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Research in karst: A model for future directions in hydrologic science?

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Interdisciplinary research on the hydrology of karst aquifers has long been practiced and is perhaps of even greater value today as a model for future directions in hydrologic science in general. Challenges to achieving a deep understanding of karst systems span the full range of current problems in hydrology. Questions in karst encompass general hydrological problems, such as conceptualizing flow heterogeneity and connectivity, transferring detailed time series of flow and geochemistry into predictive relationships, modeling multi-phase and density-driven flow, and understanding the interactions between geological history, climate, geomorphology, biological systems, geochemistry, and hydrology. Heterogeneities in subsurface flow and hydrogeologic processes that generate flow networks are central to conceptual frameworks in modern hydrology, and are exemplified by karst systems. Insights gained through the approaches used to study karst aquifers can be applied to a wide spectrum of hydrologic systems, from surficial alluvial aquifers to deep confined fractured bedrock aquifers.

Karst and analogous hydrologic systems are present in every state of the United States, either at the surface or at depth. Approximately 15% of the exposed or shallowly-buried bedrock of the United States alone has the potential for hosting karst features such as caves, sinkholes, sinking streams, and subsurface conduits (Weary and Doctor, 2011; Figure 1). This number greatly understates the extent of aquifers that have karst, paleokarst, and pseudokarst features at depth. The common perception that karst phenomena are limited to the shallow subsurface is false, and certain karst aquifers have circulation up to several kilometers depth.

Nearly one quarter (23%) of all fresh groundwater withdrawn from principal aquifers in the U.S. was from bedrock aquifers in the year 2000, and of this amount, slightly more than half (52%) was from carbonate and mixed sandstone and carbonate rocks; if basaltic rock aquifers are included in this latter percentage, it increases to 83% (Maupin and Barber, 2005). Thus, karst and volcanic pseudokarst aquifers are the most productive bedrock aquifers in the United States (Table 1). Withdrawals from the Floridan aquifer alone accounted for 26% of total bedrock aquifer withdrawals, and more groundwater is withdrawn from the Floridan aquifer than from all other U.S. carbonate aquifers combined. Stresses such as climate change, pollution, groundwater extraction, and saltwater intrusion threaten the sustainability of karst systems and warrant further integrated scientific investigation.

Given these facts, it is noteworthy that karst processes have historically received less attention in North America than in Europe or Asia (Florea et al., 2007). However, the attention is steadily growing. The number of publications on karst-related subjects has increased greatly since 1990. Yet, the AGU journal Water Resources Research has lagged behind the trend. For example, a search of the ISI Web of Knowledge shows 208 articles published in Journal of Hydrology since 1990 with the topic of "karst," whereas only 48 were published in Water Resources Research during that same time period. These numbers are 3.16% and 0.64%, respectively, of all papers published in these journals since 1990, suggesting nearly a 5-fold difference.

Despite inherent difficulties, researchers have made advances toward numerical characterization of karst systems. For example, the MODFLOW conduit-flow process (Shoemaker et al., 2008) incorporates a discrete conduit network coupled with the traditional continuum solution and also employs high-conductivity, continuum flow layers in which flow can transition between laminar and turbulent. Ongoing research is focused on unsteady and non-uniform flow within partially-filled conduits and description of turbulent flows with nonlinear gradient functions. While MODFLOW conduit-flow process is currently limited to the flow solution, future versions will incorporate additional processes, such as buoyancy forcing, solute transport, and heat exchange.

Representing permeability structure remains a major challenge to deterministic modeling of karst systems. Because conduit and fracture geometries can rarely be measured directly, new indirect techniques are needed to deduce the influence of permeability structure on system response to external stress. Inverse modeling of permeability structure using deterministic models is likely to be difficult, due to the large number of descriptive parameters required. Additional research is needed to determine the type and amount of data required to constrain representations of permeability. Stochastic methods and fractal concepts will likely play a key role (e.g., Hergarten and Birk, 2007).

