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Characterization, modeling, and remediation of karst in a changing environment

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Abstract

This introductory editorial paper provides a review and prospective outlook of the achievements and challenges in karst research under a changing environment. A brief discussion of the past and future karst research has been focused on: (1) data and new technologies; (2) modeling of karst flow and reactive transport; (3) responses of karst hydrosystems to climate variability and changes across scales.

Keywords Karst · Data · Modeling · Changing Climate

Introduction

Karst is a term used to describe a special landscape con- taining caves and extensive underground water systems that is developed by dissolution in the carbonate rocks such as limestone and gypsum (Ford and Williams 2007). Karst terrains undergo considerable dissolution to create and enlarge joints, fractures, bedding planes, and other open- ings in which groundwater flows. These terrains show dis- tinctive surface and subsurface features associated with sinkholes, springs, caves, and sinking, losing, and gaining streams, which are characterized by well-developed conduit networks having high connectivity (e.g., Xu et al. 2015a, b) and/or highly transmissive zones (e.g., Kuniansky 2016). These characteristics make some karst groundwater sys- tems highly productive and become important freshwater resources for human consumption and ecological integrity of streams, wetlands, and coastal zones (Padilla and Vesper 2018; White 2018). Karst regions underlie approximately 10% of the ice-free continental area, and karst aquifers par- tially supply drinking water resources to almost a quarter of the world’s population (Ford and Williams 2007). Stress on water resources in karst aquifers has increased significantly in recent decades, associated with the limited quantity of water supply and deterioration of water quality (Hartmann et al. 2014). Available water resources have become the major constraint for many karst regions, for example, in Southwest China (Lu 2007), where management of land, people and water resources is a critical environmental chal- lenge in rocky desertification areas (Jiang et al. 2014). In addition, many geohazards in karst areas, for instance, sinkhole collapse and land subsidence, are strongly related to over-utilization of groundwater, inappropriate limestone mining, and other human factors (Kuniansky et al. 2016).

The characteristics of large connectivity and void spaces, which make karst aquifer systems highly productive, also make them highly vulnerable to contamination (Göppert and Goldscheider 2008). Surface karst features and large per- meability in the subsurface enhance the ability to transport contaminants over long distances, particularly through well- developed conduit networks. The porous matrix of the karst rocks and the significant amount of sediments trapped in karst formations provide high storage capacity for contami- nants that can be slowly released for long periods of time. As a result, karst systems can serve as an important route for contaminant exposure to humans and ecosystems (Padilla et al. 2011). Groundwater quality impacted from point and non-point sources of contamination have been widely stud- ied in karst areas (e.g., Padilla and Vesper 2018; Xu et al. 2015b; Yu et al. 2015).

Karst systems are highly dynamic and heterogeneous, with complex hydrological, geochemical, and biological processes that affect the transport of water, solutes, and non- aqueous entities over a wide range of spatial and temporal scales. Fundamental knowledge exists on many of these pro- cesses and several predictive and characterization models have been developed and applied to karst systems. Tremen- dous challenges and uncertainties are faced when trying to characterize, predict exposure, implement remedial actions, and manage contaminated systems, particularly in a chang- ing environment, including climate change, human impacts, etc. A need exists to advance knowledge and technology for understanding the hydrological response of karst systems to those changes, and to develop appropriate management and remediation approaches.

Interdisciplinary studies, including collaborations and expertise from a full range of scientific and engineering disciplines, are in high demand for assessment of water resources availability, chemical dynamics, and potential con- taminant exposure in a karst aquifer. For example, advanced monitoring sensors and instruments for physical and chemi- cal hydrology can enhance data availability in field geol- ogy, particularly in deep subsurface karst conduit networks. Interactions between bio-geosciences, atmospheric sciences, and marine and oceanographic sciences help fully address earth system processes in karst studies. Statistical, math- ematical, scientific computing, and data sciences knowledge contributes to build the state-of-the-art physical-based and/ or data-driven modeling approaches to the study of karst hydrogeology. Collaborative works between engineers, hydro-scientists, and public health experts are mapping the way to assess direct links between contamination in karst regions and adverse health outcomes (Cordero et al. 2018).

Major achievements and challenges in karst research

Papers in this thematic issue help to summarize the knowl- edge learned in the past, to review the progress of ongoing research, and to predict major challenges in the future. This section is organized into three perspectives: (1) data and new technologies; (2) modeling of karst flow and reactive transport; (3) responses of karst hydrosystems to climate variability and changes across scales.

