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Features and Hotspots in Karst Groundwater

Ruiqiang Yuan[1*], Xinping Deng[2]

[1]School of Environment and Resource, Shanxi University, Taiyuan Shanxi
[2]The 402 Team, The Bureau of Geology and Mineral Resources Exploration of Hunan, Changsha Hunan
Email: *rqyuan@sxu.edu.cn

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Abstract

Karst covers more than 20% of lithosphere area. Karst groundwater resource is a vital water resource. However, a karst water-bearing system is a kind of dual media with distinct hydraulic properties, of which heterogeneity is significant and two mechanisms of surface water infiltration are of the same importance. The connection across precipitation, surface water and karst groundwater is very close. And the conversion among them is nonlinear with considerable complexity. Hydrologic processes, flow rates and the discharging area are readily impacted by the changing environment in a karst groundwater flow system. Discharges of karst springs are of scale effect and multi-fractal characteristics. And the composition of discharge is complicated and changeable. Furthermore, hydrogeochemical characteristics of karst groundwater are sensitive to the changing environment determined by variable hydrologic processes of karst and biogeochemical reactions. Therefore, traditional geohydrologic methods can't be applied directly in a karst basin and the common difficulties in hydrologic researches tend to be amplified. At present, researches in karst hydrology are relatively laggard. The karst in China is type diversity and representative all over the world. Studies in regard to karst hydrologic processes and the karst CO_2-H_2O-$CaCO_3$ system have made progress in China. In future, responses and feedbacks to the global change, water resource and environment, and hydrologic processes modeling of a karst groundwater flow system are the potential researching hotspots.

Keywords

Karst Groundwater, Karst Hydrology, Surface Water and Groundwater Interaction, Water Cycle

岩溶地下水特点与研究热点

袁瑞强[1*]，邓新平[2]

[1]山西大学环境与资源学院，山西 太原
[2]湖南省地质矿产勘查开发局四零二队，湖南 长沙
Email: *rqyuan@sxu.edu.cn

作者简介：袁瑞强(1980.4-)，男，山西太原人，副教授，主要从事流域水循环与水环境研究。
*通讯作者。

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摘　要

岩溶区覆盖了超过20%的地壳面积，岩溶水作为供水水源发挥的作用举足轻重。然而，岩溶介质的非均质性十分突出，是有不同水力性质的双重介质系统，使得岩溶地下水系统入渗过程亦具有二元性。岩溶区降水、地表水和地下水间的关系十分密切、转化规律呈复杂的非线性关系。这使得岩溶地下水系统的水文过程、流速和排泄范围易受外界影响而多变。岩溶泉流量变化具有明显的尺度效应和多重分形特征，流量构成复杂多变。同时，受多变的岩溶水文过程和生物地球化学作用的影响，岩溶地下水系统的水化学变化对环境十分敏感。因此，传统方法不能直接应用于岩溶地区的水文研究，水文研究常见的困难在岩溶区被成倍放大。目前，岩溶水文研究相对滞后。我国岩溶类型多样，在国际上有范例性。在岩溶水文过程和岩溶地下水CO_2-H_2O-$CaCO_3$系统的研究中取得进展。岩溶地下水系统水文过程对全球变化的响应和反馈，岩溶地下水资源和水环境，以及岩溶水文系统模拟等方面将是未来的研究热点。

关键词

岩溶地下水，岩溶水文，地表水与地下水相互作用，水循环

1. 引言

岩溶包括与可溶岩石溶解相关的全部地貌、地质和水文特征[1]。岩溶区覆盖了超过 20%的地壳面积[2]。数亿人口生活在岩溶地区，以岩溶含水层为水源。据估计，世界上大约 25%的饮用水来自岩溶含水层[2]。开展岩溶水文研究是可持续开发和保护岩溶水资源的基础，具有重要的社会意义。

