



## Preface: Five decades of advances in karst hydrogeology

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Carbonate rocks have a worldwide distribution. Karst groundwater has been an essential resource for humanity since the establishment of civilization in the karstified areas of the Middle East and Mediterranean. Goldscheider et al. (2020) estimated that 15.2% of Earth's continental surface is covered by karst aquifers, with 1.18 billion people (16.5% of the global population) living on karst areas. Karst aquifers supply drinking water to approximately 10% of the world's population (Stevanović 2019).

Interest in the intriguing nature of groundwater flow in karst has led to early scientific debates since the beginning of the twentieth century (Grund 1903; Katzer 1909; Martel 1910; Cvijić 1918). Exploring and explaining karst and its groundwater have always been challenging tasks, because of its inherent specificities: karst aquifer anisotropy and heterogeneity, mechanisms of recharge and their intensity, role of epikarst and soil cover, prevalence of turbulent regime rather than laminar flow in large channels and cavities, complex variations of karst dissolution rates depending on geochemical zoning, deep water recharge and circulation. Karst water storage and flow occur in three vastly distinct media: rock matrix, fractures and conduits, governed by radically different flow regimes. Conduits, in particular, are characteristic of karst. Conduits are relatively rare in relation to bedrock volume,

and this results in limited water storativity; however, they are responsible for the majority of flow, conveying large volumes of fast flowing water under a turbulent regime. Quick infiltration of rainfall in karst commonly results in a shortage of surface water and lack of perennial streams in the mountainous areas and high plateaux. In contrast, drainage to the erosional base level of a karst hydrogeologic system can result in the world's most powerful springs. However, even such high discharge springs may dry up during long recession periods due to the peculiar and dynamic karst hydrological regime.

High permeability also results in high vulnerability to pollution, making mitigation and remediation difficult. Any construction in karst, especially creation of dams and reservoirs, is a very delicate undertaking since prediction of the location and size of karst voids remains challenging, resulting in leakages and even failures, sometimes with catastrophic consequences.

The inherent difficulty in dealing with hydrogeology of karst terrains has led to the establishment of specialized research groups, mostly in the past 50 years. The founding of the International Association of Hydrogeology (IAH) Commission on Karst Hydrogeology (colloquially referred to as the “Karst Commission”) in 1970 reflected on, among other things, the need to collectively integrate this very specialized branch of hydrogeology. This *Hydrogeology Journal* special issue, “Five Decades of Advances in Karst Hydrogeology”, celebrates the 50th anniversary of the IAH Karst Commission. The evolution of all aspects of karst hydrogeology during these 50 years is reviewed in the following.

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### Karst hydrogeology in the past 50 years

Although the complexities of groundwater in karst were recognized long ago, the developments in the past five decades have been remarkable. These scientific and technical advances have paved the way to the establishment of a highly

specialized field of activity. The first comprehensive modern text book dealing with karst hydrogeology was published in 1974 (Zötl 1974) followed by many others (Gospodarič and Habič 1976; Tolson and Doyle 1977; Bögli 1978). The following decade witnessed a flurry of major publications, mostly led by IAH Karst Commission members (Milanović 1981; Burger and Dubertret 1984, among many others) including publications in the “Blue Books” series of IAH. The number of people involved in karst activities over the past 50 years has increased markedly, resulting in many publications dealing with specific topics in karst hydrogeology such as water tracing, isotopic hydrogeology, human impacts, modelling, and geotechnical works, among others. Reviews on the history of karst hydrogeology can be found in Legrand and Stringfield (1973), LaMoreaux (1991) and White (2007).

The last decades of the twentieth century were marked by applications of GIS technology, which is well reflected in karst hydrogeology by the introduction of several methods for determining intrinsic vulnerability of karst aquifers and assessing disturbance in karst areas. GIS capabilities allow comparisons between distributions of various parameters and creation of maps with intrinsic characteristics, but also provide a wide range of hazard and risk maps. Use of water tracing tests has intensified in many countries and several international conferences were devoted to presentation of obtained results. Springs and their discharges have been subject to intensive studies in many parts of the world.