Data and new technologies

Limited laboratory and field observational data have been a major constraint in karst research. Laboratory experiments have been extensively developed to study the groundwater and solute transport (e.g., Faulkner et al. 2009; Anaya et al. 2014), and reactive transport (e.g., Geyer et al. 2007), in the interaction among karst conduits, fractures, and porous medium. Unlike the alluvial sandstone aquifers, karst fea- tures, including sinkholes, karst windows and conduit net-works, are difficult to be successfully explored by traditional hydrogeological field methods. For example, the subsurface karst conduit networks are found at nearly 100 m below land surface in the Woodville Karst Plain, North Florida (Werner 1998), which led to difficulties in field investigation. Tracer tests have been widely applied in the studies of karst aquifers to resolve the active and often inaccessible part of cave and conduit networks, and to evaluate the hydraulic connectivity in karst aquifers (Goldscheider et al. 2008; Werner 1998). Geochemistry data were widely collected to study the global carbon cycle, including carbon flux data for biogeochemical cycle (Gill and Finzi 2016), aquatic carbonate concentration for the contribution of carbonate weathering to atmospheric CO_2 (Huang et al. 2015), and karst-related carbon sink (Zeng et al. 2016), from watershed to global scales.

Utilization of advanced instruments and technologies is critical to provide more data and detailed descriptions to gain insights into karst research, particularly in the deep subsurface conduit networks considering the difficulties and complexities of karst exploration. Xu et al. (2016) reported a flow speed, flow direction, and electrical conductivity monitoring work over a long-term period, with the help of cave divers at the 100-m deep conduit in the Woodville Karst Plain, Florida. This study discovered potential seawater intrusion through subsurface conduit networks in the coastal karst aquifer, which indicated a trend of rising sea levels, and analyzed its impacts on groundwater contamination. It is also crucial to capitalize on long-term data, where available, and accordingly to develop and maintain long-term observa- tories of karst hydrosystems. On the other hand, investiga- tion of conduit network geospatial distribution and physical geometry is in high demand in karst research by deploy- ing advanced and new monitoring techniques. In recent years, Kenney et al. (2012) developed a neutrally buoyant sensor method for mapping a water pathway in the direc- tion of subsurface conduit flow. In Weidner et al. (2017), a systematic approach for the 3-D mapping of underwater caves utilized the intersection of video light with the cave boundaries to describe the outline of the cave. Further works are required to apply these newly developed techniques in field application, improve the data resolution and quality, and transform measurements to actionable information.

Modeling of karst flow and reactive transport

Modeling karst groundwater flow and contaminant trans- port in karst systems pose particular challenges because of their highly heterogeneous nature, wide spectrum of flow regimes (ranging from laminar to turbulent flow), lack of proper data for accurate characterization, and limited applicable models with full physical processes, among others. Numerical models are often used to describe flow and trans- port trends, as long as they are applied within the limits of their realm. Several modeling approaches exist for simu- lating groundwater flow and contaminant transport in karst aquifers, for example, the lumped and distributed models of varying complexities (Ghasemizadeh et al. 2012; Hart- mann et al. 2014; Scanlon et al. 2003). Dual-permeability hydrogeological system is one of the major challenges in simulating groundwater flow in a karst aquifer, which con- sists of both high-permeability conduits and fractures, and low-permeability surrounding porous media. Different from the porous media in the alluvial aquifer, groundwater flow within the high-permeability conduits and fractures can eas- ily become non-Darcian and even beyond the upper criti- cal Reynolds numbers. The non-Darcian conduit flow and Darcian porous medium flow are computed and coupled in the discrete-continuum hybrid models (Liedl et al. 2003; Shoemaker et al. 2008), which have been widely used to simulate variable-saturation flow conditions (Reimann et al. 2011) and groundwater contamination transport issues (Xu et al. 2015a) in karst aquifers. The recharge reservoir model is developed and coupled with discrete-continuum models to simulate surface and subsurface flow in karst systems under various rainfall conditions (Chang et al. 2015; Chen et al. 2017). A density-dependent discrete-continuum model has been developed in Xu and Hu (2017) as a new mod- eling method to study seawater intrusion through conduit networks in a karst aquifer, providing a way to simulate the impacts of sea level rise under changing climate. Future work of more accurate parameterizations is highly desired and deterministic in karst modeling applications, particularly the exchange flux between conduit and porous medium, the dispersion coefficient, and friction factor within the con- duit. In addition, high-performance computing and advanced numerical methods are desired to solve the karst hydrology models more efficiently and accurately, with fully coupled physical-based processes in a finer resolution.

At regions with limited data availability, simplified karst

modeling approaches are applied that represent the domi- nant dual permeability processes of karst systems by varying combination of buckets that represent the important stor- ages of the karst system: the soil, epikarst, karst matrix, and conduits (Hartmann et al. 2014). In recent years, research focused on quantifying the uncertainty that results from those simplified karst modeling approaches (Chen et al. 2017; Adinehvand et al. 2017; Xu et al. 2018) and quantify- ing the information content of auxiliary data as hydrochemi- cal information (Hartmann et al. 2017a, b) or geophysical measurements (Mazzilli et al. 2013). Future research is nec- essary to further explore the value of auxiliary data and to link the advantages of these simplified modeling approaches and the above-mentioned physically based approaches.

