地球关键带基岩风化层生态水文研究进展

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摘要 基岩风化层作为地球关键带的主要组成部分, 联系其上层土壤水分变动和地下水补给, 在陆地表层生态水文循环中扮演着重要角色. 为阐明地球关键带中基岩风化层生态水文的研究进展, 本文回顾了Web of Science (WOS)核心合集数据库和中国知网(CNKI)学术期刊数据库中收录的相关文献, 计量可视化了当前的研究热点, 总结了基岩风化层生态水文潜在的影响途径, 展望了未来潜在的研究热点. 结果表明, 基岩风化层生态水文研究呈现地质学、水资源科学、环境科学与生态学及工程学等多学科交叉且基础理论丰富的特点; 基岩风化层生态水文效应既包含了自身特性差异, 也涵盖对土壤水分再分配、地下水补给排泄调节和植物生长调控等外部扰动; 基岩风化层生态水文潜在影响途径可能是通过阻碍土壤水分入渗流失和补给地下水来调节季节性缺水、中微小型动物活动加剧岩石风化提高水分贮存空间、植被根系贴附岩层并结合菌根菌丝参与水养传输等多种方面. 本文以期深化地球关键带科学, 拓展生态水文研究领域和鉴别植被恢复选址的合理性提供参考.

关键词 风化基岩含水层, 岩石水分, 地球关键带, 水文循环, 文献计量

地球关键带科学的深化与发展, 为全球陆地生态系统长期观测和研究提供了新的平台, 使地球表层生态水文研究从植被冠层和表层土壤延伸到基岩深处, 对全面系统认识地球表层生态水文循环极具挑战性和前瞻性^[1,2]. 基岩风化层作为地球关键带中联系上层土壤和下层新鲜基岩的过渡带, 在土壤水分重新分配和地下水补给方面具有重要的作用^[3,4]. 同时, 基岩风化层作为生态系统^[5]、风化过程^[6]、景观演化^[7]和流域水文学^[8]的关键组成部分, 在环境中也具备重要的水文、生态和生物化学功能.

以往的长期性监测发现, 水分的入渗和侧向流动并不局限于土壤层^[9-11], 以活塞流和优先流渗入的雨水能够穿过破碎的基岩风化层, 聚集在未风化基岩界面形成地下水, 然后横向流向邻近河道, 在蒸散发和径流

之间的分配起到调节作用^[3]. 基岩风化物是一种与土壤明显不同的物质, 分布在不同的地形地貌中. 基岩风化层中储存的可交换水的含量, 是有别于土壤水或地下水的重要水源^[12,13]. 直到2018年, Rempe和Dietrich^[4]才正式定义了一个描述基岩风化层中储存的可交换、动态的水含量概念, 即岩石水分(rock moisture). 然而, 由于其提出时间较短且监测困难, 国内外该方面的研究有限, 且主要集中在喀斯特地区和土层浅薄的丘陵区^[4,14,15]. 已有研究表明, 基岩风化层储水量远大于土壤含水量, 是干旱年份植物关键且稳定的水源, 基岩风化层水储量在雨季积累到最大值后, 额外的降水以径流或裂缝流形式成为基流^[3,14,16,17]. 尽管当前岩石水分研究主要集中在水分胁迫环境中植被吸水的潜在正效应, 但在雨量充沛地区, 岩石水分也对促进生物地球化

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学循环发挥关键作用^[18]. 因此, 基岩风化层水分储量作为陆地水文循环的重要组成部分, 逐渐被关注且考虑纳入新的水文和气候模型体系^[14,19,20].

陆地表层生态水文循环研究以往长期集中在植被吸水、表层土壤水分以及地下水补给排泄等方面, 很少关注基岩风化层的生态水文功能, 且在植被恢复工程中也很少探讨基岩风化层生态水文变化对植被可持续生长的影响. 然而, 近年来研究逐渐证实了基岩风化层在陆地水文循环及对植被存活的关键作用, 这可能改变现有研究的概念范式, 对观测、模拟、解译陆地表层水文循环提出新挑战. 并且, 全球大尺度范围变绿可能也受到了基岩风化层生态水文的调节作用, 特别是在干旱半干旱地区甚至湿润的喀斯特丘陵区等水分胁迫环境条件下, 乔灌木植被能够可持续生长可能也有源于基岩风化层的生态水文作用. 因此, 本研究基于文献计量方法剖析了近年来基岩风化层生态水文的研究现状, 总结了基岩风化层生态水文潜在的影响途径, 擘画了基岩风化层生态水文研究可能的热点, 以期为地球表层陆地生态水文循环和生态植被恢复可持续研究提供新思路与新依据.

