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岩溶泉水温度对降雨—流量响应的指示作用

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摘　要: 岩溶区土—岩交错、裂隙和管道发育, 加大了降雨入渗补给方式和多重水流辨识难度。文章利用贵州陈旗小流域场次降雨、泉流量以及大气、土壤和泉水温度观测数据, 识别降雨入渗补给方式、泉流量来源以及热传导机制。结果表明: 强度小、历时长的降雨, 泉水温度缓慢上升且持续时间长, 以“分散入渗补给”和热传导作用为主; 随着降雨强度增大、持续时间缩短, 泉水温度上升时段缩短、下降快速, 以“径流集中入渗补给”和“直接集中入渗补给”为主, 热传导减弱、平流作用增强。退水初期泉水温度比泉流量下降快速, 后期则相反。指示退水初期泉流量来源于大量细小裂隙水向岩溶管道中释放, 后期释放量减小并趋于稳定。

关键词: 岩溶泉; 降雨—径流响应; 泉水温度; 入渗补给

创新点: 提出岩溶区温度示踪入渗补给方式和泉水来源方法; 阐明降雨—泉流量响应特征受降雨类型、入渗补给方式的影响。

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0　引　言

我国西南岩溶地区处于湿热气候区, 裂隙、岩溶管道发育, 形成土—岩交错的入渗通道, 降雨入渗多以岩溶泉的形式出露[1]。水文地质空间结构差异对流域地下水补给、径流、排泄以及降雨—泉流量响应特征具有重要影响[2-3]。因此, 解析入渗补给方式以及泉流量来源, 对提升岩溶水文过程形成机理认知以及水资源利用、水环境保护具有重要意义[4]。

染色剂、水化学、同位素等示踪剂是示踪水流运动路径、来源以及区域水力联系的重要手段[5]。岩溶地区水文、水化学时空变化大, 需要高频次采样数据以及水化学和同位素等成分分析, 工作成本高。温度信号具有技术简单、成本低、环境友好(如无污染、不破坏土壤结构)等优势[6]。根据入渗水与不同介质(土壤、岩体)热交换和传导特性的差异, 可辨识水流在非均质介质中运动路径和混合作用, 如利用地下水水温随深度变化信息(T-D 关系), 可识别浅层和深层岩溶地下水来源及其随气象条件变化规律[7]。根据岩溶管道水流与围岩中不同尺寸裂隙的热交换特征, 判断快速水流与慢速水流之间的混合作用。Luhmann 等[8] 利用 25 个泉水、洞穴溪流流量和温度观测资料, 发现管道快速水流与围岩热交换作用弱, 而细小裂隙内的慢速水流与围岩的热交换充分, 两者之间极易达到热平衡[9]。因此, 不同水源温度信号被广泛应用于示踪裂隙水流以及河水与地下水交互作用特征[10-11]。但不同降雨类型, 入渗水在表土/岩石以及管道流运动路径、滞留时间、水热交换存在

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差异，利用岩溶地区场次降雨泉流量、土壤和泉水温度信息辨识降雨入渗方式和泉水来源还有待论证。

本文选择西南典型岩溶区的陈旗流域，选取 2016 年和 2017 年 5 月中下旬—9 月的 21 场降雨，分析降雨前后气温、土壤温度、泉水温度以及流量过程的变化特征，基于泉域土壤、表层岩溶带、岩溶管道水热传导机理，辨识不同类型降雨的入渗补给方式和快速、慢速流对泉流量消退影响，以揭示岩溶地区产流和入渗补给形成机制。

1　研究区概况

研究区位于贵州省普定县陈旗流域，面积为 0.9 km^2，属于亚热带季风气候，全年湿润多雨，雨热同期，年均气温 15 ℃ 左右，年均降雨量 1 300 mm，5—10 月降雨量占全年的 80% 以上[12]。陈旗流域以三叠系关岭组第二段第二、三亚段厚灰岩、薄灰岩夹泥云岩和少量白云质灰岩为主，形成的土层主要为碳酸盐岩土[13]。研究区为峰丛洼地地貌（图 1），海拔高度 1 340~1 530 m。土层较薄（<50 cm），山坡上表层岩溶带发育，厚度在 7.5~12.6 m 之间[14]。裂隙宽均值为 13.6 mm，均方差为 15.7 mm；裂隙间距均值为 142.3 cm，均方差为 98.6 cm[13]。且随着深度加大，表层岩溶带隙宽呈指数型衰减[15]。

