

Recent advances in karst research: from theory to fieldwork and applications

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Abstract: Karst landscapes and karst aquifers, which are composed of a variety of soluble rocks such as salt, gypsum, anhydrite, limestone, dolomite and quartzite, are fascinating areas of study. As karst rocks are abundant on the Earth's surface, the fast evolution of karst landscapes and the rapid flow of water through karst aquifers present challenges from a number of different perspectives. This collection of 25 papers deals with different aspects of these challenges, including karst geology, geomorphology and speleogenesis, karst hydrogeology, karst modelling, and karst hazards and management. Together these papers provide a state-of-the-art review of the current challenges and solutions in describing karst from a scientific perspective.



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Karst describes the slow work of dissolution exerted by water, enriched with carbon dioxide, on soluble rocks such as carbonates, evaporites and halite (White 1988; Ford & Williams 2007; Palmer 2007). Morphological effects at the surface are represented by a variety of typical landforms, the most typical being dolines and sinkholes. Below the surface, conduits of different sizes are formed by the dissolution of the soluble rocks, leading to a network of voids, of which the parts large enough to be explored by humans are defined as caves.

The term karst stems from the German derivation of the local name of the region between Italy and Slovenia (*Carso* in Italian, *Kras* in Slovene). This region is the site where the discipline of karstology was born at the end of the seventeenth century. The work of scholars such as Cvijić (1893) greatly contributed to the introduction of the term karst in the international literature. The importance of the wider region, namely the Dinaric karst area, is recognized by the use of many local terms that have become accepted in international karst terminology – for example, doline, polje, uvala and ponor (Stevanović & Mijatovic 2005).

According to recent estimates (Chen *et al.* 2017), c. 14% of the Earth's land surface consists of the carbonate rock outcrops that form karst. In Europe, much of the karst occurs beneath some of the continent's most densely populated regions, where

effective water resource management is especially crucial, such as England, northern and southern France, parts of Germany, central Italy, eastern Spain and large parts of the Mediterranean. On other continents, such as in the Middle East and Central Asia, karst terrains occupy c. 25% of the land surface. These karst terrains often host primary economic benefits, such as drinking water and building materials. Karst areas are valuable ecosystems and have high levels of biodiversity (Brancelj & Culver 2005; Pipan & Culver 2013). The numerous caves and other natural phenomena have played an important part in stimulating tourism, contributing to economic development in many countries (Ravbar & Šebela 2015).

Karst landscapes are of great importance because they host remarkable natural resources, including karst aquifers. Karst water resources have been important in the historical and economic development of many regions (Parise & Sammarco 2015) and karst groundwater is of crucial importance today for the sustainable development of the economy in many countries and regions. Karst aquifers currently supply c. 15% of the global population with drinking water and, in some regions, are the only water resource available.

Looking to the future, there are many concerns about karst regions. The predicted growth in population, which will mostly be concentrated in urban

areas, will increase pressures on karst aquifers in terms of the global supply of water, although such an increase might be partly mitigated by improvements in treatment technologies for tapping water from sources other than karst.

As a result of the peculiar intrinsic characteristics of karst and its specific processes, these resources are particularly susceptible to destruction and over-exploitation. The utilization of karst resources and populations living on karst landscapes pose specific scientific and practical challenges. There are many unresolved theoretical problems in karst processes, water flow, and mass and heat transport. The efficient and safe exploitation of geothermal resources from karst systems also needs novel practical solutions.

Following the 2007 Special Publication of the Geological Society, London, *Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis and Mitigation* (Parise & Gunn 2007), this volume deals with the most recent advances in karst research and presents an updated state-of-the-art source of the main scientific activities currently taking place in this peculiar and vulnerable environment.

This volume presents the outcomes of several sessions dealing with karst held in the last few years on the occasion of the General Assembly of the European Geosciences Union. It is designed to provide readers with an overview of studies in the peculiar and highly fragile karst environment. The volume presents a collection of papers, subdivided into four sections (karst geology, geomorphology and speleogenesis; karst hydrogeology; karst modelling; and karst hazards and management), to provide a balanced overview of the diverse approaches available to elucidate the current hot topics in karstology. It includes both theoretical models and case studies and consists of 25 papers prepared by researchers from 14 countries, covering karst areas located in 16 countries. By integrating geomorphological, speleological, hydrogeological, geochemical, geophysical and engineering geological approaches, it provides readers with new insights into the subject of comprehensive karstology and reveals important links between surface and subsurface processes and between the karst environment and society. Geologists, engineers and geophysicists interested in karst from both academia and geological or engineering consulting companies will find papers of interest. The fourth section, partly dedicated to management of karst, will be of interest to land planners, developers, and managers of show caves, natural parks and reserves in karst terrains.

Karst geology, geomorphology and speleogenesis

Karst landscapes are known worldwide for their beauty and high aesthetic value, typically expressed

by spectacular surface geomorphology and subterranean features visible in caves. Show caves are often among the most visited tourist sites in many parts of the world, which has led to karst landscapes being known by a wide range of people.

There has been much interest in karst research in recent years, from many different disciplines. Caves have been recognized as sites where remarkable remains and deposits are preserved (Sasowsky & Mylroie 2004), in contrast with the outside environment (the Earth's surface), where the same features are generally destroyed by a combination of natural (e.g. weathering, erosion or mass movements) and anthropogenic processes. The biodiversity of karst is progressively being recognized as of extreme importance and several studies involving experts in biology, medicine, astrobiology and planetary geology have started, with the aim of exploring the bacteria and other species living in difficult environments and under peculiar climatic and environmental conditions (Boston & Northup 2017). Many cave expeditions and explorations, in some of the most important cave systems in the world, are now carried out through the joint action of speleologists and karst and cave scientists. New technologies, such as LiDAR scanners, allow the high-resolution scanning of underground channels and their morphology. These areas of research have resulted in the acquisition of large amounts of data and many scientific publications in the last few decades and there has been a growing number of congresses dedicated to karst research and speleology at both national and international levels.

The cave environment has been recognized as a potential platform to create analogues for space exploration missions and caves are ideal sites for training astronauts (Fig. 1). The European Space Agency has developed a specific training programme and many astronauts from different space agencies around the world have been trained in caves over the last five years (Bessone *et al.* 2017).

The study of karst landscapes and their features is not just of interest in karst science, but has significant implications in many other fields. The multidisciplinary nature of karst studies is expressed by the number of workers from many different fields of science who are interested in carrying out research in this extraordinary environment.

Karst is relevant to oil research because carbonate rocks may host significant reservoirs of high economic importance. Many studies are being carried out to improve our knowledge of the economic aspects of karst. Karst-type reservoirs have been encountered in different parts of the world and consist of carbonate and evaporite formations with evidence of pervasive dissolution and cave formation, followed by infilling and collapse during subsequent burial (e.g. Wang *et al.* 2015; Uni Research 2016).



Fig. 1. Astronaut training at Su Benti cave (Sardinia, Italy) during the camp CAVES 2014 organized by the European Space Agency. Progression on ropes presents many operational and safety protocol analogies with extravehicular activities. Credits: European Space Agency/S. Sechi.

Palaeokarst reservoirs are difficult to characterize due to their extreme contrasts in porosity and permeability and their variability over short distances. Their analyses therefore require very detailed studies.

Linked to the issue of palaeokarst reservoirs, the first paper in this volume, by **Broughton (2017)**, reviews the origin and distribution of the regional-scale dissolution patterns that reconfigured the Middle Devonian Prairie Evaporite Formation salt basin in northeastern Alberta and southern Saskatchewan and interprets the impact of continental-scale tectonism on these dissolution processes. The dissolution trends in the formation strata accumulated across Western Canada resulted in the largest known hypogene halite karst collapse and subsidence structures. The structural configuration of the collapse subsidence features in the strata overlying the areas of salt removal resulted in traps that accumulated migrated oil in areas of northern Alberta and southern Saskatchewan (**Holter 1969**; **Hein et al. 2001**). These dissolution patterns exerted controls on the distribution of reservoirs accumulated as the Athabasca Oil Sands in northeastern Alberta. This is the largest, and commercially the most important, of the three Cretaceous bituminous sand deposits in

northern Alberta, with 45 000 km² of deposits accumulated as a hydrocarbon resource of 2×10^{11} m³ or of 10^{12} barrels. The highly detailed reconstruction of the removal of halite salt beds and the resulting collapse subsidence structures, emplaced against near-vertical normal fault planes between adjacent differentially subsided fault blocks, controlled the distribution, alignment and migration of trapped oil in this area.