In the twenty-first century, karst hydrogeology witnessed remarkable advances and matured as a highly technical field that benefited from technological advances in remote sensing, increased resolution instrumentation and more sophisticated modelling capabilities. Nowadays, satellite imagery allows for real time monitoring of large areas on a planetary scale. Real time data transfer enables the remote monitoring of karst springs and wells, without a need for time-consuming in situ measurements. The range of physico-chemical parameters that can now be measured by portable hydrochemical kits and probes is ever increasing. Fluorometric techniques have also flourished, with more precise field fluorimeters and refinements in spectroscopic techniques.

The analysis of spring recession curves has received considerable attention in recent years. The spectrum of more-sophisticated statistical and analytical tools to break down and interpret such curves is ever increasing, yielding significant advances in understanding of how various parameters change with time in relation to precipitation and global warming, and of how the complex interactions between conduit, fracture, and matrix flow occur.

The increase in computer processing power and advances in computer modelling have been nothing short of remarkable. Only a few years ago, reliable modelling of the highly heterogeneous and anisotropic karst aquifer was regarded as a target for far in the future. However, modern modelling platforms

are starting to allow the inclusion of conduits with flow governed by appropriate turbulent flow regime equations. Although there is likely a long way to go before a karst aquifer can be represented with a high degree of spatial and parametric accuracy, this goal can no longer be believed to be unreachable.

Applied karst hydrogeology has also benefited from this vast new array of techniques. The well-known “expect the unexpected” concept is still applicable to karst. However, any serious engineering intervention in karst regions should now be aware of the importance of making use of the techniques outlined in the preceding, which, in addition to currently available geophysical and other tools, will enable the more precise assessment of geometry, geology and hydrodynamics of complex karst environments.

Nowadays, a karst practitioner has at their disposal a cornucopia of techniques that makes it increasingly difficult for a single person to master, requiring instead significant collaboration and teamwork. At the same time, much easier availability of data and improvements in communications have allowed the dissemination of new techniques on a global scale, enabling developing countries to quickly become aware of and take advantage of recent advances in karst. Collaborative efforts involving the karst hydrogeology community worldwide are now frequent, due, at least in part, to the initiatives of the IAH Karst Commission.

IAH Karst Commission members were instrumental in many of the advances of the past five decades. The close-knit karst community, centered on the IAH Karst Commission, became part of a virtuous cycle in which cooperation fostered further collaborative efforts. Although the IAH Karst Commission is not the only karst commission to exist in the past 50 years (the International Geographical Union also has one) it has been, arguably, the most continuous and productive, providing fertile ground for the discussion of ideas and generation of joint projects and publications at a global scale.

Karst hydrogeology has historically evolved, sometimes independently, from research in Europe and the United States. Future decades should allow for more global interactions and involvement, with research being developed in the major karst areas of south-eastern Asia, as well as in Africa, Oceania and Central and South America. In particular, China has recently emerged as one of the major centres for karst hydrogeology, and it may now have more karst specialists than any other country.

The future, by definition, is inscrutable; however, some trends are becoming clear as global warming changes the hydrological and atmospheric interactions on the planet, which directly affect karst areas leading to new concerns. Climate changes have led to water scarcity, flooding, and many associated problems worldwide. Future population migration due to natural population growth, due to rapid urbanization or

resulting from “climate refugees”, will also exert pressure on karst water resources. Groundwater pollution and karst degradation will continue to present key issues to be addressed.

On a positive note, the future will probably witness further advances in remote sensing monitoring, as satellite instrumentation allows for on-time remote monitoring of groundwater. In particular, the challenges of climate change should funnel efforts towards ‘early warning systems’ in karst areas, as well as ways to mitigate and sustainably address the issue of groundwater overexploitation in drought-prone karst areas. Modelling approaches are now starting to take into account the dynamics of non-Darcian turbulent flow in karst conduits, and may yield more realistic predictive results. Explicit mapping of the location of karst conduits and groundwater paths, a need that has eluded research until today, may be tackled in the future by more sophisticated geophysical methods or perhaps by yet unknown techniques based on laser, acoustic or scanning transmission of signals. In this ever-changing world, it is expected that the IAH Karst Commission will keep its central role as a focus point for the exchange of ideas, fostering further valuable and productive decades of karst hydrogeology development.