流域内五号岩溶泉位于东部山坡脚下，集水面积约为 0.05 km^2（图 1 红色阴影）。根据高密度电法（ERT）探测结果[16]，泉域形成于强风化碳酸盐岩破碎带，表层岩溶带厚度在 6.1~12.6 m 之间，平均厚度为 10.2 m，沿坡面向上递减，下部为相对阻水的薄层泥灰岩，形成悬挂的含水岩体，入渗水在低坡处以泉水形式排泄[17−18]。

2　材料与方法

2.1　数据来源

陈旗流域内建有气象站（图 1），观测降雨、气温、日照等气象要素以及地表以下 20 cm、40 cm 土壤水分、温度。在泉眼下方设有直角三角堰，放置自计式水位/水温计（HOBO U20-001-01），连续观测堰前水位、水温，采用堰流公式换算为泉流量。由于泉水流速快，且 HOBO 探头浸入水下，探头实测泉水温度反映入渗水与土壤、表层岩溶带、岩溶管道热交换的

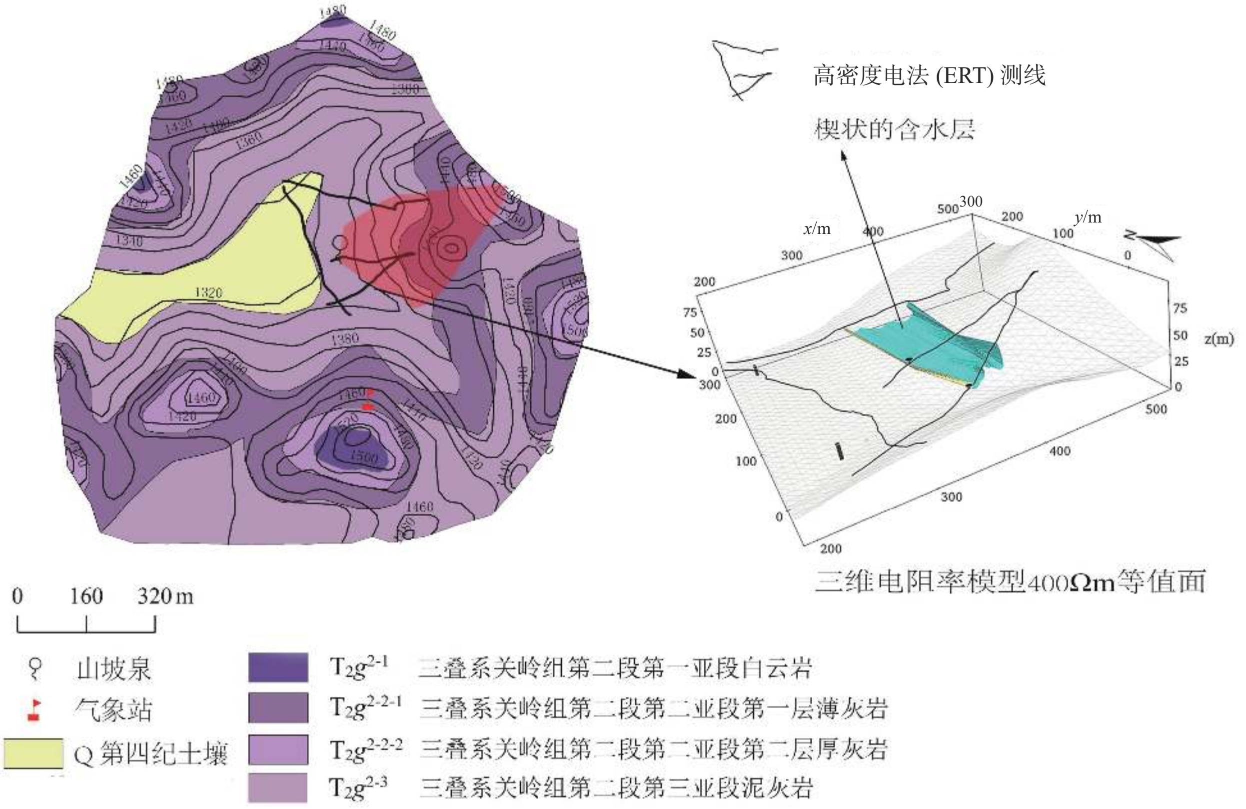

图 1　陈旗流域地形、岩性、水文气象观测站以及山坡泉域分布

Fig. 1　Distributions of topography, lithology, hydrometeorological observation stations and of hillslope springs in Chenqi basin