In addition to the economic aspects of karst research, the analysis of karst features and landforms may offer insights into other sectors of the earth sciences. A good example is represented by the contribution of **Klimchouk (2017)**, dedicated to tafoni and honeycomb structures, which are some of the most enigmatic and puzzling geomorphological phenomena. Through the example of tafoni and honeycomb structures in the Crimean Piedmont, **Klimchouk (2017)** interpreted these features as related to hypogene karstification, with their formation being predetermined by the alteration of the host rocks along fractures and karst conduits by focused rising flow. The characteristic morphological expression occurs through the removal of the alterite, which may be the result of speleogenesis in subsurface conditions or exposure to atmospheric weathering. From these

observations, **Klimchouk (2017)** proposes a new conceptual model for the formation of cavernous features, which could be applicable to other regions and to a wide range of lithologies. The proposed model also resolves the major issues inherent in previous interpretations of cavernous features, offering general applicability and important implications that go well beyond the reach of karst scholars and may also be of interest in geodynamic and palaeohydrogeological reconstructions.

The observation of karst landforms, both at the surface and underground, and the related surveys and data interpretation are often not a simple task because of problems with access and logistics and the presence of a dense cover of vegetation and/or rugged topography. The situation is even more difficult underground and specific expertise is required to survey the subterranean environment safely. A variety of logistical problems and difficulties in carrying and using delicate instruments and equipment in peculiar environments, characterized by high humidity and low temperatures, has always been at the origin of the inaccuracies in many past surveys. On more than one occasion this has resulted in wrong assumptions and conclusions based on incorrect cave surveys (**Martinucci & Parise 2012**). Nevertheless, both speleological documentation and more general surveys of karst areas are of extreme importance in providing the necessary data to better understand the landforms produced by karst processes, their evolution, and the interactions between surface and subsurface forms.

Recent advances in technology, with the availability of low-cost and light instruments, has enabled highly detailed surveys to be carried out, even in deep caves and difficult environments. It is now possible to check previous surveys in a short period of time, to verify their reliability and accuracy, and to correct previous biases. The paper by **Petrović *et al.* (2018)** is an example of this approach and reports the analysis of karst valleys, through-caves and natural bridges in the Carpatho-Balkan Mountains of eastern Serbia through the use of terrestrial laser scanning.

Analysis of the available data concerning the distribution and characteristics of caves is an indispensable tool in understanding the development and evolution of karst. The most common documents available for caves are maps, photographs and reports. Their reliability may not be high, however, especially for maps compiled decades ago, when the use of simple instruments to survey caves was common. Nevertheless, such documents represent the main tools through which cavers have been able to transfer information about the underground world to people who, for a variety of reasons, do not or cannot enter the cave. It is therefore interesting to critically analyse these documents, verify their

validity and use them in the correct way. This latter point is essential when dealing with the use of cave maps by practitioners, planners and local managers.

The paper by **Oberender & Plan (2018)** presents a classification of caves based exclusively on genetic processes, which is made possible through the use of cave maps, photographs and reports. Three types of cave are distinguished in this classification: solution caves, mainly formed by the dissolving action of underground water; mechanical weathering and erosion caves; and deposition caves. Applying this classification to a dataset of >6000 caves in eastern Austria, **Oberender & Plan (2018)** found that mechanical weathering and erosion caves are almost as common as solution caves, an unexpected result because the vast majority of analysed caves are developed in carbonate rocks. Such a classification, based on available cave documents, can be applied to a large number of caves within a reasonable time. It can also be used by decision-makers non-specialized in cave genesis as an indicator of natural phenomena, such as erosion and mass movements, or of vulnerable karst areas, thus providing important insights to non-cavers.

Surveys play a crucial part in the production of documentation about karst. However, before starting surveying, any karst scholar, or any speleologist, has first to identify the specific features to explore, map and study. The peculiarity of karst landscapes, which may show an uninterrupted series of landforms such as dolines, swallow holes and blind valleys, may sometimes lead to an under-evaluation of some elements in the landscape, which may have provided remarkable insights for the understanding of complex karst systems. In this regard, recent work in southern Italy has shown the importance of mapping and taking into consideration even small-sized karst landforms. **Parise & Benedetto (2018)** describe a small swallet in Apulia (SE Italy), which at the ground surface looks like a simple site of infiltration of water during heavy rainstorms. After several weeks of excavation, with the permission of the landowner, access was found to a remarkable underground system, reaching the deep water table at -260 m depth and going down for several tens of metres underwater, as documented by speleodiving exploration. This cave is the deepest in Apulia and, with a total depth of -324 m, represents an open window on the water table and is a perfect site at which to carry out hydrogeological investigations and to monitor groundwater quality.

A crucial element in karst is the direct connection between the surface and the underground, from which the importance of speleological explorations and research stems. Many international expeditions and explorations in recent years have combined their exploratory goals with research aims. A good example, which also involves the management of a

show cave, is presented in the paper by **Badino et al. (2018)**.

Show caves have a great variety of different management plans, from high-impact activities dedicated to tourists in caves, to simple visits with minor changes to the natural environment. The latter situation relates to only a small number of show caves worldwide, but some are worth mentioning. For instance, the Puerto Princesa Underground River, one of the largest caves in the Philippine Islands, is the most visited show cave in the country, with c. 300 000 visitors each year. The cave, which is a UNESCO World Heritage Site, is a highly protected National Geological Monument and was declared as one of the New Seven Wonders of Nature in 2012. The cave has undergone no adaptation to tourism because it was appointed as a Natural Park and World Heritage Site before its first part was opened to large flows of tourists. As a consequence, safeguarding it has always been the main concern of local and national authorities and the cave has remained well preserved in its natural state. It is also of great scientific value, which primarily relies on the fact that it is one of the largest known underground estuaries in the world, with the effect of tides visible along >7 km of the cave length. As a consequence, the complex relationships between seawater and freshwater influence not only the hydrodynamics of the system and the speleogenetic processes presently active, but also its climate and ecosystem.

Badino et al. (2018) describe some of the exploration and research carried out in this coastal karst, focused on understanding the speleogenesis of the system, notably the initial phreatic solution followed by vadose erosion with periodic marine invasion, followed by saline–freshwater mixing processes during sea-level highstands. Research has also covered aspects such as speleothem analysis, mineralogy, the analysis of palaeontological remains and biospeleology, with two large populations of bats and swiftlets sustaining a highly complex subterranean ecosystem.

Coastal karst is of great interest for a variety of reasons, including, but not limited to, tourist pressure along karst coastlines, the mixing of freshwater and seawater (leading to the possibility of marine intrusion problems), coastal evolution related to the development of karst processes and interactions with marine processes, such as wave action.

In this setting, flank margin caves (**Carew & Mylroie 1995; Mylroie & Mylroie 2007; Mylroie 2013**) are excellent indicators of sea-level position at the time of their formation because the boundary between brackish and freshwater is intimately tied to sea-level position. They form in the distal margin of the freshwater lens within a carbonate island and remain as viable terrestrial signatures of old sea-level

highstands, which may not be registered in other records such as fossil coral reefs.

Mylroie & Mylroie (2017), with the example of Guam, the largest island in Micronesia in the west Pacific, examine karst denudation on eogenetic carbonate coasts and how such denudation affects the interpretation of tectonic uplift and glacio-eustatic sea-level change. The speed at which flank margin caves form makes them reliable indicators of sea-level position, even when the sea-level is stable at a given elevation for only a few thousand years. These caves also persist through time, far longer than bio-erosion notches, sea caves and other surface features used to assess sea-level position. Flank margin caves are therefore a high-resolution and long-lasting indicator of sea-level position.

Moving to completely different climatic settings, the development of karstification in arid and semi-arid regions is generally constrained by water scarcity. In these peculiar climatic conditions, studying relict hypogene karst may be of great interest in understanding the past palaeohydrology and palaeoclimate. Ashalim Cave, a maze cave in the NW Negev Desert of Israel, is dealt with in two papers in this volume. **Frumkin & Langford (2017)** discuss the hypogene karst features of Ashalim Cave and of neighbouring caves. These features are shown to have developed as a result of the mixing of two types of groundwater flowing in opposite directions within two tiers of Cretaceous rock aquifers. Ashalim Cave can be considered as a window to understanding past groundwater flow in a desert zone, in which the groundwater flow was recharged a long distance away. Some similarities can be observed with the present situation because the general flow in the Ashalim region today seems similar, notwithstanding the drop in groundwater level.