## Celebrating 50 years in this collection of papers

As we were nearing the 50th anniversary of the IAH Karst Commission, the idea of publishing a comprehensive review article on the Commission’s history was approved at the Karst Commission Annual Meeting in Besançon, France, in 2018. The journal chosen was, quite naturally, the official journal of IAH, *Hydrogeology Journal*, which has been, over the years, a major outlet of research performed by Karst Commission members. When we approached Cliff Voss, *Hydrogeology Journal* executive editor, he suggested that, instead of a single historical review paper, we should organize a full special issue on karst hydrogeology. Unknown to us, such an idea had come up in the past, including a suggestion by Nico Goldscheider, but had not yet been implemented for various reasons. With this confirmation, the guest editors of this issue organized a proposal and invited some of the long-standing members of the IAH Karst Commission and also younger karst hydrogeologists, to participate as authors of articles, to present their studies to a wider audience. The resulting contributions found in this issue offer the reader a comprehensive and representative group of papers that provide state-of-the-art reviews and studies that describe the present status of karst hydrogeology. The global reach of the IAH Karst Commission is well represented in 29 papers (including this Preface) written by 97 authors from 20 countries, comprising a broad spectrum of interests and trends in karst hydrogeology.

The contributions found in the special issue of *Hydrogeology Journal* are briefly described in the following section. These are divided into five major topical sections: Introductory papers and reviews; innovative methods and applications; modelling of karst environments; karst protection and global changes; and, case studies with wider applicability.

## Introductory papers and reviews

This first thematic group consists of eight contributions. The first, by **Milanović P. and Stevanović**, represents an assessment of the road travelled by the IAH Karst Commission, one of the oldest and most active commissions of the IAH, over the past 50 years. From the personal documentation of the first author, but also based on many other sources of data, a comprehensive account of the creation and functioning of the commission is presented. The paper covers three periods: initial (birth and youth); maturity; and rebirth and “second youth”. Primary information on several scientific meetings and field trips, publications and joint projects is presented, while electronic supplemental material for the article contains additional facts, documents and historical photos. This wealth of data is useful not only to those who want to learn more about the work of this highly productive group of scientists, but also can help those who will be responsible for this type of chronological study in the future. The second contribution, by **Worthington**, presents a study that aims to characterize the permeability in four geographically diverse and hydrodynamically contrasting karst aquifers: the Deep Geologic Repository (Ontario, Canada), Edwards Aquifer (Texas, USA), Chalk Aquifer (England, UK) and the Arabika Massif (Abkhazia, Georgia). The author makes use of several tools, including modelling and well data. Permeability, solute concentrations and flow rates vary with depth and are influenced by the presence of less soluble layers. This study shows how to extract useful information from published data. In the following contribution, **Kovács** presents a proposal for a quantitative classification of carbonate aquifers based on hydrodynamic behaviour. The paper reviews the existing contrasting classification schemes and makes use of analytical solutions of spring and well hydrographs in order to elaborate a base-flow recession coefficient. Two distinct carbonate areas were analysed, a more classical limestone aquifer (Szinva) and a dolomite aquifer (Kádárta), both in Hungary. Dolomite aquifers may behave both as a karstic and as a fissured aquifer and such behaviour cannot be established based on geological and geomorphological analysis, but requires a robust analysis of recession parameters. **Field** presents an overview of the methods commonly used for water sampling in karst terranes. Because basic grab sampling has been recognized to be problematic in karst areas, the author provides an overview of two of the more commonly applied approaches: event-driven sampling and passive sampling. Both have advantages and