热量。气象、水文要素观测时间间隔均为 5 min。

2.2 岩溶泉水温度变化的热传导机理

泉水温度对降雨响应反映入渗水的平流传热作用以及水流与介质间的热传导作用。雨前、雨中和雨后不同介质中热的平流、传导作用及其对泉水温度影响机理概述如下：

（1）雨前，储存于细小裂隙中慢速水流是管道流主要补给源，由于慢速水流与围岩的热交换（传导作用）达到平衡，泉流量和泉水温度相对稳定。

（2）雨中，泉水温度受降雨入渗补给方式影响。夏季降雨温度低，表土/岩石温度高，因此入渗水与表土/岩石的热传导程度取决于入渗水滞留时间和入渗路径。当入渗水经大裂隙快速补给至岩溶管道（集中入渗补给），热传导弱、平流传热强，导致管道水流单位体积热量减少，泉水温度迅速下降；当入渗水经土壤和细小裂隙慢速补给至岩溶管道（分散入渗补给），热传导强，平流传热弱，表土/岩石“加热”作用的入渗水补给，使得管道水流单位体积热量增加，泉水温度上升。同时，随着管道中水位迅速上升，管道水向周边细小裂隙补给，并与周边岩土产生热交换。

（3）雨后，管道快速流水位下降，存储于细小裂隙中入渗水和热量回流到管道中，进而影响管道流热量，引起退水段泉水温度的变化。

3 结果与讨论

3.1 场次降雨的气温、表土及泉水温度变化特征

选择 2016 年和 2017 年 5 月中旬—9 月中旬 21 场降雨，统计每个月场次降雨雨前 12 h 以及雨中（降雨—结束后 12 h）的平均气温 T_a、土壤温度 T_s 和泉水温度 T_Q（表 1）。雨前表土（20 cm）T_s 最高，比 40 cm 土壤 T_s 平均高 1.78 ℃，比 T_a 平均高 0.82 ℃，远高于 T_Q（平均高 5.25 ℃）。雨中 T_a、20 cm 表土 T_s 和 T_Q 下降，且 T_Q 下降显著，但 40 cm 土壤 T_s 稍有上升，说明降雨入渗导致 T_s、T_Q 降低。

根据降雨特征（雨强、历时），将 21 场降雨分为

表 1 不同月份场次降水平均降水量以及雨前、雨中平均气温、土壤温度和泉水温度

Table 1 Average rainfall in different months and average air, soil and spring temperatures before and during rainfall

	降水量/mm	气温T_a/℃		土壤温度T_s/℃ 埋深20 cm		埋深40 cm		泉水温度T_Q/℃	
		雨前	雨中	雨前	雨中	雨前	雨中	雨前	雨中
5月（1场）	28.8	21.59	21.09	21.68	19.25	18.28	18.90	18.08	17.01
6月（8场）	42.5	22.59	19.19	23.69	19.65	20.29	20.39	17.22	17.02
7月（3场）	43.1	22.08	19.49	24.39	20.72	21.33	21.40	17.62	17.33
8月（4场）	20.9	22.23	21.66	22.49	21.24	22.86	22.93	18.21	17.77
9月（5场）	16.4	23.23	21.28	22.84	19.37	21.79	21.80	19.34	18.76
平均	30.3	22.53	20.41	23.35	20.25	21.57	21.63	18.10	17.72

表 2 不同降雨类型下泉流量、泉水温度变化特征以及入渗补给方式和泉水来源辨识

Table 2 Variations of spring flow and spring temperatures, and the identification of infiltration recharge manners and spring water sources under different rainfall types