然而，岩溶水文研究面临特殊的困难。首先，岩溶区地表和地下的岩石溶解大大超过了机械风化的效果，因而形成了独特的地貌、地质特征，使水文循环具有特殊性。岩溶地区最明显的水文地质特征是高度不均匀性。地下水流溶解可溶岩石导致含水层快速演化，水流系统有强烈的个体性、各向异性，补给来源和入渗的二元性等[3]。岩溶区地表水和地下水通常是密切联系、高度相关，组成一个单独的流动系统[4]。这种特征多由石灰岩和白云岩构成的基岩发生溶解而形成落水洞、断头河、溶洞和岩溶泉等造成[5]。岩溶过程最终可形成巨大的、延伸距离十分远的、十分复杂的三维地下管道系统[6]。一方面强烈的非均质性使岩溶地下水难以开采到，另一方面岩溶水文过程易受外界影响被污染。因此，Bakalowicz 建议如果可能的话不要使用岩溶含水层作为水源[7]。其次，水文研究常见的困难在岩溶区被成倍放大。比如，对地下水流动系统的水文过程缺乏详细的观测数据，对地下水含水系统的水文地质条件掌握不充分，以及观测和估算方法本身具有的不确定性等都由于岩溶含水系统复杂的水文地质条件而被成倍放大[3]。最后，传统方法不能直接应用于岩溶地区的水文研究。比如，调查地下水流动的区域等水位线法、抽水实验等在岩溶区多数情况下不能直接使用[4]。目前，岩溶水文研究的程度相对滞后。

岩溶水作为供水水源发挥的作用举足轻重，在环境急速变化的当代开展全面和详细的岩溶水文研究是区域水资源可持续开发和保护的基础，也是社会经济发展的迫切需求。同时，开展岩溶水文研究有助于深入了解岩溶区水文循环的规律和机理，解决面临的诸多问题和挑战。

2. 岩溶地下水系统的特点

近十几年来，岩溶水文研究逐渐增多，不断加深了对岩溶地下水系统的认识。

岩溶地区降水、地表水和地下水间的关系十分密切、转化规律十分复杂。降水和岩溶含水层补给之间呈复杂的非线性关系，一般性的降水减少可导致补给显著地减少[8]。岩溶泉水和补给区降水之间的联系可通过 $\delta^{18}O$ 和 δD 组成反映出来[9]。落水洞是岩溶区特有的地表水快速转化为地下水的通道。Schulz 等[10]用相机延时拍摄方法研究了沙特阿拉伯一处岩溶落水洞的补给，得到降水入渗补给率介于 0~0.27。Mance 等[11]发现冬季降水是岩溶泉水主要补给来源。类似的，Jeelani 等[12]发现喜马拉雅山 Kashmir 山谷内岩溶泉水春季贫化重水同位素而秋季则相对富集，显示出冰雪融水的主要影响。潜流带(hyporheic zone)低水力传导度和弱的水力梯度以及大的岩溶溶隙和裂隙造成地表水向地下水转化过程呈现复杂的非均质性，河底水生植物对河段尺度的水力条件发挥了重要影响[13]。Meyerhoff 等[14]研究了地表水在岩溶管道内的混合，发现汛期时地下水小于 50%，仅有基流时地下水占 75%。表层岩溶和非承压岩溶地下水均可向河水贡献水量[15]。在沿海地区，岩溶大泉可向海水排泄大量淡水和陆源营养盐[16]。此外，地表水补给对岩溶地下水热模式存在影响，可分为四类热模式[17]。

岩溶地下水系统入渗过程具有二元性。岩溶发育较好的含水层常由导水性好的岩溶管道和渗透性相对较低的岩石裂隙和孔隙组成，是有不同水力性质的双重介质系统。岩溶管道流和孔隙渗流混合可缓冲泉流量变化。混合后岩溶地下水中离子和同位素组成可揭示不同入渗过程的贡献。这源于孔隙渗流和岩溶管道流的水化学特征可能存在显著的不同，且两种入渗过程中蒸发浓缩程度的差异明显[18]。表层岩溶内的混合作用显著[19]，且表层岩溶地下水与空气接触良好，发生 O_2 溶解和 CO_2 去气使得 DO 和 pH 值较高；岩溶管道地下水 DO 和 pH 值较低，而 $CaCO_3$ 饱和度、悬浮固体和大肠杆菌浓度较高，$\delta^{18}O$ 和 δD 偏高[20]。Toran 和 Reisch [21]发现岩溶水中 Ca^{2+} 含量较高而降水中 Mg^{2+} 含量较高，用 Mg/Ca 比可解释岩溶孔隙水和岩溶管道水的混合关系。Mitrofan 等[22]观测到岩溶孔隙水中 Cl^- 浓度高于岩溶管道水，当岩溶泉处于高流量时岩溶管道流和孔隙渗流混合引起泉流量缓慢震荡变动，伴随着 Cl^- 通量由低增高波动。需要注意，地下水流动过程中“新水”与储存的“老水”混合可能使示踪剂浓度在季节尺度和补给事件尺度没有明显变化，只有在相对高的采样频率下才能有效地描述水文过程[23]。