Another field of importance for studying caves is palaeoclimatology. Speleothems provide one of the most valuable archives of palaeoclimatic data because of their ability to be dated with high precision and accuracy and the potential for high-resolution stable isotope records. **Vaks et al. (2017)** report the timing of humid periods from the speleothems record at Ashalim Cave, where the annual mean precipitation is 100–120 mm. No speleothem deposition is currently occurring, but the existence of old speleothems in the cave shows that water seeped into it in the past. The speleothems of Ashalim Cave in the central Negev Desert record humid periods during the last 3.1 myr, equivalent to an annual precipitation of >300 mm in an area that is currently a desert. The speleothem deposition record of Ashalim Cave, although more intermittent than that in caves further to the north, appears to be similar to other caves of the central Negev Desert and this has allowed the reconstruction of the palaeoclimate of the northern Saharan–Arabian desert margin.

Karst hydrogeology

Karst aquifers often provide abundant groundwater reserves, which are invaluable resources relevant to human health, food security and industry. The importance of aquifers with karst permeability, which already supply around a quarter of the global demand for drinking water, is increasing (Bakalowicz 2005; Ford & Williams 2007). In particular, groundwater in the Mediterranean basin is generally more abundant in karst than in other aquifers and has been extensively exploited. Five European capitals use water from large karst springs for drinking purposes: Rome, Sarajevo, Tirana, Skopje and Podgorica. Many of the major Alpine cities, such as Vienna, with a population of >1.5 million, are supplied by high-quality karst water derived from the Lower Austrian–Styrian Alps nearly 200 km away (Fig. 2). Vienna is supplied with 400 000 m³ of fresh spring water daily, which, on its way to the city, flows through hydroelectric power stations, generating 65 × 10⁶ kW h of power (Plan 2009).

In some countries, such as Slovenia, Croatia and Austria, karst water sources supply about half of the drinking water needs of the population. Many karst springs contribute to surface waters and play a major part in maintaining aquatic ecosystems and wetlands. Some of these springs discharge large amounts of water. The highest number of springs regularly discharging >2 m³ s⁻¹ are found

in Bosnia-Herzegovina and Turkey (eight springs in each), followed by Montenegro (five springs; Fig. 3). These aquifers are increasingly threatened by numerous environmental problems such as pollution, over-exploitation and the effects of climate change (Stevanović 2015).

The management of karst aquifers and their water resources is confronted by many problems related to heterogeneity and the locally high permeability of karst. This results in difficulties in defining the boundaries of karst catchments (Gunn 2007; Parise 2016), uncertainties in determining their highly irregular discharge regimes (Price *et al.* 2000; Stevanović 2015) and a high vulnerability to pollution (Zwahlen 2004; Goldscheider & Drew 2007; Parise & Gunn 2007), making karst aquifers much more problematic than any other aquifer type. For example, the origin of the Danube is at the confluence of the two streams Brigach and Breg outflowing as karst springs. Near Immendingen and Fridingen, the water of the Danube sinks into the river bed in various places. The Danube loses about 6 m³ s⁻¹ of its flow into river bed sinks and this water rises from the Aach Spring, 12–18 km away and 135–175 m lower, at the head of a major tributary to the Rhine, causing bifurcation at the North Sea–Black Sea watershed (Käß *et al.* 1996; Fig. 4).

Similar flow bifurcations can be observed in many places of the Classical Karst area in Slovenia, located on the Adriatic–Black Sea watershed. The

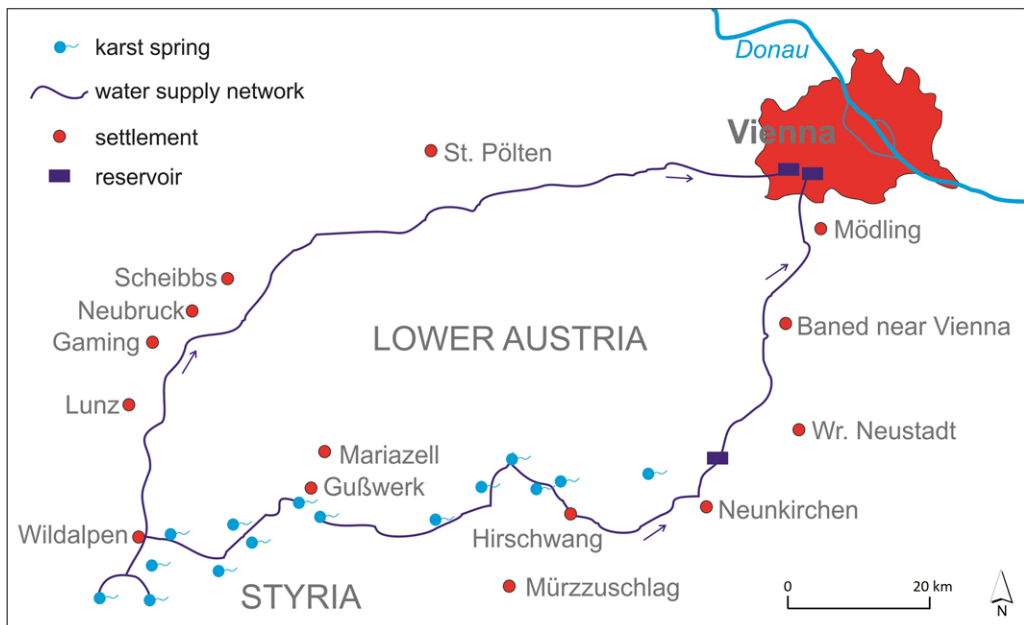


Fig. 2. Vienna is supplied with drinking water from karst springs nearly 200 km away via two long-distance mains. Modified from Vienna's Water Supply (2016).



Fig. 3. Sopot spring, located in Boka Kotorska Bay (Montenegro), has a discharge $>50 \text{ m}^3 \text{ s}^{-1}$ at high water. Photograph courtesy of Natasa Ravbar.

drainage of the Javorniki-Snežnik karst massive, which is recharged by rainwater and snowmelt, is also affected by great variabilities in flow characteristics and these are a function of the specific hydrological conditions (Fig. 5).

The geomorphological features acting as preferential pathways of intensive groundwater circulation, with turbulent flow in karst conduits and caves, and the extreme irregularity in the pattern of karst water resources, which are unequally distributed throughout the year, are at the origin of the many uncertainties existing in karst. Monitoring systems are necessary to fully understand the regime of karst aquifers and springs. This is a particular requirement in those areas supplied by karst water

sources where a shortage of water may occur during the summer season, often as a result of increased demand from tourists. This might have consequences for the reserves of the spring, putting its minimum discharge in danger.

Deepening our knowledge about flow and storage mechanisms, and better protection and management of karst water resources, are currently the most important issues in karst hydrogeology. There is therefore a need to revise the European Water Framework Directive by 2019 (Voulvoulis *et al.* 2017) and to find the best solutions to the problems of water supply authorities.

Among major societal goals are the need to maintain the high quality of drinking water, to protect it

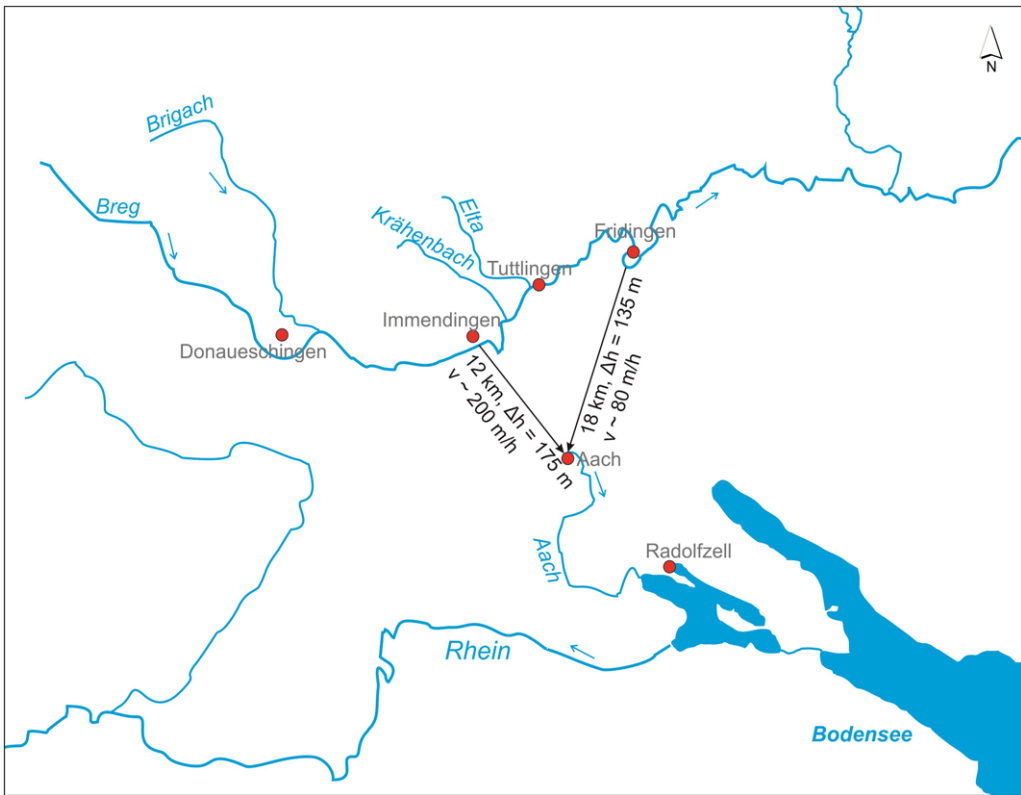


Fig. 4. The Danube River is associated with the Danube–Aach karst system of sinking and reappearing water.