The subsurface conduit network is formed by a positive feedback mechanism between dissolution by water under- saturated with respect to calcite and the amount of water percolating through a carbonate rock (Worthington and Ford 2009). Physical-based reactive transport modeling (RTM) in hydrology is important to investigate the evolution of frac- tures and conduits, and to compute carbon mass balance in multiple temporal and global spatial scales. For example, Rehrl et al. (2008) developed a discrete-continuum RTM to couple aquatic chemical reaction processes with ground- water flow and transport models to examine the interrelation between the hydrogeological environment and conduit development in a deep-seated setting. In a recent study, de Rooij and Graham (2017) presented a hydrochemical model that can be used to generate plausible karstic conduit networks that honor what is known about geology, hydrology, and topography of a karst system. Conduit evolution modeling, however, is still an oversimplification of reactive transport processes that requires further investigations in the limited number of chemistry processes, coarse spatial resolution, and lack of validation. On the other hand, sto- chastic and statistical modeling in karst conduit evolutions have been widely applied to help build the conduit networks in hydrologic numerical modeling (Jaquet et al. 2004; Pardo- lguzquiza et al. 2012). Prior information, sampling methods, computational cost, and lack of real conduit network valida- tion data are still unresolved issues and open questions for stochastic simulations of karst networks.

Response of karst hydrosystems to climate variability and change across scales

To understand the impacts of global climate change on water resources in karst aquifers, the scalability of hydrologic models becomes critical, from pore scale to regional scale. Owing to the very heterogeneous nature of the karst, such hydrosystems may display particular hydrological behaviors that need to be thoroughly analyzed and modeled. The interaction between watershed-scale hydrologic models and regional, even global-scale climate models has been investigated in a number of studies, such as the US National Water Model (currently under development, http:// water.noaa.gov/about/nwm) and European Flood Awareness System (Kauffeldt et al. 2015). None of the above, however, address the complexity of karst aquifers, or have been applied in either karst watersheds or on a large regional scale of karst land mass. Some recent work showed that the reliability of presently applied large-scale simulation tools is strongly limited (Hartmann et al. 2015, 2017). In addition, global-scale biogeochemical simulations are essential to evaluate the roles of karst regions in global carbon cycles, particular carbon sink effects in carbonate rock dissolution and weathering. The upscaling of current hydrology models in karst aquifers from the dual-permeability watershed scale to global scale becomes important to carbon budget estimation. The hydrologic and aquatic geochemistry processes in a karst aquifer, including interaction of non-linear and linear flow, and reactive transport in carbonate rock dissolution and precipitation processes, have potential impacts on global carbon cycle and should be included in future earth system modeling studies.

On the other hand, most karst distributed models are still developed based on some traditional hydrology models that only solve the Darcy equation in the aquifer, for example, MODFLOW-CFP (Shoemaker et al. 2008), with very simplified land surface processes. The hydrological interactions between atmosphere and land have been addressed in several integrated hydrology models, including PF.WRF (Maxwell et al. 2011) and WRF-Hydro (Gochis et al. 2013); however, they have rarely been integrated with dual-permeability hydrology models and applied in karst regions. These integrated hydrology models are advanced with physical-based land surface models to study the responses of increasing temperature, dynamic vegetation, precipitation variability, and human factors. For example, early snowmelt processes under changing climate control groundwater table fluctuation and then affect carbonate dissolution and water chemistry (Winnick et al. 2017). Integration of land surface models and dual-permeability hydrology models becomes the key for a successful simulation of hydrological and biogeochemical responses in karst aquifers under climate change.

Preview of the papers expected to be accepted

The scientific community of earth science has become even more aware of the significant and grand challenges fac- ing water resources and ecosystems in karst aquifers. An increasing number of karst-related research studies have been initiated and developed worldwide in recent years. For example, the number of abstracts submitted to the karst session in AGU has increased in the past 3 years (22 in 2015, 28 in 2016 and 37 in 2017). Among these, a significant number of studies have been cross-listed with biogeoscience, global environmental change, atmospheric, and oceanography.

In response to the increasing amount of karst research, this thematic issue on “Characterization, Modeling, and Remediation of Karst in a Changing Environment (AGU)” with Environmental Earth Sciences (EES) will be composed of papers on research related to the characterization, moni- toring, and modeling of hydrogeology, morphology, biogeochemistry, geohazards, and remediation of carbonate and karst water systems at multiple temporal and spatial scales.

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