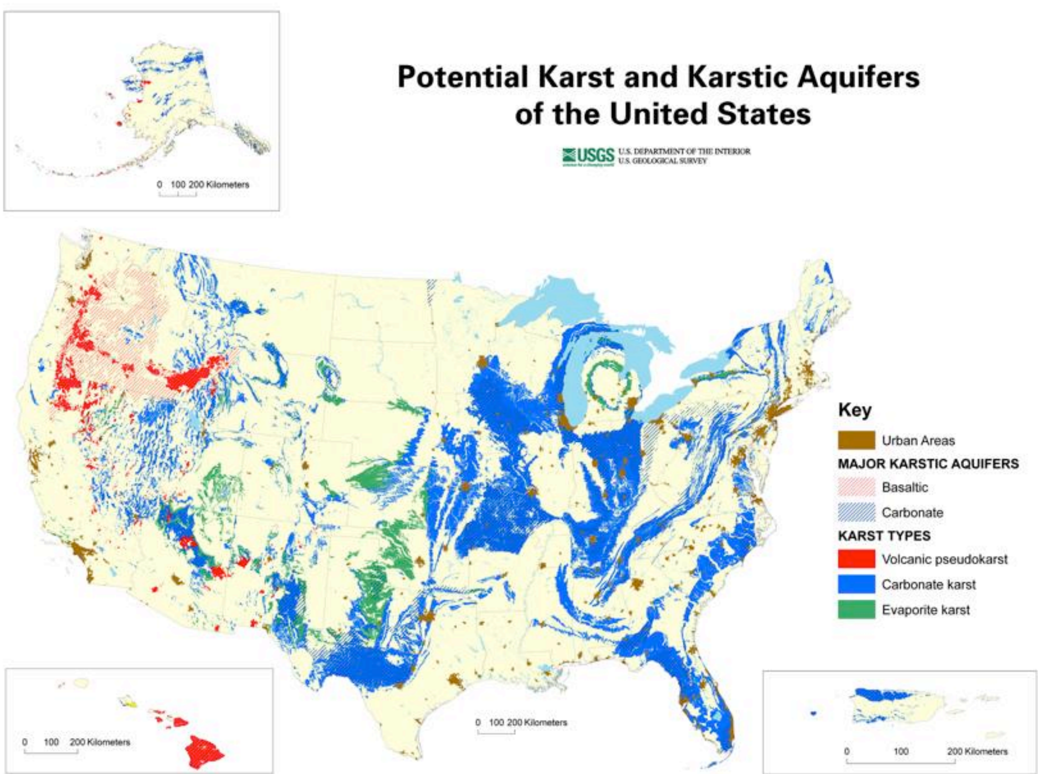

Figure 1: Map of potential karst and karstic principal aquifers of the United States (unpublished USGS data).

Model uncertainty and sensitivity are largely a function of data quality and data density; however, in most karst settings, even dense well data may not overcome uncertainty associated with aquifer permeability structure. Significant effort has been expended to develop lumped-parameter and grey-box models of karst systems (e.g., Fleury et al. 2007). These models can allow prediction of discharge and geochemistry, within observed ranges, without quantifying conduit properties. Future research that expands upon the groundwork of lumped parameterizations of karst conduit networks is needed.

The continuous measurement of flow, geochemistry, and temperature is often applied in karst, and is becoming standard practice in other hydrologic systems as technologies become less expensive and more user-friendly. Despite long-held views to the contrary, a theoretical analysis has suggested that spring hydrographs carry little information about conduit system geometry (Covington et al., 2009). Other signals, such as temperature and geochemistry provide more promise. A study by Luhmann et al. (2011) of thermal patterns at 25 springs in Minnesota suggested that temperature signals carry significant information about permeability structure and recharge mechanisms. High-frequency geochemical sampling at springs has shown utility for elucidating the dynamics of mixing between different components of a karst aquifer (e.g., Doctor et al., 2006). Dye tracing and analysis of tracer breakthrough curves remain important tools in karst hydrology and an area of continuing research with particular focus on multi-tracer approaches.

Groundwater age, or mean residence time (MRT), is an important quantity to estimate in hydrologic studies, as it provides insight into system dynamics and has implications for resource sustainability and quality. Measurement of environmental tracers with known atmospheric concentrations provides a quantitative estimate of water age; however, in most cases, the age of a single sample reflects a mixture of waters with widely disparate residence times. In karst aquifers, residence times may range across several orders of magnitude, and residence time distributions may be

Table 1: Year 2000 U.S. groundwater withdrawal from carbonate karst aquifers, mixed sandstone and carbonate karst aquifers, and volcanic pseudokarst aquifers in million cubic meters per day (Maupin and Barber, 2005).

AQUIFER	Groundwater withdrawal m^3 day^{-1} [$x10^6$]
CARBONATE KARST AQUIFERS	
Floridan aquifer system	13.8
Biscayne aquifer	3.1
Roswell Basin aquifer system	1.5
Valley and Ridge carbonate-rock aquifers	1.0
Silurian-Devonian aquifers	0.9
Ozark Plateaus aquifer system	0.6
Basin and Range carbonate-rock aquifers	0.3
North Coast Limestone aquifer system (Puerto Rico)	0.2
New York and New England carbonate-rock aquifers	0.2
Blaine aquifer	0.2
Castle Hayne aquifer	0.1
MIXED SANDSTONE AND CARBONATE KARST AQUIFERS	
Edwards-Trinity aquifer system	2.8
Intermediate aquifer system (Florida)	1.3
Mississippian aquifers	1.1
Valley and Ridge aquifers	0.4
Paleozoic aquifers	0.1
VOLCANIC PSEUDOKARST AQUIFERS	
Snake River Plain basaltic-rock aquifers	9.9
Columbia Plateau basaltic-rock aquifers	3.5
Pacific Northwest basaltic-rock aquifers	1.8
Volcanic-rock aquifers (Hawaii)	1.6

