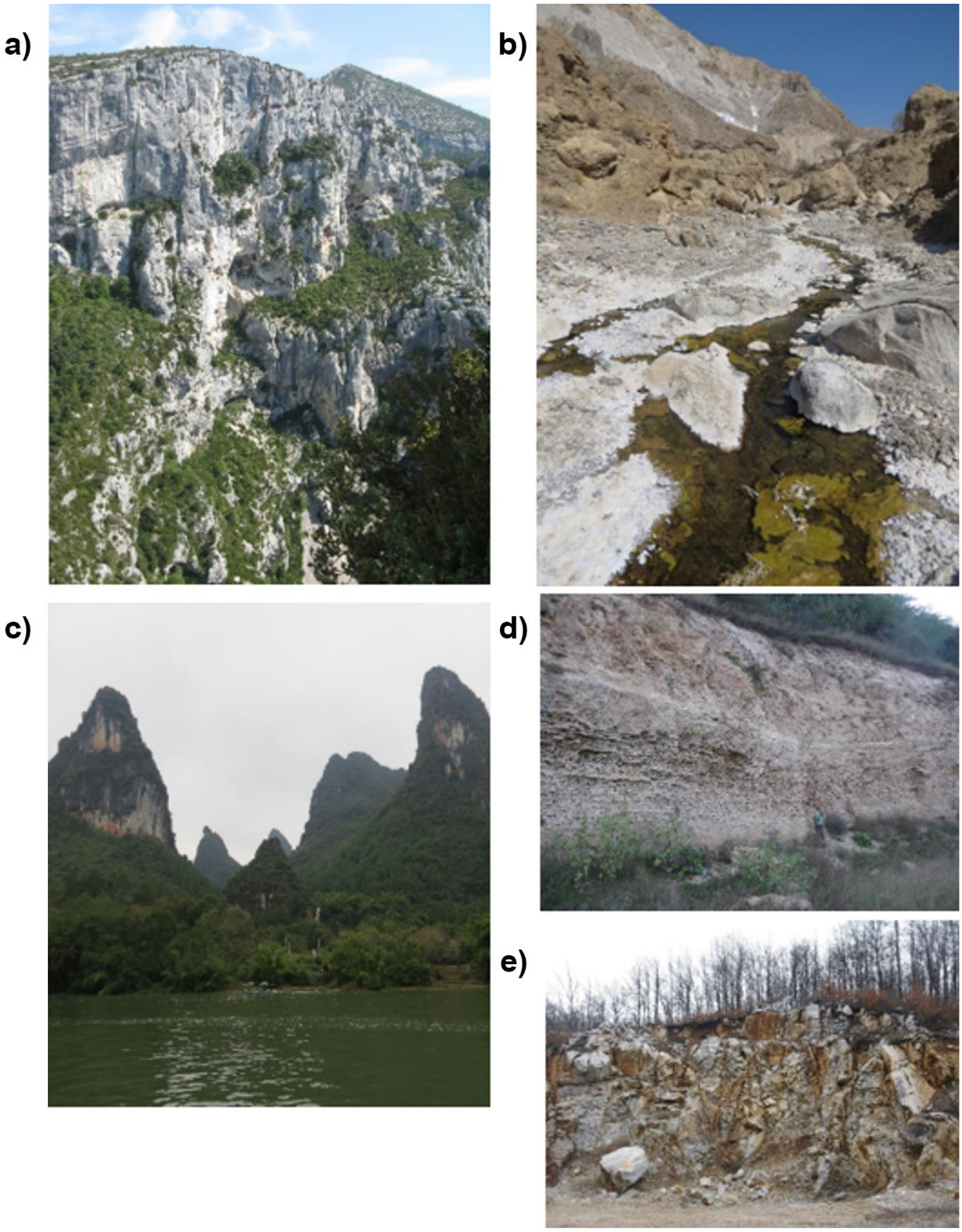

Figure Box 4-1 - a) Karst in the Verdon Canyon in southern France; b) Konarsiah salt diapir: halite deposits, southern Iran; c) Tower karst: Fengcong forms along the Li River near Yangshuo, southern China; d) Miocene limestones of vuggy porosity; and e) Epikarst in karst of central and eastern Serbia (photographs by Z. Stevanović).

Figure Box 4-2 - The Upper Cretaceous Chalk at Seaford Head, East Sussex, UK, has a high primary porosity, but the pores are so small that most groundwater circulation is through fractures and solution conduits. At the top of the cliff are dissolution pipes infilled with brown clay. At beach level, a sheet flint forms a major inception horizon that hosts many conduits and some small caves. The human figure in the lower left provides an indication of the scale (photograph by A.R. Farrant. Reproduced with the permission of the British Geological Survey © UKRI [2021]. All Rights Reserved).

Figure Box 4-3 - A. High alpine karst landscape, Zugspitze, Wetterstein Mountains, Germany (photograph by N. Goldscheider).

Figure Box 4-4 - Glacial meltwater sinking into a karst swallow hole, Tsanfleuron-Sanetsch, Switzerland (photograph by N. Goldscheider).

Figure Box 4-5 - Karst area of Kostivere, Estonia (photograph by N. Ravbar).

Return to where text linked to Box 4

Box 5 - An Example of Karst Landform and Drainage Evolution

The Waitomo area of New Zealand provides a good example of karst landform and drainage evolution. Permeable non-karst rocks of the Mahoenui Group overlie the Otorohanga limestone and a surface drainage network forms shown as Stage 1 in Figure Box 5-1. Entrenchment of the surface valleys creates hydraulic gradients and dispersed recharge of aggressive allogenic water forms conduits in the limestone. When the surface streams incise through the overlying rocks into the limestone, concentrated allogenic recharge can rapidly enlarge conduits to a point where they can accommodate all the surface flow leaving large, enclosed basins on the surface (Stage 2).

During Stage 3, the remaining non-karst rocks are gradually removed by surface erosion and the larger closed depressions are dismembered by smaller depressions that form where the structure (mainly joint intersections) favours concentrated autogenic recharge, the proportion of which grows at the expense of allogenic recharge. Underground drainage is largely perched on the Waitomo sandstone, a 5 to 10 m thick unit that is breached at structurally favourable areas, allowing conduits to form in the underlying Orahiri limestone. When the last vestiges of non-limestone have been removed from the surface, competition for recharge produces a network of depressions that are broadly comparable in size and form a polygonal karst (Stage 4).

Below the Orahiri limestone is the non-karst Aotea sandstone and the fifth stage of landform evolution is reached when the underground streams incise down to the sandstone. As further lowering of the surface by dissolution is not possible, this marks the beginning of the destruction of the karst system, which continues through stage 6 (surface drainage on the sandstone and a few depressions on the ridges) to a point where all limestones have been removed.

A key point concerning this scheme, and one that is widely applicable, is that where there is differential uplift of a carbonate rock sequence then different parts of the landscape may be at different stages in their karstic evolution. For example, one area may be at Stage 1 whereas another area a few kilometres away may be at Stage 6.

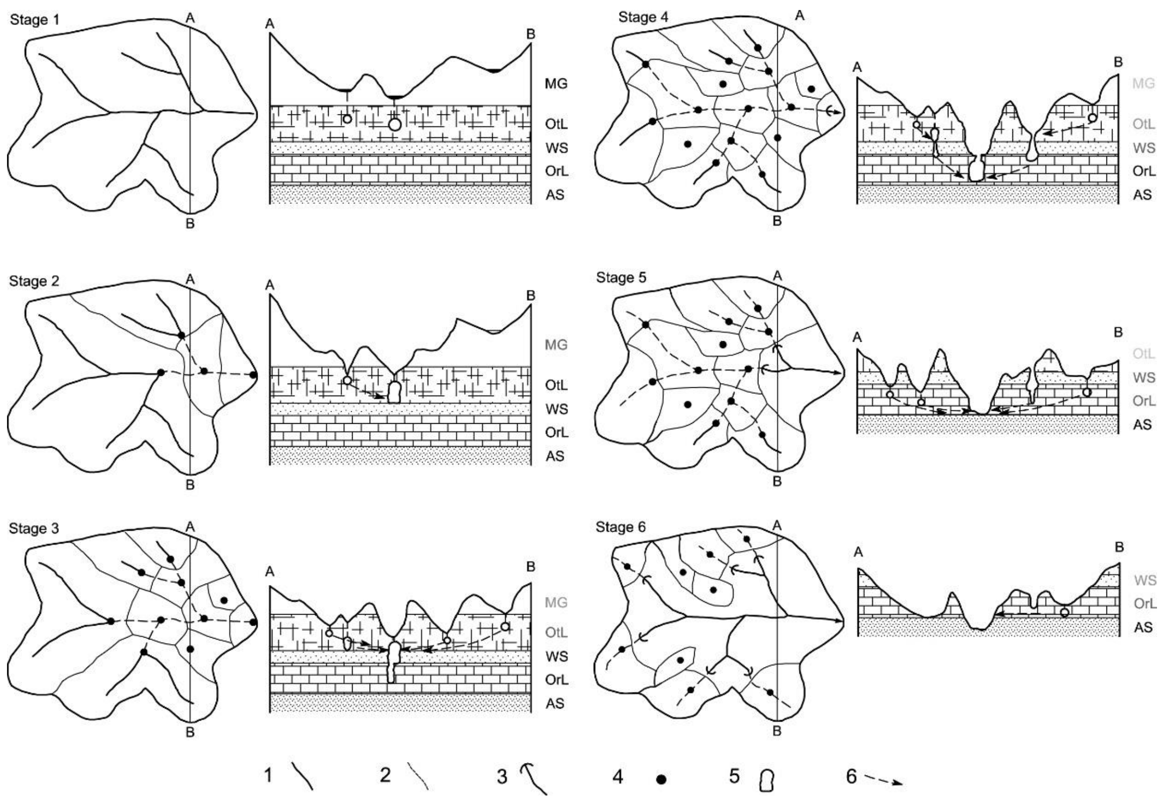

Figure Box 5-1 - A model for landform drainage evolution in a setting with two limestone units and three non-karst units (after Gunn, 1986b); the text of Box 5 explains the Stages). Key: 1 = topographic drainage divide; 2 = stream flowing on surface; 3 = spring; 4 = sinking stream (ponor) or outlet at base of enclosed depression; 5 = conduit; 6 = channel of former surface stream. MG = Mahoenui Group (the cover rocks); OtL = Otorohanga limestone; WS = Waitomo sandstone; OrL = Orahiri limestone; AS = Aotea sandstone.

Return to where text linked to Box 5↥

Box 6 - Turloughs: Closed Depressions with Intermittent Lakes

Turlough is an Irish term for closed depressions in karst that are intermittently inundated (Figure Box 6-1). Similar landforms are recognized in other countries such as Slovenia (Figure Box 6-2). In Ireland, they range in size from less than 0.1 km^2 to 6.5 km^2 and hence are intermediate in size between dolines and polje. There is no specific *turlough forming process*; they appear to be polygenetic landforms strongly associated with dissolution, karstic drainage, and underground flow routes, and—in most cases—with glaciation.

Turloughs are defined primarily based on their hydrology and their distinctive ecology, with vegetation communities that show a distinct zonation determined by water depth and the frequency and duration of filling. Hydrologically, the key feature is the lake itself, which (in most cases) is seasonal with an autumn fill cycle that is commonly rapid (hours to days) and a late spring to early summer drain cycle that may take several weeks. Less commonly, the lake may fill and drain with the tide or the fill cycle may follow periods of prolonged or intense rainfall irrespective of the time of year. Lakes are fed partly by direct precipitation onto the depression in which it is located but primarily by groundwater that commonly enters from discrete conduits. As is the case in polje, the same conduits serve to drain the lake and they are called *estavelle*. The catchment area may be local and entirely within the epikarst, but some turloughs form part of large regional groundwater systems.

Figure Box 6-1 - Fardrum Turlough, County Fermanagh, UK. Upper image a) shows the turlough during a period of high groundwater and lower image b) shows the turlough drained (photographs by J. Gunn).

a)

b)

Figure Box 6-2 - Closed depressions with intermittent lakes are common in the Pivka region of southwest Slovenia. a) Petelinjsko jezero when dry. b) The same depression when flooded (photographs by N. Ravbar).

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Box 7 - Turbulent Flow and Increased Turbidity of Spring Water

The flow of water through a karst system can be laminar or turbulent. The former is common in the fissured rock matrix (matrix flow), while turbulent flow is common in large open cavities. The critical Reynolds' number (*Re*) identifies the flow regime (laminar or turbulent flow) and is calculated with four parameters:

1. conduit diameter for fully saturated conduits or hydraulic radius for partially (or variably) saturated conduits,
2. flow velocity,
3. fluid density, and
4. fluid viscosity.

During storm events, the main parameter that is changing in fully saturated conduits is the average flow velocity (the higher the velocity the higher the Reynolds number). In partially (variably) saturated conduits, both the hydraulic radius and the flow velocity change during storms. The Reynolds number, *Re*, represents the ratio of inertial to viscous forces within the fluid and thus is a dimensionless number. The critical Reynolds number is the value of the Reynolds number above which flow is turbulent and below which flow is laminar for a specific conduit. It is a similarity law such that the onset of turbulence in any size of smooth, straight pipe occurs at the same critical *Re* (typically: $2{,}100 < Re < 2{,}300$).

For most porous media, the critical *Re* ranges from 1 to 60, and is dependent on smoothness of the grains, tortuosity of the connected pore spaces, average pore diameter, and fluid temperature, as well as other properties of the aquifer and fluid. When flow becomes turbulent, some of the flow energy is lost by the movement of water in eddies, which results in specific discharge not increasing as rapidly as the head gradient increases. In karst systems with large conduits (0.5 m or greater), flow is more similar to pipe flow and the onset of turbulence within these conduits is at large values of *Re* (500 to 2,000). Reynold's number computation is described by Kuniansky and others (2022).

There are many examples in the world that show that fast turbulent flows result in a great variation of karst spring discharge (Figure Box 7-1) and consequently in highly increased water turbidity caused by the mobilization of clastic sediment (Figure 37, Figure Box 7-1).

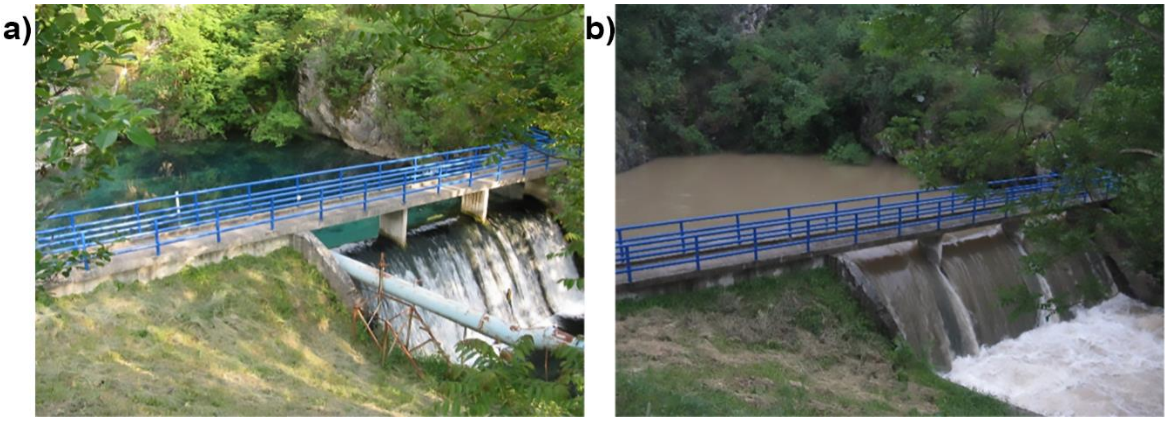

Figure Box 7-1 - Karst spring during periods of a) low water and b) high water when there is a substantial increase in turbidity due to collapse of sinkholes in the catchment and flushing of sediment from underground storage. The spring is called Modro oko (Blue eye) and (a) shows a pipe that takes water to Niš, the third largest city in Serbia. When flow becomes turbid, as in (b), the pipe is removed (photographs by Z. Stevanović).

Return to where text linked to Box 7↥

Box 8 - Early Theories about Karst Aquifers

Characterizing karst aquifers is not a simple task. Due to their complexity and heterogeneity, not even extensive research can properly explain all the details of their functionality. That is why several theories of groundwater circulation in karstified rocks have been developed.

Discussion on this topic was initiated by the Belgian Society for Geology and Hydrology in 1892 and two opposing ideas were advanced:

1. in karstified rocks the hydrodynamic regime is similar to that which characterizes rocks with intergranular porosity (aquifer system); and
2. in karstified rocks water flows in cavities and channels formed by dissolution.

In his work entitled *Die Karst Hydrographie* (1903), Grund supported the first theory by suggesting the existence of a uniform water-bearing horizon with essentially stagnant water (i.e., the aquifer) sloping gently toward the sea as the main erosional base (Figure Box 8-1). Above this horizon are karst waters that percolate downward.

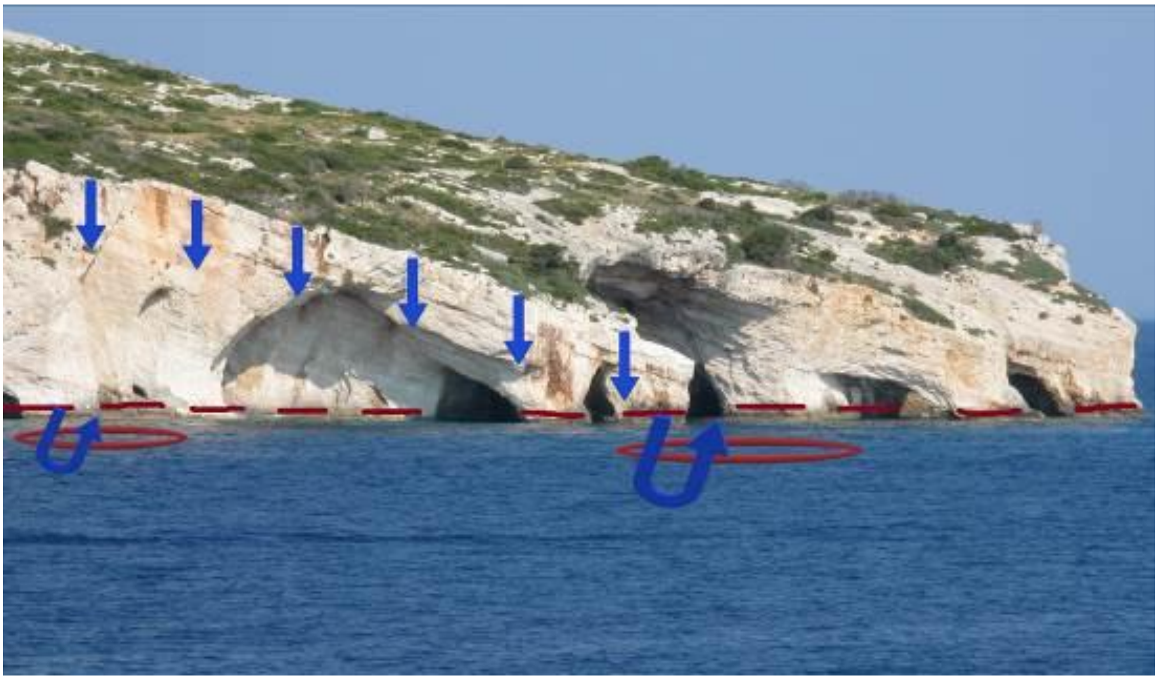

Figure Box 8-1 - Graphic interpretation of the Grund concept of a coastal karst aquifer. The dashed line shows the approximate fresh groundwater potentiometric surface indicating essentially stagnant water in the karst aquifer because it is nearly horizontal. Due to deep karstification, this water is mixing with sea water, becoming brackish and finally discharging as submarine springs at locations indicated by ovals. Vertical blue arrows represent precipitation percolating downward, driven by gravity until it reaches a stagnant water zone (photograph by Z. Stevanović).

In contrast, based on their considerable experience from speleological explorations, Katzer (1909), Martel, and several other eminent geographers and geologists suggested the existence of a network of interconnected—but also separated—underground flowpaths. Cvijić (1918), tried to reach a compromise between these two theories, and found that both include some correct concepts. He introduced three hydrographical zones that were formed as a result of the evolution of the karst process:

1. a dry zone closest to the land surface,
2. a zone with vertical percolation and horizontal circulation (transitional), and
3. a zone with continuous groundwater circulation (Figure Box 8-2).

Many other karst researchers also contributed to the theoretical discussion on water flow in karst, but the existence of karst aquifers was, in essence, no longer questioned.

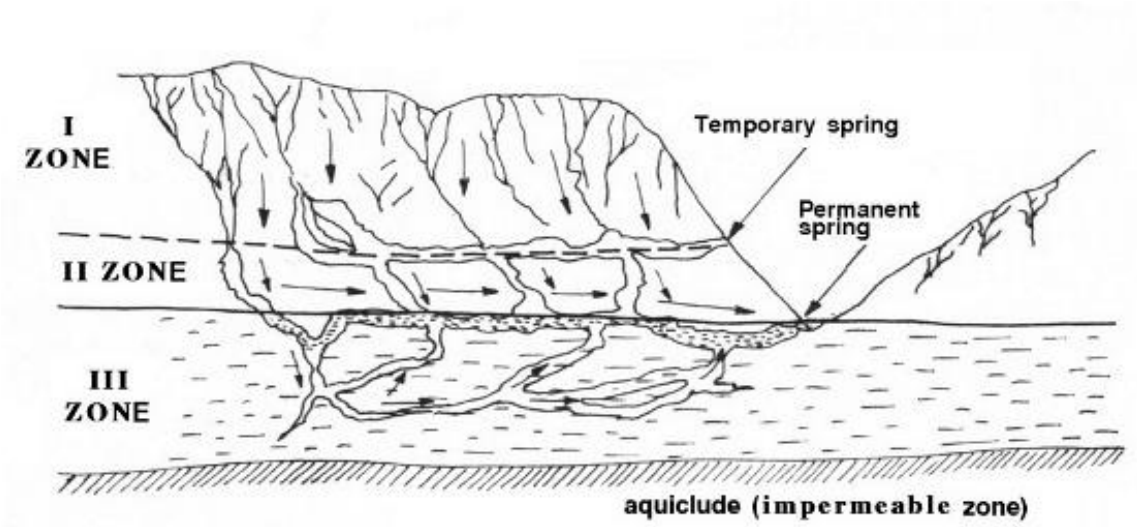

Figure Box 8-2 - Graphic interpretation of Cvijić's concept of three hydrographical zones. Zone I is predominantly under unconfined conditions and generally dry but during rain events the groundwater elevation may rise, and some water may move laterally to the upper intermittent spring. Zone II is the region where the water table fluctuates in height depending on storm and recharge events. Zone III is the fully saturated zone with a permanent base level spring (after Stevanović & Mijatović, 2005).

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Box 9 - Hydraulic Connection Between Two Karst Catchments and their Springs

Determining the boundaries of the aquifer's catchment area is an important part of hydrological analysis and serves as a basis for water resources protection, management, understanding, and modeling. However, the nature of karst aquifer systems with both convergent and divergent flow means that, in most cases, it is impossible to establish accurate boundaries and instead broad boundaries that change with time must be used. Bonacci (2015) examined the possible hydraulic relationships between adjacent karst aquifers, noting that the difference in hydraulic head is the driving force of water flow. Four examples are shown in Figure Box 9-1.

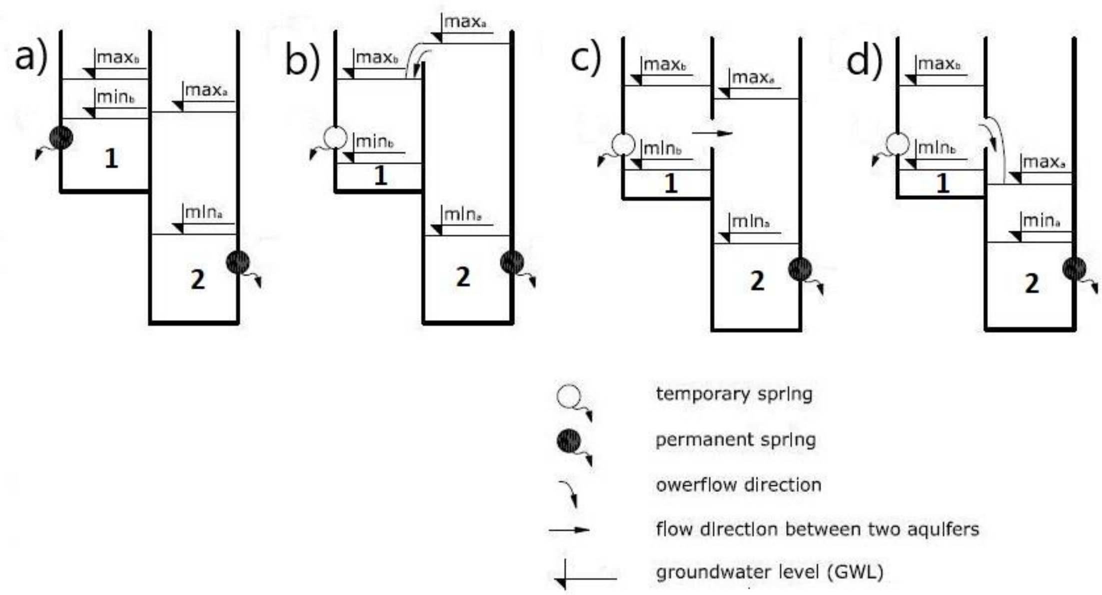

Figure Box 9-1 - Some of the possible relationships between two adjacent karst aquifers (modified from Bonacci, 2015): a) aquifers 1 and 2 are not connected, the boundary between them is impermeable, and groundwater flows are independent; b) aquifers 1 and 2 are connected and the smaller catchment, 1, receives the overflow from the larger catchment, 2, during maximal flood, and vice versa during low water periods; c) a permeable boundary between aquifers 1 and 2 and aquifer 1 drains into aquifer 2 by lateral underground flow; and d) aquifer 1 emerges at the surface via a spring and feeds aquifer 2 throughout the year because its hydraulic head is always higher than aquifer 2.

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Box 10 - Artesian Karst Aquifers

Water pressure in a confined karst aquifer can be considerable, resulting in a rise or release of water once the overlying confined bed is penetrated by drilling. If this rise enables free flow from the well, such a well is called an *artesian well* (Figure 41). The same term is applied to the potentiometric pressure at that exact point: *artesian pressure* (the term derives from an old self-flowing well in Artois, Belgium, but is rarely used today because a free flow from a well can also be caused by other factors). Figure Box 10-1 shows the release of pressure from the confined karst aquifer Pila Spi in northern Iraq (Kani Shaya village) during the drilling of a well that was to be used for local water supply and irrigation (Stevanović & Iurkiewicz, 2004).

Figure Box 10-1 - Huge and unexpected free flow with high pressure from a drilled well in the Pila Spi karst aquifer (Kani Shaya, northern Iraq; photograph courtesy of R. Karwan).

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Box 11 - Examples of Water Tracing Using Different Types of Injection Points

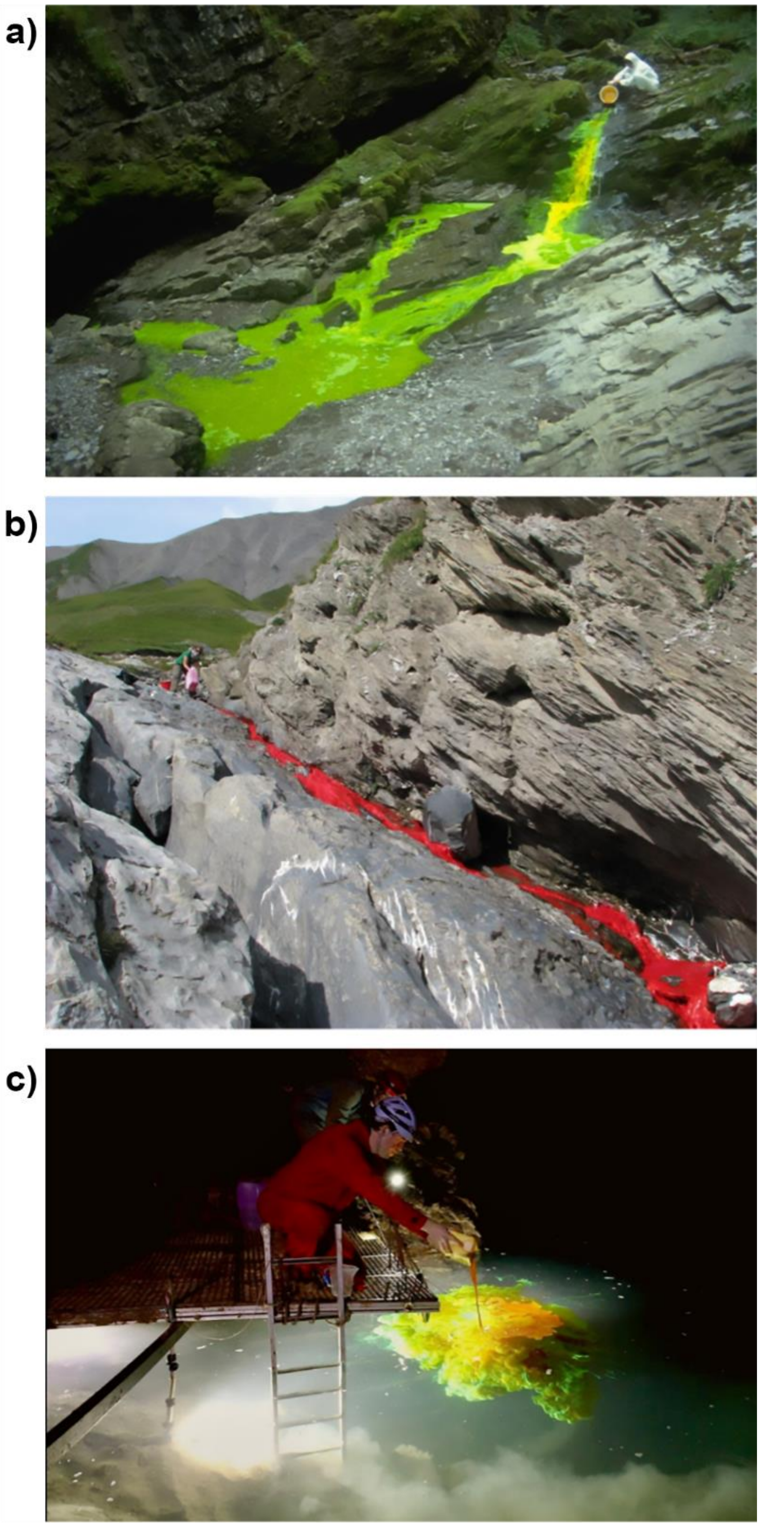

Figure Box 11-1 - a) Injection of a tracer (uranine) into the estavelle, Schwarzwasser valley, Austria; b) Injection of a tracer (Amidorhodamine G) into one ponor (swallow hole) in alpine karst, Tsanfleuron-Sanetsch, Switzerland (photographs by N. Goldscheider); c) Uranine injection in an underground lake in Blue Cave, Swabian Alb, Germany (photograph courtesy of A. Kücha).