1 数据来源与处理

文献计量能够有效快速把握当前研究热点及现状, 为深入该领域的研究提供思路. 因此, 为表征当前基岩风化层生态水文研究现状, 组合检索定位Web of Science(WOS)核心合集数据库和中国知网(CNKI)学术期刊数据库中基岩风化层生态水文相关的全部文献. 以TS= (“fractured rock aquifer” OR “fractured bedrock aquifer” OR “weathered rock aquifer” OR “weathered bedrock aquifer” OR “rock moisture” OR “rock hydrology” OR “rock ecohydrology” OR “rock hydrogeology” OR “bedrock moisture” OR “bedrock hydrology” OR “bedrock ecohydrology” OR “bedrock hydrogeology” OR “rock groundwater” OR “rock water resources” OR “rock water reserve” OR “rock water storage” OR “rock water holding capacity” OR “bedrock groundwater” OR “bedrock water resources” OR “bedrock water reserve” OR “bedrock water storage” OR “bedrock water holding capacity” OR “weathered bedrock water” OR “fractured bedrock water” OR “permeable rock” OR “permeable bedrock” OR “karst water” OR “karst hydrology” OR “karst aquifer” OR “epikarst water” OR “epikarst

hydrology” OR “epikarst aquifer”)为检索字段在WOS核心合集数据库进行高级主题检索. 以“SU % = ‘岩石水分’ OR SU % = ‘风化层水分’ OR SU % = ‘岩石含水层’ OR SU % = ‘岩石水文’ OR SU % = ‘岩石生态水文’ OR SU % = ‘风化层水文’ OR SU % = ‘风化层含水层’ OR SU % = ‘喀斯特水文’ OR SU % = ‘喀斯特水分’ OR SU % = ‘喀斯特含水层’”为检索字段在CNKI期刊数据库中进行检索. 两数据库检索范围包括标题、摘要及关键词, 时间跨度设定为1990~2020年. 对所获取的文献数据进行计量统计分析, 其中, 基本统计指标采用Origin进行绘图分析, 使用VOSviewer进行可视化剖析研究热点.

2 基岩风化层生态水文文献计量分析

2.1 研究文献分布分析

从发文国家地区来看, 基岩风化层生态水文的研究发文量的排名依次为美国(26.2%)、中国(17.5%)、德国(11.1%)、法国(9.1%)等国家. 研究区域主要集中在欧洲地中海丘陵区、美洲的丘陵山脉区以及我国西南的喀斯特地区. 我国在该领域的研究发文量仅次于美国, 占据了重要的席位(图1(a)). 对WOS中获取的文献数据进行整合, 共获得2104条文献数据, 首篇文献出现在1992年, 年发文量随时间呈现波动上升趋势($R^2=0.88$, $P<0.05$), 但年际间发文数量波动相对较大, 年增长率约为18.3%(图1(b)). CNKI中共收集到200篇文献, 首篇文献出现在1991年, 年发文量平均为7篇, 年际间呈缓慢增长态势($R^2=0.87$, $P<0.05$), 明显低于国际总体发文量(图1(b)). 根据WOS和CNKI发文量划分了3个发展阶段: 二者年发文量之和小于50篇为第一阶段(1990~2004年), 该阶段是对基岩风化层生态水文研究的初步探索, 缓慢发展; 发文量之和介于50~100篇为第二阶段(2005~2011年), 主要是基岩风化层的逐渐识别, 且发展加速; 发文量大于100篇为第三阶段(2012~2020年), 该阶段对基岩风化层生态水文研究有了深化理解, 处于快速发展态势(图1(b)). 从国内发文机构看, 高等院校(40.0%)略高于中国科学院机构(34.5%), 但二者均对深化该领域的研究起到了突出的作用(图1(c)). 综上研究文献分布分析可知, 基岩风化层生态水文作用日渐凸显, 但国内外均有可挖掘和探讨的空间.