from contamination and to ensure reliable access. This latter issue is affected by the great and diverse challenges of the characteristics of karst aquifers. **Stevanović (2018)** reports that an estimation and verification of groundwater reserves and their potential for replenishment can only be reached through a precise knowledge of the regional and local geological and hydrogeological properties. These include many different, not easily determined, parameters, such as the aquifer geometry, the groundwater table and the thickness of the saturated zone, the permeability, the storativity and the availability of water (reserves). Data from the systematic monitoring of groundwater quantity and quality and long-term pumping tests are also required and should be integrated with data on climate, hydrology and vegetation.

Most water in karst aquifers is transported through a network of solution conduits, which evolve as a result of the dissolution of the host rock along discontinuities in primary fissured aquifers (**White 1988, 2002; Worthington 2009; Kaufmann et al. 2012; Fig. 6**). Karst aquifers are characterized by fast diffuse and concentrated

infiltration, high heterogeneity and anisotropy, mainly conditioned by the position of conduits, and fast transport from inputs to the springs (**Jones & White 2012**). Unfortunately, too many of these are contaminated by nitrates and pesticides (e.g. **Liu et al. 2006; Huebsch et al. 2014; Musgrove et al. 2016**) and even less knowledge is available on pollution by emerging chemicals such as fluorinated substances, medicines (e.g. antibiotics and endocrine disruptors) and micropollutants.

The link between the karst elements visible at the ground surface and those linked to the subterranean course of water highlights the complexity of the hydrogeology in karst. Interaction among shallow and deep karst systems often occurs in ways that are not fully understood. Analysis of infiltration points, such as sinkholes, is important and these need to be related to the recharge of the overall hydrogeological system. At the same time, dye tests need to be performed to obtain information about the deep flow paths by integration with recession curve analysis via discharge data from the springs. A more reasonable understanding of the whole system may be reached by combining the outcomes from these

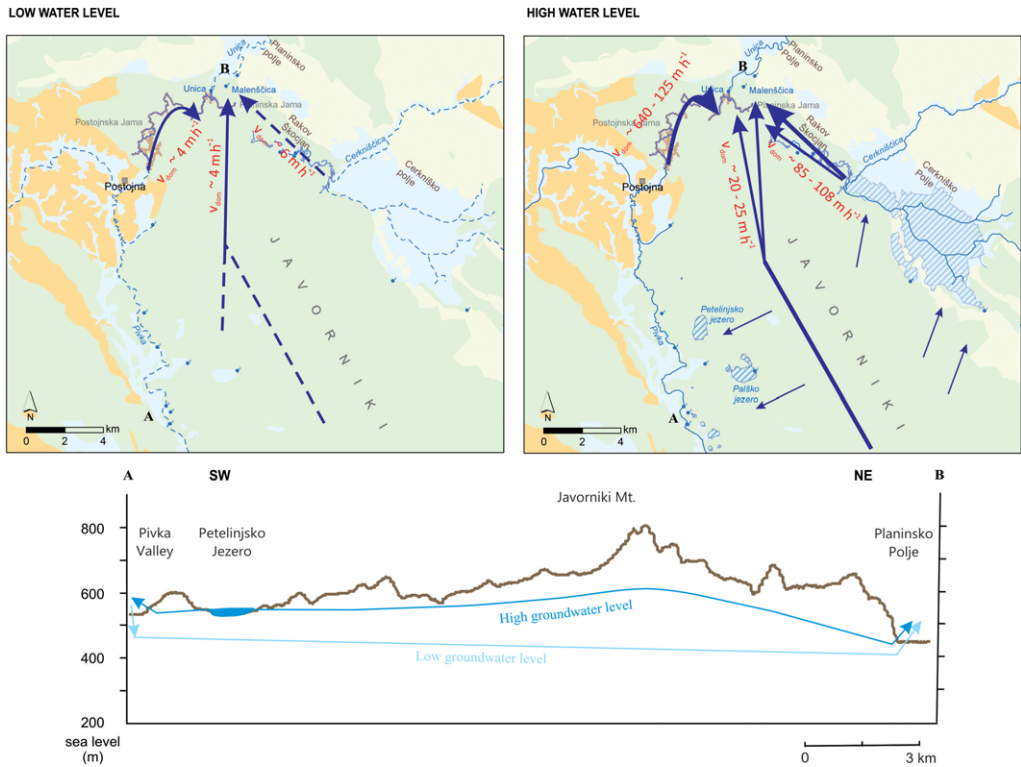


Fig. 5. Map of the water connections from the Slovene examples in Dinaric karst, characterized by significant temporal hydrological variability and consequent alterations of flow direction and groundwater divides, different types of surface–groundwater interactions, and changing flow velocities.

two different analyses. As an example of this type of study, looking at the northern rim of the Grand Canyon on the Kaibab Plateau in northern Arizona (southwestern USA), [Jones *et al.* \(2017\)](#) performed a careful study of the karst aquifer in this region, which supplies numerous large springs providing desert oasis habitats, drinking water and base flow to the Colorado River. The Grand Canyon is the second largest karst region in the US National Park System and contains >4000 km² of karst features. In this specific case study, two karst aquifers, with embedded non-karstic strata, are presented. The only way to understand the interconnection between the two aquifers is the interpretation of a dye tracer study and hydrograph analysis of discharge from the deep aquifer ([Groves 2007](#); [Fiorillo *et al.* 2012](#)).

The work by [Jones *et al.* \(2017\)](#) once again confirms that the hydrogeology of karst aquifers strongly differs from that of aquifers developed in porous or fractured media ([White 1988](#); [Bakalowicz 1995, 2005](#); [Ford & Williams 2007](#)). The inherent heterogeneity and anisotropy of karst aquifers makes it necessary to develop studies through a wide range of

approaches ([Doctor *et al.* 2000](#); [Goldscheider & Drew 2007](#)), including: classical hydrological methods involving water balances and analysis of the spring hydrographs; the use of stable and radioactive isotopes, hydrochemical methods and tracer techniques with artificial and/or natural dyes; and specifically designed modelling experiments. These are all required to reconstruct the path followed by groundwater, which is often not accessible through speleological explorations. Analysis of the chemical composition of the water drained by springs adds to these important data dealing with the structure, storage capacity and dynamics of carbonate aquifers ([Mudry 1987](#); [Mudarra & Andreo 2011](#)).

Combining and integrating the outcomes from such a variety of approaches is not a simple task, but has been proved to be the only possibility in attempts to fully characterize karst aquifers and move towards an understanding of the hydrogeological functioning of the systems, from the recognition and measurements of groundwater flow paths and velocities, to the identification of the recharge areas and groundwater residence times.



Fig. 6. Underground flow through a well-developed karst channel, Tkalca jama, Rakov Škocjan, SW Slovenia. Photograph courtesy of Matej Blatnik.

Groundwater vulnerability maps are a crucial tool in supporting decision-making and land planning, especially in environmentally protected areas, because they synthesize the main information available at the site from many different disciplines. Nevertheless, vulnerability maps may be of no help, or even provide questionable/wrong information, if they are not accompanied by the correct interpretation of the hydrogeological setting. This requires the validation of karst vulnerability maps, which may be pursued by applying several different techniques (Ravbar & Goldscheider 2009), such as tracer tests, isotope analyses and hydrograph studies.