weaknesses. The work presents a case study in a contaminated karst area in the Appalachians (USA) in which passive sampling proved to be the best approach. **Benischke** provides an overview that discusses the use of tracers in karst groundwater, one of the most widely applied techniques in karst terrains and aquifers. The review covers the evolution of tracing techniques, from a tool to investigate flow routes in early times, moving towards a method to unravel transport processes in karst terranes, and finally as a basis for groundwater protection and investigation programs. The review discusses the numerous types of tracers used and their characteristics, and the instrumentation available for detecting and monitoring tracing behaviour. In his contribution, **Milanović P.** warns of the dangers associated with dam and reservoir construction in karst areas. The unpredictability of building such structures in karst is highlighted through numerous studies worldwide; in particular, the author is able to draw from his extensive experience and provides a rich source of information. The author points out that the risks cannot be eliminated completely, but compromises can be found, allowing for an acceptable scenario. Thus, the commonly held assumption that we “should keep away” from karst must be changed to “must be familiar with” karst, illustrating how important it is to understand the karst system and its functioning. In another contribution on the same topic, **Milanović S. and Vasić** provide a comprehensive review of dams and reservoirs in karst areas. The review provides a baseline and a methodological approach to reservoir construction, dealing with the phases of planning, construction, filling, and operation. In particular, the authors stress that it is crucial to combine both conventional and nonconventional approaches in order to minimize risks. In the last contribution of this section, **Jiang et al.** combine the knowledge of several specialists in South Asia’s karst areas to come up with a thorough overview of one of world’s most important karst regions. The paper provides general data on South Asian karst areas and their environment, types of karst, hydrogeological data, karst management and associated environmental problems. It represents a very useful compilation of information not normally found in the mainstream English language literature and therefore will be of interest to specialists wishing to learn more about the region.

### Innovative methods and applications

In the second thematic section, five contributions highlight novel methods and their applications, representing recent advances in the understanding of hydrogeological processes in karst. **Sivelle and Jourde** present a useful technique to acquire hydrological data when a temporal dataset is not complete, a common situation in many karst catchments worldwide. The authors couple sparse spring data over a 30-year period with higher frequency monitoring data of piezometric

and spring levels, temperature, specific conductance and meteorological data over a shorter interval (21 months) in Oeillat Spring in southern France. Through numerical tools and lumped parameter modelling, it is possible to extract useful information. **Stevanović et al.** present a novel approach to infer vulnerability and resilience of karst aquifers in relation to climate change. The CC-PESTO method relies on the assessment of four parameters: permeability, storativity, discharge regime, and slope, and was applied to three areas in the karst of Montenegro and Serbia. The method should prove useful for management of karst aquifers, which are increasingly under stress due to the exacerbated droughts related to climate change. **Jemcov and Ćuk Đurović** introduce a way to understand the structure of a karst aquifer containing a hydraulic barrier (grout curtain) through the combined study of hysteresis diagrams and application of multivariate statistical analysis on hydrochemical data. This method was applied to a hydropower plant (Lazići) in the Dinaric Karst, Serbia, and yielded information about directions of groundwater flow and changes in geochemical processes under varying hydraulic regimes. **Fahrmeier et al.** present a novel method for single-borehole dilution tests. In this new approach, a ‘permeable injection bag’ is applied in order to achieve a uniform injection rate and allow for the estimation of aquifer parameters. This new technique is more practical than the commonly used hosepipe method, and through several tests has proved to yield consistent results. In a study of flooded areas in the classical karst of Slovenia, **Ravbar et al.** present a new procedure for defining flood-prone areas within poljes (karst plains). The comparison of flood levels in four areas allowed for the definition of flood-liable land as being areas where stagnant or overflow water is present for at least 10 days over a period of 30 years and has connections with groundwater. This practical approach has the potential for contributing to the awareness and better understanding of the frequent floods that occur in such areas.