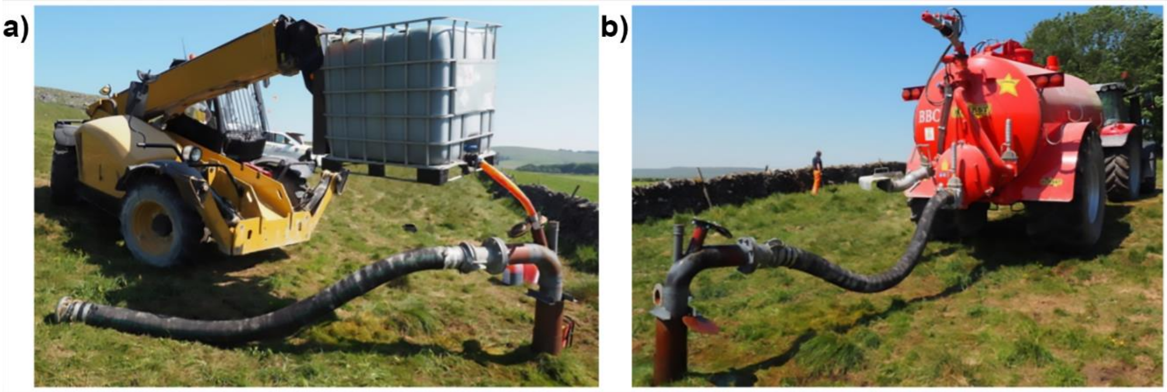

Figure Box 11-2 - Tracer injection into drilled boreholes: a) dye, dissolved in water, discharging from a 1,000 L container into the borehole; b) bowser used to flush dye after injection (photographs by J. Gunn).

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Box 12 - Tracing Tests in the Dinaric Karst

Several hundred tests have been carried out in the Dinaric Karst, most of them using uranine in quantities up to—and occasionally exceeding—50 kg (Figure Box 12-1). The aim was to understand the complexity of water loss, circulation, and discharge in many—often connected—karst aquifers, and to delineate their catchments (Mijatović, 1984; Stevanović et al. 2016).

Figure Box 12-1 – Sodium fluorescein tracing test, injection into the large Ponikve Ponor (Dabarsko Polje, eastern Herzegovina; photograph courtesy of Ž. Zubac).

Komatina (1983) examined the results from 380 tracing experiments in the Dinaric Karst and concluded that the frequency of apparent groundwater velocities (based on first appearance of the tracer) was: 70 percent less than 0.005 m/s; 20 percent 0.005 to 0.01 m/s; 10 percent more than 0.01 m/s. Based on the results of numerous experiments performed in the karst of eastern Herzegovina (Figure Box 12-2), Milanović (2001) calculated the average apparent flow velocity as 0.05 m/s, with extremes in the wide range from $2x10^{-9}$ to 0.55 m/s. The highest known apparent velocity in the Dinaric Karst, 0.81 m/s, was recorded in its most southeastern part, between the lakes Prespa and Ohrid, shared by Albania and North Macedonia (Eftimi & Zoto, 1997).

Figure Box 12-2 - Complex underground connections between ponors and springs in eastern Herzegovina (after Milanović, 1981). One spring drains water from several ponors (convergent flow), and vice versa, water from one ponor flows toward several springs (divergent flow).

In the Slovenian part of the Dinaric Karst, more than 160 tracer tests confirmed apparent flow velocities between 8.3×10^{-8} and 0.37 m/s. The highest values are associated with the flow of sinking streams through large horizontal caves toward large karst springs (Petrič et al., 2020).

During the dry season when groundwater elevations are low, water circulation in karst systems is slow. During the high-water season, water waves labelled with dye take two to five times less time to travel the same distance. Milanović (2001) presents an example: when the groundwater elevation is low and inflow is small, it takes the underground flow 35 days to cover the 34 km from Gatačko Polje to the Trebišnjica Spring (Dinaric Karst, Herzegovina), while during high-water levels and large inflow, the well-distinguished water wave covers the same distance in just five days.

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Box 13 - Evaluation of Tracer Breakthrough Curves

The primary result of a tracer test, and the basis for all further evaluation and interpretation, is a tracer breakthrough curve (BTC), which presents measured tracer concentrations (*C*) as a function of time (*t*) after injection. A complete BTC is much stronger evidence for an underground connection than a single positive detection. Concentrations are either available as discrete values obtained from water samples (shown as point symbols) or continuous data from field fluorimeters (shown as a continuous line). The BTC shown in Figure Box 13-1 is based on discrete samples.

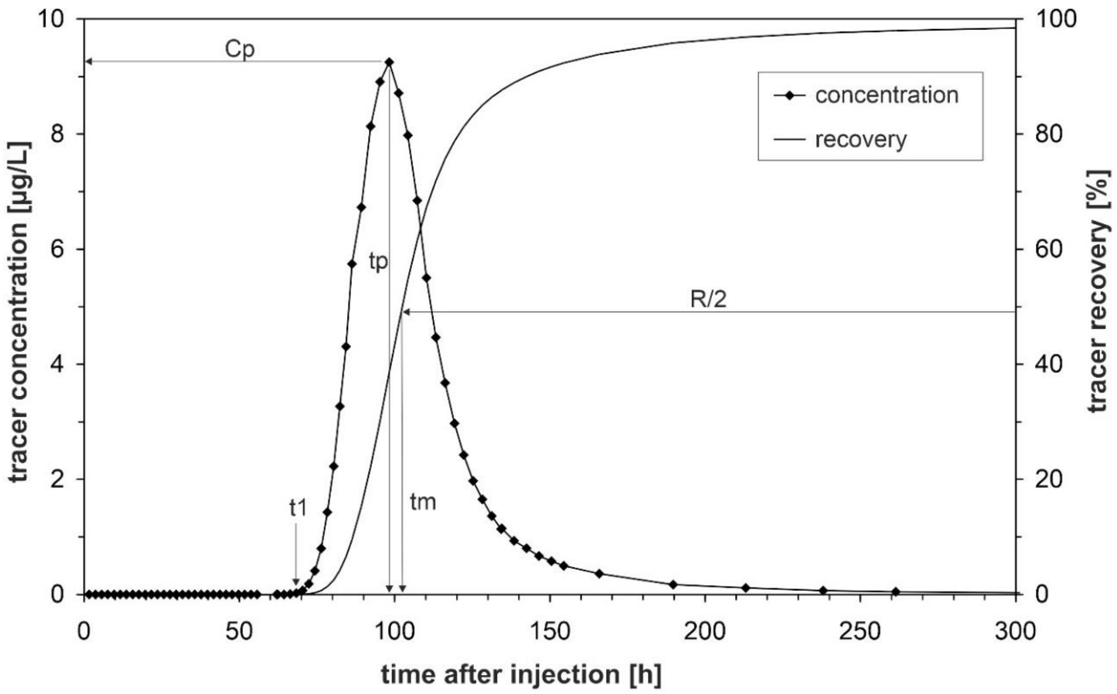

Figure Box 13-1 - Example of a tracer breakthrough curve (BTC) with illustration of parameters that can be obtained from this curve, as explained in the text (modified after Goldscheider et al., 2008).

The following parameters can be directly obtained from the BTC:

1. time of first detection (t1), which depends on the analytical detection limit;
2. the peak time (tp), the time of highest concentration; and
3. the peak or maximum concentration (*Cp*).

The time of last detection (not shown) is strongly dependent on the detection limit.

The tracer recovery (*R*) is, theoretically, the integral of the BTC times the discharge (*Q*). However, as the BTC is not a mathematical function that can be integrated, thus the recovery is calculated by determining the area below the BTC, as shown in Figure Box 13-2.

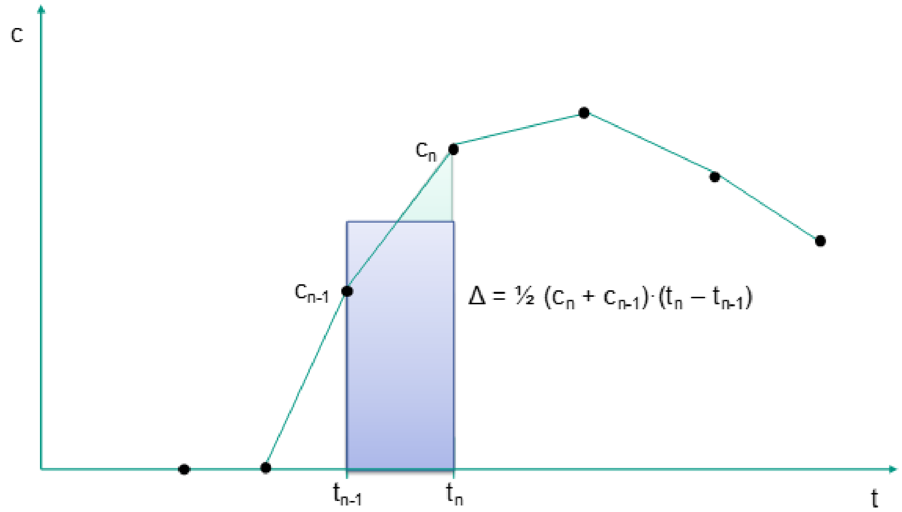

Figure Box 13-2 - Illustration of the quantification of tracer recovery from a BTC. The curve is sliced in individual segments that can be approximated as rectangles, which are then summed up. Finally, the surface below the BTC is multiplied by the discharge. Legend: t = time, c = concentration, n and $n-1$ = sample numbers, Δ = area of an individual rectangular slice of the BTC.

Recovery can be expressed as an absolute quantity (g or kg) or, better, as a percentage of the injected tracer mass. The mean transit time (*tm*) can be approximated by the time when half of the recovered tracer (*R*/2) has reached the sampling site. The BTC shown in Figure Box 13-1 almost reaches 100 percent recovery as shown on the right-side y-axis, which indicates a straightforward connection between the injection site (a cave stream) and the sampling site (the single spring draining this cave). In more complex karst systems, recoveries are typically much lower.

Relevant apparent velocities (*v*) can be obtained by dividing the linear distance between injection and monitoring site by the different transit times shown in Figure Box 13-1. The maximum apparent linear velocity is obtained from *t1*; the dominant apparent linear velocity (or peak velocity) is obtained from the peak time; and the average (or mean) apparent linear velocity is obtained from the mean transit time. Field velocities in the conduit system are always higher, as the flowpath is not a straight line. They can be approximated by assuming a flowpath tortuosity (typically around 1.4) or by determining the flowpath length from cave maps.

A more advanced interpretation of BTC requires modelling using suitable software tools. Typically, a theoretical curve is fitted to the measured data using inverse modelling which adjusts input parameters until a best-fit to the observed data is obtained. The most conventional approach is to use the Advection–Dispersion Model (ADM), which delivers advection (i.e., linear flow velocity) and dispersion (for conservative transport). More advanced models include retardation and biodegradation to account for reactive transport and parameters characterising non-equilibrium conduit–matrix exchange. Goldscheider and others (2008) explain this in more detail.

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Box 14 - Recharge in Different Settings

The percentage of precipitation that becomes groundwater varies spatially within an area, and temporally both seasonally and within individual storm events. Recharge replenishes the stored volume of water and is a crucial factor for planning and management of sustainable water use. In contrast to the changeable recharge, the effective storage volume in a karst aquifer is fixed and depends on the area, aquifer thickness, effective porosity, maximal water level, and karstification base (Issar, 1984).

Global experiences with the average annual recharge show great differences. Marbles and dolomitic rocks, such as the Paleozoic complex in South Africa, have the smallest recharge, which amounts to just a few percent of rainfall (Lerner et al., 1990). In Miocene limestone of the Middle East, recharge is usually between 20 and 40 percent of rainfall (Stevanović & Iurkiewicz, 2004; Raeisi & Stevanović, 2010). In the Mesozoic limestone of Carpathian karst, recharge ranges from 20 to 50 percent of rainfall (Kullman, 1977; Stevanović, 2015). The highest values were reported for karst of the Apennines, where recharge ranges from 69 to 78 percent of the rainfall (Boni & Bono, 1984), but more recent studies for the two karst massifs of this zone, namely Cervialto and Terminio, simulated slightly smaller values (Fiorillo et al., 2014).

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Box 15 - Examples of Different Karst Spring Types

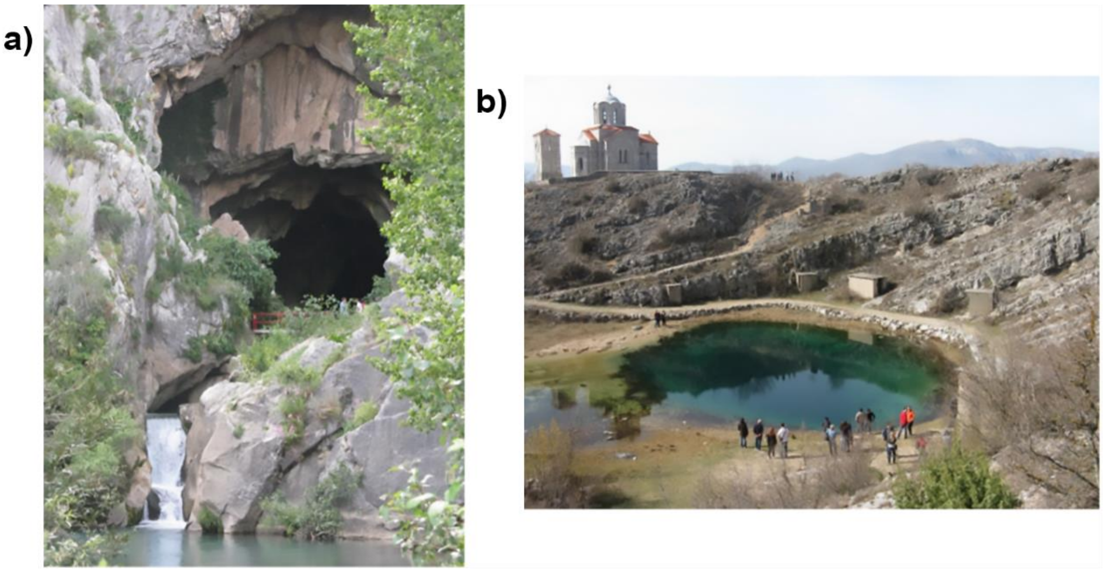

Figure Box 15-1 - a) Cave spring: Cueva del Gato, a natural monument in the south of Spain, where water is issuing after 4 km of flow through a cave system; b) Ascending siphonal spring: Vrelo Cetine in the Dinaric Karst, south Croatia (photographs by Z. Stevanović).

Figure Box 15-2 - Contact spring: Almyros. Lithological contact between Cretaceous limestones and Neogene sediments covered by recent deposits. During the period of low water, when the concentration of Cl ions rises, the spring issues brackish water (Heraklion, Crete Island, Greece; photograph by Z. Stevanović).

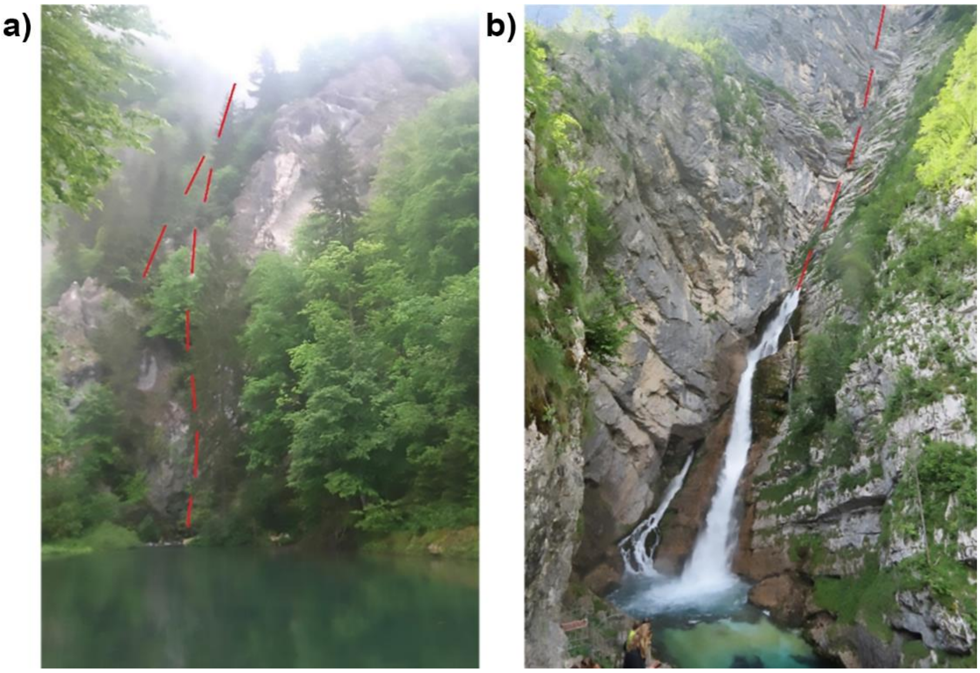

Figure Box 15-3 - a) Fault springs: Source de L'Areuse (Neuchâtel, Switzerland), left photograph, and b) Savica spring (Bohinj, Slovenia), right photograph (photographs by Z. Stevanović).

Figure Box 15-4 - a) Water discharging from a single large karst conduit: the Unica spring flowing from the cave of Planinska jama. b) Multi-orifice spring: the Sušec spring. Both springs are in southwest Slovenia (photographs by N. Ravbar).

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Box 16 - The Largest Springs in the World

The largest springs in the world issue from karst aquifers (LaMoreaux and Tanner, 2001). Although some of these springs have a markedly lower discharge during periods of drought, in high-water periods their discharge can be more than 100 m^3/s. An inventory of springs with a low-flow discharge of more than 2 m^3/s has been made for the purpose of the WOKAM project (Goldscheider et al., 2020). The largest number were recorded in Bosnia and Herzegovina and Turkey, with eight in each country. Karanjac and Günay (1980) claimed that Dumanli Spring in south Turkey was the world's largest spring, with a lowest recorded discharge of 38 m^3/s and a peak discharge estimated at 50 m^3/s. However, this spring is now covered by 120 metres of water in the Oymapinar reservoir. Three karst springs in the Adriatic basin have a larger peak discharge: Sopot (Figure Box 16-1) and Ljuta in Montenegro, and the Buna spring in Bosnia and Herzegovina. The former two are overflow springs that have peak discharges in excess of 150 m^3/s but have little or no flow during dry periods when groundwater is discharged via submarine springs. At its maximum, the Buna spring together with the adjacent Bunica spring discharges around 380 m^3/s making it a candidate for the world's largest (Figure Box 16-1).

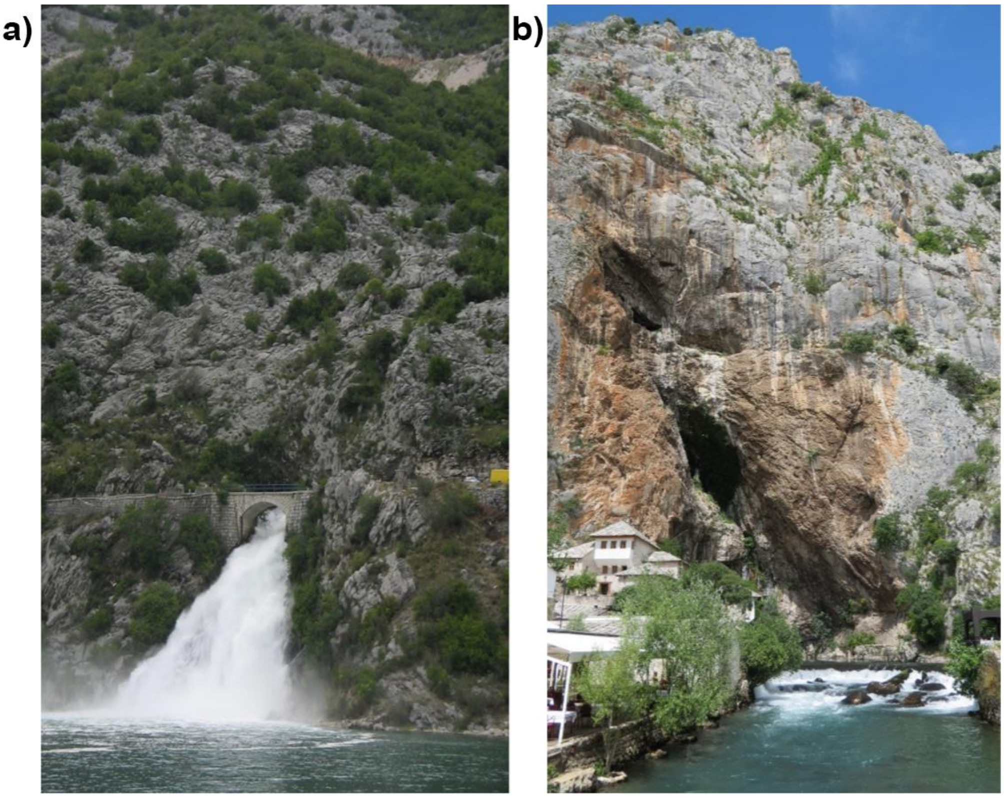

Figure Box 16-1 - Large springs: a) Sopot spring in Boka Kotorska, Montenegro, during a flood event, and b) Buna spring in Blagaj, Mostar (Bosnia and Herzegovina), which became a pilgrimage site in the late twentieth century (CE) and receives many visitors (photographs by Z Stevanović).

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Box 17 - Discharge Coefficients and Groundwater Volumes

The Seljašnica springs, located in the Dinaric Karst of western Serbia, supply the city of Prijepolje with potable water (Petrović et al., 2021). These two springs drain the same karst aquifer system (Figure Box 17-1). Their combined spring hydrograph for the recession period of the year 2015 indicates the existence of two drainage micro regimes (Figure Box 17-2). Calculated recession coefficients and the total amount of outflow are shown in Table Box 17-1.

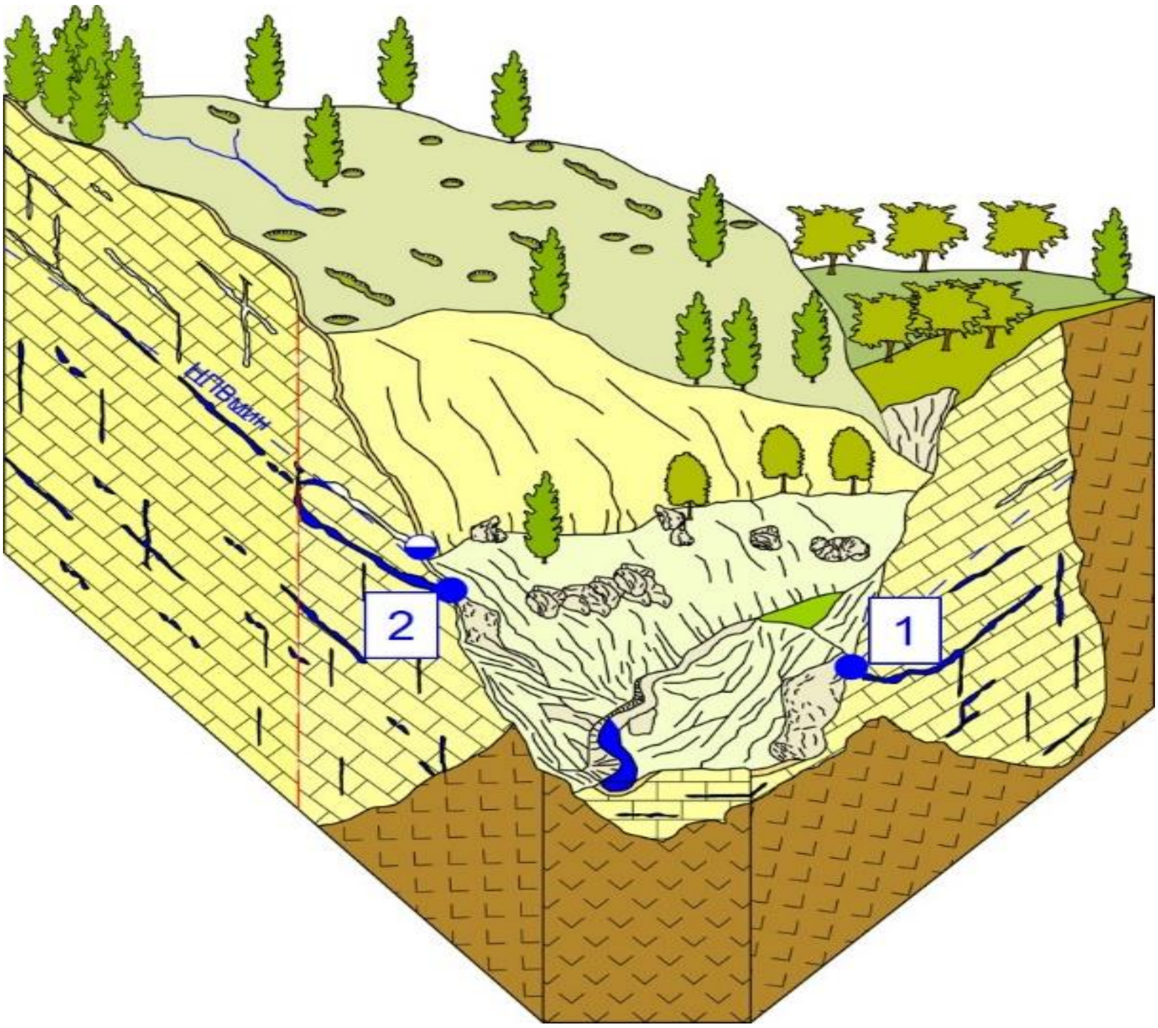


Figure Box 17-1 - Conceptual model of Seljašnica karst aquifer with two discharge points (1, 2) that drain the same aquifer.

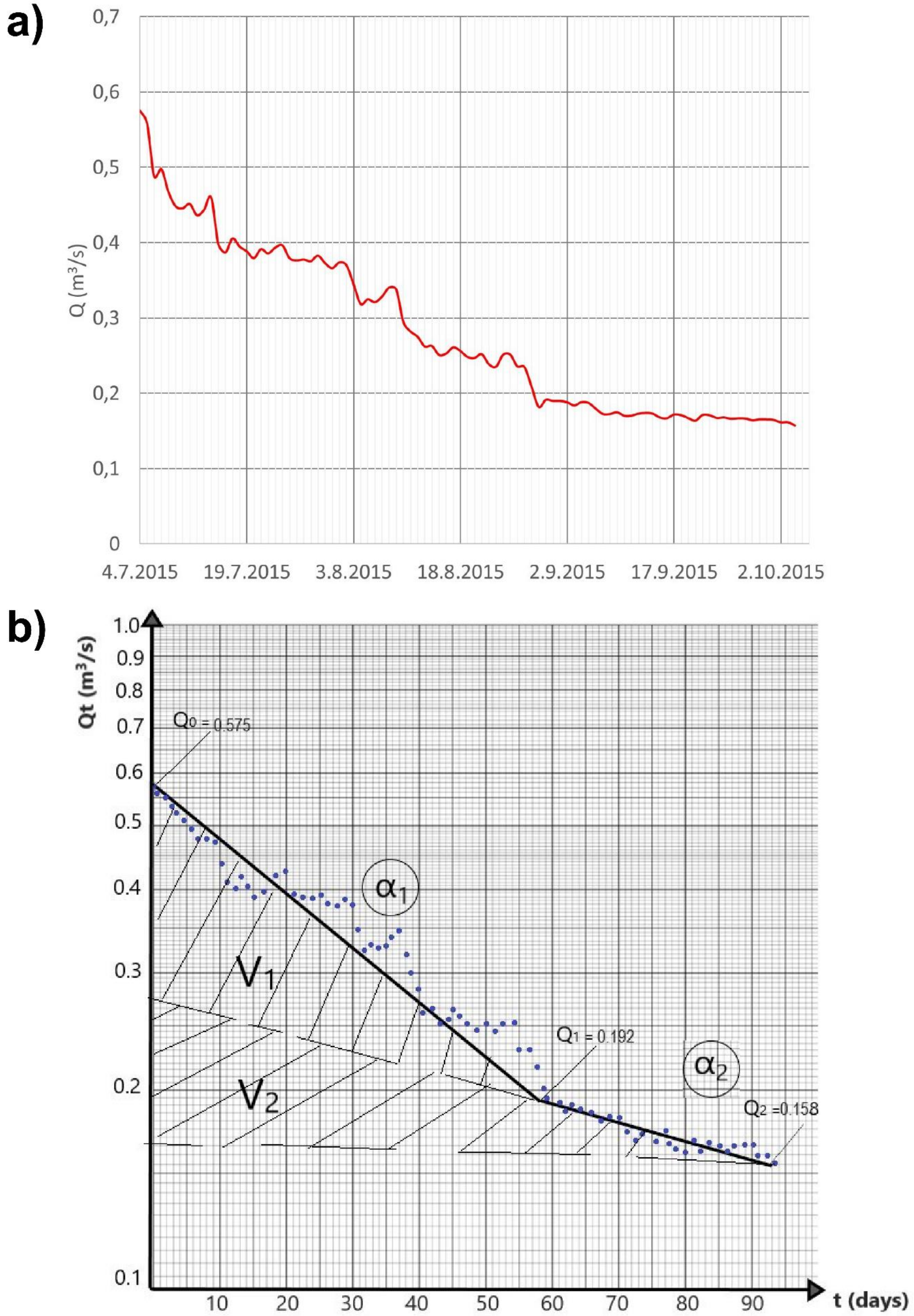


Figure Box 17-2 - Hydrograph of the Seljašnica springs during the recession phase of the year 2015: a) combined hydrograph of springs 1 and 2 of Figure Box 17-1 during the recession period from July to October 2015; b) the semi-log graph of their combined flow during the recession period of (a).

Table Box 17-1 - The two recession coefficients and volume of discharged water.

Year	Recession coefficient (α) (days^{-1})		Duration of micro regime (days)
2015	α_1	0.0189	58
	α_2	0.0055	35
	Σ		93
	Total volume of water discharged during recession period (ΣV)		2.28×10^6 m^3

Parameters in Table Box 17-1 are calculated as follows:

$$\alpha 1 = \frac{\log Q_0 - \log Q_1}{0.4343\ \ (t_0 - t_1)} = \frac{\log 0.575 - \log 0.192}{0.4343\ \ (58\text{ days})} = 0.0189\text{ days}^{-1}$$

$$\alpha 2 = \frac{\log Q_1 - \log Q_2}{0.4343\ \ (t_1 - t_2)} = \frac{\log 0.192 - \log 0.158}{0.4343\ \ (35\text{ days})} = 0.0055\text{ days}^{-1}$$

$$\Sigma V\ = V1\ +\ V2\ = \left(\frac{Q_0 - Q_1}{\alpha_1} + \frac{Q_1 - Q_2}{\alpha_2}\right)$$

$$\Sigma V = \left(\frac{0.575\,\frac{\text{m}^3}{\text{s}} - 0.192\,\frac{\text{m}^3}{\text{s}}}{\frac{0.0189}{\text{d}}} + \frac{0.192\,\frac{\text{m}^3}{\text{s}} - 0.158\,\frac{\text{m}^3}{s}}{\frac{0.0055}{\text{d}}}\right) 86{,}400\ \frac{s}{\text{d}} = 2.28\ x\ 10^6\text{m}^3$$

Based on the obtained coefficient, α, it is possible to calculate how many days it would take for the discharge of the two springs to fall from 158 L/s—that is, the discharge that was recorded at the end of the recession period—to 100 L/s if (in theory) no rain should fall in the meantime.

$$t = \frac{\log 0.158 - \log 0.100}{0.4343\ \ (0.0055\text{ days}^{-1})} = 83.17\text{ days}$$

The result of 83 days indicates that the discharge of 100 L/s (which is critical for sufficient potable water supply) will not occur because, given the local climate and its well distributed rain pattern, such a long period without recharge will not occur.

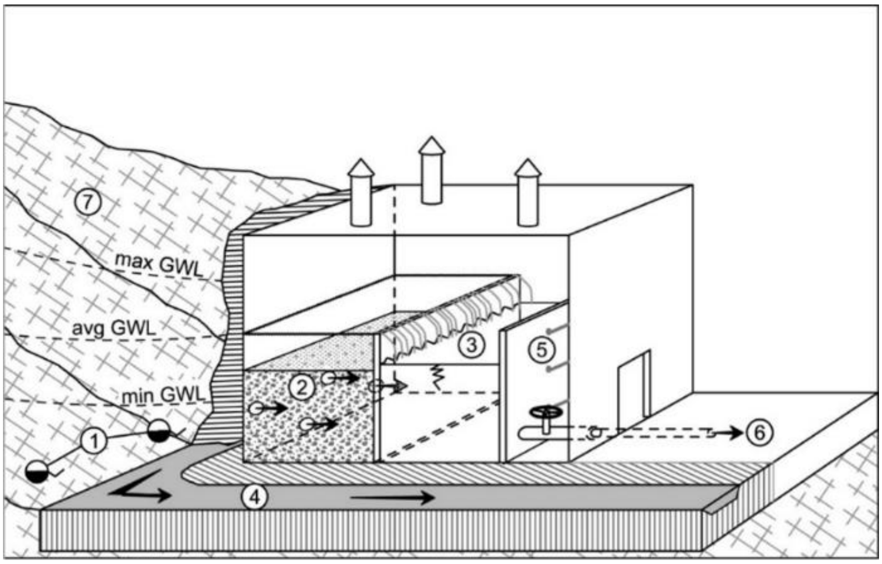
Exercise 3⮧ provides an opportunity to practice calculating the recession coefficient and water availability in a karst aquifer.

