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Editorial

Hydraulic Behavior of Karst Aquifers

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Abstract: The objective of this Special Issue, "Hydraulic Behavior of Karst Aquifers", is to focus on recent advances in karst hydrogeology in different areas of the world, focusing on topics dealing with the peculiar characteristics of karst aquifers. In particular, thirteen peer-reviewed articles were collected, focusing on hydraulic aspects and their relationship with geological features, geochemical and bacteriological aspects, tunneling and engineering mining inrush, and forecasting water resources and drought occurrences. Overall, these contributions describe several aspects of karst aquifers and are of great value for water resource management and protection.

Keywords: karst aquifer; hydraulic; recharge; discharge; karst hydrology; monitoring; in situ tests; geochemistry; isotope

1. Introduction

In many regions of the world, karst aquifers constitute a fundamental resource for water supply. Their hydraulic characteristics are very different from other aquifer types, as they are formed by a complex conduit network which is "immersed" in a low-permeability fractured limestone volume. Besides, karstification processes lead to the development of a hierarchical conduit network within the aquifer, which causes the drainage to converge at very specific points: the karst springs.

The importance of water resources in karst environments has increased over past several decades and many fundamental text-books on the subject have been written [1–5].

The objective of this Special Issue is to focus on recent advances in karst hydrogeology through studies in different areas of the world and, in particular, on the hydraulic aspects of karst aquifers.

Six papers come from China, two from Italy, and one each from France, Serbia, the USA, Croatia, and Slovakia, for a total of thirteen peer-reviewed articles collected for this Special Issue. Overall, these contributions describe several aspects of karst aquifers and are of great value for water resource management and protection.

2. Overview of This Special Issue

The topic of this Special Issue, "Hydraulic Behavior of Karst Aquifers", involves several fundamental aspects of karst hydrogeology and is based on the articles collected; the key points are: (i) hydraulic aspects and their relationship with geological features; (ii) geochemical and bacteriological aspects; (iii) tunneling and engineering mining inrush; (iv) forecasting water resources and drought occurrences.

2.1. Hydraulic Aspects and Their Relationship with Geological Features

Geological features have a fundamental role in groundwater circulation in karst aquifers. The karstification of soluble rock can be considered the most important geological phenomenon influencing the hydraulic behavior of karst aquifers, and geological contact with different rock types can highlight these hydraulic differences.

Five articles deal with water in karst aquifers, focusing on hydraulic behavior under different hydrological and geological conditions.

Sivelle et al. [6] analyzed the ability to assess the flow exchange between the matrix and the conduits in two karstified watersheds in France (i.e., Aliou and Baget) using the karstMod modelling platform. The model highlights a physical reality concerning the flow reversal between the matrix and the conduit during a significant rainfall event. Moreover, the matrix contribution in the total spring discharge is provided.

Fiorillo et al. [7] highlight the role of ascendant flux feeding karst springs of the Grassano–Telese area, where fresh springs are nearby thermal and sulfurous springs. Different data were considered (e.g., piezometric measurements, discharge, chemical–physical monitoring of springs, radon activity) and a numerical code was used to estimate the upwelling phenomenon. The ascendant flux was able to explain hydrological processes observed in this area, as an extraordinary develop of sinkholes connected to hypogenic speleogenesis.

Malik et al. [8] describe the effect of sudden recharge impulses which were recorded differently at local springs allowing interesting considerations on the geological and hydrogeological features of the western Carpathian mountains (Slovakia). In particular, the response time of spring discharge to sudden groundwater table rises appears delayed for higher water temperatures and vertical components of groundwater flux appear to play an important role.

Zhang et al. [9] investigated the hydraulic connectivity in the Jinan spring catchment (China) using karst groundwater table data. They proposed a method where the time-series of the hydraulic head is processed and compared statistically to explore the hydraulic connectivity of complicated karst aquifer systems. This method appears useful in limiting the number of experimental sites as much as possible, obtaining an overview of the hydraulic connectivity among different zones in an aquifer.

The article by Zhang et al. [10] is a good example of a survey of deep caves and buried paleokarst systems. They combined the analyses of core samples, 3D seismic recognition, and computer modeling to identify cave distributions in the Tarim Basin, China. The results are promising and show how it is possible to obtain a detailed survey of caves in a karst environment by 3D geophysical characterization of rocks.

2.2. Geochemical and Bacteriological Aspects

Water chemistry and its bacteriological content is strongly interconnected with hydraulical properties of karst aquifers. Extreme heterogeneity of hydraulical properties results in abrupt changes of karst water quality in comparison to more homogenous aquifer types. Three papers in this issue examine the water qualitative aspects of groundwater circulation in karstic terrains.