Iván & Mádl-Szőnyi (2017) applied the Slovene approach to the Gömör-Torna Karst, a transboundary aquifer straddling the border of Hungary and Slovakia. The region is protected and lies within the Aggtelek National Park and the Slovak Karst National Park. Long-term hydrograph and recession curve analyses have been particularly useful in understanding the functioning of the main spring in the area (the Kis-Tohonya spring) and the complex karst system.

As a further example of the implementation of hydrogeological studies in karst areas, Sánchez *et al.* (2017) present a practical and critical overview of the most common hydrochemical and isotopic approaches used to analyse carbonate karst aquifers.

An integration of techniques, from the hydrochemical and isotopic characterization of waters to mapping recharge areas, is applied to study the carbonate massif of Sierra Grazalema Natural Park in southern Spain. This is a strategic groundwater reserve located in a region that periodically suffers from droughts and water scarcity. The main outcomes from the study indicate that groundwater from the Sierra Grazalema aquifers shows marked differences in chemical composition, with low to intermediate mineralization and a chemical composition that is mainly controlled by the minerals forming the rocks through which the groundwater flows and by the residence time of water in the aquifer.

Water quality issues are closely related to the maintenance of healthy ecosystems (Bonacci *et al.* 2009). The complexity of karst water resources, which is related to the great variability in flow characteristics and is dependent on the hydrological conditions (Ravbar *et al.* 2011; Smith *et al.* 2015; McCormack *et al.* 2016), needs to be addressed. Fluctuations in karst groundwater can be several tens to hundreds of metres and, as a consequence, different types of surface-groundwater interaction can occur (Gabrovšek & Peric 2006). These are characteristic of areas such as the Dinaric karst, many lowland karst areas of Ireland, the karst in Estonia, the coastal karst of the Yucatan peninsula, the

subtropical areas of the South China karst, and many others. Catchment boundaries and flow directions in karst aquifers may change due to the temporal hydrological conditions.

Given the dynamics of hydrological processes, karst aquifers are particularly vulnerable to the effects of environmental changes, but are also suitable for exploring these effects on a human time-scale. Despite the important role of karst water resources, this topic is still poorly addressed. There have only been a few studies that have adequately evaluated the impact of predicted environmental changes on water quantity (e.g. Pinault *et al.* 2005; Hartmann *et al.* 2012; Finger *et al.* 2013; Jia *et al.* 2017).

The high vulnerability of karst aquifers, resulting from the spatial and temporal heterogeneity of water flow and storage, may increase further as a result of environmental changes, in particular those occurring in the hydrological cycle. Taking into account the predicted changes, such as an increase in the frequency of extreme drought periods, Ravbar *et al.* (2017) assessed the long-term climatological and hydrological trends and the short-term effects of such changes for the Mediterranean karst spring of Rižana in SW Slovenia. This is the most important water source for Slovene Istria, a region between Slovenia and Croatia containing a transboundary karst aquifer. The aquifer is important for both agriculture and tourism, and supplies water for 86 000–120 000 people.

The type of approach presented by Ravbar *et al.* (2017) shows, through detailed monitoring of the physical, chemical and microbiological parameters, that the flood pulses caused by precipitation events after a long dry period cause a significant deterioration in water quality, with a significant increase in the amount of coliform bacteria in the water. Therefore it is necessary to develop proper management strategies and actions for the continuous monitoring of karst water resources, aimed at their rational use and taking into account the anticipated climatological trends and the effects they could have on karst aquifers. Further work needs to be done to simulate site-specific hydraulic responses to different climate scenarios.

Different needs in karst areas (typically, protection issues v. tourist development) are often conflicting and it is not easy to find a balance between them. In this regard, Bonacci (2017) examines an interesting case study from the small Adriatic island of Cres, Croatia, where Vrana Lake is the only source of potable water for the whole archipelago. A dangerous drop in the water level of the lake started in 1983, driven by both global climate change and anthropogenic impacts as a consequence of over-exploitation. The lake is a complex hydrological–hydrogeological system with an average water

volume of $c. 220 \times 10^6 \text{ m}^3$. The limited natural inflows and outflows of the lake are insufficient for self-cleaning once pollution has occurred (Ožanić & Rubinić 2003). This poses a serious risk of sea-water intrusion, a widespread phenomenon in many sectors of the Mediterranean basin (Stevanović 2015) related to strong tourist pressure in specific areas during the long, hot, dry summer periods typical of the Mediterranean climate.

Interdisciplinary monitoring and co-operation between different specialists and professionals (e.g. hydrologists, hydrogeologists, ecologists and water resource managers) is clearly the only way to protect and manage these vulnerable and exceptionally valuable aquatic and terrestrial ecosystems.

The two contrasting needs – the tourist-dependent economy of Cres and the preservation of the valuable natural ecosystems, including the groundwater resources – require proper and balanced management of the water resources. This approach to management must address the need to protection and safeguard the vulnerable and valuable biological diversity of Cres and the surrounding islands, while recognizing that the landscape is one of the main factors attracting tourists to the natural beauty of the archipelago. Sustainable development is possible, but it must start with a strong emphasis on the natural resources based on a thorough knowledge of the environment through the establishment of a truly interdisciplinary approach involving different scientific disciplines (e.g. hydrology, climatology, hydrogeology, biology and ecology).

Further problems arise when karst aquifers expand over administrative borders that lack common political actions on an international basis, hampering the planning of possible encroachments or the international protection of groundwater (Turpaud *et al.* 2018). If we consider transboundary aquifer systems – those shared by two or more countries – $\geq 20\%$ of internationally shared aquifers are found in karst (Stevanović *et al.* 2016). Another problem linked to water and its role in societal conflicts is that springs in many countries worldwide have been exposed to severe contamination during wars in the last few decades. Using water as a weapon is especially dangerous in the case of vulnerable karst aquifers (Shiva 2002). Another topical issue, at present not fully developed, but which is expected to be tackled in the long term, is the exploitation of geothermal resources from karst aquifers (Goldscheider *et al.* 2010).

Karst modelling

Karst offers great challenges in terms of groundwater and engineering problems, which typically involve many uncertainties that cannot easily be addressed

by fieldwork. Large parts of karst systems are inaccessible to human exploration and sampling techniques only provide limited insights into the dynamics of a karst system, with either spot measurements (e.g. boreholes) or responses averaging over large areas (spring discharges). Quantitative approaches such as mathematical or numerical modelling provide a deeper understanding of both the evolution of karst landscapes and karst aquifer systems and the functioning of present day karst systems.

Understanding the evolution of solution conduits (i.e. speleogenesis) is one of the major challenges. By coupling equations of flow in single fractures, networks of fractures or general fractured-porous aquifers, it is possible to simulate conduit evolution in soluble rocks and search for the basic mechanisms guiding the evolution. The early work of Dreybrodt (1990), Palmer (1991) and Palmer *et al.* (1999) showed the feedback mechanisms between flow and dissolution rates in evolving fractures and introduced the breakthrough time as an important indicator of the intensity of conduit evolution. Assembling individual fractures into networks demonstrated how competition between different flow paths results in different geometries of conduit networks. Different complexities of the initial networks and approximations of the underlying processes were used. A comprehensive review of these models is given by Dreybrodt *et al.* (2005) and Kaufmann *et al.* (2012). Models were also extended to three-dimensional domains (Annable 2003; Kaufmann *et al.* 2010) and to open channel flow conditions (Perne *et al.* 2014). Some of the mechanisms of flow path competition in soluble rocks have been explored by Szymczak & Ladd (2009), who provided the mathematical background of wormhole formation in soluble porous and fractured medium.

To provide an example of karst modelling, a three-dimensional limestone evolution model is presented in Figure 7. A karst aquifer, 200 m long and 100 m wide, extends 20 m in the vertical direction. Structures in the karst aquifer are resolved to the metre scale, so that 1.15×10^6 fracture elements and 400 000 matrix elements are used. The aquifer is recharged by $2 \text{ m}^3 \text{ day}^{-1}$ from the left-hand side, with inflowing water reaching 90% saturation with respect to calcite. Along the right-hand side, a fixed-head boundary condition mimics a base level. Although the porous matrix has a low conductivity ($K_m = 10^{-7} \text{ m s}^{-1}$), the initial fracture width is assigned as a log-normal distribution. The resulting hydraulic flow field (top) indicates flow from left to right and the small-scale disturbance of the flow field results from the initial log-normal distribution of fracture widths.