### Modelling of karst environments

The third topical section deals with one of the fastest growing research areas in karst hydrogeology, which has witnessed remarkable progress in the past decades. The challenges associated with modelling the highly heterogeneous and anisotropic triple porosity typical of karst aquifers are illustrated in four contributions that present distinct approaches to dealing with such a complex environment. **Fandel et al.** applied a multi-model ensemble method in order to simulate karst conduits in the Gottesacker alpine karst system between Germany and Austria. The process made combined use of 3D geological models that enabled the generation of a conduit network through the ‘Stochastic Karst Simulator and a Storm Water Management Model’, which dealt with the fit between measured and simulated spring discharge. This approach requires

minimal initial data and helps in the definition of additional required data. **Kresic and Panday** have made use of a recently released version of the popular MODFLOW software (MODFLOW USG), which incorporates the capability of simulating turbulent flow in karst conduits. This flexibility of dealing with both conduit and porous media in a public domain package will surely be of interest to karst scientists and karst practitioners worldwide. A test example in a coastal aquifer is presented to illustrate the code's capabilities. **Gill et al.** present a study in the Irish karst in which the MODFLOW USG package was also applied in tandem with a semi-distributed approach, allowing a comparison between the methods. This has allowed insights related to flow paths (and potential contaminant transport) as well as permitted the investigation of the large contrast between the highly transmissive conduits and low transmissivity matrix, so characteristic of karst aquifers. In the final contribution of this section, **Savary et al.** applied a statistical approach that makes use of a neural network, in the chalk aquifer of Yport, in Normandy, France. Several different types of model were designed to address the precipitation/turbidity relationship, providing good capability for predicting turbidity peaks up to 24 h in advance.

### Karst protection and global changes

In this topic, five contributions address the pressing and inter-related issues of understanding and preserving karst aquifers in the context of climate change. **Gunn** provides a global overview of the protected karst aquifers under the umbrella of UNESCO's categories of protection: Biosphere Reserves (151 protected areas in 62 countries), Global Geoparks (61 in 21 countries), Ramsar sites (124 in 55 countries) and World Heritage Properties (56 in 33 countries), totalling more than 800,000 km<sup>2</sup> that may contain karst aquifers. This study should be a useful baseline for fostering future conservation efforts. **Hartmann et al.** present the first effort to remotely assess karst recharge at a global scale. The authors make use of a global soil-moisture monitoring program and a global dataset of karst-spring discharge. Soil moisture is demonstrated to be a key parameter that allows the interpretation of recharge. The results may enable improvements in karst groundwater governance by identifying karst areas under water scarcity at a global scale. **Zeng et al.** use three karst sites (two in the Alps and one in China) to assess whether the CO<sub>2</sub> sequestration associated with limestone weathering will be affected by future climate change. Temperature, runoff and land-cover were analysed in relation to carbonate weathering. Soil and vegetation cover were demonstrated to be key parameters. The results indicate that karst regions in cold regions will have an increased carbon dioxide consumption under global warming, while the opposite is to be expected for karst areas in warm zones. **Fiorillo et al.** have analysed very long, sometimes

more than 100 year-long, spring discharge records from Picentini and Matese karst aquifers in southern Italy. These records allow the investigation of the role of climate change in discharge variations, since other factors may be discarded. Through frequency analysis, a comparison was made in relation to climate parameters. The study shows that the discharge decrease observed over past decades may result not only from changes in precipitation but also from temperature increase. **Marín et al.** apply vulnerability mapping, through the concentration-overburden-precipitation (COP) methodology, to protect the water quality in the Ubrique karst system in Spain. This vulnerable site is especially fragile due to the absence of protective layers and the existence of well-developed karst features. The study stresses the need to implement an 'early warning system' to avoid changes in drinking water key parameters.