Although the dissolved Mo contents in karst groundwater is not discussed frequently, studies from the upper Xijiang River (southwest China) on draining of the carbonate terrain by Zeng et al. [11] identified the sources of dissolved Mo as the carbonates and sulfide/sulfate minerals' weathering with a seasonal contribution. The seasonal and spatial variations, ion budget, and isotopic fractionation of dissolved molybdenum was studied as well. The results show that the Mo concentrations exhibit an extensive variation along the mainstream without significant spatial patterns, but the Mo concentrations are slightly higher in the dry season than in the wet season caused by the dilution effect. Results from Reference [11] also suggest that there is no significant Mo isotopic fractionation during weathering and riverine transportation and the authors consider the dissolved molybdenum 98Mo/95Mo isotope ratio of river draining the carbonate terrain to be underestimated in the calculations of the Mo budget, which could significantly influence the redox history of oceans by the Mo isotope model.

Microbiota in karst water usually represents one of the primary factors depreciating the possibility of its exploitation for drinking water purposes. Šreng et al. [12] performed a study in the Bokanjac–Poličnik karst catchment (Zadar, Croatia), focusing on Enterococci transport and the

Enterococci die-off coefficient. Increased concentrations of Enterococci, as fecal indicator bacteria, were studied in terms of the determination of potential pollution sources. In the second step, Šreng et al. [12] constructed an analytical model aimed at resolving the processes of sorption and die-off and determining the dominant factor in the process of natural removal of Enterococci when transported in a karst environment. Both vertical percolation and horizontal seepage were incorporated into this flow and transport model. The mean value of the total die-off coefficient by transport through the unsaturated zone was k_{tot} = 8.25. Within the saturated zone, the total die-off coefficient k_{tot} was found within the limits of 0.1 and 0.5 [12].

Carbon—the most important major component present in carbonate rock masses—is the first component discussed. Many studies on carbonate bedrock weathering have focused on the dissolved inorganic carbon (DIC) flux while dismissing particulate inorganic carbon (PIC) as insignificant. The study of Paylor and Wicks [13] shows that, under certain flow conditions, particulate inorganic carbon flux may be an important term in carbonate weathering. In their study, the total inorganic carbon (TIC) flux was calculated in a fluviokarst basin. The mass of PIC within suspended sediments was quantified by cation/anion analysis of dual filtered/unfiltered samples and the flux of bed load material was calculated via stream power calculations. The analysis of recorded storm events indicated that PIC flux is moderate but can be significant during peak storm discharges. During storm events, bed load was the most significant component of the total PIC flux, exceeding the suspended load flux by an order of magnitude. When calculated on an annual basis, the data show that PIC contributes approximately 10% to total inorganic carbon removal [13].

2.3. Tunneling and Engineering Mining Inrush

Development of engineering constructions in the depths of the Earth's crust can be considered as a masterpiece of humankind's technical development. Keeping the balance with the ever-changing rock pressures and discontinuities, static quantifications of spaces within rock masses certainly cannot be considered to be a daily routine even in seemingly homogenous rock formations. Karst development, where the "unexpected should be expected", creates an everlasting challenge for the most appropriate solutions. Constant exchange of best practices, technological progress, and new ideas in this engineering segment, connected with interactions of karstic groundwater and underground constructions, continues also in our Special Issue. Three papers presented here aimed at detailed groundwater monitoring for underground structures in karsts [14], formulation of evolutionary laws on water inrush from the cavity [15], and description of the reverse fault control mechanism in the development of underground rivers [16]. Although these do not cover the entire spectrum of underground engineering problems in karsts, but due to their presence in this Special Issue, they can be considered as new gems in the mosaic of karst geotechnics.

The potential aggressiveness of karstic groundwater toward the concrete lining of the Pirot Hydropower Plant water-conveyance tunnel (southeastern Serbia) was revealed by detailed monitoring in these complex geologic/hydrogeologic conditions [14]. Čokorilo Ilić et al. [14] performed their studies both inside the empty water-conveyance tunnel and, depending on the power plant operating regime, at observation wells along the tunnel, springs, and a stream in the vicinity of the tunnel. Apart from the water's aggressiveness toward the tunnel concrete lining, observations of the quantitative parameters pointed out hydraulically critical tunnel zones. The analysis of the total water losses from the tunnel showed that they were relatively acceptable and that their distribution along the tunnel was not uniform. The closer assessment of the zone with the highest water losses pointed to the part of the tunnel where the concrete lining was unstable. The authors underline the importance of detailed groundwater monitoring in risk assessments of the adverse effects of water–rock interactions on tunnel performance in such a complex geologic/hydrogeologic environment as karsts.