岩溶地下水系统的水文过程易受外界影响而多变。第一，地下水流速变化范围大。Matić 等[24]用荧光素钠示踪得到亚得里亚海岸 Biokovo 岩溶地下水表观流速介于 0.21~0.51 cm/s 间。Jukić 和 Denić-Jukić [25]分析降水量和其他气象参数与岩溶泉流量日时间序列，发现快速流历时 14 天，中间流历时 80 天。第二，排泄范围随地下水位变化。Ravbar 等[26]证明了斯洛文尼亚 Podstenjšek 岩溶泉域降水使其汇水范围动态扩大。Hartmann 等[27]估算西班牙南部岩溶含水层补给区面积可从 28 km^2 扩大到 53 km^2。Konec 等[28]用 DNA 技术证明岩溶含水层汇水区范围以及补给来源和结构动态变化。

岩溶泉流量的变化规律十分复杂。岩溶泉流量时间序列具有明显的尺度效应和多重分形特征[29] [30]。岩溶泉流量的主要影响因素来自多个方面[31]，气温和相对湿度对岩溶泉流量亦有影响明显[32]。常用的估算岩溶地下水平均停留时间的方法：1) 直接测定环境示踪剂，如，^{3}H，^{14}C，CFCs，SF_6 等，应用数学物理方程求解；2) 求地下水系统输入和输出部分的环境示踪剂数据的卷积或者加权函数来间接估算[33]。需要注意，岩溶地下水平均停留时间的估值不稳定。这是由岩溶泉流量构成和变化的复杂性决定的。

岩溶地下水系统的水化学变化对环境十分敏感。首先，易变的水文过程引起化学组成变化。Menning 等[34]发现陆地地下水和海水水位控制了岩溶泉向海湾排泄的水化学变化。Lambán 等[35]指出补给区和排泄区的高程差对岩溶地下水水化学和同位素组成有控制作用。其次，生物和岩溶地下水通过生物地球化学过程相互影响。Mahler 和 Bourgeais [36]发现岩溶泉流量下降或温度升高时 DO 浓度下降，导致土著生物 *Eurycea sorosum* 死亡率升高。Jin 等[37]指出生物地球化学过程对岩溶地下水 DOC、DIC 和 $\delta^{13}C_{DIC}$ 有重要影响。van Geldern 等[38]

证明土壤中 CO_2 贡献了河流中 65%到 72%的 DIC，下游 CO_2 逸出导致 $\delta^{13}C_{DIC}$ 约 2‰的正偏移。

3. 我国的岩溶水文研究

中国岩溶总面积达 3.44×10^6 km^2，约占国土面积的 1/3。中国大陆碳酸盐岩古老坚硬、新生代以来大幅抬升、未受末次冰期大陆冰盖刨蚀破坏[39]。同时，中国岩溶发育类型多样，有南方亚热带潮湿型岩溶，西南高山和高原型岩溶和北方干旱半干旱型岩溶三大类型。上述特点使中国岩溶在国际上有范例性[39]。近几十年来，中国的岩溶研究紧紧地抓住岩石圈、大气圈、水圈和生物圈界面上的物质能量运动规律，先后发起和组织了多个国际对比计划研究岩溶动力学、碳循环和古气候环境变化，取得了一系列有国际影响的成果[39] [40] [41]。相对而言，在岩溶水文研究方面较为单薄，然而仍有一定的成果[42]-[52]。近年来，我国学者对岩溶水文的研究主要集中在如下方面。