Return to where text linked to Box 17⮥

Box 18 - Spring Capture Structures Adapted to Local Hydrogeology

The evaluation of a spring's potential and possible intake structure should start with the classification of the spring and analysis of the spring flow regime, chemistry, and microbiology. These are the most crucial points in the decision of whether to tap a spring, and how to do it. Two examples of capture structures used for different spring types are shown in Figure Box 18-1.

a)



b)

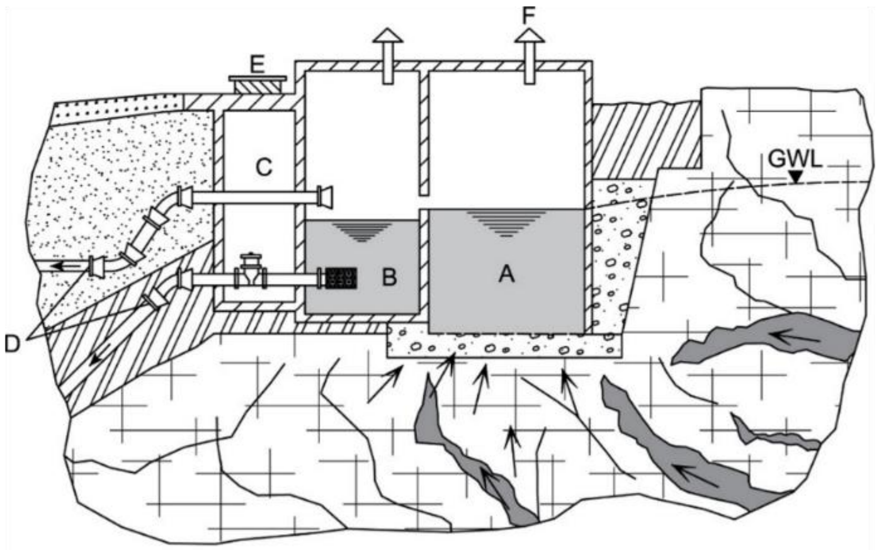


Figure Box 18-1 - Capture structures for a) a descending karst spring and b) an ascending spring (modified from Stevanović, 2015). Legend: 1. Small seepage springs, 2. Reservoir of clean water, 3. Overflow, 4. Evacuation canal, 5. Valve, 6. Delivery pipe, 7. Karst aquifer, A. Sediment box, B. Reservoir of clean water, C. Maintenance room with valves, D. Overflow and delivery pipes, E. Entrance, F. Vent.

Return to where text linked to Box 18↑

Box 19 - Pumping Test in Variable Flow Conditions

Although it looks simple, pumping is an expensive test that requires proper organisation due to consumed energy and labour. Pumping should be adapted to *steady flow* or *non-steady flow* conditions. Steady flow assumes constant hydraulic conditions: drawdown is stabilized for the chosen and fixed pump capacity. Under a non-steady flow regime, the potentiometric surface is depleted during the test for the same, constant pumping rate (Figure Box 19-1).

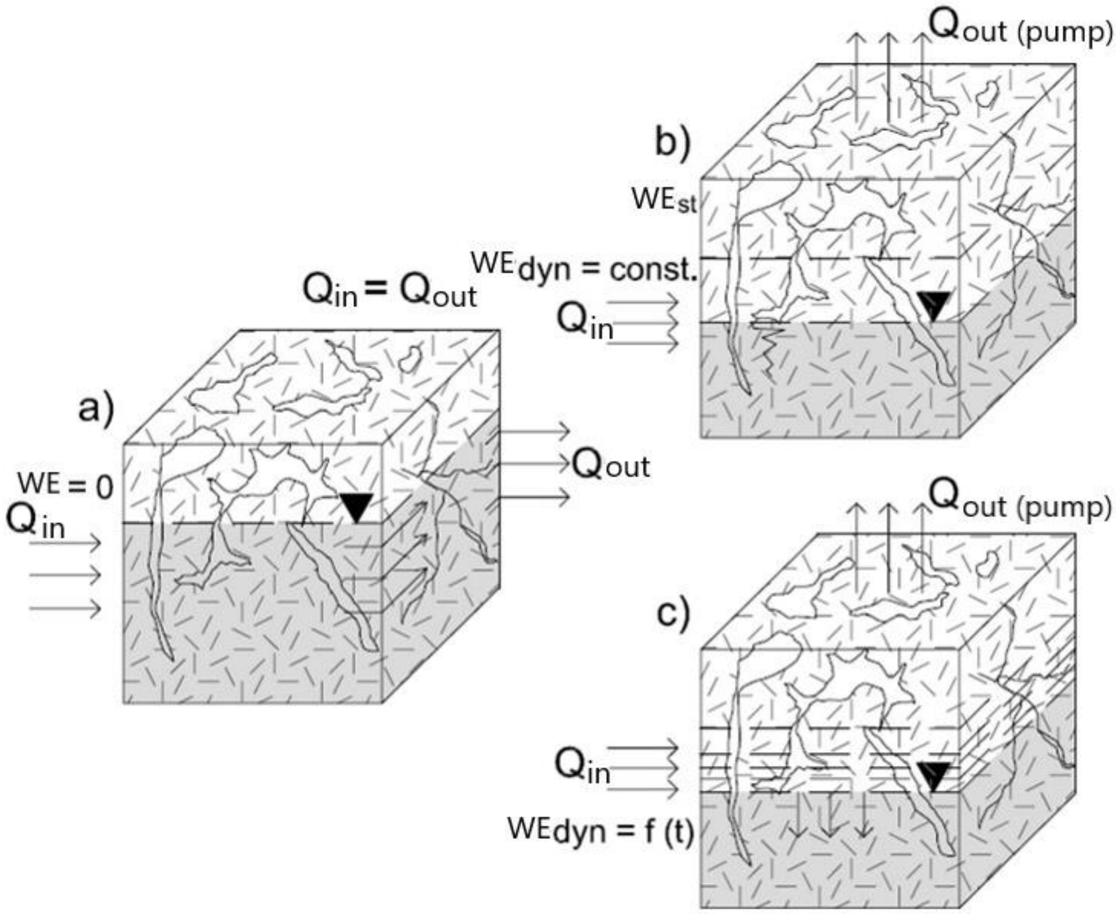


Figure Box 19-1 - Groundwater flow regimes. a) steady state flow with no extraction (pumping), inflow (Q_{in}) is equal to the outflow (Q_{out}), stagnant groundwater elevation (drawdown, $WE = 0$); b) steady state flow, where there is pumping of groundwater, but inflow (Q_{in}) is equal to the extraction rate ($Q_{out\ (pump)}$), drawdown (WE_{dyn}) is stabilized and becomes stagnant; c) non-steady state flow, where there is pumping of groundwater, and extraction rate ($Q_{out\ (pump)}$) is larger than the inflow (Q_{in}) causes drawdown to increase (WE_{dyn}) as a function of time (t) (modified from Stevanović & Milanović, 2017).

The two common single-well tests for sizing pumps and determination of well yield is the specific capacity test and the step-drawdown test. Well development is the procedure taken after the well is drilled to remove any drilling muds remaining in the well bore or in the screen and gravel pack if the well is not open hole. A specific capacity test is conducted by measuring the static water level and then pumping the well at a constant rate (Q_{out}) until the drawdown (WE_{dyn}) is stabilized (usually 0.5 to 4 hours), calculating the final drawdown at the well (static water level minus the final dynamic water level), and recording the pumping rate divided by this drawdown ($Q_{out}/\Delta WE_{dyn}$). A step-drawdown test is a single-well test that is frequently conducted to determine the efficiency of the well and sizing of the production pump. The first step of the test is accomplished by pumping at a relatively low, constant discharge until the water level in the well stabilizes (steady state flow). For the second and additional steps, discharge is increased to a new constant rate that is held constant again until the water level stabilizes. This must be done at least three times with the pumping rate held constant until the change in drawdown is small (0.5 to 4 hours per step depending on how long it takes for drawdown to stabilize). The step-drawdown test is like running multiple specific capacity tests. Woessner and others (2023) provide more details on conducting and analysing these tests.

Return to where text linked to Box 19↥

Box 20 - Water Shortage in Karst

In mountains high above erosional bases, the only way to provide water to local villagers and their livestock is to build cisterns or similar structures for collecting rainwater or melted snow (Figure Box 20-1).

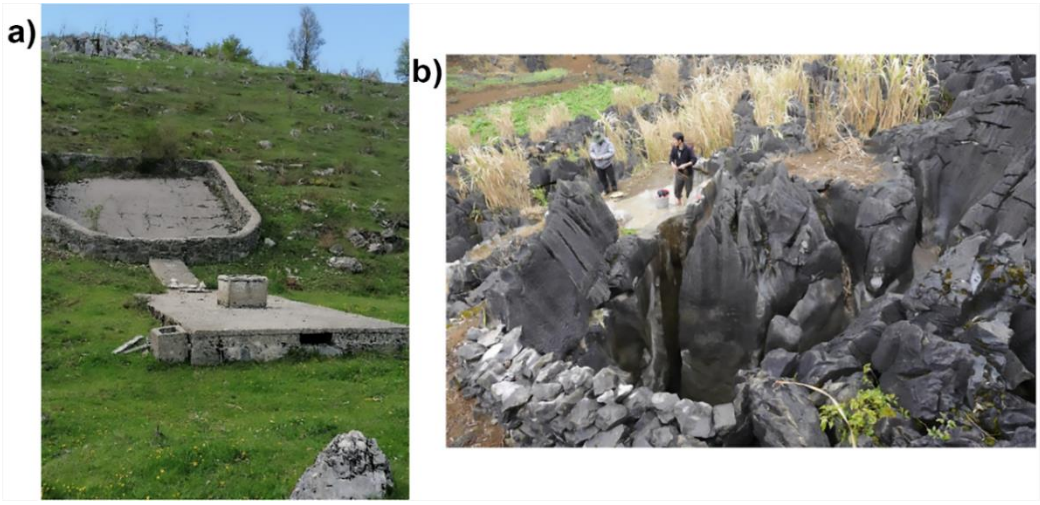


Figure Box 20-1 - Water supply in high karstic mountain regions: a) rainwater collector in high mountains of the Piva River basin, Montenegro (photograph by Z. Stevanović); and b) water storage in an epikarst structure, Vietnam (photograph by N. Goldscheider).

Another problem often faced by local populations is a large discharge variation, a characteristic typical of many karst springs, particularly gravity springs. There are springs that can discharge several tens of m^3/s during wet periods but be completely dry in low water seasons (Figure Box 20-2). Another problem can be drainage in littoral karst (Figure 8), where springs are often exposed to saltwater contamination.

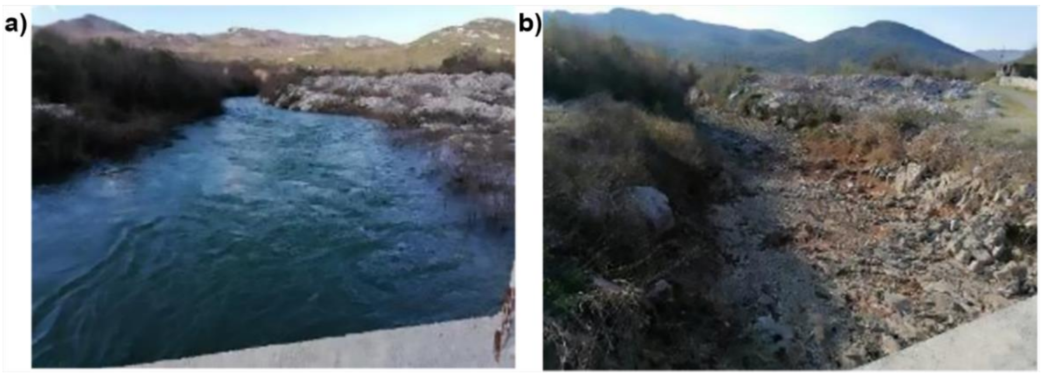


Figure Box 20-2 - Riverbed of the spring Kaludjerovo oko: Sinjac (Skadar Lake basin, Montenegro): a) its discharge in January 2021 was 13 m^3/s; while b) the same section was completely dry in June 2021 (photographs by Z. Stevanović).

Water shortage situations, especially in arid and semi-arid karst, can result in migration of local villagers, livestock reduction, and limited amounts of crops (Stevanović, 2015, 2018).

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Box 21 - Vienna Waterworks: Engineering Masterpiece of the Nineteenth Century (CE)

Vienna obtains water through a 130 km-long mountain aqueduct, the first stage of which was completed in 1873. Long concrete tunnels and channels tap water from the Kaiserbrunn spring in the foothills of Mounts Rax and Schneeberg (Figure Box 21-1). The system was extended in 1900 (Second Water Main) and included other captured springs such as Kläffer (Plan et al., 2010).

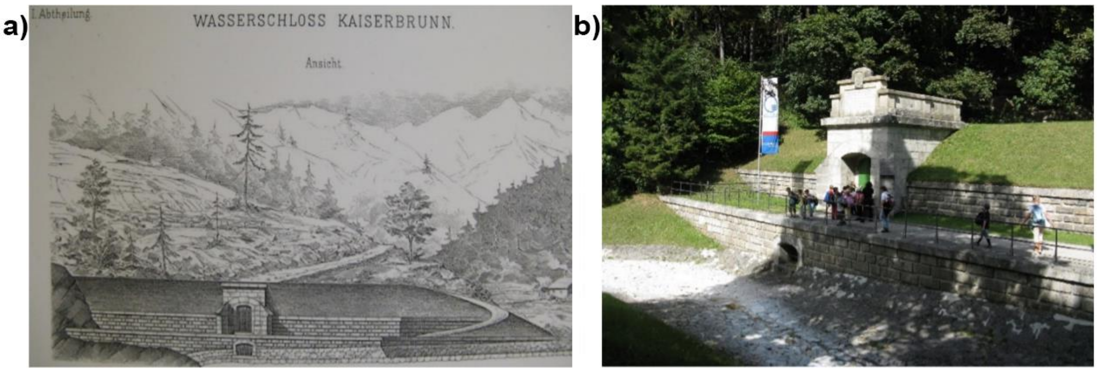

Figure Box 21-1 - Vienna's engineering masterpiece. a) Original drawing of the Kaiserbrunn intake (courtesy of the Kaiserbrunn Museum, Vienna). b) Entrance to the spring intake today. Below the entrance gate is an evacuation channel for peak flows (photograph by Z. Stevanović).

The groundwater is of excellent quality and no treatment is necessary other than chlorination. Every day, the city is supplied with 400,000 m^3 of spring water that flows through hydroelectric power plants on its way to Vienna and generates 65 million kilowatt hours of electricity (Figure Box 21-2).

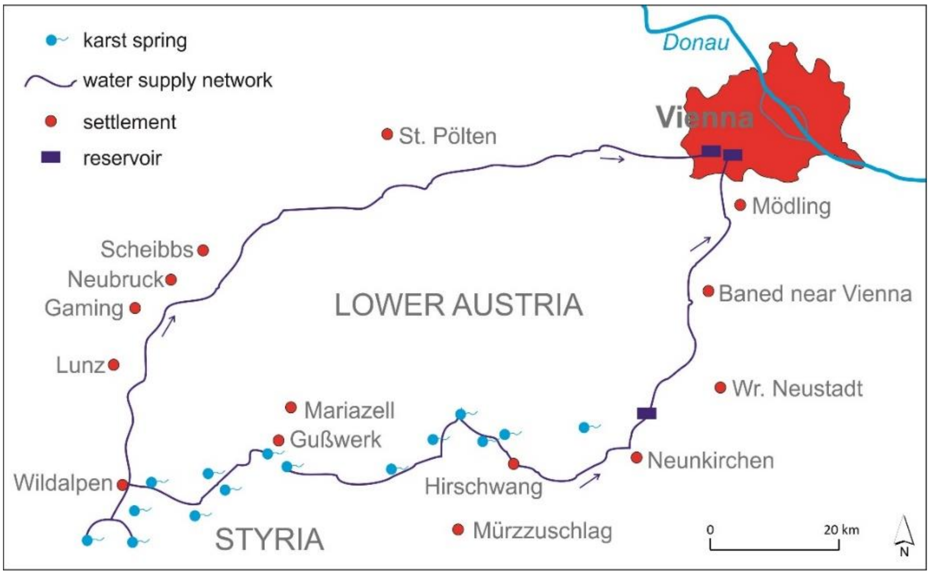

Figure Box 21-2 - Vienna is supplied with drinking water from karst springs via two long-distance pipelines with a combined length of more than 200 km.

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Box 22 - Measuring or Estimating the Main Water Budget Elements

Precipitation (*P*) consists of rain and, in some climates, snow. Rainfall is one of the most widely measured climatic parameters and there is an extensive literature on the different measurement methods and their relative accuracy (e.g., Shaw et al., 2011). The two most commonly used devices are storage gauges (Figure Box 22-1a) and logging gauges, both of which provide spot measurements, but increasingly catchment rainfall is being estimated remotely using weather radar. Storage gauges simply provide the total catch over the period between emptying which may be daily, weekly, or even monthly. The total catch may be sufficient for water budgeting, but for hydrograph analysis more detail is needed and data logging rain gauges are used. These have the advantage that they can be connected to a telemetry network and downloaded remotely. In larger catchments where there are several rain gauges, the average catchment rainfall can be estimated using isohyets maps, Thiessen polygons, regression between rainfall and ground elevation, or other statistical methods such as kriging. These analyses are often accomplished using a Geographic Information System (GIS).

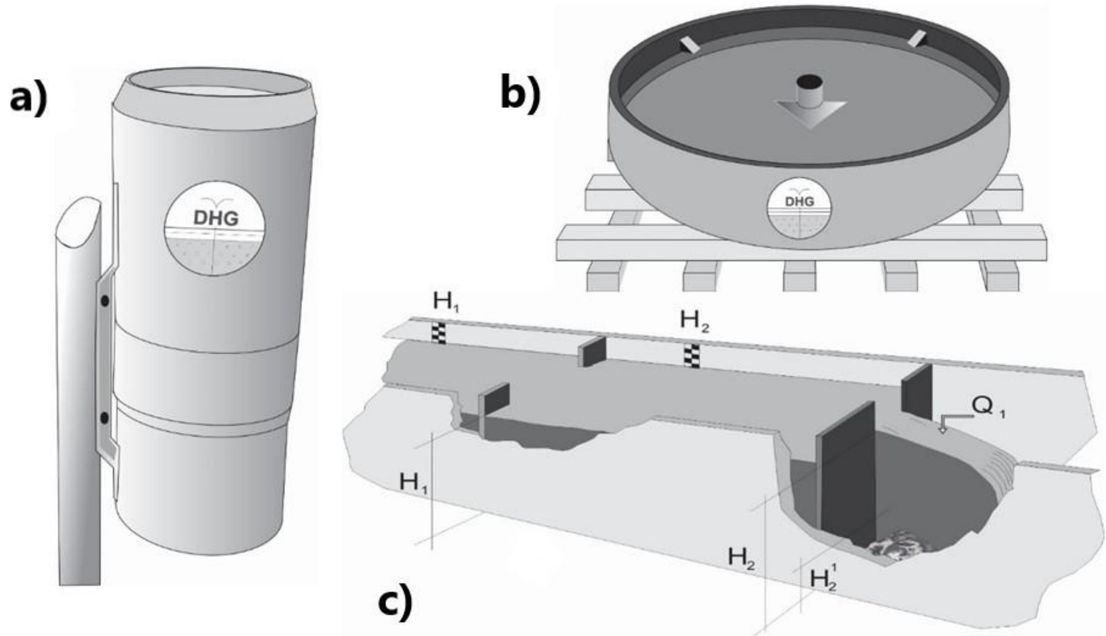

Figure Box 22-1 - Common devices for measuring water budget elements: a) storage rain gauge, b) evaporation pan, and c) two, successive, rectangular-notch, weirs with control gauges for measuring water heights (*H*).

Water is lost to the atmosphere by evaporation (*E*) from open water surfaces, bare wet soil, and water stored (intercepted) on vegetation; as well as by transpiration (*T*) by plants. The two components are commonly lumped together as evapotranspiration (*ET*). Evaporation can be recorded using different types of pans (Figure Box 22-1b) although a pan coefficient is needed to convert evaporation from the pan (a relatively small, shallow water body) to evaporation from larger, deeper water bodies. The transpiration component is much more difficult to measure but ET can be measured using a weighing lysimeter or a correlation eddy tower.

A weighing lysimeter is an isolated block of vegetated soil set flush with the land surface that can be weighed to determine changes in soil moisture storage (ΔS), which is negative for loss of weight and positive for gain. Using the change in storage along with data on the amount of rainfall on the lysimeter surface (P) and percolation output (O) collected beneath the lysimeter, the evapotranspiration can be calculated by re-arranging the water balance equation as shown in the following equation.

$$ET = P - O + \Delta S$$

Large lysimeters are difficult to construct and maintain especially in karst, but small lysimeters using large cans that are weighed by hand can provide good results in by soil covered karst and epikarst zone. Nevertheless, empirical formulae based on meteorological data and assuming the soil has an infinite supply of stored water are the most common means of estimating evapotranspiration rate. Most empirical formulas (e.g., Thornthwaite, 1948; Turc, 1954) predict *potential evapotranspiration* as a theoretical maximum value that could occur in the study area. This is commonly higher than *actual evapotranspiration* because when the soil moisture content decreases plants reduce their transpiration. Since the late 1990s, use of the modified Penman-Monteith method for calculating ET has been recommended by the FAO (Allen et al., 1998). A photograph of a meteorological data collection station is provided in Figure Box 22-2.

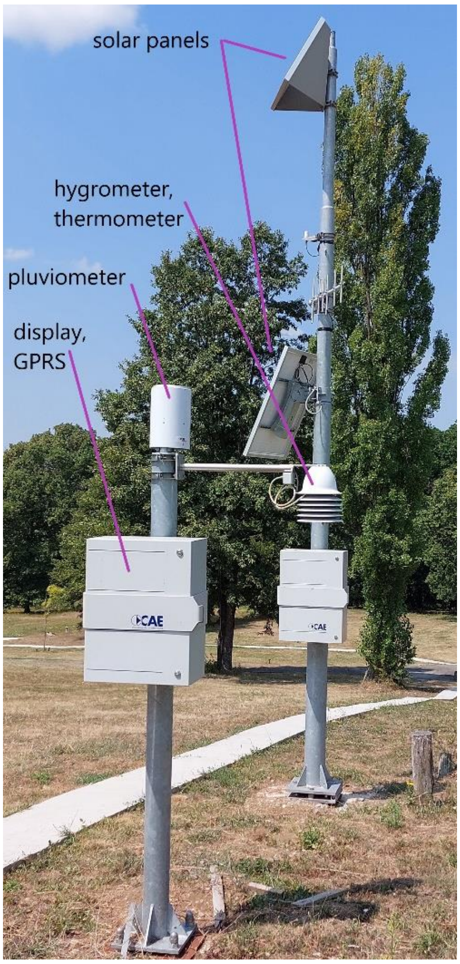

Figure Box 22-2 - Automatized and remotely controlled mini meteorological station (rainfall, humidity, air temperature). Snow is melted using energy provided by solar panels to convert it into a water column (photograph by Z. Stevanović).

Surficial inflow (I_s) is the entry of surface water (e.g., streams, rivers, lakes, reservoirs) into the ground. The water may be of allogenic or autogenic origin and can be a very important part of the water balance in many karst systems. Surface water entering via swallow holes (ponors) can be quantified by measuring the discharge upstream of the ponor. Seepage of sinking streams through the bed can be calculated as loss of streamflow based on discharge measurements conducted on successive sections of the stream. In coastal areas, sea water intrusion—which causes salinization of karst fresh water—is another type inflow to karst.

Measurement of the discharge of surface streams and rivers (R_f) and of springs (Q_s) is essential for water budget calculations and hydrograph analysis. In karst systems, discharge may be measured at karst springs, sinking streams, or underground in cave streams. Discharge measurement can be done at discrete times or continuously. Discrete methods include current metres or Doppler radar for streambed and velocity scanning, and the salt-dilution method of flow measurement. Continuous methods involve measurements at control structures (flumes and weirs; Figure Box 22-3) or natural stream sections using water-depth loggers such as pressure probes and capacitance loggers. Many loggers now offer the possibility of remote data transmission. Flumes and weirs usually have a theoretical rating curve that allows the discharge to be calculated directly from the water depth. For natural stream sections it is necessary to undertake discrete methods of flow measurement during different flow conditions to obtain stage-discharge curves, which can then be used to translate continuous water-level measurements into continuous discharge time series—that is, into karst spring or stream hydrographs.

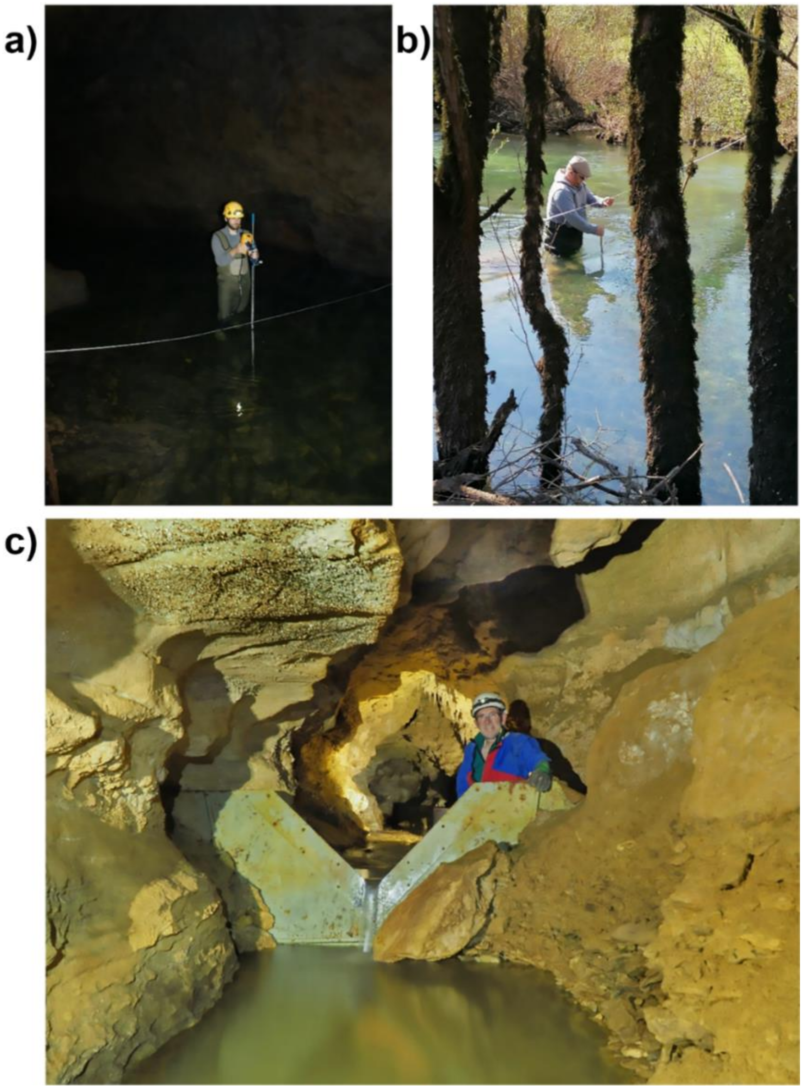

Figure Box 22-3 - Measurement of stream discharge. Use of current meters to measure stream velocity so that discharge can be calculated using the velocity-area method, a) in a cave (photograph by N. Ravbar) and b) in a surface river (photograph by Z. Stevanović). c): A sharp-crested 90-degree v-notch weir used to measure discharge in Mangapohue Cave, Waitomo, New Zealand (photograph by J. Gunn).

Subsurface inflow (I_g) and subsurface drainage (Q_{sb}) are difficult to assess, as discussed in Section 3.3.

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Box 23 - General Water Budget and Global Rate of Utilization of Karst Aquifers

This topic is discussed in detail by Stevanović (2019). The general water budget equation is applied here, with values that are roughly averaged at the global level as shown in the following equation that expresses the annual yield of karst water.

$$Q = P \ A \ Ie$$

where:

Q	=	annual yield of karst water in m^3
P	=	average global annual precipitation: 820 mm (L'vovich, 1974; FAO AQUASTAT 2016)
A	=	total global karst aquifer surface area: $19.3x10^6$ km^2 (Goldscheider et al., 2020)
Ie	=	roughly averaged global effective recharge in karst from precipitation (I_e): 20 percent of precipitation (Hartmann et al., 2014a; Stevanović, 2015)

With these inputs, the general budget equation shows the average-annual, global, renewable dynamic flux of karst groundwater (dynamic flux, Q) of 3,165 km^3, which is equal to 26.4 percent of the total groundwater flux calculated by L'vovich (1974) and FAO AQUASTAT (2016). Considering that karst extends over 15.2 percent of ice-free land, the contribution of karst aquifer flux to global water flux is greater than that of other aquifer systems.

Stevanović (2019) also estimated the percentage of currently utilized dynamic flux of karst aquifers. Based on the statistics of FAO, UNICEF, and other UN organizations, the average specific consumption of the global population using karst aquifers ranges widely: from > 50 to < 500 L/day/capita. Since the majority of the population in karst areas still does not have adequate sanitation conditions, specific consumption can be roughly averaged at ≈ 100 L/day/capita. By assuming 100 L/day/capita, the currently utilized dynamic flux by an estimated 700 million consumers would be around 1 percent of the total dynamic flux, which is a much lower rate than in the case of other aquifer systems estimated by Margat and van der Gun (2013). However, averaging a small rate of utilization at the global scale is different from the situation in the field, where many aquifers are overexploited. Due to the unequal distribution of karst water, as well as other water resources, many parts of the world are suffering shortages of clean fresh water.

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Box 24 - Why Appropriate Hydrogeologic Knowledge Should be Considered in Karst Aquifers

Following a heavy rain event that swept across Ontario, Canada, in May 2000, a sudden bacteria-related outbreak hit the town of Walkerton. This resulted in the death of seven people and illnesses in around 2,300 others, many of whom suffered lifelong side effects. The main cause of the epidemic was contamination of municipal water with *E. Coli*. After the storm, bacteria from cattle manure applied to a nearby farm was washed toward the drinking water system. Due to the karst nature of the area, the contamination reached the water source quickly and without significant attenuation. Since the cause of the infection could not be determined for some time, the aftermath was protracted; in addition to human casualties, the businesses that relied on water were severely affected.

Subsequent hydrogeological investigations showed that groundwater flow rates and the vulnerability of the karst were initially highly underestimated. Above all, the Walkerton case emphasizes the importance of considering appropriate hydrogeologic knowledge when utilising karst aquifers.

The Walkerton water source pollution ranks among world's largest public health disasters (Figure Box 24-1). The case became known throughout the epidemiological and karstological scientific communities as an example of malfunction when a preventive approach to karst water source protection and early warning is not taken (Burke, 2001; Salvadori et al., 2009; Worthington et al., 2012).

Figure Box 24-1 - The memorial plaque set by the Municipality of Brockton next to Walkerton's well number 5 that supplied potable water to the local waterworks between 1978 and May 2000, when accidental pollution of the karst aquifer occurred and the well was abandoned (photograph by J. Gunn).