The evolved karst aquifer is shown after 10 000 years for two different log-normal distributions.

For a mean initial fracture width of 0.1 mm and a standard deviation of 0.0001 mm (lower left-hand panel), the enlarged fracture zones form clusters, mainly in the direction of the main pressure gradient, with no strong coupling between the different clusters. The central cluster of enlarged fractures becomes the most dominant and provides the first efficient connection between the input and output sides, with fractures enlarged to 10 cm in size.

When the standard deviation is increased to 0.05 mm, with all other parameters remaining the same, the evolution of the enlarged fractures is different (lower right-hand panel). As before, several clusters of enlarged fractures grow from left to right, but they now develop in a more sinusoidal way, leading to more interactions between clusters and a stronger exchange flow.

The evolution of karst landscapes and solutional rocky features has attracted less attention from modellers. Kaufmann & Braun (2001) presented a comprehensive model of landscape evolution by coupling surface creep and planar dissolution. Fleurant *et al.* (2008) modelled the evolution of cockpit karst and stressed the importance of spatial anisotropy in landscape evolution. Modern modelling approaches, such as computational fluid dynamics, have been used to model the evolution of scallops under turbulent flow conditions (Grm *et al.* 2017).

In most soluble rocks, the timescale of karst evolution is much longer than the timescale of processes observed in real time. This allows a separation between genetic models and present state models. Several approaches have been taken to model the functioning of karst aquifers. Lumped parameter (black box) models are often applied because the spatial distribution of the relevant parameters is not known (Hartmann 2017). Distributed models are used when the spatial distribution of parameters is known.

The majority of models study heat or mass transport in karst aquifers. A general theoretical framework of signal propagation through karst aquifers was proposed by Covington *et al.* (2012), who introduced the concept of process length scale to karst systems.

Numerical models are more often used with observational data from the surface (e.g. springs) and from cave systems through direct exploration by speleologists to estimate the cave geometry and conduit paths (Palmer *et al.* 1999; Gabrovšek & Peric 2006; Covington *et al.* 2013; Chen & Goldscheider 2014; Kaufmann *et al.* 2016). These numerical simulations can be extended with indirect measurements of the surface and subsurface structure by geophysical mapping techniques, such as gravity, electrical resistivity imaging and ground-penetrating radar surveys (e.g. Kaufmann *et al.* 2015; Kaufmann & Romanov 2016).

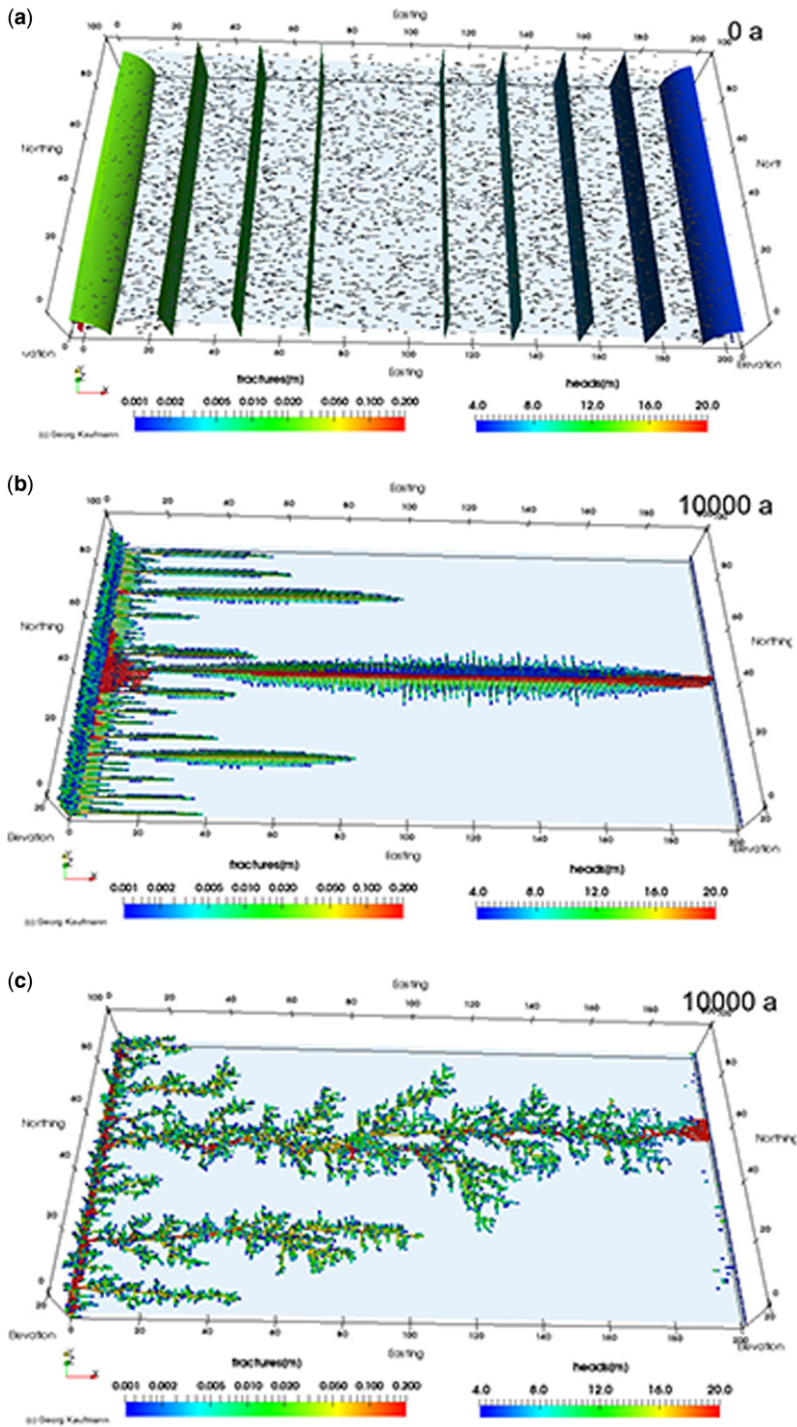


Fig. 7. (a) View towards the karst aquifer, with inflow on the left, base level on the right and hydraulic heads colour-coded. The small arrows indicate flow velocities. (b) Evolution of fractures after 10 000 years starting with an initial mean fracture width of 0.1 mm and a standard deviation of 0.0001 mm. (c) Evolution of fractures after 10 000 years starting with an initial mean fracture width of 0.1 mm and a standard deviation of 0.05 mm.

The main goals of modelling in karst are typically a better understanding of the hydraulic and hydrogeological flow of water and analysis of the microclimatic conditions characterizing cave systems.

Modelling of groundwater flow in karst aquifers is difficult because the position of solution conduits is largely unknown. When the geometry is known, assessed or assumed, different algorithms are used to account for the turbulent flows in conduits embedded into the fracture–matrix system. Several of these approaches are embedded into MODFLOW, a United States Geological Survey modelling environment, which is the model most widely used in groundwater modelling. An example of such an approach is given by [Kresic & Panday \(2017\)](#), who present MODFLOW-USG (UnStructured Grid), which takes advantage of unstructured grids and finite volume numerical solutions. This new version of MODFLOW enables hydrogeologists to accurately translate even the most complex conceptual site models in karst into a numerical environment, thus eliminating the need for surrogate modelling solutions based on an equivalent porous medium approach.

As a significant percentage of high-quality, potable water comes from karst aquifers, the high vulnerability of karst waters must be taken into account, with particular emphasis on human-induced, often irreparable, pollution and over-exploitation. Sustainable management of these resources is not an easy task and should rely on the maximum possible amount of information from hydrogeological studies. These studies should represent the basis for developing hydrological models for karst, with the goal of both quantifying the water volumes available and assessing their sensitivity to changes in climate or land use.

Different modelling approaches are available to simulate karst hydrology, but guidance on the application of these approaches is scarce. [Hartmann \(2017\)](#) provides insights into the application, calibration and evaluation of lumped karst hydrological models by discussing model calibration and sensitivity analyses. He presents three case studies of karst model applications at different scales (plot, aquifer and continental scales) and with varying data availability, which apply model calibration and sensitivity analysis to obtain realistic simulations.

Aimed at identifying the likely hazards in karst, and at prevention measures to avoid catastrophic collapses, geophysical techniques may be successfully used to contribute to the mitigation of the sinkhole risk. Mechanically unstable structures close to the surface, of both natural and anthropogenic origin, are among the features highly prone to collapse. They therefore represent a clear hazard to the infrastructure above and may be located through geophysical investigations.