### Case studies with wider applicability

This special issue closes with six case studies that illustrate highly distinct scenarios and approaches, including "blue holes" hydrogeology, hydrothermal springs, sandstone-karstified aquifers, and classical karst aquifers under distinct geological settings in the USA and Slovakia. These case studies illustrate how vastly different karst aquifers can be, with increased understanding requiring a holistic approach and a good understanding of the local geological and hydrogeological constraints. The first **Malík et al.** paper provides a comprehensive analysis of 117 karst springs in the Western Carpathians, Slovakia. The study shows that discharge represents a complex interaction of slow and fast flow components, linked to the type of carbonate (dolomite or limestone) and linked to the influence of epikarst and the unsaturated zone. The contribution illustrates both the complexities of and the potential in interpreting karst spring recession curves. The enigmatic hydrogeology of the Blue Holes of the Bahamas is the subject of a study by **Smith et al.** Stable isotopes and physicochemical parameters were monitored at Church and Inkwel Blue Holes, in an attempt to decipher the role played by tidal oscillations in the complex interaction between the fresh and saline water zones. The results indicate that both fresh and saline waters are of meteoric origin, the latter becoming saline due to aerosol contributions. The next study presented indicates that although the Kentucky (USA) karst is among the best researched in the world, containing the world's largest cave system, the lesser-known Haney Limestone had not been, up to now, subject to a more in-depth study. **Arpin and Groves** provide such a comprehensive description of the Haney limestone karst features, focusing on controls on cave-passage direction. Both fractures and bedding planes play a role in passage orientation. Caves tend to have single conduits and to represent the resurgence of springs fed by allogenic recharge. Unlike nearby major caves

such as Mammoth cave, caves in the Haney limestone do not appear to be controlled by the incision of the Green River. In another study, it is shown that sandstone formations can behave as karst aquifers, although this topic has received limited attention in the literature. **Meus and Willems** aim to bridge this gap, with a pioneering tracing study in the strategic sandstone aquifer of Luxembourg. This aquifer had previously been interpreted as a porous medium. Extensive tracer tests involving 112 injections and 102 springs demonstrate that, in fact, fractures play a major role in flow routes and the aquifer should be modelled as a dual porosity medium. The study provides a robust framework to help delineate protection zones in such strongly heterogeneous aquifer. The **D'Angeli et al.** contribution deals with the sulphuric acid thermal system of Santa Cesarea, in Apulia, southern Italy. This coastal system comprises four caves where rising thermal water mix with seawater resulting in an aggressive solution that dissolves the rock and create abundant deposits of native sulfur. A comprehensive set of parameters, including S, O and H stable isotopes, hydrochemical data and atmosphere monitoring allowed the discrimination of two hydrogeological domains, comprised of rising acidic water and marine water. The second **Malík et al.** contribution presents a study of the Kopa Mountain karst aquifer in the West Carpathians, Slovakia. Planning for a highway required the drilling of nine boreholes that were monitored for 40 months, allowing for a detailed characterization of groundwater levels and flow velocity and how these vary over time, as well as allowing calculation of storage and specific yield values.

**Acknowledgements** IAH was still in its youth when a group of hydrogeology researchers proposed to establish, in 1970, an IAH Commission (the third IAH Commission to be created) to deal with karst hydrogeology. It is to this group of enthusiasts that we dedicate this special issue of *Hydrogeology Journal*, as part of a more comprehensive set of events celebrating the 50th anniversary of the IAH Karst Commission.

As editors we would like to express our appreciation for having the privilege to lead this work on behalf of the IAH Karst Commission. We gratefully acknowledge *Hydrogeology Journal* Executive Editor Clifford Voss, who suggested this special issue and supported the overall publication process, and the hard-working Susanne Schemann and Sue Duncan, from the *Hydrogeology Journal* editorial office, who guided us through the peer-review and technical editorial processes. We would like also to thank the several reviewers and authors who responded swiftly to our calls, almost with no delays, even considering that most of the process took place under the somewhat distressing conditions of the

COVID-19 pandemic in 2020. We hope this special issue will represent a useful glimpse into the wealth of knowledge generated by the IAH Karst Commission and will serve as basis for many future decades of accomplishments. This special issue represents a contribution to UNESCO's 2021 International Year of Caves and Karst.

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