non-stationary and multi-peaked. For modeling groundwater age, two approaches are common: 1) direct measurement of environmental tracers of groundwater age in a water sample (e.g., ^3H, ^{14}C, CFCs, SF_6) ; and 2) indirect estimation of MRT based upon convolution or weighting functions of input-output environmental tracer data, such as water stable isotope values ($\delta^{18}O$ and δD) (Plummer et al., 2003). Estimation of groundwater MRT using the convolution integral approach can provide an independent estimate of ground water age, but is highly dependent upon input and output data obtained at high frequency, and the transit time distribution applied in the model. Technological advances in continuous measurement of isotopic and chemical parameters will make estimation of MRT less expensive and facilitate wider use of the method. Great potential lies in the application of field-deployable laser-based isotope analyzers for continuous measurement of water stable isotopes at springs (Berman et al, 2009).

Karst systems provide opportunities to test new hydrogeophysical technologies. Electrical resistivity surveys have proven very effective for site-specific investigations in karst, but the limited scope of individual electrode arrays generally make them impractical for regional studies. Advances in airborne electromagnetic surveying (Smith et al., 2005) and audio-magneto tellurics (AMT) hold great promise for future regional karst aquifer characterization.

Many avenues of inquiry remain open concerning the relationships and feedback among karst ecosystems, hydrology, and geomorphology. With the absence of light, karst ecosystems have no primary production. Thus, karst ecosystems are truncated (Gibert and DeHarveng, 2002) and dependent on externally derived organic matter or on autogenically generated organic matter. Within karst aquifers, transformation of detritus into usable organic matter is driven by microorganisms frequently with the generation of carbonic acid that can drive additional dissolution and subsequent flowpath changes. Given the importance of microorganisms in the ecology of subterranean and phreatic ecosystems, more research is needed in karst areas to try to understand how nutrients and organic carbon are delivered to, processed in, and removed from aquifers. High-resolution time series of ecologically important geochemical constituents, such as carbon, nitrogen, sulfur, trace metals and their stable isotopes will advance knowledge of mixing between near-surface and deeper aquifer components, and will provide insight into the role karst aquifers play in global biogeochemical cycles.

On longer time scales, karst hydrology can provide a framework within which ecologists can interpret the life history of stygobionts (obligate groundwater-dwelling species). For instance, how have the episodic changes in discharge, temperature, sediment load, and water chemistry shaped life histories? As karst basins are subjected to anthropogenic stress, will these stygobionts adapt? As the global climate changes, the ability of these animals to migrate with the changing climate is non-existent. How do we attempt to conserve these ecosystems? How much change in conditions can the stygobionts accommodate? Addressing these questions will require collaboration between hydrologists and biologists.

Hydrological boundary conditions, geologic stratigraphy, geomorphological forces, and landscape history control karst aquifer structure. Knowledge of the processes of cave formation are crucial to conceptualizing and quantifying karst aquifer structure, and for informing management strategies for preserving water quality. Advances continue to be made in the quantification of geomorphological processes in karst, and often systems display signatures from multiple hydrological or climatic regimes. For example, Gulley et al. (2011) show that episodic flow reversals of Suwannee River springs force conduit growth in the Floridan aquifer, thus highlighting the long-term history of surface water-groundwater interaction in this important karst aquifer.

Solving the remaining conundrums that karst presents requires addressing many of the open questions in the field of hydrology at large. Given the great importance of karst aquifers as water resources, the American community of hydrologic scientists can no longer afford to largely ignore these complex hydrologic systems. Clearly, the future of hydrologic science will benefit from additional research in karst.

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Creating a research space for Water and Society

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Editor's Note: *The Hydrology Section has recently formed a Water and Society Technical Committee, jointly with AGU's Societal Impacts and Policy Sciences Focus Group. The author is a co-Chair of the committee (the second co-Chair will be named soon). This article describes the motivation for the committee, which will meet for the first time in San Francisco. It also describes a session (H61, "The Evolution of Water Management Paradigms," sponsored by the TC, to be held in San Francisco.*

The subject of water and society is at the heart of the study of water as a resource. Water is essential to human activities and to ecosystems. It is a vital input to food and energy production, and, yet, is also a destructive hazard. The hydrologic cycle is an integral element of Earth's climate system, but the fact that it is modulated by human alteration of the land surface and atmosphere is a fact that is often ignored in the climate context, notwithstanding that anthropogenic manipulations have severely altered the land surface hydrologic cycle in many respects. Society demands, withdraws, competes, uses and wastes the resource in dynamic counterpart.

The science of water management emerges from this field at the nexus of engineering and geoscience, with substantial influence from economics and other social sciences. The spatial scales of analysis range from a single smallholder farm, in the case of a rainwater harvesting system, to the entire Earth, in the case of global flow of water in agricultural production. Within this purview are some of the most pressing environmental questions of our time, such as