2.2 研究文献分类分析

研究文献所属学科类别主要集中在地质学

Figure 1 (Color online) Statistics of literature on weathered bedrock ecohydrology. (a) Proportion of the countries, which mainly publish the literature does not add up to 100 because there is crossover among the countries when publish the literature. (b) Annual volume of documents published. Blue indicates the fit curve of the published documents in the Web of Science, and red indicates the fit curve of the documents published in the CNKI. (c) Main publishing institution in China

(57.54%)、水资源科学(53.61%)、环境科学与生态学(31.46%)、工程学(20.87%)等领域(表1), CNKI数据库内收录文献的学科领域与WOS相似, 表明基岩风化层生态水文研究主要以地球科学研究为主体, 多学科交叉, 研究基础理论丰富. 研究文献刊发的主要英文期刊包括*Journal of Hydrology*(11.79%)、*Environmental Earth Sciences*(7.65%)、*Hydrogeology Journal*(6.37%)等地球科学老牌高水平期刊(表1), 国内则集中在生态学报(9篇)、应用生态学报(9篇)、农业工程学报(4篇)及水科学进展(3篇)等期刊, 表明基岩风化层生态水文是当前地球水文基础科学研究的重点关注领域.

对基岩风化层生态水文研究高被引论文分析发现, 主要以喀斯特等特定条件下土层浅薄区域为平台, 重点聚焦了喀斯特水文模型方法、水文资源分布、生态风险、岩土界面、岩性差异对植被的影响以及基岩地下水的交互作用, 研究范围趋向区域大尺度综合性研究. 国内喀斯特开展的研究相对较早, 对喀斯特地区土壤水分空间异质性进行了详尽的讨论, 为该领域研究提供了参考(表2). 综上分析可知, 基岩风化层生态水文研究跨学科交叉, 多种科学技术手段综合应用, 近30年取得了丰硕的成果, 但受限于研究技术、手段、方法、区域等的制约, 仍亟待进一步深入挖掘、量化表征.

2.3 研究文献聚类可视化分析

利用VOSviewer对WOS中收集到的文献进行聚类可视化分析^[30],以摘要中词频最少出现10次进行聚类,共筛选出相关字段754个,形成聚类区块5个,连接线

82107条, 总连接强度为161579(图2)。聚类分析表明, 基岩风化层生态水文的研究分布在五个方面, 分别是自身特性(Cluster #1, 242个字段, 风化岩石含水层、渗透性、导水管、裂缝连接网络、水平衡、模拟等)、外部扰动(Cluster #2, 201个字段, 地下水补给排泄、岩水交互、气候变化、洞穴、季节波动等)、粒子效应(Cluster #3, 172个字段, 浓度、组成、地球化学、无机碳、碳酸钙等)、研究区域(Cluster #4, 124个字段, 喀斯特、矿山、地图、资源、活性等)以及其他特性(Cluster #5, 15个字段, 海岸带区域、盐水、海底地下水等)。由此可知, 基岩风化层生态水文受到自身特性、外部关联、粒子效应等多方面的影响, 在喀斯特土层浅薄地区研究案例较多, 而在整个关键带(特别是干旱半干旱区)中作为一个普遍性的科学研究还有所欠缺。

3 基岩风化层生态水文研究现状与展望

梳理基岩风化层生态水文文献, 将其研究现状及未来可能的研究热点进行归纳分析(图3), 可以发现: 基岩风化层是地球关键带的重要组成部分, 其生态水文变化对整个地球关键带剖面生态水文调节作用是不可忽视的; 从地球关键带剖面角度来讲, 基岩风化层生态水文的研究现状主要集中在基岩风化层水分分布、对地下水补给、土壤水分再分配以及对植物生长的影响等方面; 未来研究的热点可能聚焦在基岩风化层中水分储量及其动态变化、出流特征, 与生物互作过程及机理, 与地下水补给交换过程及机理, 与土壤界面水分交换过程及机理, 对植被根系和植物长势的作用机制, 以及地球关键带大气-植被-土壤-基岩风化层-地下

表 1 基岩风化层生态水文研究文献的学科领域与主要刊发期刊^{a)}

Table 1 Research areas and publications on weathered bedrock ecohydrology

学科类别与研究方向	文献比例(%)	期刊名称	文献比例(%)
Geology(地质学)	57.54	Journal of Hydrology	11.79
Water Resources(水资源科学)	53.61	Environmental Earth Sciences	7.65
Environmental Sciences Ecology(环境科学与生态学)	31.46	Hydrogeology Journal	6.37
Engineering(工程学)	20.87	Water Resources Research	3.61
Geochemistry Geophysics(地球化学与地球物理学)	6.08	Environmental Geology	3.57
Marine Freshwater Biology(海洋淡水生物学)	5.13	Hydrological Processes	3.33
Physical Geography(自然地理学)	3.04	Acta Carsologica	3.09
Chemistry(化学)	1.71	Water	2.66
Mechanics(力学)	1.71	Ground Water	2.47
Science Technology Other Topics(科学技术其他主题)	1.66	Science of the Total Environment	2.38