降雨		入渗期		退水期	
类型	降雨特征	泉流量和温度	入渗方式和热传导作用	泉流量和温度	泉水来源
I类	雨强小（≤10 mm·h^{-1}）、历时长（$H\geqslant 10$ h）	泉流量和泉水温度缓慢上升，流量峰值维持时间长；土壤温度缓慢下降，但高于泉水温度	分散入渗，热传导	初期泉流量比泉水温度下降慢；后期泉流量迅速下降至平稳状态，泉水温度接近雨前温度	初期大量细小裂隙水的释放；后期细小裂隙水释放量降低，趋于稳定
II类	雨强大（>10 mm·h^{-1}）、历时短（1 h≤H<10 h）	泉流量迅速上升，泉水温度先上升后快速下降；土壤温度迅速下降，接近泉温度峰值	径流集中入渗，热传导和平流传热	泉流量下降与上述类似，泉水温度初期下降迅速，后期低于雨前温度	
III类	雨强大（>10 mm·h^{-1}）、历时极短（H<1 h）	泉流量迅速上升，泉水温度快速下降或短暂上升后下降；土壤温度下降迅速	直接集中入渗，平流传热	泉流量下降与上述类似，泉水温度初期下降迅速，后期远低于雨前温度	

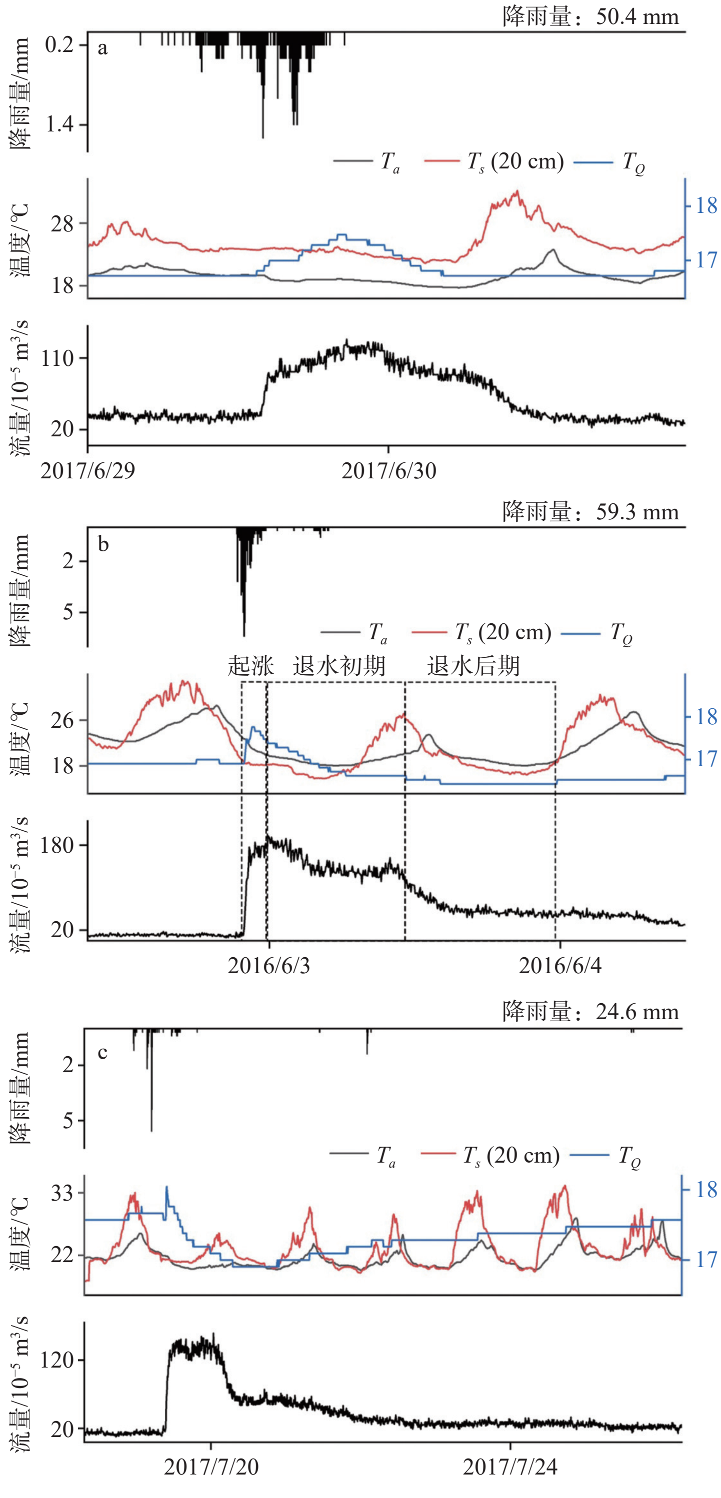

图 2　不同降雨事件气温（T_a）、土壤（T_s）和泉水温度（T_Q）和泉流量（Q）变化

Fig. 2　Variations of temperatures of air (T_a), soil (T_s) and spring water (Ts), and spring flow (Q) in different rainfall events