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Box 25 - Long-term Forecasting of a Karst Spring's Discharge

The scenario of climate change A1B has been applied in the project Climate Changes and Water Supply (CCWS). Forecasted air temperature and precipitation based on ENSEMBLES regional climate models (RCMs) provide data for the period until the end of the twenty-first century. The RCMs have a resolution of 25 × 25 km and cover most of the European territory. Bias correction and output localization based on local daily observations has been applied. In the case of one of the test areas, namely Beljanica Mountain in the karst of eastern Serbia, bias correction has been applied to the last 50 years of records (Stevanović et al., 2012). After the necessary adjustment of air temperature and precipitation, forecasted data have been inserted into multiple linear correlation functions for the largest local karst spring Mlava, created based on long-term historical discharge data. Figure Box 25-1 and Figure Box 25-2 show annual average discharges of the Mlava spring (both historical and calculated data), and seasonal, average six-month "summer" (April to September) and "winter" (October to March) discharges.

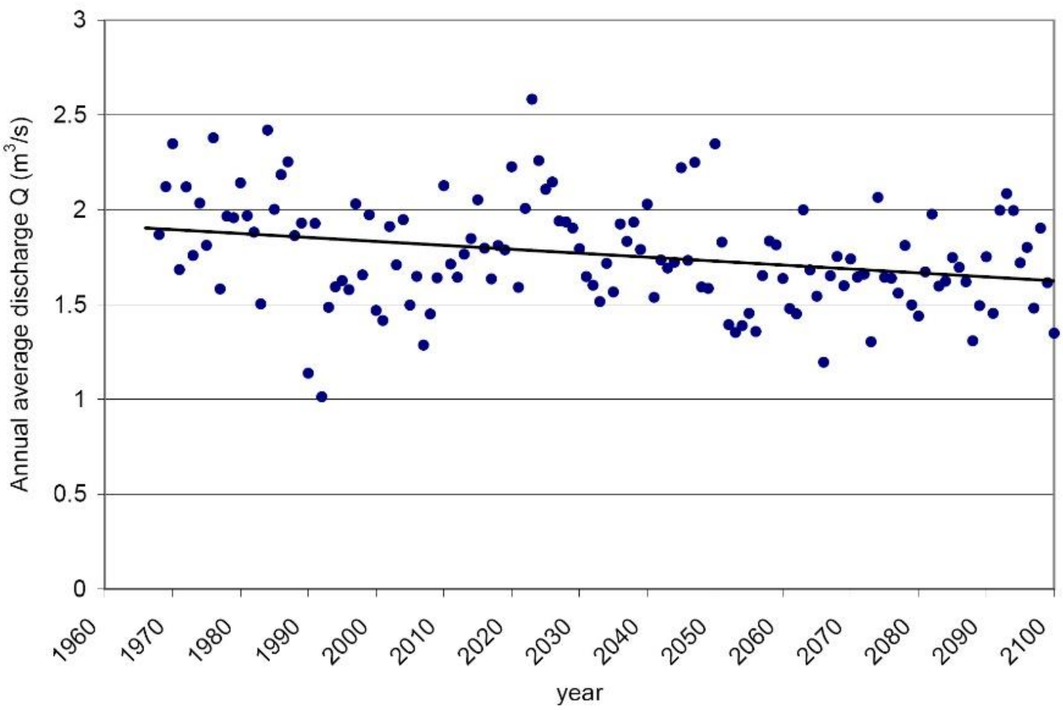
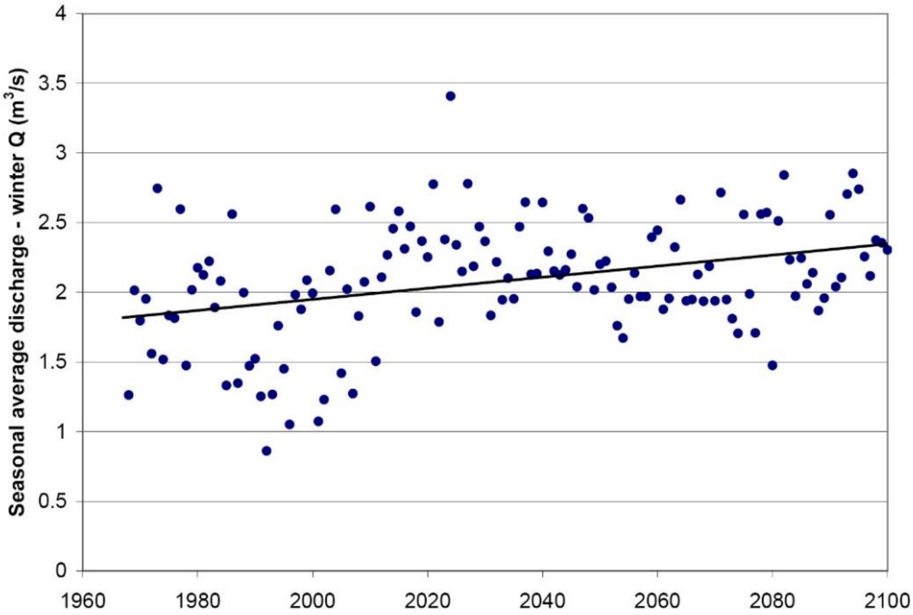


Figure Box 25-1 - Historical and modelled annual average discharge of karst spring Mlava, eastern Serbia, until the year 2100 (Stevanović et al., 2012).



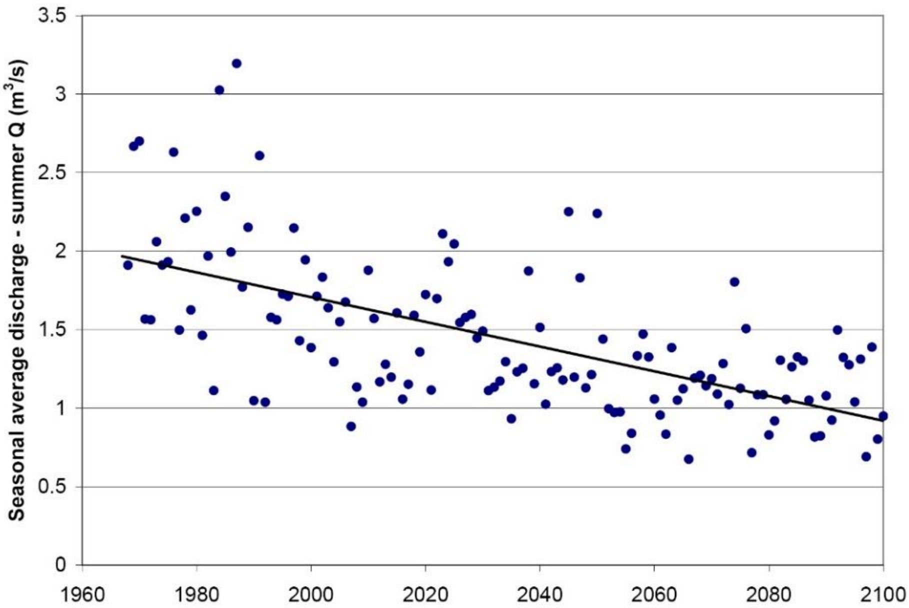


Figure Box 25-2 - Historical and modelled average discharge of the Mlava spring, eastern Serbia, during two six-month seasons: "winter" (top: October to March) and "summer" (bottom: April to September) (Stevanović et al., 2012).

The model predicts that the multiannual average discharge of the spring will decrease by the end of twenty-first century. For instance, the multiannual discharge of about 1.9 m^3/s, recorded in the period 1960 to 2008, is predicted to drop to around 1.7 m^3/s in the period 2071 to 2100 (−10 percent). Although the average discharge during the winter season is expected to rise when compared to these same periods (+24 percent), the average discharge in the already problematic summer seasons may drop by about 40 percent.

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Box 26 - Importance of Continuous Monitoring in Karst

Although the WFD (EU, 2000) recognizes the exclusivity of dynamic karst aquifer regimes and suggests more frequent measurements and groundwater quality control than in the case of other kinds of aquifers (water bodies), there is a need for systematic and preferably continuous observations. The example below illustrates different outputs that resulted from different observation frequencies.

A water depth logger programmed to take a reading every 30 minutes was installed at the Glava Šavnika spring (Durmitor Mountain, Montenegro) and the discharge was estimated using a rating curve. Figure Box 26-1 shows the aquifer's behavior over a period of six months based on the data logger (30-minute data) and spot measurements taken at intervals of five and 15 days. The spot measurements miss the fine detail recorded by the logger.

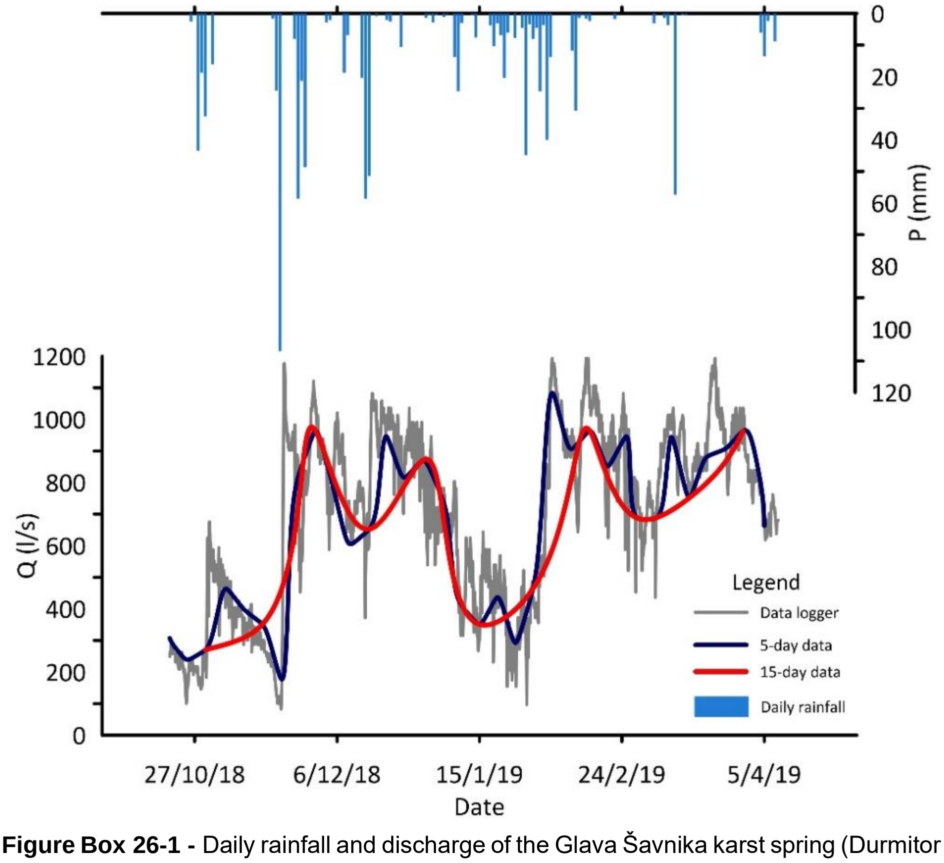

Figure Box 26-1 - Daily rainfall and discharge of the Glava Šavnika karst spring (Durmitor Mountain, Montenegro), recorded at 30-minute and at five-day and 15-day intervals (Stevanović & Maran Stevanović, 2021).

The differences are considerable and may have negative effects on potential water supply projects. Extreme minimal discharge from 30-minute data is 90 L/s but from five-day frequency data it is 180 L/s, while for 15-day data, it is three times higher at 270 L/s.

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Box 27 - One of the Largest Successful Projects in Highly Karstified Terrains

The Grančarevo Dam (Figure Box 27-1) and Bileća Reservoir, as part of the Trebišnjica Multipurpose Hydrosystem, are excellent examples of successful large structure construction in the highly karstified Dinaric Karst (Milanović, 2014). The project of Trebišnjica Hydrosystem in eastern Herzegovina was initiated in the early 1950s to control the flow of the Trebišnjica sinking river (the largest in Europe) and prevent flooding of arable land in karst poljes. Stepwise disposition of karst poljes allows optimal multipurpose use of great water potential from elevations of 1,000 m to the Adriatic Sea level. The Trebišnjica Hydrosystem consists of seven dams, six reservoirs, six tunnels, and four canals (with a total length of 74 km). The Bileća Reservoir, with a volume of 1.3×10^9 m^3, is completely situated in karstified carbonates without leakage. It is one of the largest and most successful reservoirs built in karst.

The system completely satisfies the demands of hydropower generation, irrigation food production, fish farming, water supply, and recreation, while simultaneously also providing secondary benefits including decreasing the strong emigration trend from the region. Important lessons that were learned during its investigation, design, construction, and operation have greatly contributed to the development and promotion of scientific and engineering karstology (Milanović, 2014).

a) b)

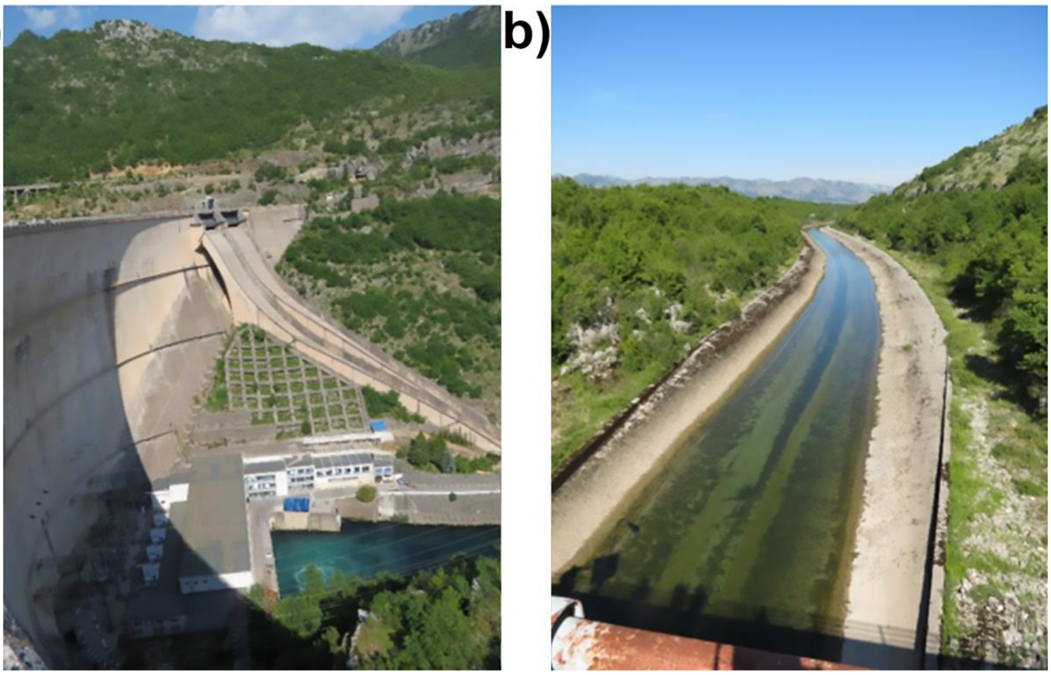

Figure Box 27-1 - A successful large dam project in karst. a) Massive concrete arch dam Grančarevo and b) downstream channelled Trebišnjica River in the karstic Popovo polje, eastern Herzegovina (photographs by Z. Stevanović).

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Box 28 - Lez: An Engineering Compromise between Water Demands and Ecology

One of the most successful projects in engineering regulation of karst aquifers was completed for the water supply of the city of Montpellier in southern France (Avias, 1984). To assess whether it would be possible to increase the natural minimal discharge of the karst spring Lez (0.4 m^3/s), a multidisciplinary research project was undertaken in the early 1960s. The techniques employed included cave diving; geophysical, geoelectrical, and geomagnetic prospecting; and pumping tests of a deep siphon discovered in the karst interior. Based on these results, a shaft 80 m deep and 5 m wide containing a large pumping room was designed and constructed. The pumping capacity obtained was over five times larger than the natural minimum and reached 2.2 m^3/s. More importantly from an ecological point of view, a horizontal gallery connects the natural spring site and the shaft at a depth of 23 m and delivers water to the surface, thereby ensuring minimal flow of the Lez River (Figure Box 28-1). This excellent example of finding a compromise between water utilization and ecology motivates many engineers worldwide to search for similar solutions in karst environments.

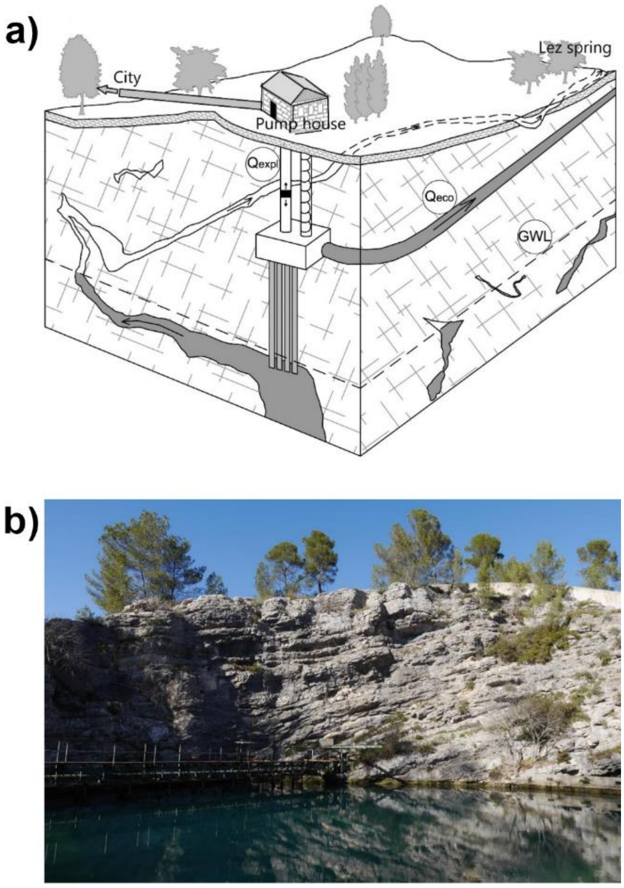

Figure Box 28-1 – Engineering regulation of Lez spring: a) source and intake scheme (from Montpellier waterworks leaflet, modified by Stevanović, 2015). Legend: GWL = groundwater level; Q_{expl} = groundwater flow extracted for water supply of the city; Q_{eco} = guaranteed groundwater ecological flow diverted to spring orifice. b) photograph of spring (by N. Goldscheider).

Exercise 5↴ concerns assessment of available exploitable groundwater resources of a karst aquifer while ensuring ecological flow for dependent ecosystems.

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Box 29 - A Discrepancy in Current Approaches to Protecting Karst Water Sources

In the small Alpine community of Rečica ob Savinji in northern Slovenia, two springs named Z1 and Z2 were tapped in the past for water supply. To protect them, a basic hydrogeological mapping of their catchment area was carried out. On this basis, the protection zones were designated (Figure Box 29-1a). In the 1990s, the springs were excluded from the public drinking water supply due to the poor quality of the spring water, most notably microbiological contamination. A later tracer test indicated the possibility of recharge of the springs from the Suha sinking stream, which was not included in the protected area.

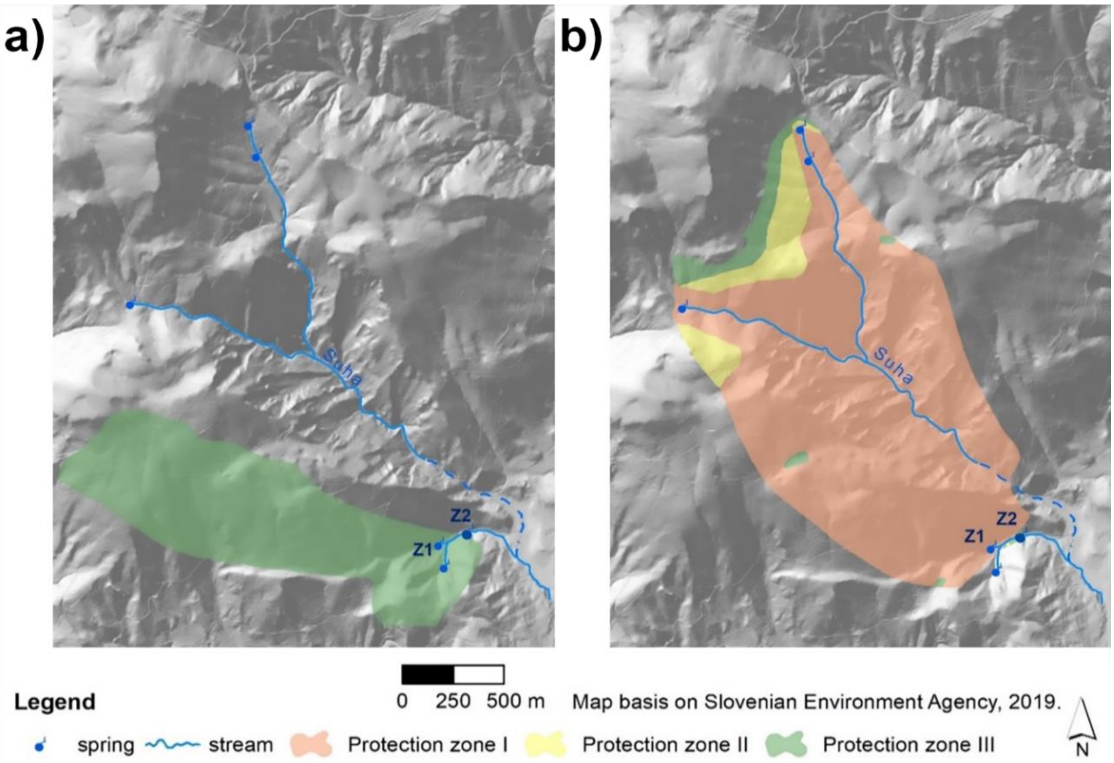

Figure Box 29-1 - Protection zones established based on a) basic hydrogeologic knowledge and distance criteria and b) a comprehensive study that included geological and hydrogeological mapping, natural and artificial tracers monitoring, water balance, and groundwater vulnerability assessment (from Ravbar et al., 2021).

Since the local community plans to reuse the Z2 spring for water supply, an investigation of the spring's characteristics and optimized protection strategies was carried out. The investigation comprised geological and hydrogeological mapping, monitoring of the spring, tracer tests, water balance, and groundwater vulnerability assessment (Ravbar et al., 2021).

Water protection zones were proposed that are more than twice the size of those that were currently in effect (Figure Box 29-1b). They include the sinking river drainage area, which was proved to be associated with springs. Compared to the currently applicable water protection zones, which appear to underestimate the high vulnerability of the area, this study proposes different and more stringent protection regimes justified by tracer tests and groundwater vulnerability assessment. It can be concluded that protection zoning based solely on fundamental hydrogeological knowledge, general predictions of groundwater residence times, or distance criteria may result in a high degree of inaccuracy. This suggests that, in general, current protection measures may be subject to large uncertainties and the high vulnerability of karst areas may be underestimated. Detailed reconnaissance and in-depth knowledge are critical for adequate protection.

In addition to existing legal requirements for designating protection zones for karst water sources, consideration should be given to natural and artificial tracers that most reliably confirm the directions and characteristics of groundwater flow in karst. Similarly, mapping the vulnerability of groundwater to contamination may be of particular importance for the implementation of freshwater protection and land use planning, at least in karst-rich countries.

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Box 30 - Classifying Subterranean Fauna

The entrances of caves represent a transition zone between the surface and underground environments, but beyond this zone lies an absence of light and a stable temperature regime. Creatures living under these conditions adapt to them by enhancing their senses of touch and smell; fully adapted fauna have enlarged antennae or elongated appendages, as well as specialized organs to detect vibration. Eyes are commonly reduced in size or even absent. These features are termed troglomorphy, and terrestrial animals of this kind are termed troglobionts, while their aquatic counterparts are termed stygobionts.

Subterranean fauna can be classified according to the position and duration of their dwelling in the underground environment as troglo- or stygo-bites (only live underground), troglo- or stygo-philes (adapted to the underground but can live outside), and troglo- or stygo-xenes (mainly surface dwellers but spend time underground, typically to sleep or hibernate). Blind cave fish and the cave salamander *Proteus anguinus* (Figure **97**) are examples of cave-adapted stygobionts.

Subterranean fauna, and particularly stygofauna, can be found in non-karst environments, but caves and karst groundwater systems offer a greater diversity of habitats and larger voids. Therefore, the subterranean fauna of karst generally has a higher biodiversity than in non-karst subterranean environments. Subterranean communities are often characterized by a high number of rare and endemic species because of their high degree of isolation.

Return to where text linked to Box 30↥

Box 31 - Cave and Karst Geoheritage Protection in the United Kingdom

The United Kingdom comprises four nations, each of which has its own nature conservation body: Natural England, Natural Resources Wales, Northern Ireland Environment Agency, and Scottish Natural Heritage. In Great Britain (i.e., England, Scotland, and Wales), a Geological Conservation Review (GCR) has been undertaken to identify those sites of national and international importance needed to show all the key scientific elements of the Earth's heritage. A similar exercise was undertaken in Northern Ireland where it was called an Earth Science Conservation Review. The GCR commenced in 1977 and to date over 3,000 GCR sites have been selected in around 100 categories (GCR Blocks) that encompass the range of geological and geomorphological features of Britain. Caves and Karst are in separate GCR Blocks, although inevitably there is overlap between them. The results of the GCR program are being published in a Geological Conservation Review Series; *Karst and Caves of Great Britain* (Waltham et al., 1997) was the twelfth volume in the Series. In that volume, 89 sites are described; subsequently, others have been added and as of 1 January 2022 there were 50 cave GCR sites and 52 karst GCR sites. The fact that a site has been recognized as a GCR site does not automatically mean it is protected, but most GCR sites have been notified or are being considered for notification as *Sites of Special Scientific Interest* (SSSIs) that are legally protected.

The boundaries of GCR and SSSI are drawn to reflect the location of features of scientific interest, but for practical purposes must map onto easily identifiable features, commonly field boundaries. This works well for karst sites where boundaries can be drawn to reflect the features of interest (e.g., limestone pavement or dolines) and allow for their conservation. Any damage or threats to the features will be readily apparent and action can be taken. However, the situation is more problematic for caves as they are complex three-dimensional entities that only connect with the surface at entrances and, for the most part, are "out of sight" other than to speleologists. In addition, a series of caves may be hydrologically connected to form a cave system without there being any connection between them that can be accessed by humans.

The boundaries of the cave GCR/SSSI were drawn to best reflect the underground conditions, and this means that in some cases they encompass a single cave and in others there may be many caves. For example, in the Castleton Caves GCR site in Derbyshire, England, there are 45 individual caves although not all of them are described in Waltham and others (1997). Some of the caves in GCR/SSSI are fed by allogenic water and, while the sink points are commonly inside the site boundary, that is rarely the case for the allogenic catchment, which can be problematic.

The majority of Cave GCR sites were identified, and SSSI designated, by the mid-1980s but there was no information on the number of caves and the length of cave passages protected until 1989 when a British Cave database was constructed listing the number and combined length of caves in each of the karst regions of Great Britain together with how many caves were in SSSI. At that time, 31.7 percent of the 2,710 caves were in SSSI, but this included all the major caves as 75.9 percent of the 632.36 km of cave passage was in SSSI. Caves differ from most other types of geoheritage in that the number and length of known cave increases every year as a result of the exploratory zeal of speleologists. Between 1989 and 2016, over 2,400 caves with over 344 km of passage were discovered, although it is not known how many caves and how much passage is within GCR/SSSI.

The fact that so much cave passage is within GCR sites, and the majority is in SSSI should offer a high degree of protection. However, unlike virtually all other GCR/SSSI in Britain, it is not possible for those working for the statutory agencies to access caves to assess their state of conservation. In England, the problem has been solved by cavers who undertake assessments while on recreational visits. To enable them to do this, cave scientists carried out inventories of scientifically interesting features in caves within SSSI, providing a brief description and marking the locations of these features on a cave survey. The surveys were converted into cave monitoring forms that can easily be used by recreational cavers to assess the conservation status of each feature.

Return to where text linked to Box 31↥

Box 32 - Lists of Internationally Designated Protected Areas with Information on each Area

- The World Network of Biosphere Reserves https://www.unesco.org/en/mab↗
- Ramsar Sites Information Service https://rsis.ramsar.org/↗
- World Heritage List https://whc.unesco.org/en/list/↗
- List of UNESCO Global Geoparks https://en.unesco.org/global-geoparks↗

Return to where text linked to Box 32↥

7 Exercises

Exercise 1 - Assessing the time required to fill a cave system with water

Aim: Determine the storage capacity of part of a heterogenous karst aquifer.

Background: Section 2.2 and Section 2.3 (links are provided at the end of Exercise 1).

Speleological practice: In carbonate rocks, highly karstified segments with well-developed systems of cavities are commonly surrounded by poorly permeable or essentially impervious materials. Only by undertaking speleological exploration of a cave system is it possible to assess and measure underground flow. Although there are many other methods applied in hydrogeology practice, such complex porosity and heterogeneity cannot be properly assessed from the surface by any of them.

Problem: Calculate the time required for a large cave chamber to fill with water.

Conditions: In Figure Exercise 1-1, the dimensions of the cave chamber (V) can be approximated as 15 m by 20 m by 15 m. The groundwater inflow is Q_{in} = 20 L/s, while gravity outflow toward the outlet is limited to Q_{out} = 1.5 L/s by the size of effectively porous channels. How long will it take for the chamber to be fully filled with water?

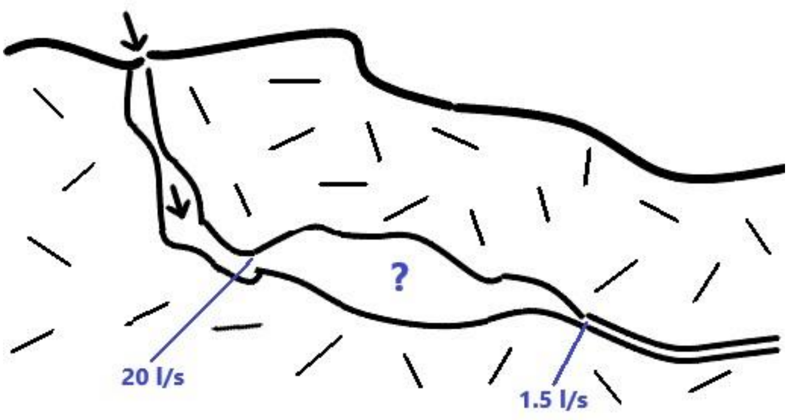


Figure Exercise 1-1 - Cave chamber scheme.

Solution to Exercise 1↴

Return to where text linked to Exercise 1↥

Exercise 2 - Assessing the average effective recharge for a karst system

Aim: Understand karst aquifer recharge.

Background: Section 3.2 and Section 4.2 (links are provided at the end of Exercise 2)

Hydrogeological practice: Effective recharge to an unconfined karst system can be assessed by using a simplified water budget equation and comparing the main input (recharge = rainfall minus evapotranspiration) and output (discharge of the springs) in the case of a system with no runoff component (i.e., no surface water flow).

Problem: Estimate the effective recharge (I_{ef}) in the catchment of a karst aquifer with dominantly autogenic recharge. Rainfall stations are well distributed over the entire catchment, while hydrometric stations have discharge data for all the main springs (Figure Exercise 2-1).

Conditions: The catchment area (A) of the karst aquifer is around 100 km^2, average annual discharge of all springs that drain the aquifer (Q_{av}) is 2 m^3/s, and annual precipitation (P) averages 1,000 mm. The water budget considers an average hydrological year (T) and assumes the system is in equilibrium (i.e., there is no change in storage) and the area feeding the spring is accurately known.