a) 文献比例表示隶属于该学科类别、研究方向或期刊的文献数量占检索到2104篇的百分比,用%表示;由于每篇文献所属研究领域之间存在交叉,文献比例加和不等100%

表 2 基岩风化层生态水文研究高被引论文^{a)}

Table 2 Highly cited papers in weathered bedrock ecohydrology

文献类型	发表年份	参考文献	标题	期刊来源
国际文献	2014	[21]	Karst water resources in a changing world: Review of hydrological modeling approaches	Reviews of Geophysics
	2014	[22]	Storage dynamics in hypopedological units control hillslope connectivity, runoff generation, and the evolution of catchment transit time distributions	Water Resources Research
	2017	[23]	The World Karst Aquifer Mapping project: Concept, mapping procedure and map of Europe	Hydrogeology Journal
	2018	[4]	Direct observations of rock moisture, a hidden component of the hydrologic cycle	Proceedings of the National Academy of Sciences of the United States of America
	2019	[24]	Potential health risk assessment for fluoride and nitrate contamination in hard rock aquifers of Shanmuganadhi River basin, South India	Human and Ecological Risk Assessment
国内文献	2005	[25]	贵州喀斯特地区河流的研究——碳酸盐岩溶解控制的水文地球化学特征	地球科学进展
	2006	[26]	喀斯特地区典型峰丛洼地旱季表层土壤水分空间变异性初探	土壤学报
	2005	[27]	贵阳市地表水地下水水化学组成: 喀斯特水文系统水-岩反应及污染特征	水科学进展
	2008	[28]	西南喀斯特山区土壤水分研究	农业现代化研究
	2006	[29]	喀斯特地区典型峰丛洼地表层土壤水分空间变异及合理取样数研究	水土保持学报

a) 国际文献的高被引论文是指在WOS中同一领域、同一出版年份内的论文被引次数排名前1%的论文;国内文献高被引论文则根据CNKI中所有年份的总被引用数量确定

水连续体生态水文模型构架与应用等六大方面。因此,基岩风化层生态水文的研究是一个庞杂的研究体系,多方面问题亟待解决,需结合多种学科知识与技术手段进行联合攻关。

3.1 基岩风化层生态水文研究现状分析

3.1.1 基岩风化层水分分布的研究现状

基岩风化层水分是由岩石自身吸水量和由水势平

衡差异而贮存于风化岩层层间裂缝水共同组成,其影响因素包括原始基岩的岩性^[31]、成分和结构^[32]、上覆土壤的厚度^[33,34]、岩面的渗透性^[35]以及蒸发蒸腾^[36,37]、生物扰动^[38]、水力侵蚀过程等^[5,36]多种因素。风化花岗岩^[39]、石化钙积层^[40]、风化砂岩和喀斯特^[41,42]等蓄水能力通常在 $0.1\sim0.2\text{ m}^3/\text{m}^3$,与颗粒较粗的土壤性质相似,但孔隙度比土壤略小;风化岩石的饱和导水率分布范围较大,介于 $1\times10^{-10}\sim1\times10^{-5}\text{ m/s}$ ^[35,43]之

图 2 基岩风化层生态水文研究文献聚类可视化分析

Figure 2 Bibliographic coupling network visualization analysis of weathered bedrock ecohydrology

图 3 基岩风化层生态水文研究现状及未来的研究热点

Figure 3 Current advances and future potential research hotspots of weathered bedrock ecohydrology

间; 基质势跨度水平也很大, 介于 $-0.01 \sim -1.5$ MPa之间; 基岩风化层、岩溶层和胶结土层的蓄水厚度可达数十米^[12], 其中约有55%的水分储存在基岩风化中, 11%的水分靠基岩吸水能力贮存^[44]。然而, 由于地形、气候等差异, 根据岩芯钻探、探地雷达、电阻率层析成像法

等技术手段确定的岩石风化层的厚度在不同地区厚度也有所不同, 对水分的贮存利用效率也有很大的差异。例如, 研究发现, 美国西部的内华达山脉南部花岗岩有几米厚^[45], 美国东南部的北卡罗来纳州皮德蒙特高原片麻岩和片岩的腐泥土有几米^[46]甚至几十米厚^[47]。此

外,基岩风化层水分补给也取决于上覆土壤层、基岩表面地形、裂隙连通性和孔隙度、裂隙间距以及覆岩与裂隙界面的性质等诸多因素^[48,49],表现出内部构造和外部扰动交叉影响等特点.因此,近年来的基岩风化层水分分布的研究也得出了不同的结论,这些结论有待于进行长期监测和进一步深入的验证.