三种类型，每一类型降雨的泉流量和泉水温度变化特征可归纳为表 2，具体表述为：

I 类型降雨（5 场）：雨强小（≤10 mm·h^{-1}）、持续时间长（H>10 h）（图 2a）。在泉流量 Q 上升期，T_Q 随 Q 缓慢上升，T_Q 峰值比 Q 峰值持续时间短；T_s 缓慢下降，但高于 T_Q。退水初期 Q 下降缓慢，T_Q 比 Q 下降快；后期 Q 迅速下降至平稳状态，T_Q 接近雨前 T_Q 平稳状态。

II 类型降雨（6 场）：雨强大（>10 mm·h^{-1}）、持续时间较短（1 h≤H<10 h）（图 2b）。Q、T_Q 上升快速，而 T_s 迅速下降，接近 T_Q 峰值。退水初期 Q 下降缓慢，T_Q 也比 Q 下降快；后期 Q 迅速下降至平稳状态，但

T_Q 低于雨前 T_Q。

III 类型降雨(10 场):雨强大(>10 mm·h^{-1})、持续时间极短(H<1 h)(图 2c)。Q 迅速上升,但 T_Q 短暂上升后迅速下降,T_s 下降更为迅速。退水初期 T_Q 迅速下降,远低于雨前 T_Q;后期 Q 变化与 II 类型,但 T_Q 远低于雨前 T_Q。

3.2 温度变化指示的入渗补给方式和泉水来源

3.2.1 降雨入渗补给方式

降雨在土壤、表层岩溶带中入渗(I)补给至岩溶管道(q)通常划分为两种补给方式(图 3):集中入渗补给(q_c)和分散入渗(q_d)补给。温度示踪表明,集中入渗补给 q_c 又可划分为直接集中补给和径流集中补给,前者指降雨 P 落在大的裂隙和漏斗中直接入渗 I_c 补给至岩溶管道,后者指降雨形成浅表径流(q_s)经大裂隙或漏斗快速入渗补给岩溶管道。

根据不同降雨类型入渗水的热传导、平流传热作用强弱,推断入渗补给方式为(表 2):

I 类型降雨,热传导控制的分散入渗补给(图 3 中 I_d-q_d)。降水与表土的热传导作用,使得 T_s 缓慢下降。由于始终保持 T_s>T_Q,入渗补给水 q_d 逐渐“加热”,T_Q 随 Q 缓慢上升。

II 类型降雨,热传导和平流传热共同控制的径流集中入渗补给(图 3 中 q_s-q_d)。大部分降水形成浅表径流 q_s,浅表径流与表土热交换迅速,使得 T_s 下降迅速;同时浅表径流的平流传热使得补给至管道的入渗水 q_s 迅速“加热”,导致 T_Q 随 Q 快速上升,且 T_Q 峰值≈T_s 低值。

III 类型降雨,平流传热控制的直接集中入渗补给(图 3 中 I_c-q_d)。降雨入渗 I_c 与表土热交换极为短暂,使得 T_s 快速下降,而 T_Q 短暂上升后快速下降。

3.2.2 泉流量退水段管道流来源

退水段 Q 来源于充填在细小裂隙中的入渗水(图 3 中 q_d 和 $Q_{2\text{-}1}$)向管道中释放(图 3 中 $Q_{1\text{-}2}$),Q、T_Q 变化指示的泉流量来源表述如下(表 2):

(1)退水初期,Q 下降缓慢,T_Q 迅速下降,甚至低于雨前 T_Q(图 2b~2c),表明细小裂隙水向管道中再释放量大,且细小裂隙水和管道流与温度低的深部围岩热传导加强。

(2)退水后期,Q 快速下降后缓慢趋于稳定,T_Q 缓慢下降至最低温度,表明细小裂隙水向管道释放量降低,且管道流与围岩热传导趋于平衡。

4 结 论

利用陈旗小流域山坡泉流量和泉水温度,结合气温、土壤温度及降水实测资料,根据泉域热量传输机理,判别了不同降雨—泉流量响应特征的入渗补给形式及泉流量水分来源,得到以下主要结论:

(1)上涨期泉流量和泉水温度变化反映降雨入

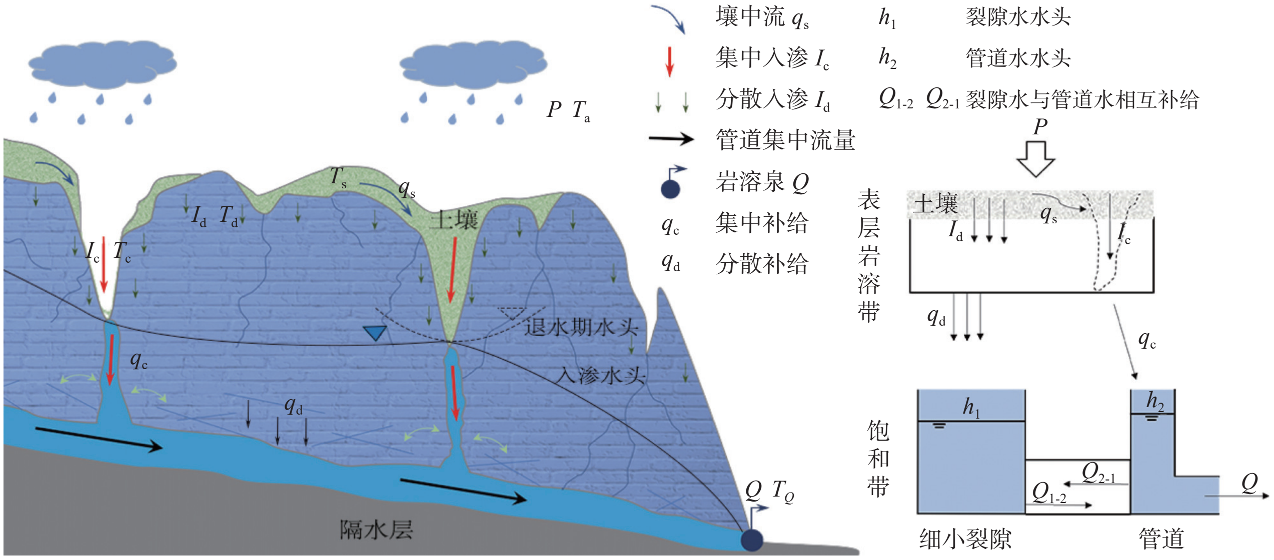

图 3 泉域降雨入渗补给以及管道与裂隙水流交换过程(右图)及其概化图(左图)

Fig. 3 Rainfall infiltration recharge in the spring area and flow exchange between conduits and fissures (the right picture) and the schematic diagram (the left picture)

渗补给方式的差异。雨强小、持续时间长的降雨，入渗水与表土/岩石热传导作用强，泉域主要以“分散入渗补给”为主；雨强大的降雨产生浅表径流，入渗水与表土/岩石热传导减弱、平流传热增强，泉域以“径流集中入渗”为主；雨量较小的短历时强降雨，平流传热强，泉域主要以“降雨直接集中入渗”为主。

（2）消退期泉流量和泉水温度变化主要受围岩裂隙水补给影响。退水初期，管道流持续接受大量细小裂隙水补给，泉流量高、泉水温度迅速降低；后期细小裂隙水补给减弱，泉流量迅速降低并趋于稳定，泉水温度趋于最低。

（3）由于岩溶导水介质的非均质性，水流路径和径流对降水响应复杂多样，且温度为“非保守”示踪剂，增加不同介质和水流温度观测资料，特别是表层岩溶带和管道中温度观测资料，以及水热传输机理，将提升岩溶地区温度示踪水文过程的可靠性。

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Indicative function of karst spring temperatures on rainfall-flow response

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Abstract Karst in Southwest China is located in hot and humid climate region. Strong dissolution produces various combinations of soil, rock fractures and conduits. Therefore, the hydrogeological heterogeneity in this area contributes the difficulty to the identification of various precipitation recharge formations and multiple flow components. Tracers, such as stable isotopes, electrical conductivity, and chemical ions, have been widely used to aid our understanding of hydrological processes. Compared to these tracers, the temperature is a much cheaper alternative for high spatial-temporal resolution monitoring. In this study, the dynamics of hydrograph and temperatures in atmosphere, soils and spring water were used to trace hydrological processes of precipitation infiltration, recharge into conduits and flow exchange between conduits and fractures. Taking a hillslope spring of Chenqi basin in the karst area of Southwest China as the study area, we compared variations in atmospheric temperatures, soil temperatures, spring water temperatures before and after 21 rainfall events from the middle May to the middle September in the years of 2016 and 2017. In addition, on the basis of heat-water transfer mechanism of soil, surface karst zones, and karst conduits in spring areas, we identified the infiltration and recharge modes of different types of rainfall and the effects of fast and slow flows on the decline of spring discharge, in order to reveal the formation mechanism of runoff and infiltration recharge in karst areas.