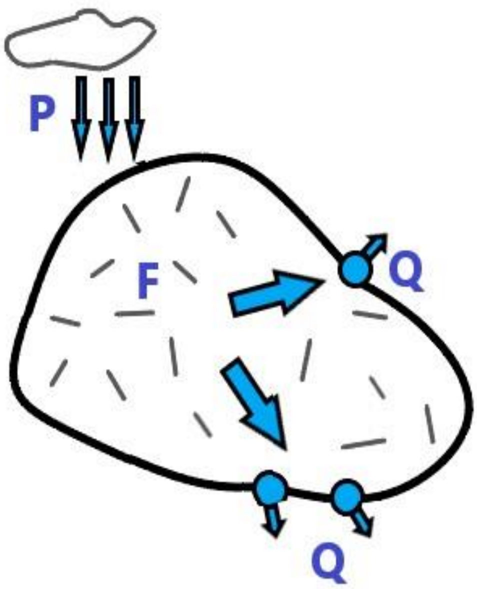


Figure Exercise 2-1 - Catchment area scheme.

Solution to Exercise 2↴

Return to where text linked first to Exercise 2 from Section 3.2↥

Return to where text linked second to Exercise 2 from Section 4.2↥

Exercise 3 - Calculate the recession coefficient and water availability in a karst aquifer

Aim: To understand the discharge mechanism and different regimes of a karst aquifer.

Background: Section 3.3 and Box 17 (links are provided at the end of Exercise 3)

Hydrogeological practice: Exploring the behavior of a karst aquifer during periods of drought and its drainage mechanism is of crucial importance for safeguarding the water supply for populations and entire ecosystems. This is especially the case in arid areas where prolonged droughts are common. Ascending springs with more stable discharge regimes are likely to have larger groundwater storage than gravity springs with large fluctuations of water table and spring discharge. At the start of the recession period which is when there is no longer significant recharge, and drainage of the aquifer begins (Figure 52), discharge is higher and usually characterized by a turbulent regime, with time drainage slows and the regime may become laminar. By calculating recession coefficients for the laminar phase recession periods (α_2 and α_3 in Figure 53), it is possible to estimate the time without recharge after which the spring may dry out.

Problem: Calculate recession coefficients for the laminar discharge regime as shown in Figure 53. Analyse the karst spring hydrograph shown in Figure Exercise 3-2 and estimate the time it will take for the spring to decline to a discharge of 0.001 m^3/s if there is no further rain in the catchment area.

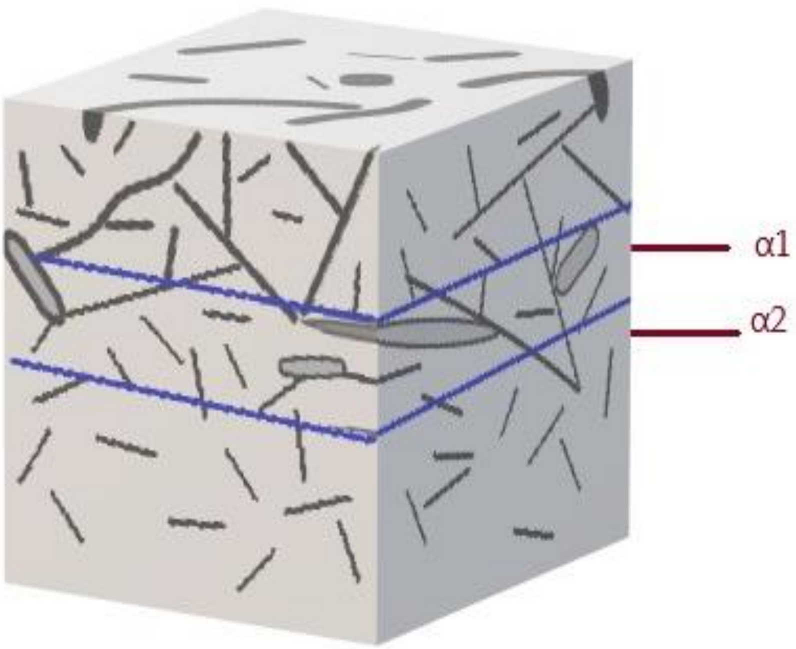


Figure Exercise 3-1 - Scheme of a karst aquifer block with different degrees of fissuration and cavities. Drainage zone α_1 is more karstified (permeable) so stored groundwater drains quickly, while drainage zone α_2 is dominantly fissures and pores so stored groundwater drains slowly.

Conditions: The discharge of the karst spring (Q_0) at the start of the recession period (t_0) was 1.36 m^3/s. After $t_1 = 12$ days the discharge had declined to $Q_{t1} = 0.72$ m^3/s. Then, during $t_2 = 44$ days the discharge declined to $Q_{t_2} = 0.38$ m^3/s. After 56 days of no rainfall the recession period ended. Calculate the theoretical period without rainfall (t_n) after which this spring would critically decline, that is, almost stop flowing (e.g., discharge reduced to $Q_{t_n} = 0.001$ m^3/s). This also provides an indication of the aquifer's storage capacity.

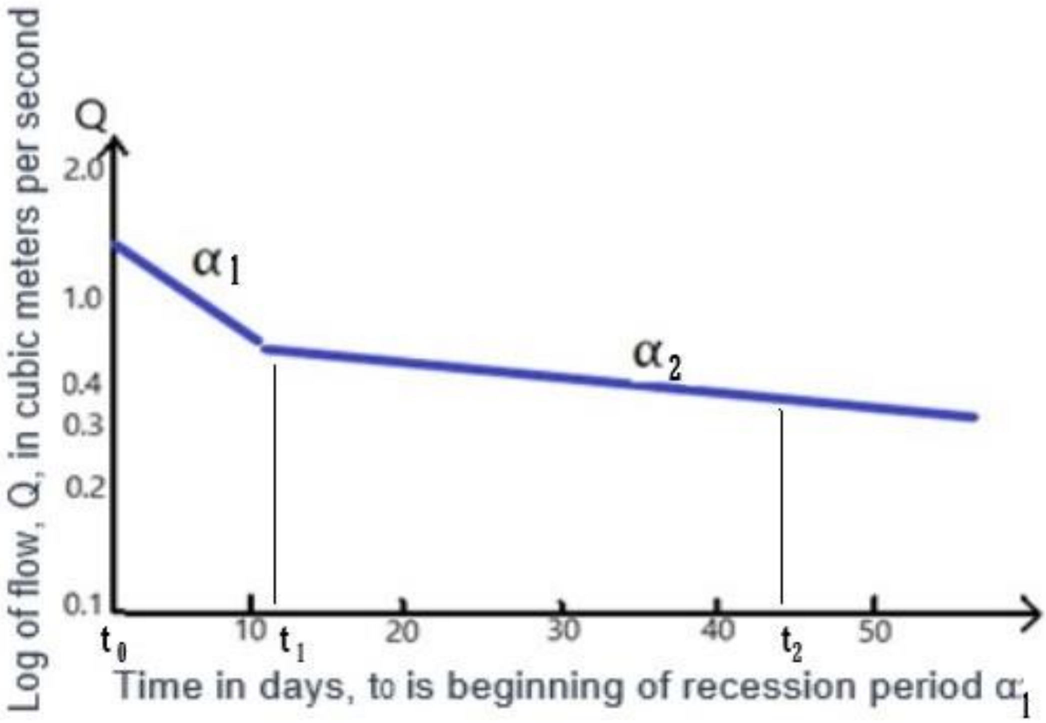


Figure Exercise 3-2 - Semi-log spring hydrograph during recession period of a hydrograph like the one shown in Figure 52 with two stages of laminar drainage.

Solution to Exercise 3↴

Return to where text linked first to Exercise 3 from Section 3.3↥

Return to where text linked second to Exercise 3 from Box 17↥

Exercise 4 - Water budget components estimation

Aim: Present a way to assess some of the water budget components.

Background: Section 4.2 (links are provided at the end of Exercise 4)

Hydrogeological practice: In the case of a binary karst system, monitoring stations should preferably cover all allogenic recharge points at the contact of non-karst and karst. Some water budget elements for which determination is complicated, such as evapotranspiration, can be estimated from the water budget equation when other elements are known.

Problem: Calculate the annual diffuse, autogenic recharge (*R*) and evapotranspiration (*ET*). Calculate the surface areas of the autogenic karst spring catchments in square kilometres.

Conditions: The schematic map (Figure Exercise 4-1) shows a karst aquifer system with a total surface area (*A*) surrounded by non-karst area. The karst system receives allogenic point recharge from a stream sinking into a swallow hole (S) and autogenic diffuse recharge from precipitation on the karst surface. The aquifer is drained by three karst springs: B, C, and D. Spring B is a temporary spring that is only active during high-flow conditions; C and D are permanent springs. A tracer test performed during high-flow conditions demonstrated connection from S to B and C, but not to D.

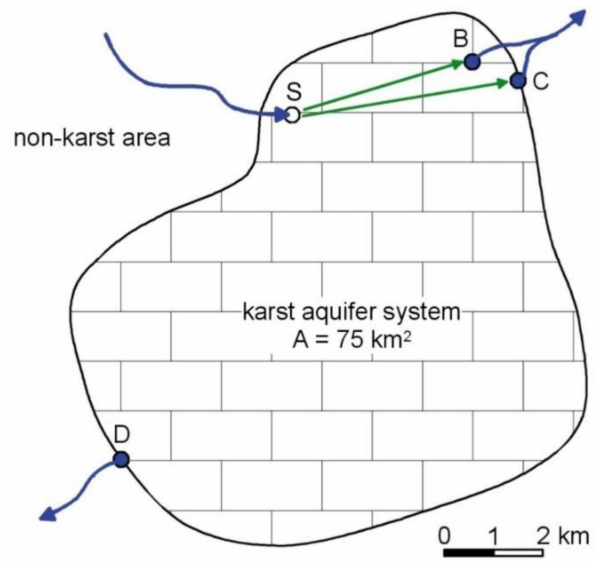


Figure Exercise 4-1 - Scheme of examined karst aquifer.

Mean annual discharges (*Q*) entering the swallow hole and discharging from springs are $Q_S = 260$ L/s; $Q_B = 125$ L/s; $Q_C = 340$ L/s; and $Q_D = 1{,}440$ L/s. Mean annual precipitation (P) = 1,000 mm/year and total surface area (A) is 75 km^2.

Solution to Exercise 4

Return to where text linked to Exercise 4

Exercise 5 - Assessing the available exploitable groundwater resources of a karst aquifer while ensuring ecological flow for dependent ecosystems

Aim: Present sustainable development of a karst aquifer using engineering intervention.

Background: Section 4.2, Section 4.4.2, and Box 28 (links are provided at the end of Exercise 5)

Water engineering practice: Determination of ecological flow (*EF, i.e.,* Q_{eco}) is especially challenging in karst where there is great variation in spring discharge. EF is particularly important during droughts, or in recession periods, which commonly coincide with summer months.

Problem: Calculate the exploitable reserves (Q_{expl}) of the karst aquifer system for water supply consumers (Q_{ws}) as a sum of the total dynamic (Q_{dyn}) and portion of static reserves (Q_{st}), reduced for ecological flow (*EF*, i.e., Q_{eco} in Figure Exercise 5-1). To support water provision, temporary pumping of stored static water reserves using a battery of wells is possible as a "loan" during critical summer months. Intake consists of tapped spring water (Q_s) and water abstracted from wells (Q_a).

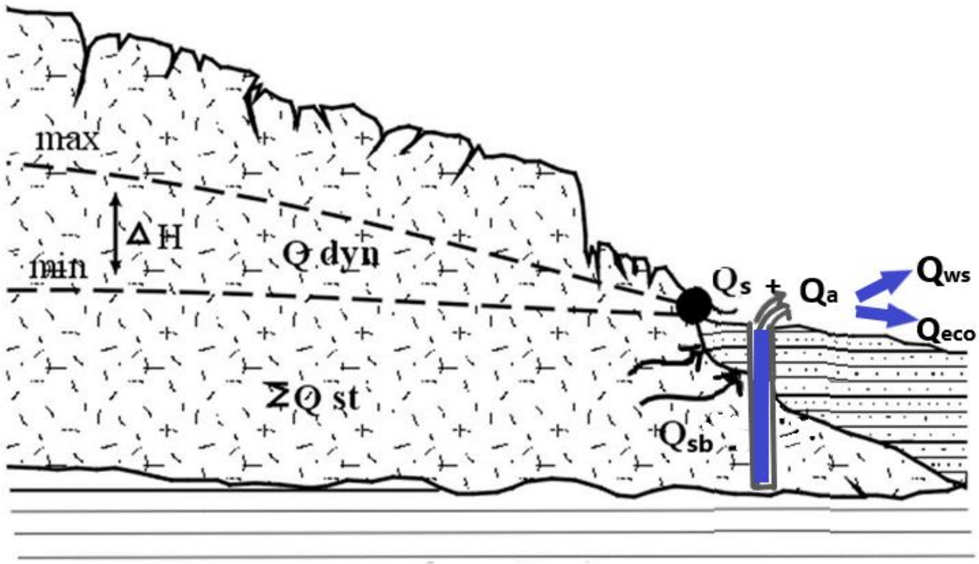


Figure Exercise 5-1 - Schematic cross section of karst aquifer for *EF* calculations.

Conditions: Table Exercise 5-1 contains mean monthly spring discharges equal to dynamic reserves. Based on a long period of observation, the mean monthly discharge of the karst springs for nine wet months with effective recharge is $Q_{av9} = 0.6\ m^3/s$, while during three critical months of drought (July, August, September) is $Q_{av3} = 0.19\ m^3/s$. The restrictive use (R_{est}) of total static groundwater reserves allows pumping a maximum of 10 percent of total Q_{st} during the three summer months over the period of 15 years. Mandatory provision of an ecological flow is 20 percent of Q_{expl}. The catchment area is A = 50 km^2, the depth from the minimal groundwater level to the base of karstification (H_{av}) is 120 m, while the karst aquifer storativity (S) is 2.5 percent.

Table Exercise 5-1 - Monthly average values ∑Qsprings = Qdyn

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Q(m^3/s)	0.45	0.65	0.8	0.65	0.45	0.4	0.25	0.18	0.14	0.45	0.75	0.8

Solution to Exercise 5

Return to where text linked first to Exercise 5 from Section 4.2

Return to where text linked second to Exercise 5 from Section 4.4.2

Return to where text linked third to Exercise 5 from Box 28

Exercise 6 - Assessing arrival of potential contamination to a spring

Aim: Estimate how long a contaminant would take to travel from the point of pollution to a spring. This residence time influences the aquifer's attenuation capacity and helps to delineate sanitary protection zones for springs.

Background: Section 4.3 (link provided at the end of Exercise 6)

Problem: Assume that near a swallow hole, contamination with harmful water-soluble substances enters the sinking river and drains directly into the subsurface. The swallow hole is in the catchment area of the drinking water source. The subsurface flowpaths between the swallow hole and the spring follow developed karst channels estimated to be 5,244 m long. Past tracing experiments have shown that the flow rate of water through the cave system is up to 95 m/h. Calculate when contamination of the spring can be expected.

Solution to Exercise 6↴

Return to where text linked to Exercise 6 from Section 4.3↥

Exercise 7 - Plan karst water quality monitoring

Aim: Establishing appropriate monitoring of karst water quality.

Background: Section 4.4 (link provided at the end of Exercise 7)

Problem: Figure Exercise 7-1 shows the response of a typical karst spring to a recharge event, the discharge dynamics, and the behaviour of natural parameters measured in situ. Mark the period in the diagram when water quality can best be measured to determine the most adverse conditions.

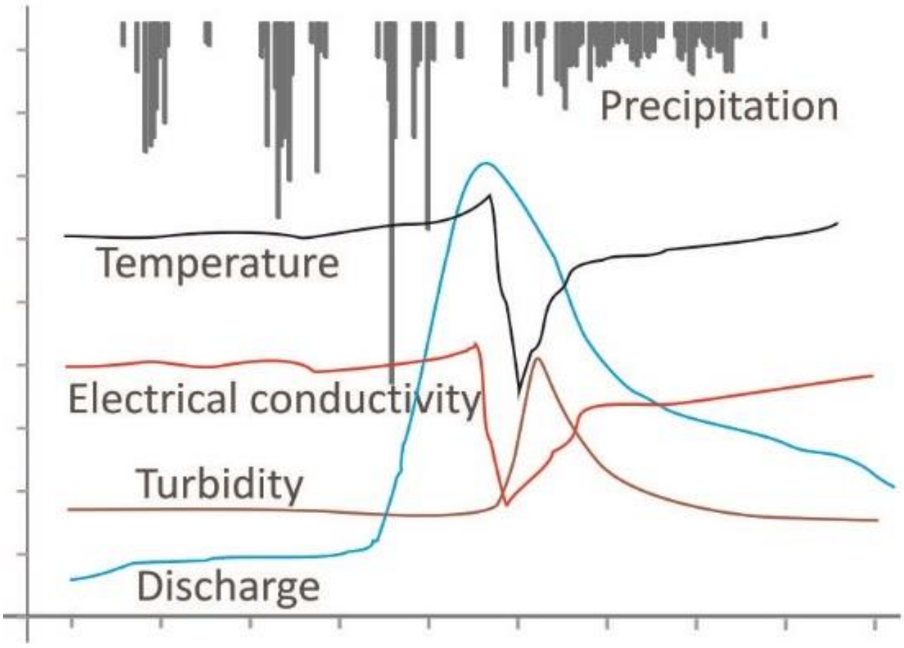


Figure Exercise 7-1 - Karst spring response to a recharge event.

Solution to Exercise 7↴

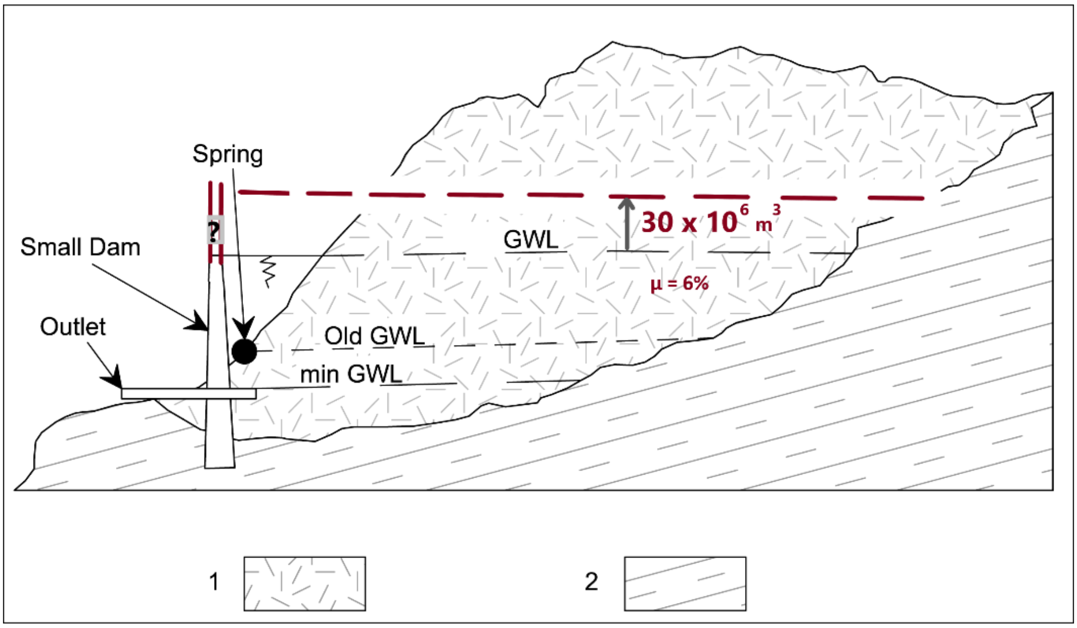
Return to where text linked to Exercise 7 from Section 4.4↥

Exercise 8 - Increase water storage within a karst aquifer by increasing the height of an existing underground dam

Aim: Managed aquifer recharge (MAR): An intervention to enlarge a karst aquifer's storage capacity.

Background: Section 4.4.2 (link provided at the end of Exercise 8)

Water engineering practice: An underground reservoir could be constructed at a spring by building a surface dam and blocking the discharge point (orifice of the spring) by using a concrete plug or a grout curtain. Implementation of anti-seepage works to prevent bottom or lateral losses through the karst mass is recommended to achieve maximum operational capacity (Figure Exercise 8-1).



Legend: 1. Karst, 2. Non-karst

Figure Exercise 8-1 - Underground karst reservoir details.

Problem: How much should the height of the existing dam at the spring be raised (ΔH) to increase the groundwater storage within a karstic underground reservoir by a specified amount?

Conditions: The storativity value is used to represent the average effective porosity of the karst hydrogeological system is $S = 6$ percent, while the catchment area is $A = 50$ km^2. The current dam is $H = 30$ m high and enables storage of 90×10^6 m^3 within the current underground reservoir. The volume of additional water required is $V = 30 \times 10^6$ m^3.

Solution to Exercise 8↴

Return to where text linked to Exercise 8 from Section 4.4.2↥

8 Questions

Question 1

Which three types of porosity are present in most karst aquifers?

Answer to Question 1↴

Question 2

Why is speleogenesis a self-amplifying process?

Answer to Question 2↴

Question 3

In karstification of a single fissure, what is the effect of the initial fissure aperture on the breakthrough time?

Answer to Question 3↴

Question 4

Name one karstic rock that is characterized by large primary porosity but small effective porosity.

Answer to Question 4↴

Question 5

What is the difference between orogenic belt (geosynclinal) and platform karst?

Answer to Question 5↴

Question 6

Provide a general classification of karst types based on lithology.

Answer to Question 6↴

Question 7

List in order the percentage of karst in each of the world's continents.

Answer to Question 7↴

Question 8

What is the difference between epigene and hypogene karst development?

Answer to Question 8↴

Question 9

List the main groups of surface and underground karst landforms.

Answer to Question 9⤵

Question 10

Name and explain the differences among the four main types of karst valley.

Answer to Question 10⤵

Question 11

In what ways do dropout dolines differ from suffosion dolines?

Answer to Question 11⤵

Question 12

What are the four main stages in the development of an epigenic cave?

Answer to Question 12⤵

Question 13

What are the influencing factors that determine if flow in a karst conduit is laminar or turbulent?

Answer to Question 13⤵

Question 14

Why do conventional groundwater models often deliver incorrect results when applied to karst aquifers? How can these models be improved?

Answer to Question 14⤵

Question 15

Which parameters can be obtained from a tracer breakthrough curve (BTC)? Explain briefly how these parameters can be obtained.

Answer to Question 15⤵

Question 16

Why is it important to measure the discharge at all sampling sites (typically, karst springs) during a tracer test?

Answer to Question 16⤵

Question 17

Why is it important to monitor the entire breakthrough curve (BTC) and not stop after the peak has been reached?

Answer to Question 17↴

Question 18

What does it mean if the tracer recovery at a karst spring reaches 100 percent? Does this occur frequently or is it rather an exceptional result? Why?

Answer to Question 18↴

Question 19

What is difference between autogenic and allogenic recharge of karst aquifer?

Answer to Question 19↴

Question 20

Classify karstic springs according to type of flow and hydraulic head.

Answer to Question 20↴

Question 21

What are the two most frequently applied drilling techniques in karst aquifers?

Answer to Question 21↴

Question 22

What is the chemical formula of limestone/calcite dissolution as it commonly occurs during the process of karstification?

Answer to Question 22↴

Question 23

What are the effects of chemical impurities (Mg^{2+}), mineralogical impurities (clay, sand), and crystal size on the solubility of calcite/limestone?

Answer to Question 23↴

Question 24

Define autochthonous and allochthonous turbidity. Which of the two types is commonly associated with high levels of TOC and *E. coli*, and why?

Answer to Question 24↴

Question 25

Write the groundwater budget equation and indicate the meaning of the symbols (variables) for all input/output parameters.

Answer to Question 25⤵

Question 26

1. Write the equation used to calculate static water reserves.
2. Write an equation that determines the exploitable reserves concerning demands of water dependent ecosystems.

Answer to Question 26⤵

Question 27

What are the types of organized monitoring?

Answer to Question 27⤵

Question 28

Name four major engineering interventions that aim to regulate groundwater flow in a discharge zone.

Answer to Question 28⤵

Question 29

What are sanitary protection zones and which criteria should be considered when delineating sanitary protection zones in karst?

Answer to Question 29⤵

Question 30

Under what hydrological conditions should water quality monitoring in karst areas be carried out and why?

Answer to Question 30⤵

Question 31

Why are karst aquifers more vulnerable to contamination compared with other aquifers?

Answer to Question 31⤵

Question 32

Describe the concept of karst groundwater vulnerability assessment and what it is based on.

Answer to Question 32↴

Question 33

Name some of the karst-specific vulnerability mapping methods and briefly present the main information sources that these methods are based on.

Answer to Question 33↴

Question 34

How do Ramsar Sites (RS) differ from the other three categories of Internationally Designated Areas (IDAs)?

Answer to Question 34↴

9 Photograph Album: Karst Around the Globe

A. Karst Landforms

Photograph Album 1 - Alpine karst landscape with karren development, Hochifen-Gottesacker, Austria/Germany (photograph by N. Goldscheider).

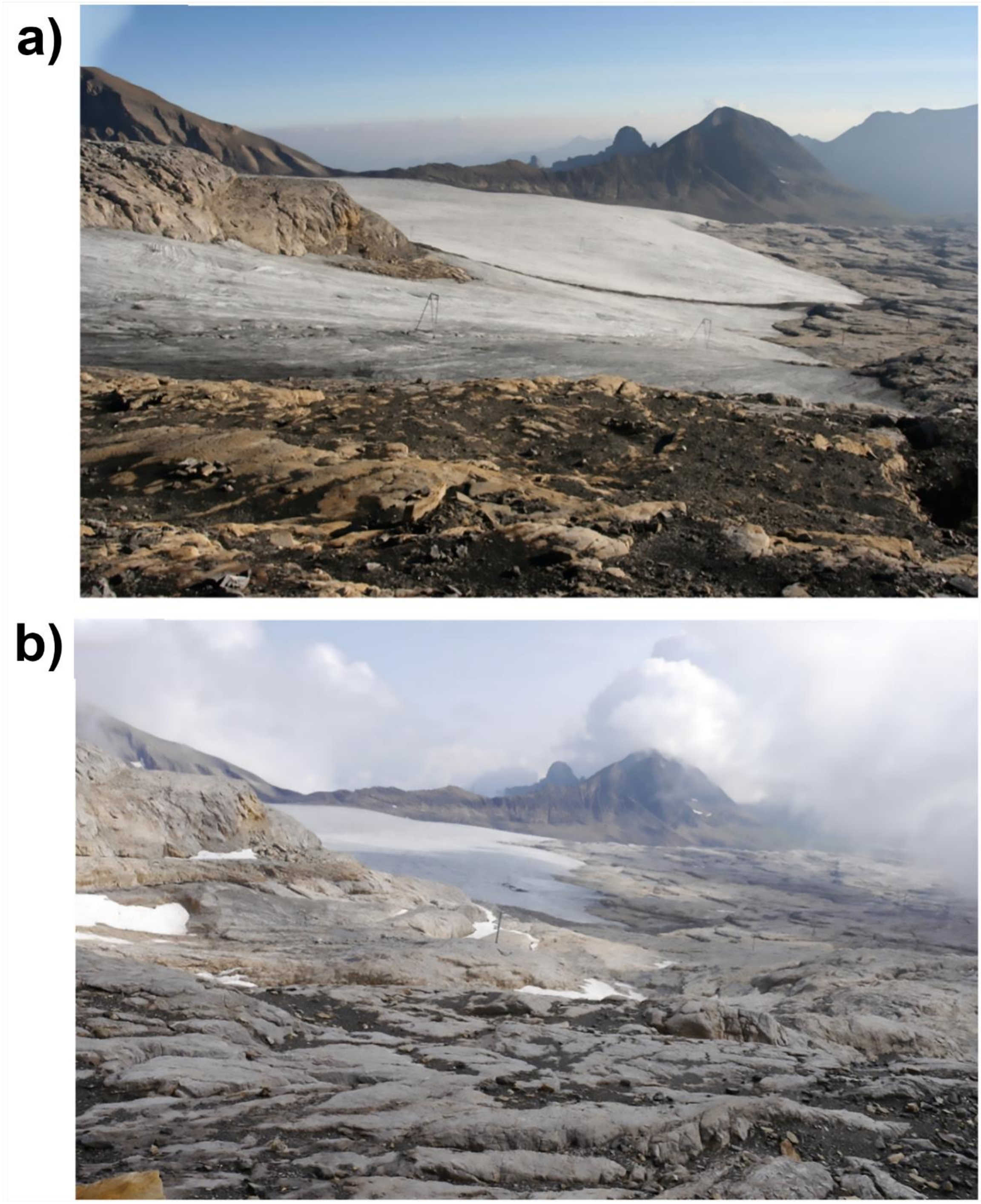
Photograph Album 2 - Karrenfield in the Swiss Alps, with Lake Thun in the background (photograph by N. Goldscheider).

Photograph Album 3 - Karrenfield in Ponoarele area, Mehedinti, Romania (photograph by Z. Stevanović).

Photograph Album 4 - Karrenfield and pothole in highly karstified limestones at Skadar Lake shoreline, Montenegro (photograph by Z. Stevanović).

Photograph Album 5 - Kamentiza (solution pits), Malta. The pits hold rainwater, most of which is lost as evaporation (photograph by J. Gunn).

Photograph Album 6 - Littoral karst on Zakynthos Island, Greece (photograph by Z. Stevanović).



Photograph Album 7 - The Tsanfleuron glacier lies above a regional karst aquifer, Valais, Swiss Alps. a) The glacier in 2005; b) the same perspective in 2018 illustrating the rapid retreat of the glacier (photographs by N. Goldscheider).

Photograph Album 8 - Epikarst development in the recharge area of the Siebenhengste-Hohgant cave system Switzerland. As of August 2022, this was the fourteenth longest (164.5 km) and twenty-fifth deepest (1,340 m) cave in the world (photograph by N. Goldscheider).

Photograph Album 9 - Epikarst development at Torcal de Antequera, Andalucía, Spain (photograph by N. Goldscheider).

Photograph Album 10 - Alpine karst in the Arabika Massif, Georgia, where the vadose zone is over 2,000 m thick (photograph by J. Gunn).

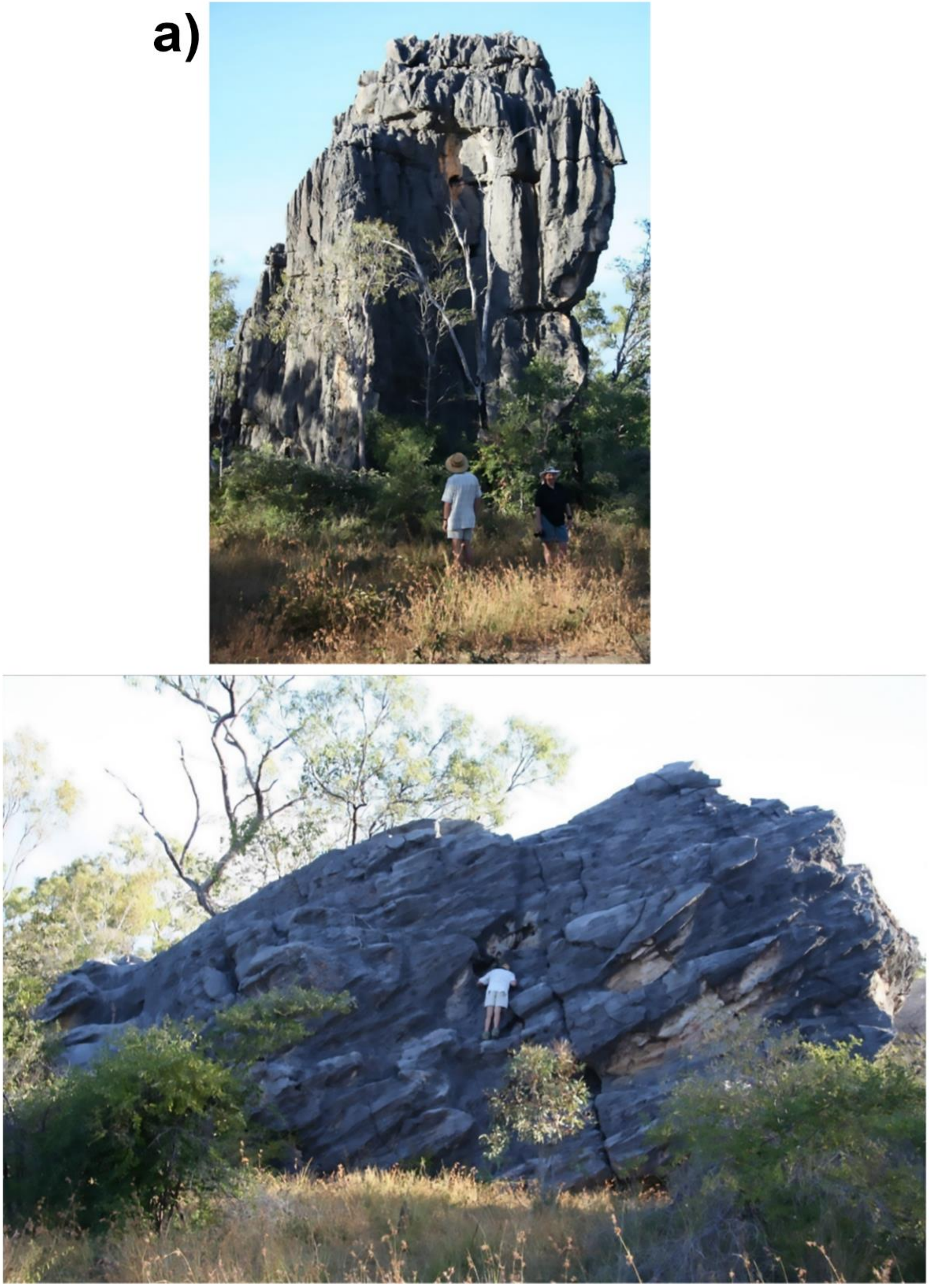
Photograph Album 11 - Tropical fluviokarst, Shibing, China (photograph by J. Gunn).