第一，岩溶泉流量变化。Hao 等[53]指出响应时间包括表层岩溶带的入渗时间和地下水压力传导的时间，有无黄土覆盖导致岩溶泉流量响应时间由 7 年变化为 1 年。Fu 等[54]用相关函数研究年尺度和降水事件尺度岩溶含水层的响应特性。Wu 等[55]用时间序列模型研究了开采前后辛安泉流量波动，表明人类活动使泉流量序列出现异方差性。在人类活动和气候变化共同影响下，岩溶泉出现断流的风险加大。Fan 等[56]用一个极端值统计模型得到娘子关泉流量在 2021~2023 年间出现断流的概率为 1%，概率随着时间增大。类似地，Liu 等[57]的研究结果表明娘子关泉 2025 年断流的概率为 1/80，到 2030 年则迅速增大到 1/10。

第二，岩溶水文过程。Zhang 等[58]建立了分布式水文－土壤－植被模型研究岩溶流域的主要水文过程。Chang 等[59]基于 MODFLOW-CFP 模块发现岩溶管道湍流对受到点补给的早期水文过程有强烈影响，而岩溶管道层流对整个水文过程有影响，岩溶管道储水量的变化对泉水水文过程线也有明显的影响。表层岩溶内的混合作用使其具有潜在的水量调节能力[60]。西南灰岩盆地表层岩溶的研究表明约 70%的降水进入表层岩溶，其储水能力直接影响了地表径流产生[61]。

第三，岩溶地下水 CO_2-H_2O-$CaCO_3$ 系统。与人类活动有关的硝酸和硫酸加速了灰岩溶解，在西南岩溶区硝酸和硫酸平均贡献了地下水 DIC 的 38% [62]。白天水生生物的光合作用使得 DO 和 $\delta^{13}C_{DIC}$ 增加，而 DIC 减少，无机碳转化为有机碳；夜间呼吸作用使得水中的方解石矿饱和，$\delta^{13}C_{DIC}$ 降低[63]。类似地，Liu 等[64]对比观测了岩溶泉和受其补给的池塘，发现泉水各项参数没有明显变化，而池塘中水生生物的光合作用和呼吸作用控制了参数变化。温度、pH、DO、Sic、$\delta^{13}C_{DIC}$ 在日间明显升高而夜间则显著降低，水中减少的 DIC 同化为有机碳。Zeng 等[65]基于连续 6 年的观测提出流量对碳汇通量(CSFs)发挥了主要影响，HCO_3^- 变化的影响次之，土壤层、植被和基岩岩性对 CSFs 有间接影响，三个岩溶区 CSFs 均值介于 29 ± 3 到 39 ± 8 t-CO_2 $km^{-2} \cdot a^{-1}$，约为相同水文条件下硅酸盐岩风化的 15 倍。

4. 岩溶水文研究的热点

未来岩溶水文研究需要在以下方面加强，并有望形成研究热点。

第一，岩溶地下水系统水文过程对全球变化的响应和反馈。工业化以来全球大气 CO_2 浓度持续升高，尤其是近五、六十年来增速明显增高，与此伴随着明显的全球升温[66]、极端降水增多和干旱区面积扩大，干旱程度加剧[67] [68] [69]。全球变化已经对水文循环、碳循环和生态水文过程产生明显影响[70] [71] [72]。全球增温、干旱化和极端降水增多可能对岩溶地下水系统的补给和排泄过程，以及水化学特征产生明显的影响。岩溶发育地区干旱问题值得关注。同时，全球升温和大气 CO_2 含量增加将引起 CO_2-H_2O-$CaCO_3$ 体系再平衡，岩溶地下水系统水循环和碳循环问题应引起重视。

第二，岩溶地下水资源和水环境问题。主要包括：1) 储量变化方面[73] [74]，2) 脆弱性方面[75] [76] [77]，3) 污水示踪[78] [79] [80] [81]，4) 有机污染方面[82] [83] [84] [85] [86]。

第三，岩溶水文系统模拟方面的研究。例如，部分填充的管道内的非稳定流和非均匀流和用非线性梯度函数描述紊流过程[87]，岩溶管道中受到压缩的地下水流动的描述，以及耦合模拟岩溶管道流、灰岩连续体内渗流以及地表水流，耦合溶质的溶解和沉淀过程[88] [89] [90] [91]。然而，支撑岩溶地下水系统水文过程模型研究的观测数据不足仍是亟需解决的问题[92]。

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