Results show that soil temperatures were much higher than spring discharge temperatures, and rainfall infiltration could sufficiently lowered soil temperatures and spring discharge temperatures in the study period. However, for the 21 rainfall events, the discharge temperatures varied in the rising phase of hydrograph because of different extents of heat mixture between the cool infiltration water and warm soils/rocks at ground surface. These differences were proven to be related with three types of precipitation infiltration and recharge, i.e. recharge by dispersed infiltration, recharge by concentrated infiltration of shallow runoff and direct recharge by concentrated rainfall. The study indicates that the recharge by dispersed infiltration occurred in the rainfall that was not heavy but lasted for a long time. In such type of rainfall, the spring discharge temperatures showed a slow rise with the increase of discharge. This phenomenon was attributed to the fact that the long-term thermal conduction in soils or small fractures heated infiltration water. However, as rainfall became more intensive but lasted for shorter time, the recharge by concentrated infiltration of shallow runoff and the direct recharge by concentrated rainfall dominated the rise of hydrograph. When the shallow runoff was developed, the spring discharge temperatures showed a decline after a rapid increase in the rising phase of hydrograph.

This research finding indicates that both thermal conduction and convection affected discharge temperatures. The thermal conduction of infiltration in soils or small fractures played a role in heating infiltration water, and thus in raising discharge temperatures. In contrast, the thermal convection via large fractures and sinkholes made the cool water (e.g., the rainfall and runoff in the flow peak) into conduits, which lowered discharge temperatures. The direct recharge by concentrated rainfall only occurred in extremely heavy but short rainfall. For such type of rainfall, the spring discharge temperatures showed a short and rapid increase in the rising phase of hydrograph, which can be inferred that the thermal convection may control discharge temperatures. Furthermore, in the recession period of hydrograph, variations in the spring discharge and temperatures can be used to distinguish mixture of the cool water in small fractures (slow flow) with conduit flow (fast flow). In the early recession period, the hydrograph maintained a high discharge and receded at a slow rate but discharge temperatures declined at a great rate, which indicated that there was a large amount of cool water in small fractures releasing to conduits. In the late recession period, the spring

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depopulation. There are less population outflows in basin areas, with depopulation. Population outflows are very common with prominent depopulation in the intersected areas between mountains and basins. (2) Regional differences of farmland abandonment are obvious. Farmland abandonment is the most severe in mountain areas, followed by the areas intersected between mountains and basins, and farmland abandonment in basin areas was less severe. Abandonment or transformation of farmland has caused the changes of utilization types and functions of the farmland. (3) From the perspective of homestead use, the number of homesteads increased and the space of homestead expanded to outside but was deserted inside. Structures and functions of homestead changed noticeably. (4) Rural depopulation drove the change of land use, which was mainly driven by socio-economic change and regional population migration from rural to urban areas. Various factors affecting the changes of land use and the processes of these changes are interdependent and restrict each other, which has constituted a dynamic coupling phenomenon.

To sum up, the spatial-temporal variation characteristics of land use evolution in mountain areas, intersected areas between mountains and basins and basin areas are different in different periods. The research results are helpful to guide the rural farmland utilization and protection, homestead activation and utilization in mountain–basin systems with different geographical conditions, socio-economic development levels, traffic conditions and geological backgrounds in Guizhou Province. It is of reference value for us to realize the sustainable development of society and economy in terms of mountain–basin system.

Key words　mountain–basin system, land use change, rural depopulation, farmland, homestead

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discharge receded to a stable state and its temperature remained steady and lowest, which can be inferred that water release from small fractures to conduits significantly reduced. The study results demonstrate that the temperature information is useful in tracing the complicated hydrological processes while more observations particularly those in epikarst and conduits are needed to increase the tracing reliability.

Key words　karst spring, rainfall-flow response, spring temperature, rainfall infiltration

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