Photograph Album 12 - Subtropical tower karst landscape, Li River near Guilin, China (photograph by Z. Stevanović).

Photograph Album 13 - Dehang canyon in the Xiangxi UNESCO Global Geopark, south China (photograph by Z. Stevanović).

a)

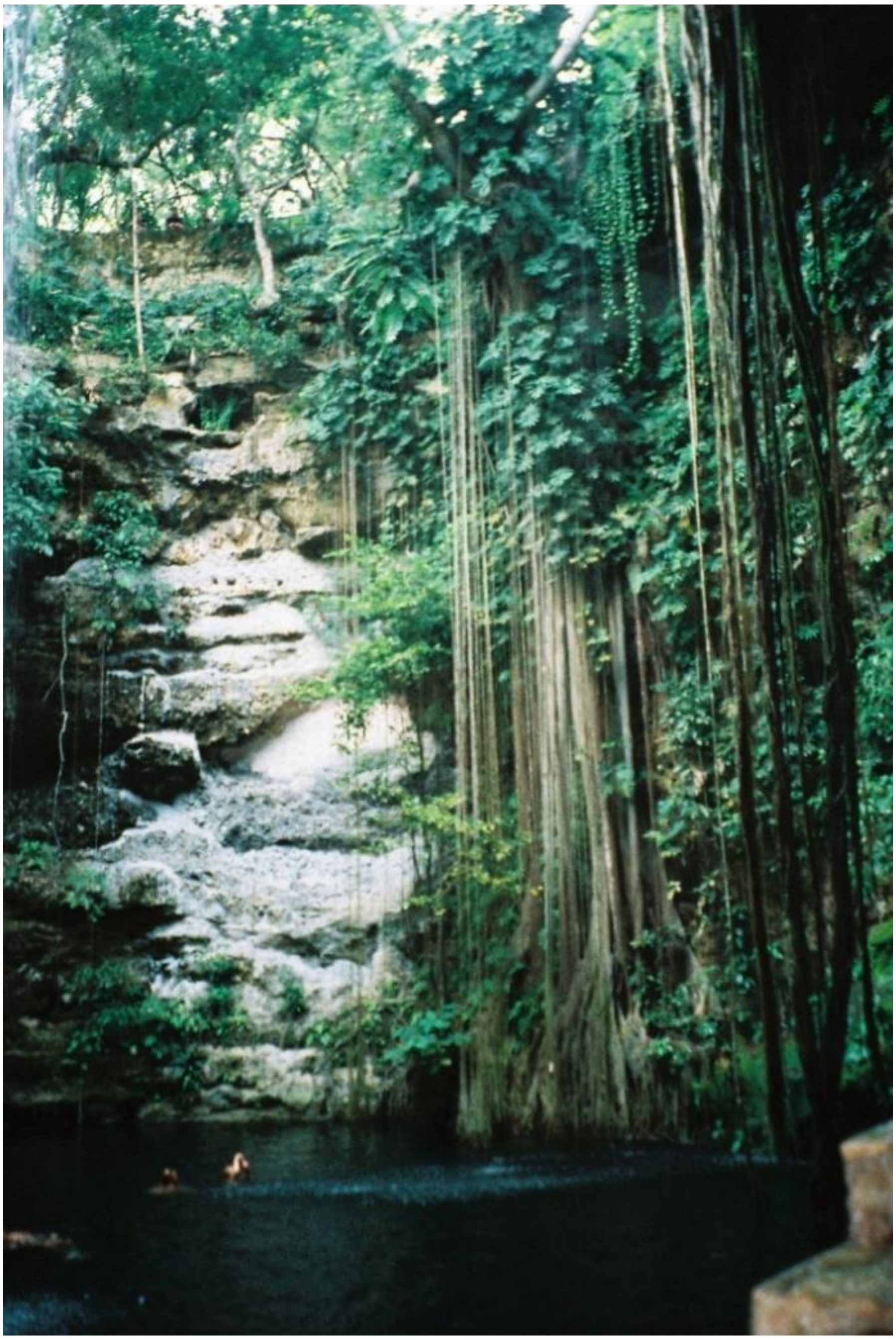
b)



Photograph Album 14 - Relict (ruinform) karst, Chillagoe, Australia. a) A relict tower and b) a tower that has toppled. The person is looking into a former epikarst cave (photographs by J. Gunn).

Photograph Album 15 - Solution dolines in an alpine karst, Kirktau Massif, Uzbekistan (photograph by J. Gunn).

Photograph Album 16 - Groundwater-fed intermittent lake in a doline (similar to a turlough) on Mljet Island, Croatia (photograph by Z. Stevanović).



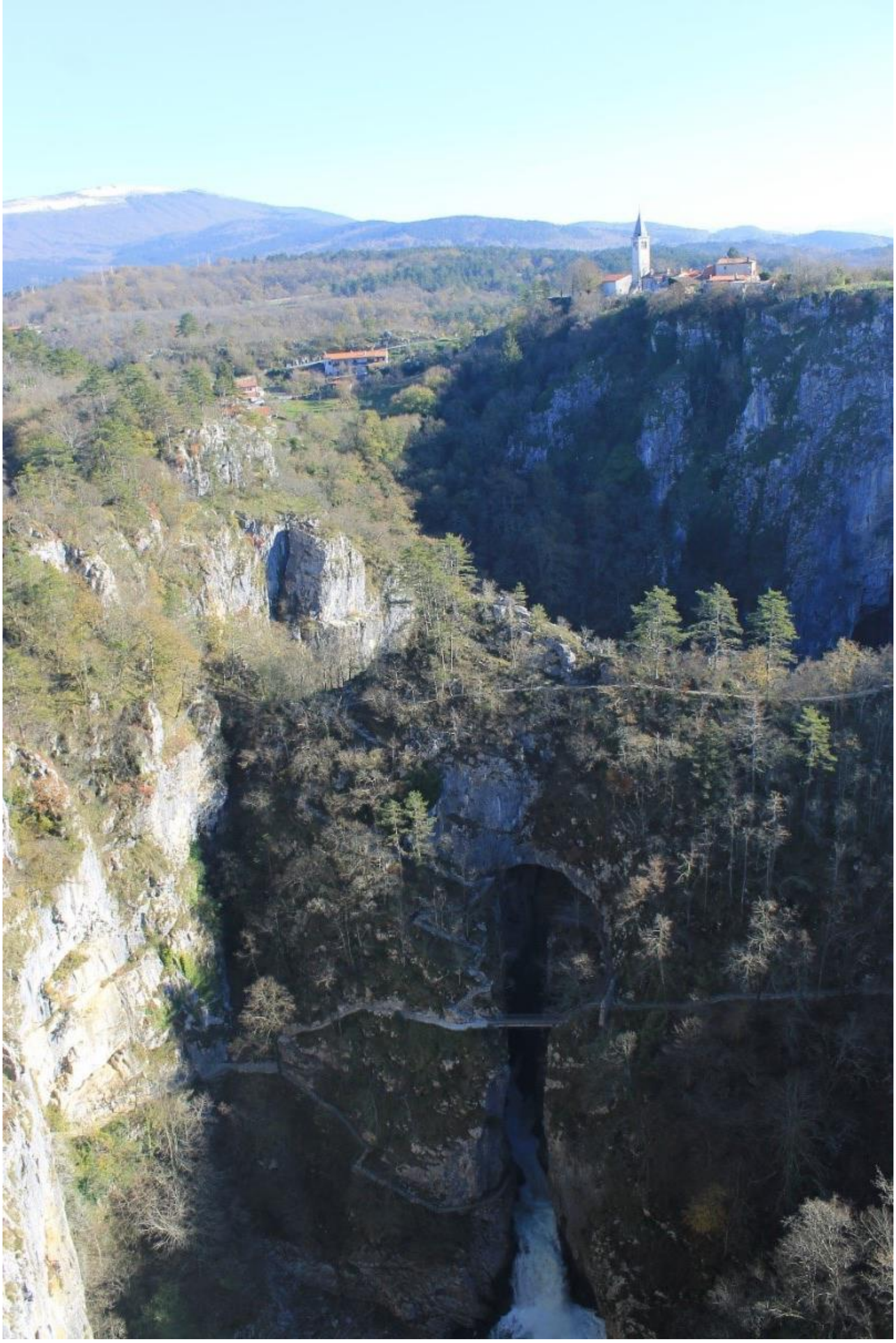
Photograph Album 17 - Cenote, Yucatan Peninsula, Mexico. Cenotes are deep natural well-like dolines directly connected to a groundwater body. In the Yucatan karst, a dense network of underground conduits extends inland for several kilometres. Many of these are large enough to be explored by divers. These open structures are vulnerable to sea water intrusion and pollution (photograph by Z. Stevanović).

Photograph Album 18 - Cultivated land in a karst polje within the Dong Van Karst Plateau UNESCO Global Geopark, northern Vietnam. Also visible is quarrying of a karst hill and tipping of waste onto the slope below (photograph by N. Goldscheider).

Photograph Album 19 - A karst valley: The Uvac River meanders through the Pešter plateau, Serbia, in a gorge that is up to 100 m deep (photograph by N. Ravbar).

Photograph Album 20 - A blind valley: In marked contrast to the deep gorge of the Uvac River, the valley of the Tuhala River in northwest Estonia is only a few metres deep. The river is rich in humic material and sinks into a shallow karst aquifer (photograph by N. Ravbar).

Photograph Album 21 - Kravica Waterfall, a large tufa cascade in Bosnia and Herzegovina (photograph by N. Ravbar).



Photograph Album 22 - Before sinking into the Škocjan Caves (Slovenia), the Reka River runs across the floor of two large collapse dolines: Velika Dolina (foreground) and Mala Dolina. The caves, dolines, and the Škocjan village (background) are a UNESCO natural and cultural World Heritage Site (photograph by N. Ravbar).

Photograph Album 23 - Modro Jezero [Blue Lake], a giant doline [tiankeng] in southern Croatia (700 m long, 400 m wide, and 290 m deep). The lake ranges from 0 to 100 m deep in response to seasonal rainfall. The tiankeng was formed by collapse into a void that may have been of hypogenic origin (photograph by J. Gunn).

Photograph Album 24 - Kizoren Obruk, a collapse doline in the centre of the Turkish Central Anatolian steppes, 65 km northeast of Konya. The doline is 180 m long, 150 m wide, and up to 145 m deep and was formed by collapse into a hypogenic void. The lake is the only source of fresh water in the area and the buildings in the background are part of a caravanserai on the Silk Road thought to date from the Byzantine era (circa1245–1250 CE). The area has been designated as a Ramsar Site (photograph by J. Gunn).

a)

b)

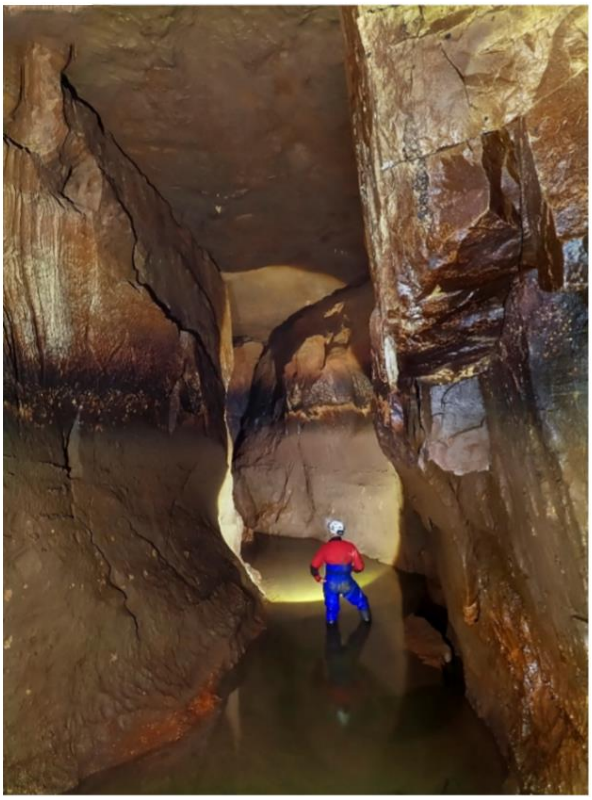
Photograph Album 25 - The 1,240 m deep Iljukhina cave system in the Arabika Massif, Georgia. The cave was largely formed by sub-glacial water during the Pleistocene and under present conditions receives recharge from rainfall and snowmelt. a) Entrance to the cave. b) Groundwater tracing tests have shown that the cave drains to large springs on the coast about 2,300 m below the entrance (photographs by J. Gunn).

Photograph Album 26 - Snežnica vrh Snežnika is a 31 m deep vadose shaft in south Slovenia (photograph by N. Ravbar).

Photograph Album 27 - Looking out of the entrance to Pollasumera Cave, County Fermanagh, Northern Ireland, UK. During dry periods all the river flow is absorbed by upstream sinks and the entrance is dry. However, as the discharge increases the upstream sinks are overwhelmed and the excess water flows down to Pollasumera. Downstream, the passage is constricted and under the highest flows the cave is full of water, as evidenced by the branch lodged in the roof (photograph by J. Gunn).

a)

b)



Photograph Album 28 - Speedwell Cavern, Castleton, England. a) Water enters through a phreatic (water-filled) passage that has been explored by cave divers to a depth of over 75 m. b) Immediately downstream of the phreatic inlet is a section of vadose streamway in which the water depth ranges from about 0.2 m during dry periods to over 2.5 m. The floodwater elevation is the line separating mud-covered and clean rock (photographs by J. Gunn).

a)

b)

Photograph Album 29 - Ana Ahu Cave, ʼEua Island, Tonga. a) Sodium fluorescein dye injected into an allogenic stream sinking at the edge of the 70 m deep shaft. b) View from the foot of the shaft. Red circle shows a caver on-rope (photographs by J. Gunn).

a)

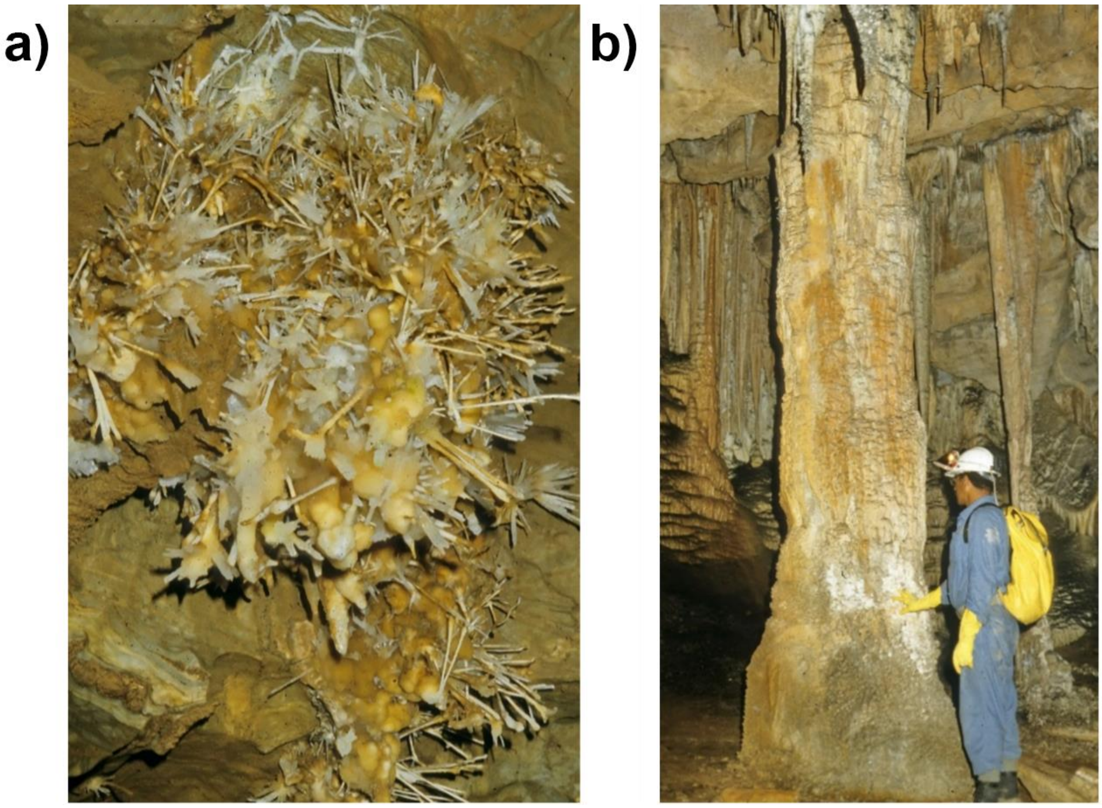
b)

Photograph Album 30 - Hollow Hill Cave, Waitomo, New Zealand. a) Abundant speleothem (stalactites and stalagmites) are formed by autogenic recharge entering this relict section of passage. b) The modern cave stream is incising into a substantial sediment fill that provides evidence of higher flows in the past (photographs by J. Gunn).

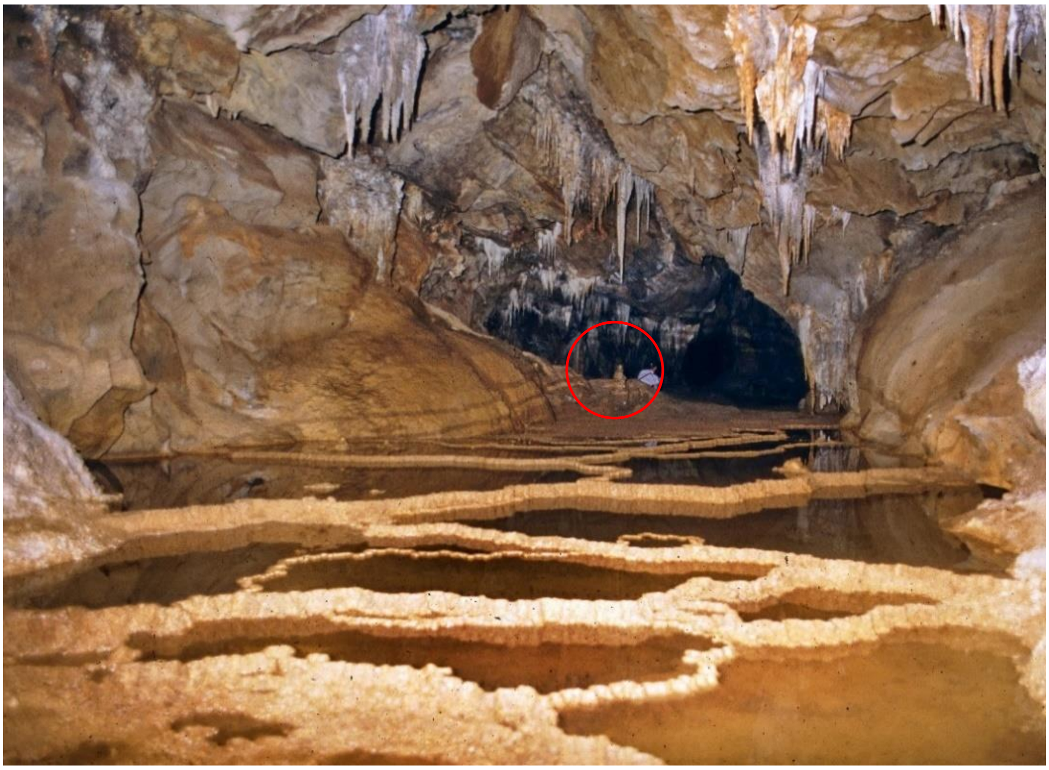
a)

b)

Photograph Album 31 - Harrison's Cave, Barbados. a) Actively forming stalactites, stalagmites, and flowstone are fed by percolating water from autogenic recharge, but the coarse clastic sediments beyond the figure provide evidence that the cave stream is partly fed by allogenic recharge from a surface stream. b) An unusual subaqueous speleothem (cave string) has formed in an isolated pool (photographs by J. Gunn).



Photograph Album 32 - Speleothems formed by percolating water. a) Anthodites in Ochtinská Aragonite Cave, southern Slovakia. b) Column in Gran Caverna de Santo Tomas, Cuba (photograph by J. Gunn).



Photograph Album 33 - Rimstone pools formed by a shallow, percolation water-fed, stream in Gran Caverna de Santo Tomas, Cuba. The caver in the background gives scale (photograph by J. Gunn).

Photograph Album 34 - When the air temperature in a cave drops below 0 ºC, percolating water freezes, forming seasonal ice speleothems. Velika Ledena Jama at Paradana, the largest ice cave in Slovenia, is a typical cold-air trap ice cave (photograph by N. Ravbar).

Photograph Album 35 - In addition to seasonal cave ice, there are some caves in which water has been stored as ice for millennia. This example is in Dobšiná Ice Cave, Slovakia, which is part of the Caves of Aggtelek Karst and Slovak Karst World Heritage Property (photograph by J. Gunn).

a)

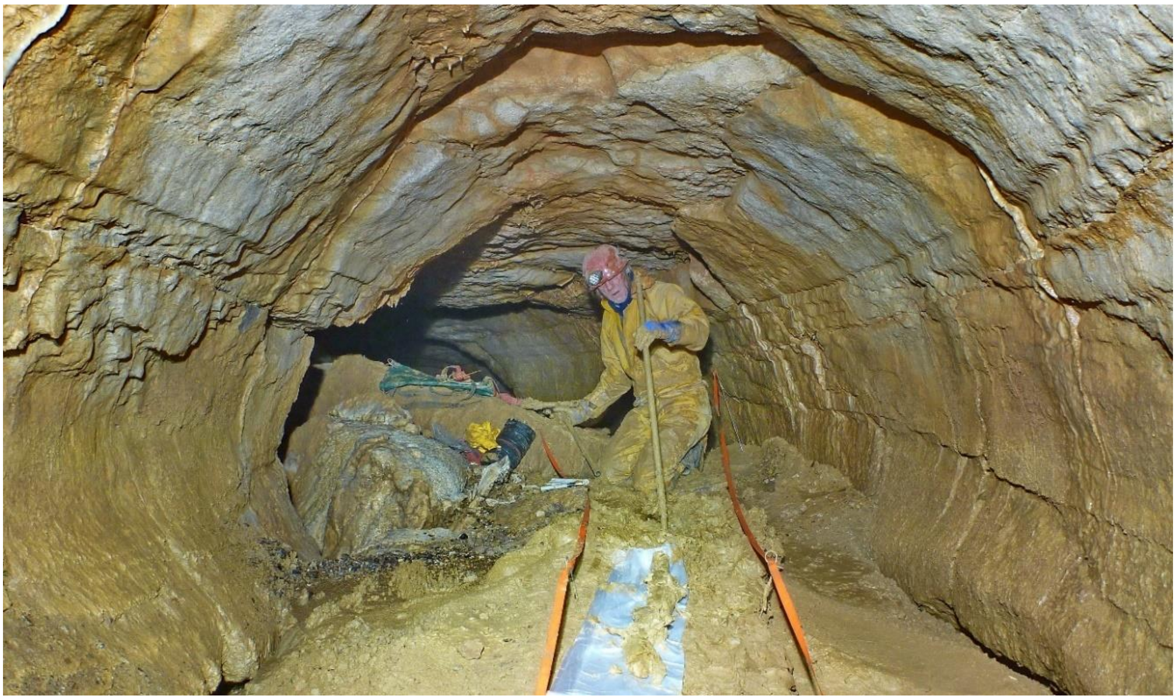
b)

Photograph Album 36 - First Cave, ’Eua Island, Tonga. a) The cave entrance lies at the bottom of this solution doline. b) Looking up 36 m from the bottom of the entrance shaft (photographs by J. Gunn).

Photograph Album 37 - Casa de Pedra Cave, Brazil carries a large river (photograph by J. Gunn).

Photograph Album 38 - The large cave river in Sof Omar Cave, Ethiopia, is analogous to a "surface stream with a roof." This photograph was taken in the dry season. In the wet season, the water depth can exceed 3 m (photograph by J. Gunn).

Photograph Album 39 - Under present conditions, this small passage in Crag Cave, County Kerry, Ireland, is relict for most of the year. The sediment on the floor is over 1 m deep and the bedrock passage is much larger than is apparent from the photograph. The active stream passage is at a lower elevation, but during large rainfall events the lower passage cannot accommodate all the flow and the water rises and flows down the higher-level passage (photograph by J. Gunn).

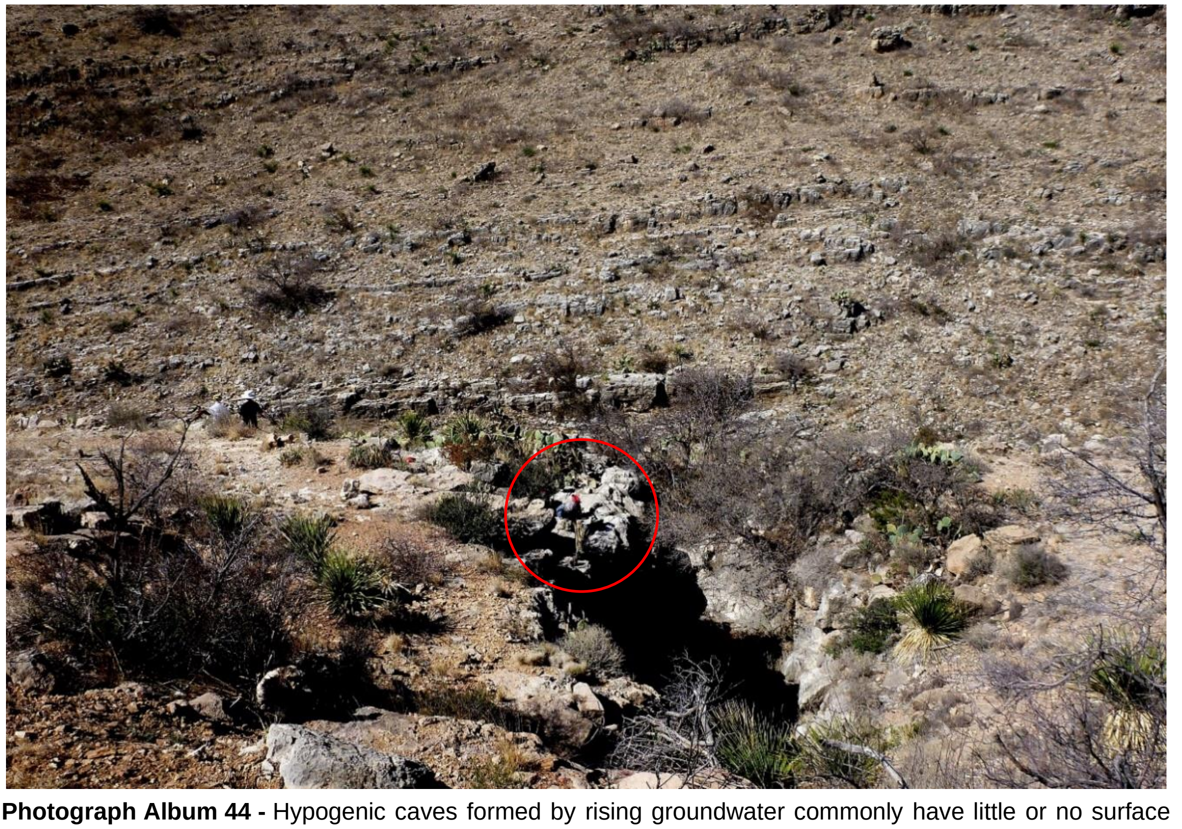


Photograph Album 40 - Relict passage in Water Icicle Close Cavern, Derbyshire, England, UK. The passage formed over 1 million years ago but has been partially filled with sediment that is over 1 m deep. Beyond the caver, the passage is completely filled with sediment and effectively 'fossilized' (photograph by J. Gunn).

Photograph Album 41 - Prestreljeniško okno (Mount Kanin, Slovenia) is a natural arch that is all that remains of a former cave. The former passage that has been removed by erosion can be projected on either side of the rock and is sometimes referred to as a “cave in the sky’” (photograph by N. Ravbar).

Photograph Album 42 - The opening through Moon Hill near Yangshuo (Guangxi, China) is another example of a relict cave that formed in the phreatic zone. The passage that once extended on both sides of the hill is now a ’cave in the sky’ (photograph by N. Ravbar).

Photograph Album 43 - Relict speleothem, Kirktau Massif, Uzbekistan (lens cap: 62 mm.) The cave in which this speleothem was deposited has been completely removed by glacial erosion but the post-glacial climate is semi-arid and many pieces of speleothem have survived on the surface (photograph by J. Gunn).

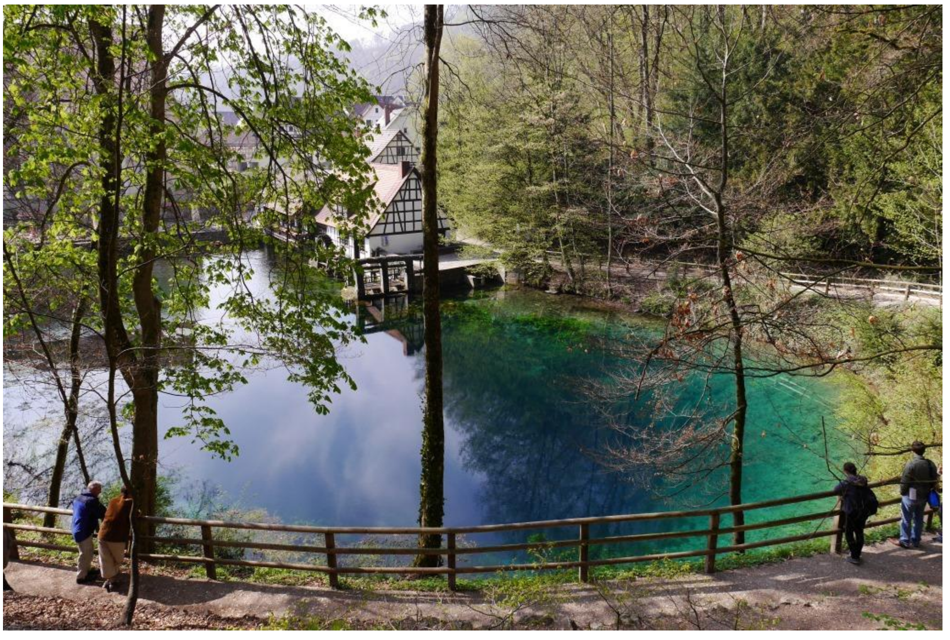


Photograph Album 44 - Hypogenic caves formed by rising groundwater commonly have little or no surface expression. The caver with the red helmet in the red circle (lower centre of the photograph) is above the only entrance to Lechuguilla Cave, New Mexico, USA, which has over 242 km of explored passage and extends to a maximum depth of 484 m. The entrance was breached by surface lowering (photograph by J. Gunn).