3.1.2 基岩风化层水分对土壤水分再分配影响的研究现状

基岩风化层水分动态变化对上层土壤水分再分配因上覆土壤的厚度不同有所差异.在土层较薄时,如地中海丘陵地带^[3,4]和喀斯特地区^[41,50],基岩风化层水分能够补给干旱季节土壤水分,缓解土壤水分匮乏;而在丰水年,基岩风化层能够更多地吸纳贮存土壤中的水分,调节土壤水涝灾害^[38].研究表明,水从风化基岩流进土壤层的速率为0.5~3.3 mm/d,基岩风化层对上层土壤水分再分配作用显著^[51];风化基岩电导率场的非均质性可能导致水分沿渗滤梯度返回土壤中^[52~55],返回土壤层的水有助于产生饱和的陆上水流,但岩土界面稳定性降低,可能导致边坡失稳^[53,56~60].进一步的研究发现,当土壤饱和导水率比下伏基岩高2个数量级时,集水区将以土壤流为主,基岩的储存和释放在总水量中扮演次要的角色.但是,当基岩的饱和导水率在土壤的2个数量级以内时,基岩开始控制可用储水量,并且分水岭的很大一部分排放量可能来自基岩循环^[35,61].因此,下伏基岩风化层可以改变土壤饱和状态和坡面储藏水分动态.

3.1.3 基岩风化层水分对地下水补给排泄影响的研究现状

基岩风化层位于地下水补给带或上方的位置,与地下水交互,其存在对地下水的补给、径流与排泄途径、时间、元素富集等方面产生了影响^[11,62~65].近年来,遥感技术、地理信息系统^[66]、环境示踪法^[54,62,67,68]、电阻层析成像^[69]等多种方法、技术被用来研究基岩风化层地下水补给^[35,70,71].研究表明,雨水渗透经过土壤后,会穿过破碎的基岩风化层,以地下水的形式聚集在未风化基岩界面上,然后横向流入邻近的河道^[3,9,52].这部分基岩内的水分流动比例占到了14%~95%,并随着降水增加而增加^[11,51,59,62,67,72].原位深入剖析发现,砂岩和页岩中基岩风化层地下水补给的主要来源是岩隙裂缝^[53,71,73].其中,基岩上部30~40 m中的地下水流主要由几个水平裂缝构成,而稀疏排列的垂直裂缝则使这些裂缝之间的联系减弱^[68].

同时,也有研究表明,当上覆土壤层厚达10 m及以上后,其裂隙含水层中的地下水位仍能对降雨事件产生快速响应^[74].地下水位高度不同,风化岩层对地下水流动也有所差异;高水位条件下,土壤下层腐泥土和风化的花岗岩之间的界面控制了地下水的流动;低水位条件下,含水层由于裂缝数量随深度减少而呈现侧向分割特征^[69].此外,风化剖面上部(黏土质蚀变)与下部(过渡带-裂隙片岩杂岩体)的相互作用表明,由于排水孔隙度的差异,上部压力水头普遍高于下部压力水头^[19].因此,基岩风化层的介入对区域地下水的调节作用不容忽视.