[Kaufmann & Romanov \(2017\)](#) compiled a large dataset of geophysical surveys in and above two caves in northern Germany, selected because they have a shallow overburden of 10–40 m and are characterized by both small passages and large rooms. In these settings, the known and surveyed cave passages can be traced with both gravity and electrical measurements, which reflect the lower density and the different electrical resistivities of the cave voids and host rock. Using these indirect geophysical observations, a structural model for both cave sites was obtained by numerical modelling and was successfully calibrated against the Bouguer gravity data.

Caves present a unique atmospheric environment, where several driving mechanisms (e.g. heat exchange between air, water and rock and changes in the external atmospheric pressure) force air exchange between the cave and the outside atmosphere. The microclimate of caves is receiving increasing attention from the scientific community because its understanding might help to reveal past climates from cave sediments and protect fragile recent ecosystems. Many important contributions on the physics of the underground environment have been published by Giovanni Badino (1953–2017). The present volume includes one of his last papers, in which he analyses the three major problems in cave micrometeorology: the concept of the temperature of a cave and its phenomenology; the internal energy flows and consequent local entropy production; and a non-hydrostatic physical model of the underground convective air circulation ([Badino 2018](#)). This study highlights how important it is to understand, and to find a correct way to measure and monitor, processes such as thermal stratification, seasonal variations and the effects of the external morphology on the cave environment. This fascinating topic, definitely worthy of more studies and analyses, will probably be one of the main issues in the physics of caves in the near future.

Karst hazards and management

The presence of karst landscapes in large parts of the world, and karst aquifers supplying important regions and many metropolitan areas with drinking water, is evidence of the great significance of karst and the need to preserve karst landscapes and their natural resources. At the same time, karst is recognized as an extremely fragile environment, susceptible to a variety of natural and anthropogenic hazards ([Gutiérrez 2010](#); [De Waele *et al.* 2011](#); [Gutiérrez *et al.* 2014](#)).

Sinkhole hazards are the most typical geohazard in karst. Even though several different genetic processes for sinkhole formation have been identified ([Waltham *et al.* 2005](#); [Yeichieli *et al.* 2006](#); [Gutiérrez](#)

et al. 2008, 2014), the most worrying, in terms of likely damage to human activities and infrastructures, are collapse and cover-collapse sinkholes, which generally occur in a catastrophic way with little or no warning. From studies of sinkholes in karst, related to natural karst caves and to the presence of underground conduits, the attention of many researchers has recently included anthropogenic sinkholes – that is, those related to the presence of artificial cavities (e.g. mines and quarries; see *Parise et al.* 2013), which are generally distributed below inhabited areas and pose greater risks to the population (*Brinkmann & Parise* 2012; *Parise* 2012, 2015). Efforts to conduct research to evaluate sinkhole hazards are important in civil defence and land planning, responding to a specific societal need and the need to mitigate the risk from geohazards. The occurrence of sinkholes in urban areas has become common in many built-up areas (*Hermosilla* 2012) as a consequence of the closure of these artificial voids and the loss of records of their presence.

Southern Italy, as a result of its geological features – including extensive areas of soluble rocks and of easily excavated volcanic and sedimentary rocks – is an interesting case study for sinkholes related to both natural caves and, because of the long history of the region, to artificial cavities, a high number of which were excavated in past epochs for a variety of purposes. *Fiore et al.* (2018), by considering the instability problems and related sinkholes resulting from anthropogenic cavities in the karst of Apulia, the SE region forming the heel of the Italian boot, developed charts for use by practitioners and technicians through parametric analyses as an important step in an assessment of possible use by the public to classify anthropogenic cavities. This approach can give a preliminary assessment of the stability conditions and provide a basis on which further, site-specific, analyses can build, taking into account the local geometric, stratigraphic and geomechanical features. In addition to providing a preliminary evaluation of stability, this approach follows the recent Apulian regional law L.R. 33 2009 Safeguard and Promotion of the Geological and Speleological Heritage. This approach could be of practical use in the development of new opportunities for landowners to exploit these underground sites, which are considered as part of the cultural and historical heritage of the area, for tourism and to present favourable stability conditions.

The quantity and quality of karst aquifers makes them extremely important for society. Apart from their use as potable water, karst water resources are of interest for the generation of hydroelectric power and many dams have been built in karst areas to impound artificial lakes, facing severe problems in the construction phases to avoid losses through karst conduits and voids (*Milanovic* 2000,

2002). In general, the management of karst resources and the design of engineering works in karst are still difficult because of the often insufficient level of knowledge we have about the hydrogeological properties of aquifers and of the high vulnerability of karst aquifers to pollution (*Milanovic* 2000; *Zhou & Beck* 2011; *Parise et al.* 2015). As the water quality in karst aquifers deteriorates when pollutants are present (*Calò & Parise* 2009), the only way to manage such situations is to eliminate any possible sources of pollution or to establish sanitary protection zones (*Doerfliger & Zwahlen* 1997; *Goldscheider* 2005; *Vias et al.* 2006; *Ravbar & Goldscheider* 2007).

Raising awareness in the local population living in karst regions about the importance of preserving the quality of water resources is crucial and should be pursued in every project located on karst lands. This is one of the main actions that actually protects karst and its resources.

Some human activities, such as land use modifications, the alteration of surface drainage and the opening or blocking of cave entrances, may have a great effect on karst hydrology or ecology. There is an urgent need to understand how human activities directly affect the recharge and flow of groundwater in karst because there are important consequences if karst lands are inundated during heavy and torrential rainstorms. This potentially leads to flash floods, which, in addition to sinkholes, represent the most common and dangerous hazard in karst (*López-Chicano et al.* 2002; *Parise* 2003; *Bonacci et al.* 2006; *Jourde et al.* 2007, 2014; *Najib et al.* 2008; *Kovačič & Ravbar* 2010). There is a great need to improve our understanding of flood dynamics in karst terrains to contribute to the assessment and management of flood risks (*European Council* 2007).

In such a delicate environment, the complex hydrological and hydrogeological behaviour of karst terrains poses unique challenges in flood risk management. Effective flood risk management requires an understanding of the recharge, storage and transport mechanisms governing water movement across the landscape during flood conditions. Lowland karst landscapes can be particularly susceptible to groundwater flooding due to a combination of low aquifer storage, high diffusivity and limited or absent surface drainage.

Naughton et al. (2017b) present a detailed example of the phenomenon of groundwater flooding in the lowland karst terrains of western Ireland following the dramatic floods that occurred during the winters of 2009 and 2015. These floods caused widespread damage and disruption to communities across the country, particularly in the extensive karstic limestone lowlands on the western seaboard (*Naughton et al.* 2017a). Backwater flooding of sinks, high water levels in ephemerally flooded basins

(turloughs), the overtopping of depressions, and discharges from springs and resurgences have repeatedly been observed during these flood events. Field observations provide an understanding and description of the main hydrological and geomorphological characteristics influencing flooding in these complex lowland karst groundwater systems.

A future aspect of research in this region would involve the establishment of a permanent monitoring network to provide long-term quantitative data at flood-prone locations, together with the development of methodologies for improving groundwater flood hazard maps and real-time flood monitoring.

In addition to the direct and indirect effects of flood events, and because an increase in the frequency of extreme hydrological conditions affects various socioeconomic activities, it is necessary to evaluate the role of karst aquifers in flood attenuation and maintenance of the baseflow, which is especially important in terms of water supply.

The management of karst lands requires a deep knowledge of the natural processes acting in karst and a careful understanding of the likely effects of human activities on karst and its natural resources. To reach such a goal, a common effort must be pursued, involving decision-makers, legislators, land planners, karst scientists, speleologists and, last but not least, the population living in karst regions. The latter should be the first to appreciate the importance, but at the same time the fragility, of karst and their direct involvement is therefore of crucial importance in any action dedicated to sustainable development in karst. The main sites where karst information is transferred to the wider public is represented by show caves and by visits to reserves or protected areas and parks in karst.

Karst is known to the public essentially as a result of the beauty of caves, which can be visited and admired in show caves. Opening a show cave is seen by many scholars as 'killing a cave' because the operations necessary for making a cave available to the public change the environmental and climatic conditions of the site, inevitably altering the pristine conditions. Nevertheless, show caves represent the first and most direct visiting card of karst to people. When properly managed, show caves can also be used to transfer information from karst science to the public, such as the importance and fragility of the natural resources contained in karst (particularly groundwater), and therefore raise the environmental awareness of the local residents, who should be the first to act and live in a sustainable way in the surroundings of the cave.