Photograph Album 45 - Extensive speleothem deposits in József-Hegyi-Barlang, Budapest, Hungary. This is a relict hypogenic cave that was formed by rising thermal groundwater (photographs by J. Gunn).

B. Karst Springs

Photograph Album 46 - The Orbe spring emerges from the Vallorbe Cave near the community of Vallorbe in the Swiss Jura Mountains close to the border with France. There is a very large range in discharge, from 2 to 80 m^3/s (photograph by N. Goldscheider).

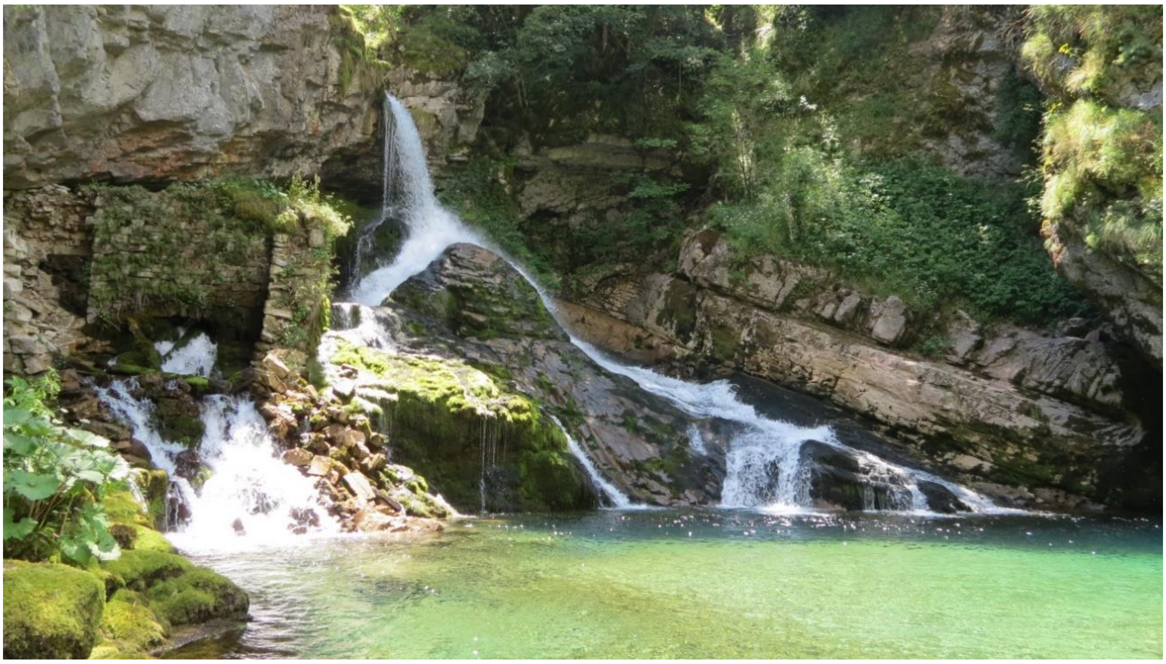


Photograph Album 47 - The Blautopf ascending spring emerges from the famous Blauhöhle (Blue Cave) in the Swabian Alb, Germany. The cave has been explored by divers and discharge from the spring ranges from about 0.3 to 32.5 m^3/s (photograph by N. Goldscheider).

Photograph Album 48 - Contact spring at the geologic contact between fractured and karstified limestone overlying an impervious shale, Ontario, Canada (photograph by N. Goldscheider).

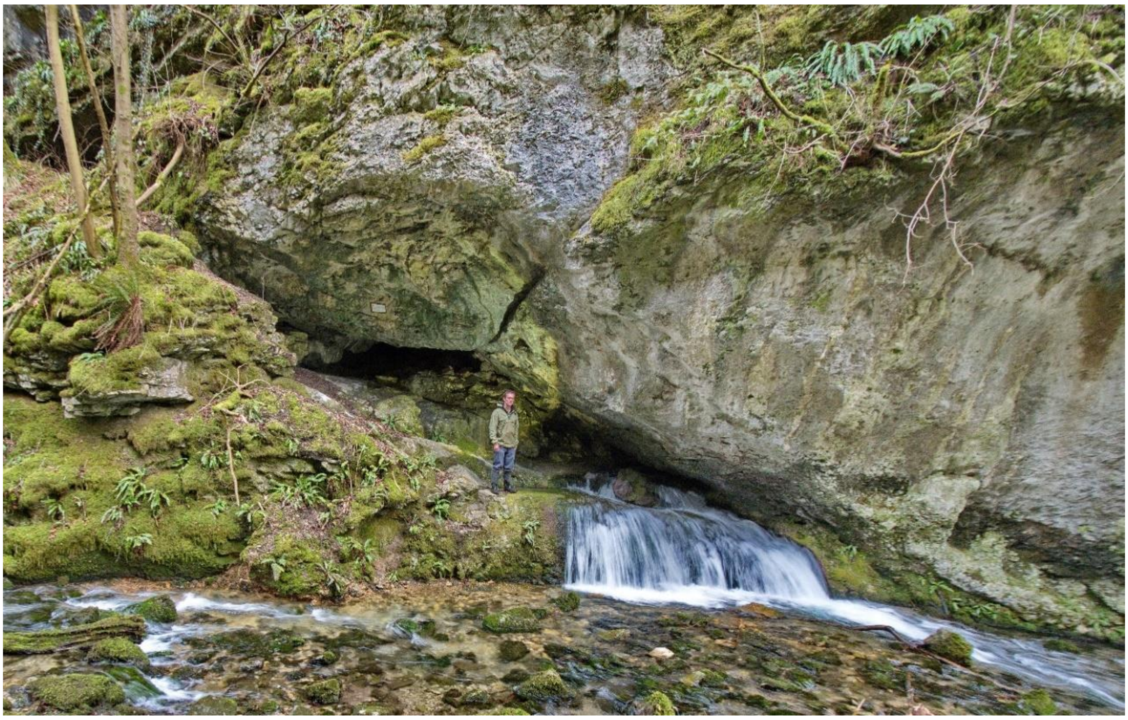
Photograph Album 49 – Waterfalls issuing from caves. a) Margoon waterfall spring near Shiraz, Iran (photograph by Z. Stevanović). b) Boka waterfall spring, Bovec, Slovenia (photograph by N. Goldscheider).

Photograph Album 50 - Locations where springs fall over thick tufa deposits. a) Sopotnica karst spring, west Serbia. b) Veliko vrelo spring, east Serbia. Both are protected as natural monuments (photograph by Z. Stevanović).



Photograph Album 51 - Oko Bijele spring, Piva River basin, Montenegro (photograph by Z. Stevanović).

Photograph Album 52 - Ascending karst spring Syri i Kaltër [Blue eye], Bistrica River basin, Albania. In the early 2000s, the Albanian and Italian Governments discussed the possibility of constructing a 70 km pipeline under the Adriatic Sea to transfer water from this large spring (average discharge 20 m^3/s) to Puglia Province (photograph by Z. Stevanović).

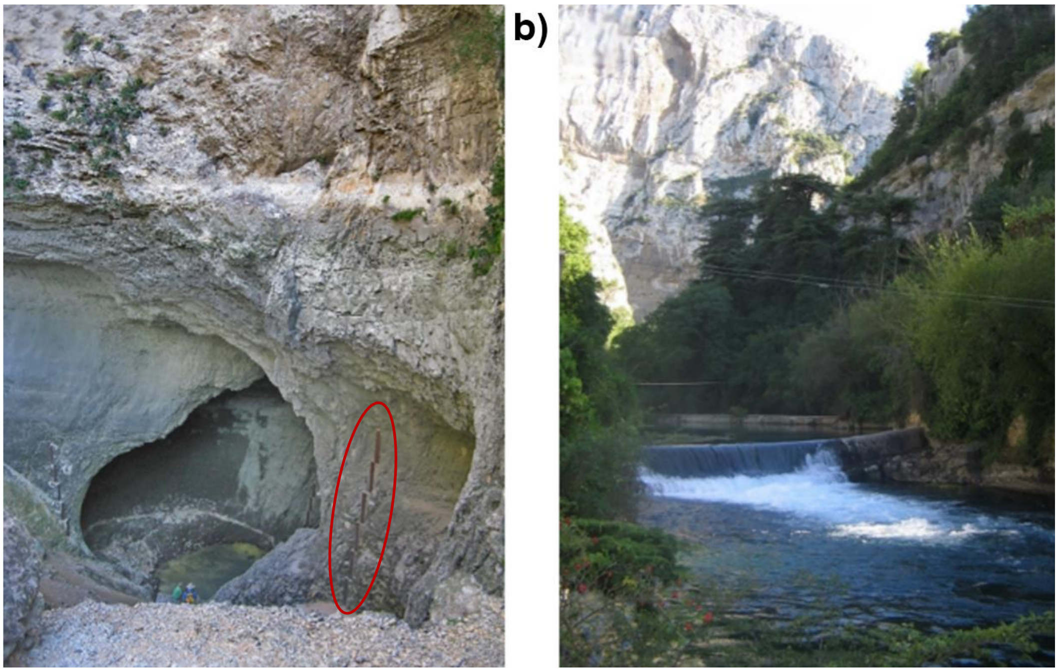


Photograph Album 53 - Lumb Hole, Cressbrook Dale, Derbyshire, UK. This is an intermittent spring that discharges over 250 L/s in winter but dries completely in summer. The spring is the only known location of Derbyshire feather-moss (*Thamnobryum angustifolium*), which is listed as Critically Endangered in the IUCN Red Data Book and has its own individual Biodiversity Action Plan (photograph by J. Gunn).

Photograph Album 54 - Karst spring, Fuente de los 100 Caños, in Andalusia, Spain (photograph by N. Goldscheider).

Photograph Album 55 - Jinci spring and temples near the city of Taiyuan in the Shanxi Province, China. The temples were built around the spring, but the spring ran dry due to aquifer over-pumping. Therefore, water from another source is pumped to the spring, to mimic and replace the natural discharge (photograph by N. Goldscheider).

a) b)



Photograph Album 56 - The famous karst spring Fontaine de Vaucluse in southern France (Provence), which gave its name to all ascending springs (vauclusian type). The spring is also important for having the world's longest discharge record. a) Gauges were installed in 1878 (indicated by the red oval). Excellent records since then have been used to investigate how this karst system functions and to reconstruct the impact of climate variables on discharge. The photographs were taken during a low water period during which the spring water, seen at the bottom of (a), flowed through a sediment fill and b) emerged at the surface around 100 m downstream (photographs by Z. Stevanović).

Photograph Album 57 - Karuč sublacustrine karst spring, Skadar Lake gulf, Montenegro. There was a proposal to tap the spring and use the water to supply municipalities along the Montenegrin Coast. However, the project was cancelled due to the spring's orifice being at the bottom of the 20 m-deep lake. Another sublacustrine spring, Bolje Sestre, which has a shallower orifice was later tapped for the same purpose (photograph by Z. Stevanović).

a)

b)

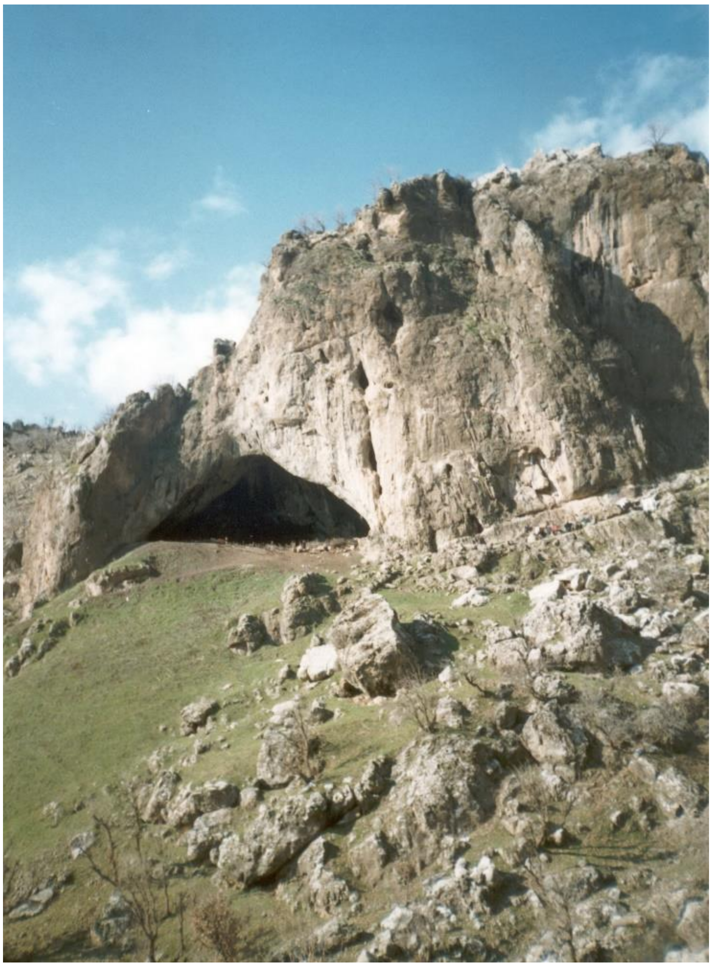
Photograph Album 58 - The largest estavelle in the European Alps, located in Schwarzwasser valley, Austria. a) Under low flow, all the water from the surface stream sinks at the estavelle and the surface channel downstream is dry. b) Under high flow, up to about 4 m^3/s of groundwater discharged from the estavelle joins the surface flow from upstream and the combined flow continues down the surface channel (photographs by N. Goldscheider).

C. Humans and Karst

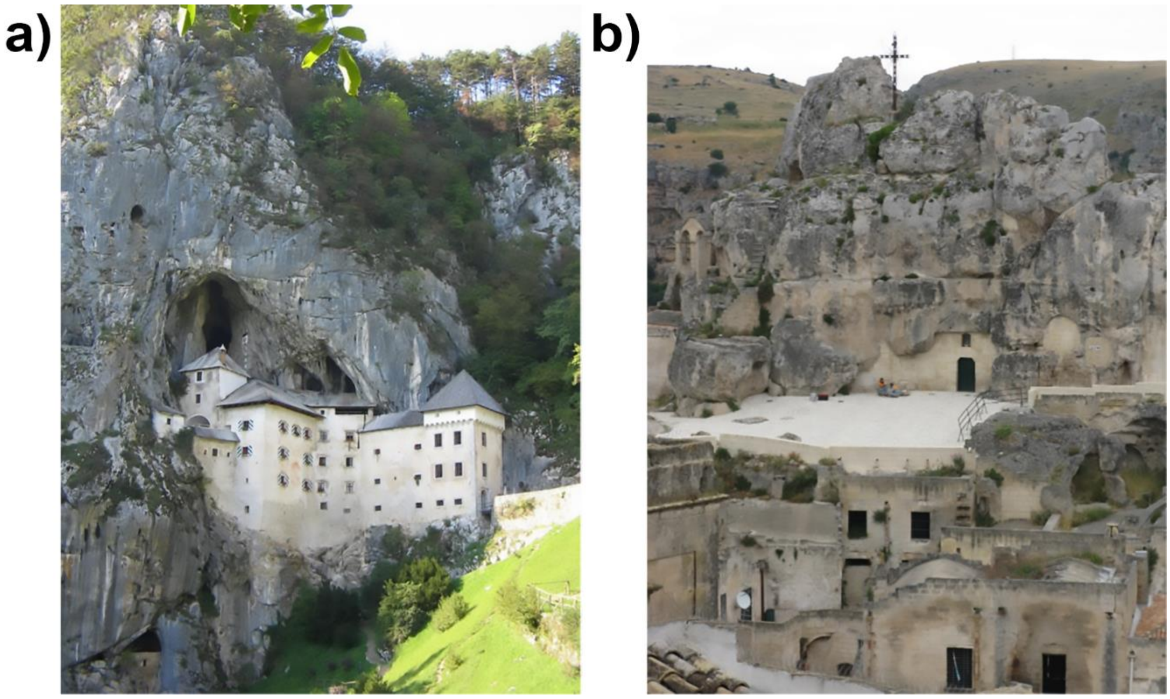
Photograph Album 59 - Trebinje city (Bosnia and Herzegovina) is on the edge of a large karst polje in the Dinaric karst that is surrounded by high mountains (photograph by Z. Stevanović).

Photograph Album 60 - Land cultivation on karst in the Dong Van Karst Plateau UNESCO Global Geopark, northern Vietnam (photograph by N. Goldscheider).

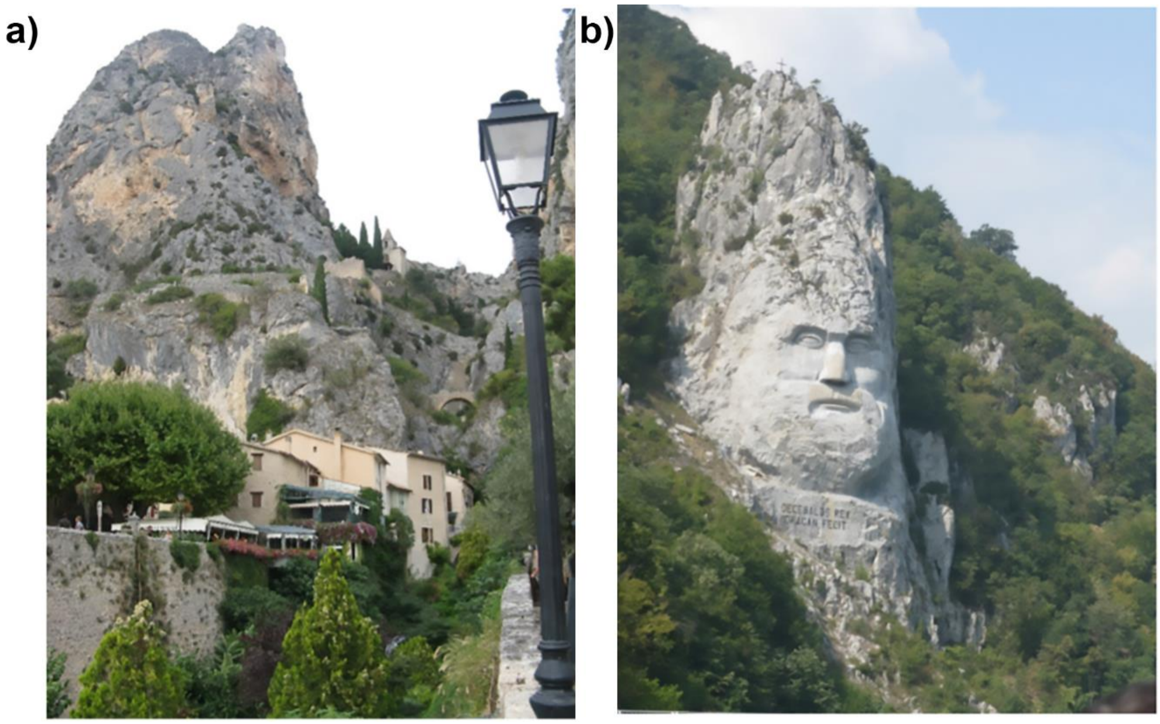
Photograph Album 61 - The roof and walls of Niah Cave, Sarawak, Malaysia, are covered by bamboo scaffolding and ropework placed by local people to facilitate harvesting of bird's nests (photograph by J. Gunn).



Photograph Album 62 - Shanadar Cave in northern Iraq contains the oldest discovered and investigated human settlement in the Middle East (surveyed from 1951 by Ralph Solecki). There are four cultural layers, including Neanderthal remnants that are about 60,000 years old, the most famous being a male known as Nandy. The discovery of pollen grains around the skeleton provides evidence of Neanderthal funeral rituals (photograph by Z. Stevanović).



Photograph Album 63 – Dwellings constructed in karst. a) Predjama castle, Slovenia. b) Matera historical city, Basilicata, Italy (photographs by Z. Stevanović).



Photograph Album 64 – A village and a sculpture in karst. a) Moustiers St. Marie en Provence, France. b) Dacebal sculpture, Danube bank, Romania (photographs by Z. Stevanović).

Photograph Album 65 - The historical town of Persepolis in the foothills of Kuh-e Rahmat (Zagros Mountain chain, southern Iran) was founded by the Persian emperor Darius the Great about 512 BCE. Most of the palaces and temples were built from limestones of the Upper Cretaceous Sarvak Formation, while for the potable water supply deep quadratic stone wells were excavated in this formation (photograph by Z. Stevanović).

Photograph Album 66 - This spring near Cusco, Peru, was a religious site for the Inca people. It drains Cretaceous limestones that are widely present on the central-southern margins of the Andes (photograph by Z. Stevanović).

Photograph Album 67 - Children collecting water at a karst spring near Tam Duong, Vietnam (photograph by N. Goldscheider).

Photograph Album 68 - Collecting water from a spring south of Fes, Morocco (photograph by J. Gunn).

Photograph Album 69 - The spring that emerges from Ana Peka Beka, 'Eua Island, Tonga, is contaminated by guano from the many cave swifts (Peka Beka) that nest in the large chambers near the entrance. Pipes carry water to the surface from an upstream sump (water-filled passage) before it can be contaminated (photograph by J. Gunn).

Photograph Album 70 - Two springs issue from Karkar limestones in the Buuhoodle area, Puntland, Somalia. Although they have small discharge, they are essential water sources for local villagers and their livestock. (photograph by Z. Stevanović).

Photograph Album 71 - St. Naum spring discharges on the shore of Ohrid Lake in North Macedonia. It drains Mount Galičica and is partly supplied by water that sinks at the outlet of Lake Prespa, which is shared among Greece, Albania, and North Macedonia. The average discharge of St. Naum spring is over 5 m^3/s, and this flow is essential to maintain the endemic ecosystem of Ohrid Lake, which was designated as a UNESCO World Heritage Property in 1979 (photograph by Z. Stevanović).

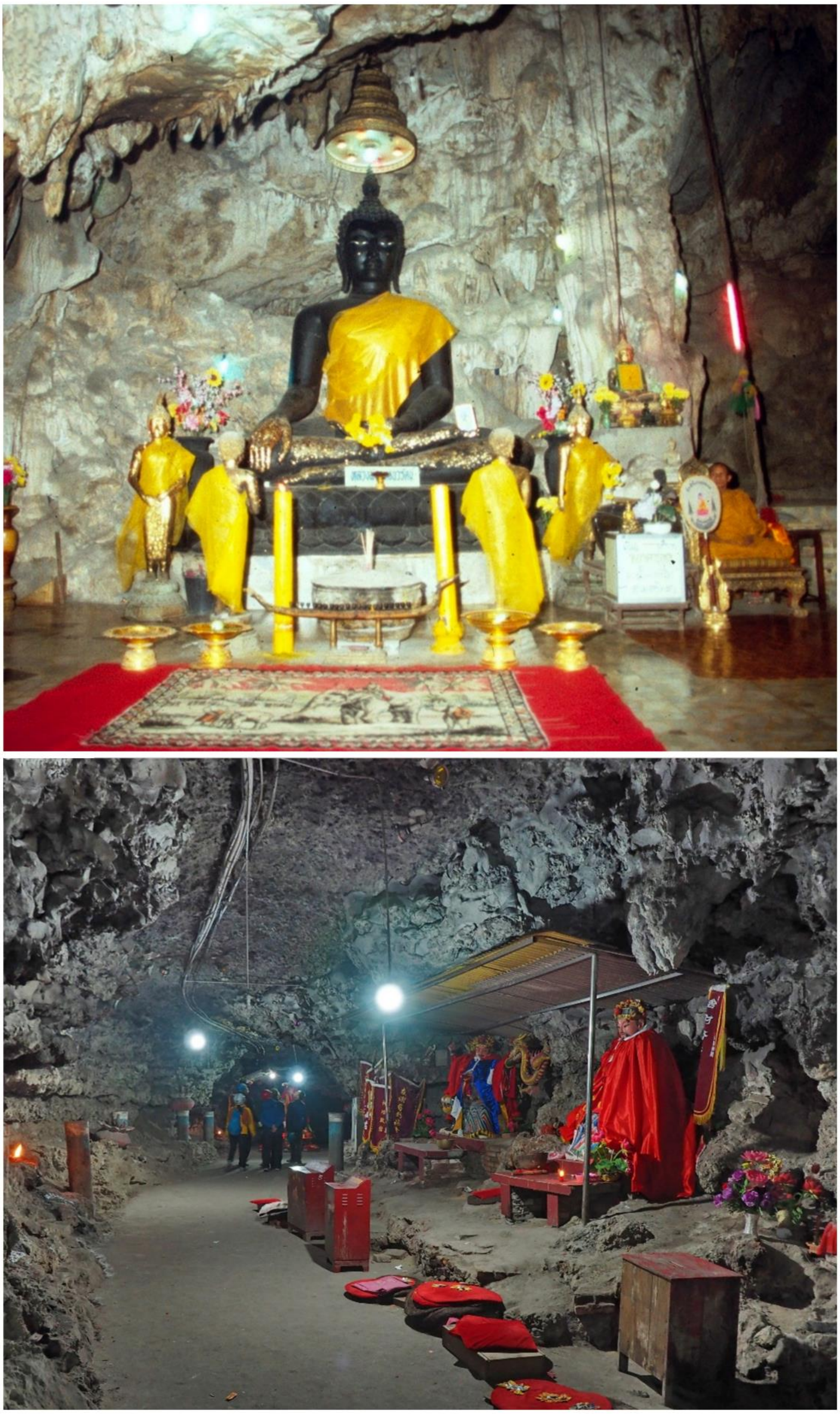
Photograph Album 72 - Groundwater monitoring well with open cap in an artesian karst aquifer in Portugal, illustrating that the potentiometric surface in the aquifer is above the land surface (photograph by N. Goldscheider).

Photograph Album 73 - An empty reservoir at Hammam Grouz in the karst of northern Algeria. Following remedial measures to reduce water losses, the reservoir operated successfully for about 20 years until several new swallow holes formed, completely draining the reservoir (photograph by Z. Stevanović).

Photograph Album 74 - The Montejaque dam in Andalucía, southern Spain, is a good example of the consequence of failing to understand karst hydrogeology. Built in the 1930s, the gravity arch dam is 84 m high and has an 84 m crest length. The reservoir has never completely filled with water due to the very permeable karstified rocks around the dam site and consequent water losses (photograph by Z. Stevanović).

a)

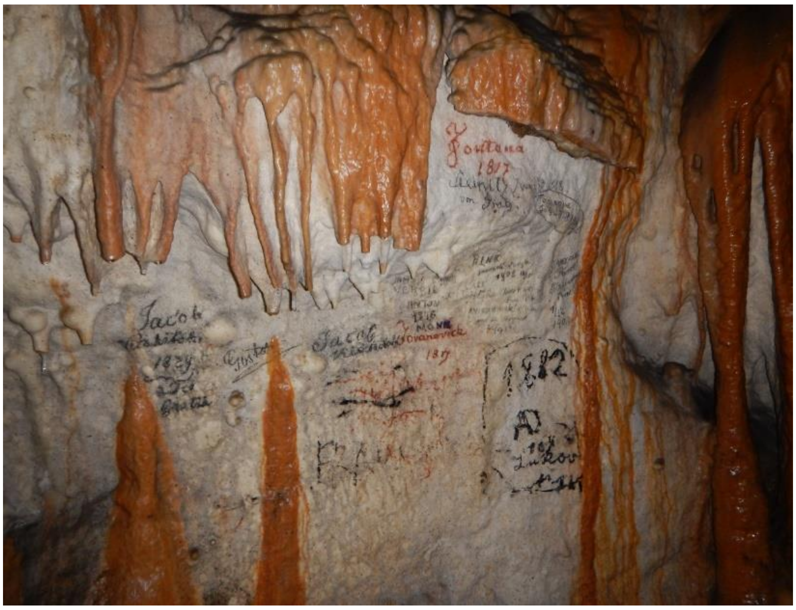
b)



Photograph Album 75 - In Asia, caves are commonly used as temples. a) Wat Tham Sri Wilai cave temple, Thailand. b) Temple in Guanyin Dong, Shannxi Province, China (photographs by J. Gunn).

Photograph Album 76 - Upper and Middle Paleolithic culture rock art in Magura Cave, Bulgaria (photograph by Z. Stevanović).

Photograph Album 77 - Native-Australian rock art, Chillagoe, Australia (photograph by J. Gunn).



Photograph Album 78 - Many caves contain old inscriptions from early explorers as in this example from Postojnska jama, Slovenia. Unfortunately, as well as leaving signatures early visitors commonly broke stalactites and stalagmites, which they removed as souvenirs of their visit (photograph by N. Ravbar).

Photograph Album 79 - Across the globe many hundreds of caves have been developed to facilitate access by tourists and these provide an opportunity for those hydrogeologists who are not cavers to view the inside of a karst system. A shale cover above Doolin Cave (Pol an Ionain), County Clare, Ireland restricts water percolation so there are few stalactites. However, a fracture allows water to enter at a single point and the resulting Great Stalactite is around 6 m long (photograph by J. Gunn).

Photograph Album 80 - Human impacts on karst south of Fes, Morocco. a) Depression visually similar to a natural doline but formed by collapse into workings of a mine. b) Mine galleries exposed in the wall of a more recent quarry (photographs by J. Gunn).

Photograph Album 81 - As part of the development of the Kunming Changshui International Airport (Yunnan, China), which opened in 2012, soil and 'stone teeth' were removed from 23 km^2 of karst (photograph by N. Ravbar).

10 Exercise Solutions

Exercise Solution 1

Solution:

Volume (V) = 15 × 20 × 15 = 4,500 m^3; Q_{in} = 0.02 m^3/s; Q_{out} = 0.0015 m^3/s;

$\Delta Q = Q_{\text{in}} - Q_{\text{out}}$ = 0.0185 m^3/s

time = $V/\Delta Q$ = 4,500 m^3/ 0.0185 m^3/s

time = 243,243 s = 2 days, 19 hours, 34 minutes, 3 sec

Conclusion and interpretation: The calculation suggests that the chamber would fill with water in 2 days 19.5 hours. However, this will only be achieved if the surrounded blocks are fully impermeable, and the outlet does not allow Q_{out} > 1.5 L/s. In practice, as the head of water in the chamber increases, this is likely to force water through the outlet at a faster rate. Also, it is common in karst for there to be higher level relict conduits that may be activated and allow more outflow as water levels rise.

Return to Exercise 1↑

Return to where text linked to Exercise 1↑

Exercise Solution 2

Solution:

$$I_{\mathrm{ef}} = \frac{\text{Discharge}}{\text{Recharge}} 100$$

$$I_{\mathrm{ef}} = \frac{Q_{av}\, T}{A\, P}\ 100$$

$$I_{\mathrm{ef}} = \frac{2\,\dfrac{\mathrm{m}^3}{\mathrm{s}}\ 365\ \dfrac{\mathrm{d}}{\mathrm{yr}}\ \dfrac{86{,}400\ \mathrm{s}}{1\ \mathrm{d}}}{100\ \mathrm{km}^2\,\dfrac{1\mathrm{x}10^6\ \mathrm{m}^2}{1\ \mathrm{km}^2}\ 1000\,\dfrac{\mathrm{mm}}{\mathrm{yr}}\,\dfrac{1\mathrm{m}}{1000\ \mathrm{mm}}} 100$$

$$I_{\mathrm{ef}} = 63 \text{ percent}$$

where:

Q_{av}	=	average spring discharge in cubic metres per second
T	=	number of seconds in a year
A	=	area in square metres
P	=	annual precipitation in metres

Conclusion and interpretation: The estimated rate of effective recharge for the average hydrological year indicates that the studied aquifer is well karstified and may receive and probably store a considerable amount of rainfall.