3.1.4 基岩风化层水分对植物生长影响的研究现状

植物连通大气、土壤和地下水,其根系分布及深度对干旱胁迫等极端环境能够灵敏感知^[75].基岩风化层厚度通常比覆盖的土壤厚度多几倍,是植物生长过程中一个不可忽略的重要可用水库,其储水量对季节性干旱环境中乔木和灌木的生存至关重要^[5,45,76,77].研究表明,木本多年生植物的根系可以生长在基岩风化层或基岩裂缝中^[78,79],且植物根系能够进入基岩风化层吸收水分的最小裂缝为100 μm ^[13],根系可穿透的最大阻力为4 MPa^[80,81].例如,在美国亚利桑那州某露天矿场距地表60 m深的基岩垂直裂隙中仍有牧豆树根系生长^[82].基岩裂缝中生长的根系可能比通过深层土壤生长的根系遇到的机械阻力小得多,为植物根系生长提供相对开放的空间,同时因深层人为和土壤动物扰动较小,根系寿命可能更长,深根吸水率更高.即便是植物的根系在下扎过程中碰到岩石裂隙等障碍物时,也会逐渐降低生长速率,开始生长侧根^[83,84].量化研究发现,植物根系可穿透到风化基岩中>4 m的深度,在干燥季节,从2.9 m厚的风化基岩吸取394 mm水,大约是从0.35 m厚的土壤中可吸水的10倍^[81],基岩风化层作为储水器,提供了生长季节树木所需的至少70%的水^[76].然而,先前研究也指出,仅在土壤水分吸收部分枯竭而减少后,基岩风化层水分才可能成为重要的植物有效水源^[4,45,81~86],且从基岩风化层中提取的水是植物可利用的最后一种来源^[87~90].该部分水分仍对植被分布、持续生长、年度蒸腾和植被生产力起到至关重要的作用^[4,91~94].此外,在岩石风化过程中,根的穿插生长可以增加基岩孔隙度和破碎度,将惰性岩石转化为可为植物和微生物提供水分与营养物质的非土壤基质,其基岩风化层裂隙中的黏粒组成、矿物类型、可溶性有机碳、可矿化性C、N与上伏土壤层相似,同时还含有大量的Ca、Mg、P、K等营养元素,在相对贫瘠地

区植物深根能插入基岩风化层中充分利用其养分和水分^[18,91,95,96]。例如,对我国喀斯特地区研究发现,基岩化学特征能够解释55%的植被生产力差异性^[50]。因此,基岩风化层水分对植物可用水及部分元素补给意义重大,但其在生态水文循环过程中的调节功能、影响程度和作用机理仍需进一步研究与量化。

3.2 基岩风化层生态水文的研究展望

3.2.1 潜在影响途径

基岩风化层存在对生态水文过程的潜在可能影响途径可以归纳为四个方面(图4)。一是在基岩风化层存在的情况下,阻碍了水分进一步向下渗透,将原本可能的浅层地下水位提高,促使基岩风化层上覆土壤水分再分配^[18,97](图4(a));二是风化层本身可以贮存部分水,其中风化层间的垂直裂缝和水平缝隙(层状岩石)可能贮存大量的水,而岩石本身也会贮存少量的水^[4,77](图4(b));三是岩层中存在中小微型动物,它们的活动将原本存在的岩隙裂缝进一步扩大,使得上层水分以优先流的形式补给到地下水,部分水分在毛管力的作用下贮存于岩缝中(图4(c)),最终达到水势平衡状态,贮存大量可用水^[38];四是在某些植物根部附着菌根菌丝,这部分微生物的存在有助于提高植物可利用有效水的范围,同时也为植物生长所需的营养元素提供了运输通道^[12,98](图4(d))。以上所述的4种潜在影响途径是一种或多种共同作用于整个风化层内,进而影响着整个地球关键带的生态水文过程^[4,12-14]。此外,本文所述的潜在可能的影响途径仅是对目前研究成果的总结与假设,需在未来研究中进一步验证与完善。

3.2.2 可能的研究热点及展望

基岩风化层是一个独立而与土壤、植被、生物等外部成分密切联系的界面系统。目前对基岩风化层的研究主要集中在喀斯特关键带等土层浅薄的地区^[4,14,15],对黄土高原关键带、一般的丘陵沟谷地区及平原地带等相对土层较厚的区域关注较少^[99],且干旱地区基岩风化层中水分的补给循环及其状态对整个区域暖干化的如何响应,全球变暖和人类活动对生态系统的影响,能否从基岩风化层的水分盈亏变化表现出来,也仍待进一步的研究与探讨。综上提炼该领域的研究现状可以发现,基岩风化层生态水文未来可能的研究热点及展望集中在六个方面(图3)。

(1) 基岩风化层中水分储量及其动态变化、出流特征^[4,14,38,40,44]。基岩风化层内的水分储量在不同地形地貌及不同基岩种类中可能有不同的含量,随季节干湿交替也可能表现出不同的变化特征,进而影响整个关键带的水分储量。特别是在干旱半干旱区,季节性降雨差异较大,对基岩风化层中水分储量有明显的扰动。此外,也需明确基岩风化层中存在裂缝或孔洞的数量、长度、宽度及分布特征,基岩风化层水分的时空变化特征、基本水力学性质,剖析基岩风化层水分垂直与侧向运动特征。