The paper by [Debevec *et al.* \(2017\)](#) deals with one of the most important and historical show caves in the world: the Škocjan Caves in Slovenia. This is an important site for karst and for the history of karst research. At Škocjan Caves, the Reka River

sinks underground and has created an impressive canyon in an area characterized by a number of large collapse sinkholes. This is a place of geological contact between flysch deposits (where the Reka River flows at the surface, from its source at the boundary between Croatia and Slovenia) and carbonate rocks ([Jurkovsek *et al.* 2016](#)). At Škocjan, the underground course of the river begins and extends for *c.* 40 km, before emerging at the Bocche del Timavo spring near Trieste in NE Italy. The river is accessible by many caves during its underground course and was explored by cavers between the end of the nineteenth and the first decades of the twentieth century ([Guidi & Torelli 2017](#)). A study by [Gabrovšek *et al.* \(2018\)](#) provides an in-depth analysis of groundwater dynamics along the flow path of the Reka–Timavo system.

The Škocjan Caves are included in UNESCO's World Heritage List and in the Ramsar Directory of Wetlands of International Importance. Together with their wider surface area, the site is also known as the UNESCO Karst Biosphere Reserve. The area of influence of the Škocjan Caves Regional Park encompasses the entire Reka River watershed and covers 450 km².

[Debevec *et al.* \(2017\)](#) describe the main steps of managing the reserve, aimed at protecting and preserving its outstanding universal value for future generations. Among these activities, monitoring of the water quality in the Reka River and meteorological surveys on the surface are of primary importance. In addition, monitoring of the cave microclimate focuses on measuring the effects of tourism and checking the levels of radon, with the aim of ensuring the safety of the park's employees and the status of the underground habitats and species laid down in the Natura 2000 management programme. The park staff carry out awareness-raising and educational activities, with an emphasis on understanding the importance of protecting the underground water and the unique and vulnerable karst land. At the same time, particular attention is paid to ensuring high-quality, safe visits to the caves.

Policy-based strategies for the management and protection of karst landscapes in developed countries are often inadequate and have, in many cases, only been implemented during the last few decades ([Fleury 2009](#)). This is particularly true with respect to the management of water resources and the natural environment.

The vulnerability of karst aquifers derives from their high permeability and rapid recharge, two factors which play a crucial part in making them susceptible to contamination. The unpredictability of groundwater movement in karst, and significant differences from water circulation in other settings, requires a specific approach to evaluate the possibility of pollution in karst settings. Although fairly

straightforward, this simple concept has not been fully understood and in many countries groundwater vulnerability in karst is evaluated through methods and approaches that are not suitable in karst.

Aimed at presenting karst-specific approaches, the karst disturbance index (KDI) was proposed by [van Beynen & Townsend \(2005\)](#), and later modified by [North *et al.* \(2009\)](#), to assess the impact of human activities on the karst environment. The KDI covers five categories (geomorphology, atmosphere, hydrology, biota and cultural factors), each composed of several attributes, which are, in turn, subdivided into a number of indicators. Since its proposal, the KDI has been applied in a number of karst areas worldwide ([Calò & Parise 2006](#); [North *et al.* 2009](#); [Day *et al.* 2011](#); [Van Aken *et al.* 2014](#); [Porter *et al.* 2016](#)).

In this volume, [Kovarik & van Beynen \(2017\)](#) combine this approach with a groundwater vulnerability map to provide a tool for developing management strategies in a subcatchment of the Rio la Venta watershed in the state of Chiapas, southern Mexico. Their analysis shows that the opportunity exists to prevent major human impacts on vulnerable areas and the entire ecosystem of Reserva de la Biosfera Selva el Ocote, but only if local stakeholders are incorporated into the process of limiting development. Such a combination recognizes both human

disturbance and how the physical nature of the karst will affect this impact. In practice, the composite model allows resource managers to quickly identify the areas of highest concern and the implementation of adaptive holistic management strategies to mitigate these problems. Providing a snapshot of the environmental state of the area will allow future studies to evaluate whether remediation efforts have been successful.

It is essential that local residents and natural resource managers work together to create a plan for mitigation by developing an awareness of the value and fragility of karst. Many case studies (e.g. [Elke *et al.* 2007](#); [Bocchino *et al.* 2014](#)) have shown that environmental education of the locals greatly improves the possibility of success, basing the project on the relations between environmental issues and everyday life.

[Auler *et al.* \(2017\)](#) review the existing protocols for establishing the importance of caves and provide a statistical assessment of the criteria applied in Brazil to determine the level of importance. Despite the difficulties encountered in dealing with both quantitative and subjective criteria, their analysis is a useful example for decision-makers in clarifying the classification schemes and the selection of speleological sites worthy of environmental protection. A primary issue is represented by the selection of



Fig. 8. Cavers at work in the incredible setting of the gypsum giant crystals in the Naica Cave, Chihuahua, Mexico (see [Forti 2017](#)). Photograph courtesy of Paolo Patrignani/La Venta.

the parameters to be considered. The protocols vary significantly from country to country, but in many cases require working on a long, impractical lists of parameters, many of which actually have low significance or are extremely subjective. These drawbacks may lead to evaluations that differ in the function of the people involved and in the non-repeatability of the approach. To provide an example, 70 parameters are included in the analysis by [Auler et al. \(2017\)](#). Of this large number, 30 deal with cave parameters, but on average less than five of these parameters occur together at each cave. This suggests that the relevant parameters should be selected carefully, avoiding those where high subjectivity is inherent and at the same time trying to balance biotic v. abiotic features.

An effort must be made by karst scientists to provide clear and repeatable classifications of caves because the need for these is increasing in many countries worldwide. [Auler et al. \(2017\)](#) state that, 'to achieve an objective and repeatable classification of the importance of caves and thus enabling the ranking of caves by conservation priority is a challenging proposition'. Karst scientists may contribute significantly to such a goal by sharing their experience to develop well-balanced, scientifically robust and non-debatable approaches.

An interesting example of the interaction between human activities and karst science is provided by [Forti \(2017\)](#). The Naica caves in the state of Chihuahua, Mexico are probably one of the best examples of hypogenic speleogenesis ([Klimchouk 2009](#)) and have become famous as a result of the large gypsum crystals they host ([Fig. 8](#)). The caves were intersected by mine works in 2000 and, from 2006, became the object of a multidisciplinary research project with a variety of goals. Extensive research conducted over the past decade in the framework of the Naica Project, and briefly summarized by [Forti \(2017\)](#), has made the thermal caves of Naica probably the most studied cavity systems in the world. Among the many outcomes of the project, it recorded the presence of ten new cave minerals and the fluid inclusions trapped in the gypsum crystals allowed the salinity and temperature of the feeding water at the time of their deposition to be determined, thus giving an insight into the palaeoenvironment and palaeoclimate of the Naica region ([Garofalo et al. 2010](#)). For the first time, well-preserved pollen grains were found inside euhedral crystals in the caves ([Holden 2008](#)). Such a wonder had, unfortunately, a short life, at least for scientific research. In 2015, mining works intersected a completely unexpected major thermal vein, which started flooding the lower levels of the mine. Because it was not possible to continue dewatering to stop the progressive rise of groundwater, procedures to close and abandon the mine were started at the end of 2015.

Concluding remarks

Karst terrains are, as a result of their particular nature, extremely fragile areas. At the same time, these landscapes represent a remarkable natural heritage and, due to the wide occurrence of carbonate rocks worldwide, have high economic importance, both nationally and regionally. Comprehensive economic and urban development in recent years has resulted in increased pressure on karst landscapes from the intensive and unsustainable spread of settlements, infrastructure and industry, the development of tourism and intensive agrarian land use. Once damaged, karst ecosystems (including the surface landforms and underground resources) take a long time to recover and the process is difficult. For this reason, karst must be holistically managed in an appropriate and careful manner.

There is therefore an urgent and continually increasing need to raise public awareness about karst. One of the main points on which the karst science community definitely agrees is that the population living in a karst area cannot be excluded from the process of learning to live sustainably in such a setting. Local residents must be the first to protect, with their daily habits, the natural resources contained in karst. This is a great challenge, which directly involves the scientific world in the effort to transfer our studies and research outcomes to people living in karst, in a language not intended for technicians only, but understandable to all, starting with the younger generation. Didactic actions should be performed in schools of different grades to show children what karst is, its importance and the need to preserve this treasure for generations to come.

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