Return to Exercise 2⮥

Return to where text linked first to Exercise 2 from Section 3.2⮥

Return to where text linked second to Exercise 2 from Section 4.2⮥

Exercise Solution 3

Solution (using *t* values in units of days)***:***

$$\alpha_1 = \frac{logQ_0 - logQ_{t1}}{0.4343\,(t_1 - t_0)}$$

$$\alpha_1 = \frac{log1.36 - log0.72}{0.4343\,(12)}$$

$$\alpha_1 = \frac{0.133 - (-0.14)}{5.21}$$

$\alpha_1 = 0.0524$ day^{-1}

$$\alpha_2 = \frac{logQ_{t1} - logQ_{t2}}{0.4343\,(t_2 - t_0)}$$

$$\alpha_2 = \frac{log0.72 - log0.38}{0.4343\,(44)}$$

$$\alpha_2 = \frac{(-0.14) - (-0.42)}{19.11}$$

$\alpha_2 = 0.0146$ day^{-1}

$$t_n = \frac{logQ_{t2} - logQ_{tn}}{\alpha_2\, 0.4343}$$

$$t_n = \frac{(-0.42) - (-3)}{0.0146\; 0.4343}$$

$$t_n = \frac{2.58}{0.0063}$$

$t_n = 409$ days

Conclusion and interpretation: This aquifer is characterized by two drainage regimes during a drought causing a long recession. The first occurs when larger joints and cavities are emptying (α_1), and the second when water from smaller fissures is discharging (α_2). Considering the obtained recession coefficient α_2, the theoretical time for spring drying is longer than one year (409 days), which provides evidence for large groundwater reserves in the deeper part of the aquifer.

Return to Exercise 3↥

Return to where text linked first to Exercise 3 from Section 3.3↥

Return to where text linked second to Exercise 3 from Box 17↥

Exercise Solution 4

Solutions:

1. Annual autogenic recharge (R) and evapotranspiration (ET):

   Input $=$ Output

   Although tracing indicated a connection from S to B and C but not to D, the budget needs to account for all flows in and out of the karst system,

   Autogenic Recharge + Allogenic Recharge $=$ Discharge

   $(R\ A) + Q_S = Q_B + Q_C + Q_D$

$$R = \frac{(Q_B + Q_C + Q_D - Q_S)}{A} = \frac{\left(125\,\frac{\text{L}}{\text{s}} + 340\,\frac{\text{L}}{\text{s}} + 1440\,\frac{\text{L}}{\text{s}} - 260\,\frac{\text{L}}{\text{s}}\right)}{75\ \text{km}^2}$$

$$= \frac{1{,}645\ \frac{\text{L}}{\text{s}}\ \frac{1\text{x}10^6\ \text{mm}^3}{\text{L}}\ \frac{86{,}400\ \text{s}}{\text{d}}\ \frac{365\ \text{d}}{\text{yr}}}{75\ \text{km}^2\ \frac{1\text{x}10^6\ \text{m}^2}{\text{km}^2}\ \frac{1\text{x}10^6\ \text{mm}^2}{m^2}} = 692\,\frac{\text{mm}}{\text{yr}}$$

$$ET = P - R = 1{,}000\,\frac{\text{mm}}{\text{yr}} - 692\,\frac{\text{mm}}{\text{yr}} = 308\,\frac{\text{mm}}{\text{yr}}$$

   where:

R	=	autogenic (diffuse) recharge
Q_S	=	flow into the swallow hole (allogenic recharge)
Q_B, Q_C, Q_D	=	the discharge flows for springs B, C, and D, respectively
A	=	the area of the exposed karst (autogenic recharge area)
P	=	precipitation over the karst area
ET	=	evapotranspiration over the karst area

   These equations and calculations would only be true if there is no exchange of water with deeper parts of the hydrogeological system. Surface runoff is assumed null.

2. Estimation of autogenic recharge areas of individual springs (A_B, A_C, A_D):

   Preliminary consideration: B and C cannot be treated as separate springs. They are two connected orifices of the same flow system, as demonstrated by the tracer test and their discharge behavior.

   Water Balance for D: $R \cdot A_D = Q_D$

$$A_D = \frac{Q_D}{R} = \frac{1440\,\frac{\text{L}}{\text{s}}\ \frac{1\ \text{km}^3}{1\text{x}10^{12}\ \text{L}}}{692\,\frac{\text{mm}}{\text{yr}}\ \frac{1\ \text{m}}{1000\ \text{mm}}\ \frac{1\ \text{km}}{1000\ \text{m}}\ \frac{1\ \text{yr}}{365\ \text{d}}\ \frac{1\ \text{d}}{86{,}400\ \text{s}}} = 65.6\ \text{km}^2$$

$$A_{BC} = A - A_D = 9.4\ \text{km}^2$$

Conclusion and interpretation: The aquifer receives both autogenic and allogenic recharge. Spring D would be most suitable for freshwater supply, as it is not impacted by potential contaminant input from the swallow hole S and has a larger discharge. The total surface area of the required protection zone would be about 66 km^2 large.

Return to Exercise 4↥

Return to where text linked to Exercise 4↥

Exercise Solution 5

Solution:

$$Q_{\text{expl9}} \text{ during 9 wet months } = Q_{dyn} - Q_{eco}$$

$$Q_{\text{expl3}} \text{ during 3 dry months } = \left(Q_{dyn} + \frac{Q_{st}}{R_{est}}\right) - Q_{eco}$$

where:

Q_{expl9} = exploitable groundwater reserves during nine wet months expressed as a discharge rate (m^3s^{-1})

Q_{expl3} = exploitable groundwater reserves during critical three dry months expressed as a discharge rate (m^3s^{-1})

Q_{dyn} = dynamic groundwater reserves expressed as a discharge rate (m^3s^{-1})

Q_{eco} = ecological flow (m^3s^{-1})

Q_{st} = portion of static groundwater reserves expressed as a discharge rate (m^3s^{-1})

R_{est} = restricted amount of static groundwater reserves for utilization expressed as discharge rate (m^3s^{-1})

$$Q_{\text{st}} = (AH_{\text{av}}S) = 50 \text{ km}^2 \frac{1x10^6 \text{ m}^2}{1 \text{ km}^2} 120 \text{ m } (0.025) = 1.5\text{x}10^8 \text{m}^3$$

where:

Q_{st} = static groundwater reserves expressed as a volume (m^3)

A = catchment area

H_{av} = the depth from the minimal groundwater level to the base of karstification

S = storativity

10 percent $Q_{\text{st}} = 1.5\text{x}10^8 \text{ m}^3 (0.1) = 1.5\text{x}10^7 \text{ m}^3$

Static reserve volume expressed as a rate for the 90-day critical period over each of the 15 years:

$$R_{\text{est}} = \left(\frac{0.1\ V_{\text{st}}}{15\ y \frac{90\ d}{y} \frac{86{,}400\ s}{d}}\right) = \left(\frac{1.5\text{x}10^7 \text{ m}^3}{15\ y \frac{90\ d}{y} \frac{86{,}400\ s}{d}}\right) = 0.13 \frac{\text{m}^3}{s}$$

That is, 0.13 $\frac{\text{m}^3}{s}$ could be abstracted by wells (Q_{a}) during the 3-month critical period of each of the 15 years.

Then the water supply for consumers for each month is determined by starting with the dynamic reserves discharge rate for each month, adding the allowable restricted amount for each of the 3 critical months, and subtracting 20 percent of that flow so it can be used to support ecosystems as shown in Table Exercise Solution 5-1 and illustrated in Figure Exercise Solution 5-1.

Table Exercise Solution 5-1

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$Q_{dyn}=Q_s$ (m^3/s)	0.45	0.65	0.8	0.65	0.45	0.4	0.25	0.18	0.14	0.45	0.75	0.8
$Q_{st}/Rest$ (m^3/s)	—	—	—	—	—	—	0.13	0.13	0.13	—	—	—
Q_{eco}(m^3/s)=20% of Q_{dyn} + $Q_{st}/Rest$	0.09	0.13	0.16	0.13	0.09	0.08	0.076	0.062	0.054	0.09	0.15	0.16
$Q_{ws\ expl}$ (m^3/s)	0.36	0.52	0.64	0.52	0.36	0.32	0.30	0.25	0.22	0.36	0.60	0.64

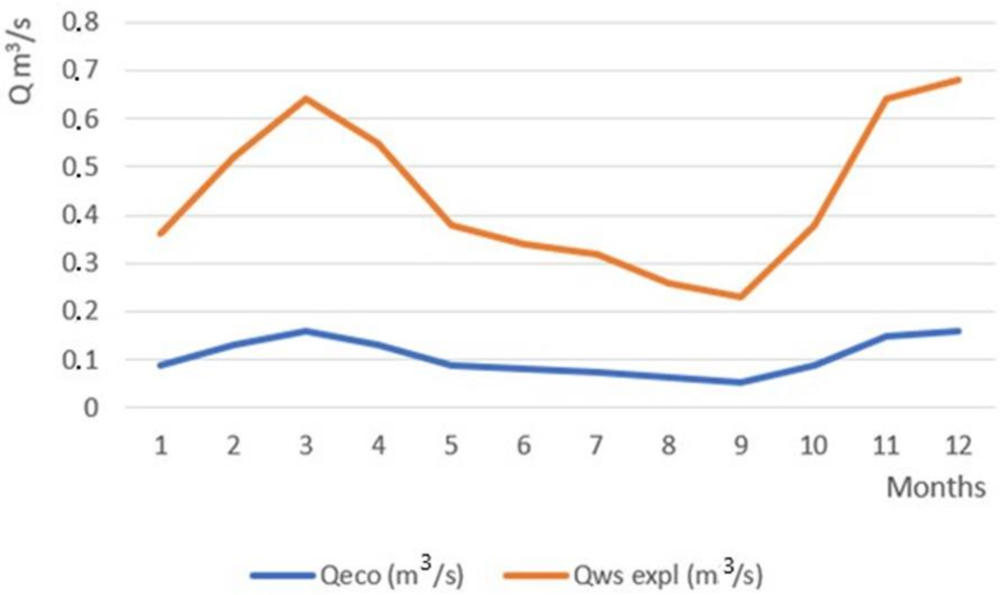


Figure Exercise Solution 5-1 - Exploitable water resources of karst aquifers.

Conclusion and interpretation: Optimal intake design (spring capture and drilled wells) and over-pumping during the critical three dry months may satisfy demands of both the local settlement (Q_{ws}) and downstream ecosystem (Q_{eco}). Pumping from the wells enabled increased *EF* (Q_{eco}) during the critical drought period. Such an aquifer regulation solution is not possible everywhere, however, and the prerequisite for its implementation is good aquifer storage and sufficient replenishment potential (recharge) to compensate the "loan" that is made.

Return to Exercise 5↥

Return to where text linked first to Exercise 5 Section from 4.2↥

Return to where text linked second to Exercise 5 Section from 4.4.2↥

Return to where text linked third to Exercise 5 from Box 28↥

Exercise Solution 6

Solution:

Pathway (s) is 5,244 m, transport velocity (v) is 95 m/h

Travel Time (t) can be estimated by

$t = s/v = 5{,}244\ \text{m}/95\ \text{m/h} = 55.2\ \text{h} = 2\ \text{days and 8 hours}$

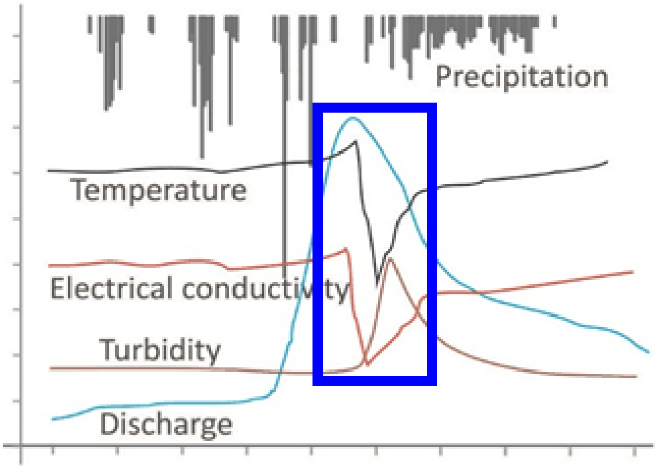
Conclusion: Contaminant can be expected to arrive at the spring within 2 days and 8 hours. In many cases, the distance is simply measured as a straight line between the input location and spring; however, the actual distance will be greater so transit time may be longer and travel time may vary from dry to wet seasons.

Return to Exercise 6↥

Return to where text linked to Exercise 6 from Section 4.3↥

Exercise Solution 7

Although each karst aquifer system is unique, an individual monitoring plan is required. Poor water quality is most likely to be detected during a flood pulse following a long dry period, which usually results first in a flushing-out of contaminants stored in the vadose zone and in flushing of material from the bed and banks of the sinking rivers. The most favourable period for sampling coincides with an increase in discharge, a change in temperature, decreased electrical conductivity, and increased turbidity as indicated during the period indicated by the blue rectangle.



Return to Exercise 7↥

Return to where text linked to Exercise 7 from Section 4.4↥

Exercise Solution 8

Solution:

$$\Delta H = \frac{V}{A\,S}$$

where:

ΔH	=	necessary rise in the height of the dam
V	=	desired volume of water
A	=	catchment area
S	=	storativity or effective porosity

$$\Delta H = \frac{30\text{x}10^6\ \text{m}^3}{50\ \text{km}^2\ \dfrac{1\text{x}10^6\ \text{m}^2}{1\ \text{km}^2}(0.06)}$$

$$\Delta H = 10\ \text{m}$$

Conclusion and interpretation: Underground reservoirs, if properly constructed and maintained, enable manipulation of stored water and their utilization in accordance with demands.

Return to Exercise 8↥

Return to where text linked to Exercise 8 from Section 4.4.2↥

11 Question Answers

Question Answer 1

The three types of porosity present in most karst aquifers are:

1. intergranular (primary) porosity,
2. fracture / fissure / bedding plane (secondary) porosity, and
3. conduit (tertiary) porosity.

The first two types are commonly referred to as *the fissured rock matrix* and modelled as a single porosity/permeability group.

Return to Question 1↥

Question Answer 2

Speleogenesis is self-amplifying because the wider the fissure, the higher the through flow; the higher the through flow, the higher the dissolution rate; the higher the dissolution rate, the wider the fissure. Therefore, the process is very slow at the beginning but then accelerates.

Return to Question 2↥

Question Answer 3

The initial fissure aperture is critically important for the breakthrough time as a wider initial fissure aperture will drastically reduce the breakthrough time (if all other parameters are the same).

Return to Question 3↥

Question Answer 4

Chalk is a rock with large primary porosity of intergranular type but with little or no effective porosity.

Return to Question 4↥

Question Answer 5

The first is the result of sedimentation in large basins in which, following sea water retreat, intensive orogeny occurred resulting in highly deformed (folded and faulted) rocks. Platform karst is characterized by less-intense tectonic movements and less-highly deformed (sub-horizontal) strata.

Return to Question 5↥

Question Answer 6

One of the common classifications is:

1. limestone karst,
1. dolomite karst,
2. marble karst,
3. chalk and marl karst,
4. gypsum-anhydrite karst, and
5. salt karst.

The first four types are carbonate karst and the last two are evaporitic karst. While all types originated in sedimentary basins, marble karst forms on metamorphosed rocks.

Return to Question 6↑

Question Answer 7

1. Europe (21.8 percent),
2. North America (19.6 percent),
3. Asia (18.6 percent),
4. Africa (13.5 percent),
5. Australia (6.2 percent), and
6. South America (4.3 percent).

Return to Question 7↑

Question Answer 8

In general, epigenic karst is the result of *top-down* karstification, whereas hypogenic karst is *bottom-up* in the sense that it is driven by rising groundwater. Epigenic karst is formed in areas where dense, compacted karst rocks crop out at the surface (*open karst*) or underlie a cover of soils and superficial deposits (*covered karst*).

In contrast, hypogenic karst is driven by upwelling fluids from hydrostratigraphically lower units. The fluids are derived either from deep sources (commonly thermal) or from distant recharge that has been confined by lower permeability units. In epigenic systems, carbon dioxide is the main driver for karstification and is dominantly produced in the soil zone. In hypogenic karstification, other acids—most notably sulfuric acid—commonly play a more dominant role than carbonic acid. Where carbon dioxide is involved, it is produced at depth by a variety of chemical and biological degradation processes.

Return to Question 8↑

Question Answer 9

The three primary groups of surface karst landforms are karren, valleys, and closed depressions (dolines and poljes).

Underground: caves.

Return to Question 9↑

Question Answer 10

Four broad types of karst valley are commonly recognized:

1. through (allogenic) valleys,
2. blind and semi-blind valleys,
3. dry valleys, and
4. pocket valleys.

Through valleys are formed by rivers that have their origins on non-karst lithologies, maintaining perennial flow through the karst to the output boundary.

Blind valleys end abruptly where a stream (usually one that has its source outside the karst area) sinks underground.

Pocket valleys (also called steepheads) are the reverse of blind valleys since they occur in association with large springs close to the margins of karst areas. They are commonly short and most form by headward recession as water from the spring undermines the rock above it, or by cavern collapse.

Dry valleys are commonly found between the points where streams sink underground and the springs where the water emerges.

Return to Question 10↑

Question Answer 11

Dropout and suffosion dolines both form in superficial materials above karstic bedrock and both form because material is transported down into the karst. However, dropout dolines form in cohesive deposits, which means that as material is lost to the karst a void grows upwards. When the void gets close to the surface the roof becomes unstable and collapses. This means that a dropout doline may have been forming for months or years before there is a spectacular collapse that takes a matter of seconds and initially has very steep sides.

In contrast, suffosion dolines form in non-cohesive materials; as these materials are transported down into the karst, a cone-shaped void forms that is open to the surface.

Return to Question 11↑

Question Answer 12

There are four main phases in the development of an epigenic cave: inception, gestation, growth, and abandonment, which is followed in some cases by destruction.

Return to Question 12

Question Answer 13

Conduit diameter (which could be represented by hydraulic radius), flow velocity, fluid density, and fluid viscosity are the parameters used to calculate the dimensionless Reynolds number (*Re*), which represents the ratio of inertial to viscous forces. Generally, the main parameter for calculation of the Reynolds number for fully saturated conduits is the flow velocity. The Reynolds number changes during a storm event: as the velocity increases, the value of *Re* increases. In partially saturated conduits, the hydraulic radius will also change during storm events.

The critical *Re* is the characteristic value of the *Re* for a conduit shape where below that value flow is laminar and above that value flow is turbulent. Additionally, conduit roughness and tortuosity also influence the onset of turbulence. Increased roughness and tortuosity reduce the critical Reynolds number for the conduit and thus the onset of turbulence occurs and lower velocities.

Return to Question 13

Question Answer 14

Most single continuum distributed parameter groundwater models are based on Darcy's law and simulate laminar flow though porous media. However, if these models consider the special features of karst—such as heterogeneity and anisotropy—and if turbulent flow through conduits is not a factor for longer stress periods, they may be useful for water supply problems. They can be improved by including high-permeability cells or discrete conduits in the model and incorporating turbulence if necessary (Kuniansky et al., 2022).

Return to Question 14

Question Answer 15

Time of first detection, peak time, and peak concentration can be directly obtained from the BTC. Recovery is obtained by multiplying the area below the BTC by discharge. Mean transit time can be approximated by the time when half of the tracer is recovered. Apparent velocities are obtained by dividing the distance from injection site to recovery point by the respective transit times. More advanced parameters such as dispersion and retardation can be obtained by modeling.

Return to Question 15

Question Answer 16

Tracer recovery is a very important result of a tracer test but can only be calculated if discharge data are available (recovery = area below the BTC multiplied by discharge).

Return to Question 16

Question Answer 17

Tracer recovery and relevant transport parameters can only be obtained if the complete BTC is available.

Return to Question 17

Question Answer 18

One hundred percent recovery means there is a straightforward connection between the injection site and the spring without bifurcation or any other drainage locations. In most karst system, the drainage system is complex, and not all discharge locations are accessible. Furthermore, degradation and other processes can cause loss of tracer. Therefore, complete recovery is an exception.

Return to Question 18

Question Answer 19

Autogenic recharge comprises rain and snow that has fallen onto an area where karst rocks crop out at the surface or are present beneath a soil/sediment cover. Allogenic recharge comprises rain and snow that has fallen onto non-karst rocks and enters the karst either via a sinking stream or as percolation through a permeable caprock.

Return to Question 19

Question Answer 20

There are descending (gravity) springs and ascending (artesian) springs.

Return to Question 20

Question Answer 21

The two most frequently applied drilling techniques are: 1. rotary drilling and 2. down-the-hole hammer. In direct rotary drilling, the drilling fluid is pumped down the drill rod and through the bit, while drilling with a hammer in hard rocks is faster and requires use of air or foam for cooling and removing particles. The combination of these two—hammer drilling with small rotation—produces the best results by far in the drilling of limestones.

Return to Question 21

Question Answer 22

$$\mathrm{CaCO_3 + CO_2 + H_2O = Ca_2 + 2HCO_3^-}$$

Return to Question 22

Question Answer 23

Chemical impurities increase solubility because they destabilize the crystal lattice. Mineralogical impurities decrease solubility; rocks with more than 25 percent of insoluble components are generally not karstifiable. However, karstic groundwater circulation is possible even at lower purities.

Return to Question 23

Question Answer 24

Autochthonous turbidity is caused by the remobilization of sediments from inside karst conduits due to a hydraulic pressure pulse at the beginning of a high-flow event. Allochthonous turbidity at a spring indicates the arrival of freshly infiltrated water from the soil and sinking streams. Therefore, it often coincides with high levels of organic carbon and faecal bacteria.

Return to Question 24

Question Answer 25

$$\text{Recharge} = \text{Discharge} + \Delta\text{Storage (i.e., Groundwater Reserves)}$$

$$P + I_s + I_g = R_f + E_t + E_g + Q_s + Q_{sb} + Q_a + \Delta S \ + E$$

where:

P	=	volume precipitation in autogenic part of the basin
I_s	=	volume of surface inflow from allogenic part of the basin or another catchment
I_g	=	volume of groundwater inflow from adjacent catchments including hypogenic flow
R_f	=	volume of runoff from the autogenic part of the catchment
E_t	=	volume of evapotranspiration
E_g	=	volume of evaporation where groundwater body is exposed at the surface
Q_s	=	volume of spring discharge
Q_{sb}	=	volume of groundwater discharge to adjacent catchments
Q_a	=	volume of artificial withdrawal such as extraction from wells
ΔS	=	change in groundwater storage
E	=	error, a positive value indicates volume of inflow exceeds volume of outflow

Return to Question 25↥

Question Answer 26

1. To calculate static water reserves:

$$Q_{st} = A\,H_{av}\,S$$

where:

Q_{st}	=	volume of static groundwater reserve
A	=	surface area
H_{av}	=	saturated thickness below the minimal groundwater level
S	=	storativity of the deeper part of the karstic aquifer

2. To determine the exploitable reserves concerning demands of water dependent ecosystems:

$$Q_{expl} = Q_{dyn} - Q_{eco}$$

where:

Q_{expl}	=	discharge of exploitable groundwater reserves
Q_{dyn}	=	discharge of dynamic reserves
Q_{eco}	=	ecological flow, i.e., discharge required for water dependent ecosystems

Return to Question 26↥

Question Answer 27

The types of organized monitoring are:

1. manual (spot measurements are made by an observer);
2. semi-automatic (an instrument is used to collect and store data, but it must be downloaded by an observer);
3. fully automated (the data logger can be interrogated remotely removing the need for an observer to visit the site); and
4. remote sensing using satellite imagery.

Return to Question 27↥

Question Answer 28

The four major engineering interventions that aim to regulate groundwater flow in a discharge zone are:

1. over-pumping the spring,
2. drilling wells or other supplementary intakes,
3. constructing a subsurface (underground) reservoir, and
4. artificial recharge.

Return to Question 28↥

Question Answer 29

Sanitary protection zones are legally defined areas of a catchment of a water source where restrictive measures are taken at various levels to limit or prohibit activities that could threaten the quality of the water source. In karst, in addition to velocity and distance criteria, delineation of sanitary protection zones should consider the characteristics of water flow in karst such as:

- the role of protective layers,
- the heterogeneity and complexity of groundwater recharge (for example, concentrated recharge from sinking allogenic streams and in dolines), and
- changes in the velocity and direction of water flow under different hydrologic conditions.

Return to Question 29↥

Question Answer 30

The characteristics of groundwater flow in karst areas are such that sampling at regular intervals (for example, every month) may not necessarily provide representative values for the water quality. The quality of karst water at springs changes most significantly following recharge events. Therefore, monitoring of karst water quality should be undertaken during periods of more intense or prolonged precipitation when the most intensive washing of material from land and contaminant transfer occurs. After prolonged dry periods, it is advisable to sample water quality shortly after precipitation, as this is when very rapid deterioration in quality is expected.

Return to Question 30↥

Question Answer 31

Karst aquifers are highly vulnerable to contamination because they are characterized by rapid recharge and rapid transmission. Rapid recharge via sinking streams, dolines, or directly into areas with thin or no soil cover, is not filtered in contrast to diffuse recharge through a soil cover, which acts to remove contaminants. Water flow in karst is commonly conduit dominated, rapid (up to several hundred metres per hour), turbulent, and strongly influenced by the heterogeneous permeability of the aquifer. The general lack of overlying layers, the high velocity of water flow in karst, and the concentration of flow through conduits, fissures, and voids are reasons why contaminants chemically, biologically, or physically cannot be degraded. Due to the complexity of the interrelationships and the extreme changes in the various hydrological conditions, the course of underground water in karst is difficult to predict, although water tracing can be used to establish linkages.

Return to Question 31↥

Question Answer 32

The concept of vulnerability mapping or assessment was developed to identify those areas of the groundwater catchment that need the greatest protection and to optimize land use in the catchment areas of captured water sources. It assumes that the natural protection of the hydrological system from contamination varies according to differences in the intrinsic characteristics of the environment. The assessment encompasses the geological, hydrological, hydrogeological, and other natural characteristics of a karst system and is independent of the characteristics and behavior of individual contaminants. Depending on the purpose, two types of vulnerability assessment are available: for resources (i.e., the aquifer water) and for sources (e.g., a well or spring).

Return to Question 32↥

Question Answer 33

Several different methods have been developed for assessing and mapping the vulnerability of karst aquifers, considering differences among karst aquifer systems, accessibility of data, and economic opportunities. These methods have been widely used and tested at various test sites around the world. The EPIK method, the COP method, and the Slovene approach are commonly used. The methods are based on information about the soil and unsaturated zone, recharge conditions, and other characteristics of the aquifer.

Return to Question 33↥

Question Answer 34

Biosphere Reserves, UNESCO Global Geoparks (UGGp), and World Heritage Properties are designated by UNESCO, but Ramsar Sites (RS) are designated by an International Convention with UNESCO as Custodian.

Return to Question 34↥

12 Notations

Parameter dimensions are dark green font with mass as M, length as L, time as T)

A = catchment area supplying recharge (L^2) typically km^2

A_{aq} = aquifer surface area (L^2) typically km^2

α = recession coefficient (T^{-1}) typically $days^{-1}$

ΔS = change in aquifer storage (L^3) typically m^3

E = budget error (L^3) typically m^3, a positive value indicates inflows exceed outflow

E_g = volume of groundwater evaporation where the groundwater body is open to the surface (L^3) typically m^3

E_t = volume of evapotranspiration (L^3) typically m^3

ET = evapotranspiration rate (LT^{-1}) typically mm/day

H_{av} = average thickness of saturated part of an aquifer (L) typically m

H_{st} = saturated thickness below minimal groundwater level (L) typically m

I_e = average global effective recharge in karst from precipitation (dimensionless)

I_{ef} = effective aquifer recharge as a percent of precipitation (dimensionless)

I_s = surface inflow via streams with their headwater in the allogenic part of the catchment (L^3T^{-1}) typically m^3/s

I_g = groundwater inflow from adjacent catchments including allogenic water from sinking streams and hypogenic inflow (L^3T^{-1}) typically m^3/s

P = precipitation (L) typically mm

Q_a = discharge of artificial withdrawal such as well extraction (L^3T^{-1}) typically m^3/s

Q_0 = initial discharge at the beginning of a recession period (L^3T^{-1}) typically m^3/s

Q_{dyn} = dynamic reserve expressed as annual discharge rate (L^3T^{-1}) typically m^3/s

$Q_{eco}(EF)$ = discharge required to maintain water dependent eco-systems (L^3T^{-1}) typically m^3/s

Q_{expl} = exploitable reserve expressed as annual discharge rate (L^3T^{-1}) typically m^3/s

Q_s = spring discharge (L^3T^{-1}) typically m^3/s

Q_{sb} = subsurface discharge (underground outflow to adjacent aquifers) (L^3T^{-1}) typically m^3/s

$Q_{(t)}$ = discharge at the end of recession episode (L^3T^{-1}) typically m^3/s

Q_{st} = volume of static groundwater reserve (L^3) typically m^3

Q_{tot} = total discharge or yield abstracted from the wells (L^3T^{-1}) typically m^3/s

Q_{ws} = discharge for drinking water supply (L^3T^{-1}) typically m^3/s

R = autogenic recharge rate (L^3T^{-1}) typically m^3/s

R_{est} = restrictive use of static groundwater reserves (L^3T^{-1}) typically m^3/s

R_f = runoff generated in the autogenic part of the catchment (L^3T^{-1}) typically m^3/s

S = storativity, the fractional volume of water released from a unit area of aquifer per unit decline of hydraulic head (dimensionless)

t = duration of recession (T) in days

V = total volume of water discharged by the springs and abstracted from the well (L^3) typically m^3

13 About the Authors

Zoran Stevanović is a retired Professor and Head of the Centre for Karst Hydrogeology at the Department of Hydrogeology of the University of Belgrade - Faculty of Mining & Geology, Serbia. He is a consultant to the United Nations organizations FAO (Food and Agriculture Organization) and UNESCO (United Nations Educational, Scientific and Cultural Organization) with extensive international experience in implementation of projects involving hydrogeological exploration, groundwater management, aquifer utilization and protection in North and East Africa, the Middle East, and Balkan countries. He is also an invited lecturer and participant in many international cooperative research programs. Dr. Stevanović has published more than 350 papers, four textbooks, and authored and edited 20 monographs including *Karst aquifer - Characterization and Engineering* (Springer, 2015) and *Karst Without Boundaries* (CRC, 2016). He served as Chair of the IAH (International Association of Hydrogeologists) Karst Commission and is the Co-Chair of the Board on Karst and Speleology of the Serbian Academy of Science and Arts. He is Past President of the Serbian Geological Society. He is a member of the Scientific Society of Serbia, a corresponding member of the Academy of Engineering Sciences of Serbia, an honorary member of the Hungarian Geological Society, and a member of the Bulgarian Geological Society. Dr. Stevanović is the recipient of several awards.

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Nico Goldscheider is professor for hydrogeology at the Karlsruhe Institute of Technology (KIT) in Germany. He studied geology and geoecology in Karlsruhe and completed his PhD in karst hydrogeology in 2002. Subsequently, he was lecturer and researcher at the Centre of Hydrogeology in Switzerland (2002-2010), and professor for hydrogeology and geothermics at Technical University Munich (2010–2011), until he was appointed at KIT in 2011. His research includes karst and alpine hydrogeology, tracing techniques, groundwater quality and management, and microbiological and ecological aspects of groundwater. From 2009 to 2017, he served as chair of the IAH Karst Commission. In 2017, he accomplished the World Karst Aquifer Mapping (WOKAM) project, and he is leader of an international project on karst water resources in the Mediterranean area (KARMA, 2019–2023). He has served as associate editor, editor-in-chief and guest editor of several journals, has published an international textbook on karst hydrogeology, several book chapters, and more than 120 scientific papers. Since 2022, he has been chair of the German Hydrogeology Association (FH-DGGV).

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