(2) 基岩风化层与生物互作过程及机理^[12,38,98]。菌根菌丝的存在,有利于植物根系吸收基岩风化层中的水分,且加剧基岩进一步风化,也为生物生长提供了吸收部分营养元素的途径。但该理论假设尚存在争议且作用机理需进一步明确。并且,动物在岩石中构筑洞穴、爬行等活动形成的裂缝通道对基岩风化层也存在

图4 基岩风化层对生态水文影响潜在影响途径。(a) 基岩风化层阻碍上层土壤水分入渗。(b) 基岩风化层贮存水分。(c) 动物活动扰动基岩风化层水文。(d) 菌根菌丝透过裂缝汲取水分和养分

Figure 4 Potential influence pathways of weathered bedrock ecohydrology. (a) Inhibit the topsoil water infiltration by weathered bedrock. (b) Water storage in the layer of weathered bedrock. (c) Animal activity disturbs the weathered bedrock hydrology. (d) Mycorrhizal and hyphae absorb water and nutrients through cracks in the weathered bedrock

一定的影响,需细致探究其影响过程。

(3) 基岩风化层与地下水动态补给交换过程及机理^[3,9,19,35,51,74]。基岩风化层位于地下水上方或地下水中,基岩风化层内地下水一般以第四纪松散层孔隙潜水、基岩孔隙裂隙潜水和基岩裂隙承压水等形式出流,需较长时间序列监测基岩风化层地下水水位、温度及电导率等基本指标的时间变化特征,才能深入剖析与评估基岩风化层对区域地下水的综合影响。

(4) 基岩风化层与土壤界面水分交换过程及机理^[25~29]。基岩风化层水分变化对上层土壤水分波动有所影响,但其影响程度、范围、时效及作用机理尚不得而知。并且,近年来基岩风化层生态水文与土壤界面水分交换过程主要在较薄土层的丘陵山区地带开展,对土壤厚度相对较大的水分渗透深度可能无法到达下伏基岩风化层的黄土区、地势较为平缓的平原区较少关注。而该区域也存在土层相对较薄的地域,实地调研也发现土层较薄时水分条件良好且有大型乔灌分布的现象。因此,后续需重点研究该区域内基岩风化层的生态水文功能。然而,基岩风化层作为地球关键带重要的组成部分,在自然界广泛存在,其是否对缓解土壤干层、截断土壤水分下渗及补给季节性土壤水分匮乏具有显著作用仍需进一步研究。此外,基岩风化层与土壤界面水分交换作用机理是否仅仅只有简单的物理作用,其是否存在化学、生物过程也需要更深的探索。

(5) 基岩风化层对植被根系、植物长势的作用机制^[12,15,38,75,94]。基岩风化层可能为植被根系与植物长势提供了必要的水分和一定程度的养分来源,对植被分布产生了影响。特别是在缺水年份或者缺水地区,基岩风化层的存在对于植物分布、存活、可持续生长起到了至关重要的作用^[4,14]。植物根系从基岩风化层吸水主要包括直接无接触吸水、根部接触吸水、菌根附着在植物根系吸水及上述共同作用^[38]。但是,基岩风化层对于植被根系、植物长势的物理-化学-生物混合作用机制尚不明确,亟待研究深化。

(6) 地球关键带大气-植被-土壤-基岩风化层-地下水连续体生态水文模型构架与应用^[4,14]。先前大量的研

究主要集中在大气-植被-土壤综合体,生态水文模型重点关注土壤水分分配、植被耗水及地下水补给等领域,而低估了基岩风化层对生态系统的供水调节能力。但是,近年来的研究逐步凸显了基岩风化层对地球关键带生态水文循环的重要性。因此,十分有必要将其纳入模型构架与应用中,建立新的生态水文模型,为生态系统耗水、植被高效用水及土地整治工程节水提供可靠的预测与评估。