Two articles from China refer to water inrushes—geological hazards that are often encountered in tunnel construction, especially in karst media. A multi-type water-inrush model test system is introduced by Yang et al. [15]. The test system described here can be a precursor to large-scale studies, handle multiple types, and perform serialization and visualization. Evolutionary laws of water inrush from the cavity, including the initiation of fractures in the aquifuge rock, formation of water-inrush channels, and subsequent rupture of the aquifuge rock were revealed by the model by analyzing the seepage pressure changes at the monitoring points of the aquifuge rock. The water-inrush process of the cave was divided into a rack generation stage, holing-through of fracture and forming of water-inrush channel stage, and the final water-inrush stage [15]. According to the test results, the multi-type water-inrush model test system was stable and reliable, only requiring a short test period, and can be used to guide large water-inrush testing and related projects. Zhang et al. [16] then discuss the traditional idea that the reverse fault is not easily developed for an underground river (conduits), which means that the tunnel elevation design is not considered adequately. Taking the Qiyueshan Tunnel site as an example, on the premise of the anatomy of the control mechanism of the reverse fault on the development of the underground river, based on the multiperiod typical structural traces of the tunnel and surface outcrop, it was found that stratifications, dip joints, transverse joints, and tension joints of good aperture grade should be the important control factors. Intermittent uplifting of regional structures provides hydrodynamic conditions for the development of conduits, causing the hydraulic gradient to be inconsistent, meanwhile, the cut blocks easily lose their stability and provide space for karst development. The authors further considered the effect of the vertical zoning of the fault structure and the excavation disturbance, and, drawing on the experiences from the relative location at the same site in the same field, put forward the suggestion that the construction of the follow-up tunnel in the study area should be slightly higher than the elevation of the underground river [16]. The research results discussed here can provide useful reference for similar engineering problems in the future.

Groundwater inrush is a typical hydrologic natural hazard connected with mining activities. Groundwater inrush hazards from a grouted karst collapse pillar in longwall mining were investigated by Ma et al. [17]. The karst collapse pillar represents a common geological structure in northern China coalfields, often acting as an important groundwater inrush pathway in underground mining as it contains a significant number of granular rocks, which can easily migrate under high hydraulic pressure. Although grouting of this zone can mitigate the risk of groundwater inrush hazards, the fracture or instability of the coal pillar near this zone can cause instability in surrounding rock and even groundwater inrush. To evaluate the risk of groundwater inrush from an aquifer that is caused by a coal pillar's instability within a grouted karst, collapsed pillar, an in situ investigation on the deformation of the surrounding strata was conducted. A mechanical model with a floor–pillar–roof system was established, followed by a numerical model to evaluate the continuous instability and groundwater inrush risk. The criteria for the system stability assessment were defined based on comparison of the collective energy and stiffness in the floor–pillar–roof system [17], aimed at eliminating groundwater inrush hazards in coal mines which, in the past, were responsible for casualties in the hundreds of miners.

2.4. Forecast of Water Resource and Drought Occurrences

As karst springs have been used for water supply in various regions of the world, discharge measurements will be available for many years. These hydrological time-series have been correlated with rainfall and temperature in order to find any relationships inside local hydrological circles.

Sappa et al. [18] provided a cross-correlation between rainfall and spring discharge in order to simulate the effect of variations in rainfall on water resources. The example of a spring (Capodacqua di Spino) in central Italy is shown, where missing spring discharge data were estimated by the proposed method. The article appears interesting also because it is based on simple hydrological time-series data, which can be easily applied to other hydrogeological contexts.

3. Conclusions

Karst aquifers are an exceptional type of aquifer, as their groundwater outlets are naturally concentrated into single-point discharges and they have the ability to cover the drinking water needs of large regions. The same aquifer properties, on the other hand, are responsible for complicated engineering solutions that must be implemented in order to cope with the risk of destructive groundwater inrushes into tunneling and mining constructions. These properties, first of all, indicate the existence of a complex hierarchical conduit network immersed in low-permeability fractured volumes, which can cause an extraordinarily intensive communication of groundwater surface waters (point recharge through swallow holes/ponors) and make karstic aquifers vulnerable to abrupt change of groundwater quality and quantity. Karst aquifers, therefore, represent a natural challenge for scientists trying to study them in their complexity. Also, in this Special Issue, several investigation areas were touched on: characterization of inner hydraulic properties and their relation to geological features, variations in karstic water quality in both its chemistry and microbiology, engineering solutions in karstified rock masses, and water resource sustainability in drought periods possibly influenced by climate change. The papers presented here certainly do not represent the full extent of the problems encountered, but we hope they can be considered as one of the many steps on the staircase for proper understanding of karstic aquifers.

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