4 结论

基岩风化层在生态水文循环中扮演着不容忽视的角色,对土壤水分再分配、地下水循环补给、植物有效水利用率提高具有显著的作用,亟待纳入生态水文模型。本研究分析了Web of Science核心合集数据库及CNKI期刊数据库中收录的与基岩风化层有关的文献数据特征,计量可视化当前研究重点发现,地球关键带基岩风化层生态水文研究是涵盖地质学、水资源科学、环境科学与生态学及工程学等多种学科的交叉研究,基础理论丰富,研究尺度从点位到流域的综合性不断扩大。整理剖析基岩风化层生态水文研究现状表明,基岩风化层对生态水文的影响既有内部性,也有外部性。内部性体现在基岩风化层分布、原始基岩岩性、成分、结构、水分渗透特性等;外部性则表现为基岩风化层在整个关键带中对土壤水分再分配、地下水补给排泄及对植被生长供水供养的调控影响等方面。总结讨论发现,基岩风化层生态水文潜在的影响途径可能是通过阻碍土壤水分入渗流失和补给地下水来调节季节性缺水、增加动物活动性拓展基岩裂隙储水和联合菌根菌丝参与水养传输等起到影响。并且,未来研究热点趋势可能包括基岩风化层自身特性、与生物互作、与地下水交换、与土壤界面水分变化、植物长势影响,及关键带连续体模型构架与应用六个方面。此外,在未来研究中应重点关注干旱半干旱区基岩风化层存在对植树造林种草工程的生态水文效应,探索下伏基岩风化层与植物根系相互作用机制,为水资源短缺区域的植被建设提供理论基础。

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Summary for “地球关键带基岩风化层生态水文研究进展”

Progresses of weathered bedrock ecohydrology in the Earth's critical zone

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Weathered bedrock is crucial in the Earth's critical zone, which connects soil moisture dynamics and shallow groundwater recharge, and therefore plays an essential role in the ecohydrological cycle on the terrene surface. The exchangeable water stored in weathered bedrock is an essential source of water that is different but parallel to soil water or groundwater. This water in the weathered bedrock, namely, rock moisture, is much greater than that in the soil, which is a pivotal and stable water source for plants, especially in dry years or arid and semiarid areas.

When rainfall occurs, the infiltration and lateral flow of water are not limited to the soil layer. The rainwater that infiltrates by piston flow and preferential flow can pass through the fractured or weathered bedrock layer and collect at the fresh bedrock interface to form groundwater. Then, it flows laterally to adjacent river channels, where it also plays an important role in the distribution of evapotranspiration and runoff. Moreover, after weathered bedrock water storage accumulates to its maximum in the rainy season, the additional rainwater becomes base flow in the form of runoff or fissure flow. However, research on the ecohydrological cycle of the terrestrial surface layer has long focused on vegetation water absorption, surface soil moisture, and groundwater replenishment. Little attention has been given to the ecohydrological changes in the weathered bedrock layer and their external effects, and review articles are relatively scarce. Therefore, to clarify the latest research progress on weathered bedrock ecohydrology, the relevant documents collected in the Web of Science core collection database and the China National Knowledge Infrastructure (CNKI) journal database in the past 30 years were retrieved. The developments of the current focuses of research and potential research directions were quantitatively visualized using VOSviewer and bibliometrics, and the potential influential pathways of weathered bedrock ecohydrology were then drawn.

The results show that weathered bedrock ecohydrological research is interdisciplinary and has a rich theoretical foundation of geology, water resources, environmental science ecology, and engineering. The number of published articles has gradually increased annually, and major mainstream Earth science journals wish to report these new findings; however, there is room for expansion and discussion in the international arena. The research area in this field mainly uses a shallow overlying soil layer, such as karst, as the platform and focuses on the karst hydrological model, the distribution of hydrological resources, the ecological risk, the lithologic characteristics of vegetation, and the interaction between bedrock and groundwater. Unfortunately, less attention has been given to areas with relatively thick soil layers, such as the hilly valley region.

Moreover, ecohydrological effects of weathered bedrock include not only differences in the characteristics but also external disturbances, such as soil water redistribution, groundwater recharge, excretion regulation, and plant growth regulation. Future research might focus on the following: Water storage and its dynamic changes in the bedrock weathered layer, outflow characteristics, the process and mechanism of organism interactions, the process and mechanism of exchange with groundwater recharge, the process of water exchange with the soil-bedrock interface, the action of the vegetation root system and plant growth, and the framework and application of the ecological hydrological model of the atmosphere-vegetation-soil-weathered bedrock-groundwater continuum in the Earth's critical zone.

Furthermore, potential influential pathways of weathered bedrock ecohydrology might be regulating seasonal water shortage by inhibiting soil water infiltration, groundwater runoff, and replenishment; expanding bedrock fissure water storage by increasing animal activity; and transporting water and nutrients by participating in mycorrhizal hyphae. This study might provide a reference for deepening critical zone science, expanding ecohydrology research, and providing rational management for vegetation restoration.

weathered bedrock aquifer, rock moisture, Earth's critical zone, hydrological cycle, bibliometrics

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