

Karst Trough Control of Solute Transport Processes at Two Karst Groundwater Flow Systems, Western Hubei, Central China

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ABSTRACT: To investigate groundwater flow and solute transport characteristics of the karst trough zone in China, tracer experiments were conducted at two adjacent typical karst groundwater flow systems (Yuquandong (YQD) and Migongquan (MGQ)) in Sixi valley, western Hubei, China. High-resolution continuous monitoring was utilized to obtain breakthrough curves (BTCs), which were then analyzed using the multi-dispersion model (MDM) and the two-region nonequilibrium model (2RNE) with basic parameters calculated by CXTFIT and QTRACER2. Results showed that: (1) YQD flow system had a complex infiltration matrix with overland flow, conduit flow and fracture flow, while the MGQ flow system was dominated by conduit flow with fast flow transport velocity, but also small amount of fracture flow there; (2) They were well fitted based on the MDM ($R^2 = 0.928$) and 2RNE ($R^2 = 0.947$) models, indicating that they had strong adaptability in the karst trough zone; (3) conceptual models for YQD and MGQ groundwater systems were generalized. In YQD system, the solute was transported via overland flow during intense rainfall, while some infiltrated down into fissures and conduits. In MGQ system, most were directly transported to spring outlet in the fissure-conduit network.

KEY WORDS: Central China, conceptual model, karst trough zone, multi-dispersion model and two-region nonequilibrium model, solute transport processes, tracer tests, solute transport, groundwater flow.

0 INTRODUCTION

Karst aquifers are very important water resources that provide drinking water for approximately 25% of the world's population (Veress, 2020; He et al., 2019; Worthington and Ford, 2009). However, they are highly susceptible to contamination due to rapid infiltration and transportation of contaminants in karst conduits (Chen et

al., 2022; Huang et al., 2021; Qian et al., 2020; Su et al., 2014). Elucidating the mechanism underlying geological structure of karst aquifers is imperative to controlling hydrological dynamic processes of groundwater (Jiang et al., 2021; Ding et al., 2020; Liu et al., 2016; Liu and Brancelj, 2014). However, this faces enormous challenges due to coexistence of pore-fissure-conduit network and high heterogeneity (Liu et al., 2016; Pardo-Igúzquiza et al., 2012). It is even more complicated in the karst trough zone in Central China (Qiu et al., 2022; Liu et al. 2020).

Multiple methods had applied to investigate hydrological characteristics of karst aquifers, such as geophysical techniques (Torrese, 2020), pumping tests (Giese et al., 2018), tracing experiments (Liu et al., 2020; Barberá

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et al., 2018; Wu et al., 2015) and numerical modeling (Vuilleumier et al., 2019). However, these have not effectively enough predicted groundwater flow and transportation of contaminants in karst, owing to a high non-homogeneity and anisotropy, coupled with the difficulty to access the processes even between adjacent conduits. Notably, the tracer test is an effective tool for evaluating water flow path and quantitatively analyzing conduit properties (Li et al., 2016). Currently, it is widely used to calculate groundwater flow velocity, determine water system boundary, reveal the interconversion between groundwater and surface water, verify water system connectivity, and reflect water dynamic characteristics (Goldscheider et al., 2008). Previous studies have affirmed the effectiveness of this technique, especially during application of high-resolution continuous measurement of artificial tracers (Mudarra et al., 2014). This is because they can be easily operated under the field conditions, thereby resulting in more accurate continuous concentration-time series, i.e. tracer breakthrough curves (BTCs). Additional research evidences have shown that BTCs reveal numerous details regarding hydrological variation and solute transport processes, such as asymmetric patterns with long tailings and multiple peaks, which can be controlled by hydrogeological structure of water flow path (Cholet et al., 2017; Goldscheider et al., 2008; Geyer et al., 2007).

In karst, water flows in different patterns within different water-bearing media (pore - fissure - conduit). For example, Majdalani et al. (2018) showed that in conduits, groundwater flow is mostly turbulent, while tracer transports as mechanical dispersion. Notably, different numerical models have been established in order to accurately describe water flow and solute transport processes. For instance, the solute transport process in one-dimensional flow can be portrayed by the advection-dispersion model (Majdalani et al., 2018). Advection-dispersion model, the simplest model developed in 1984 for porous (Jayawardena and Lui, 1984), has been adapted to different flow and dispersion parameters for practical dispersion prediction (Majdalani et al., 2018). Moreover, a two-region non-equilibrium model (2RNE) for mass transport, which is based on tracer exchange between mobile and immobile regions within the conduits, was developed with the aim of describing the BTCs of tracer tests in karst conduits (Field and Pinsky, 2000; van Genuchten and Wierenga, 1977). Consequently, this model has been applied in different karst aquifers (Mudarra et al., 2014; Göppert and Goldscheider, 2008; Geyer et al., 2007; Field and Pinsky, 2000). Moreover, a multi-dispersion model (MDM), which considers multi-peaks as a superposition of different flow paths, was established in order to accurately describe the BTCs with multi-peaks (Field and Leij, 2012; Werner et al., 1997). In this model, the curve generated by the advection-dispersion equation is superimposed on each measured peak, to obtain a combined model fitted to a subsequent set of estimated velocity and longitudinal dispersion coefficient. Furthermore, a fitted model of the multi-peak BTC has subsequently been developed based

on this method (Lauber and Goldscheider, 2014; Werner et al., 1997).

BTCs of tracer tests have been applied to investigate groundwater flow and solute transport across different karst regions of the world. In the karst trough zone of China, further explorations are needed to elucidate the mechanism underlying this specific geological structure in controlling hydrological and hydro-chemical processes of groundwater. This region is characterized by a steep terrain of middle-low mountains and deep ravines that are made up of complex karst landforms and great topographic relief (Liu et al., 2020; Luo et al., 2016), and karst troughs are widely distributed here with numerous sinkholes at the bottom of slopes. While the overland flow still can generate occasionally, especially when the intense rains occurs, which causes pollutants transportation even more complicated. To our knowledge, relevant studies in karst trough zone are still greatly needed. In order to reveal the control mechanism of karst geological structure on solute transport processes in the karst trough zone of Central China, two typical adjacent karst groundwater flow systems, namely Yuquandong (YQD) and Migongquan (MGQ) in Sixi Valley of western Hubei were investigated. Specifically, this study aimed to: (1) determine variations in BTCs across the karst trough zone; (2) assess the water flow and solute transport processes in karst using numerical models; and (3) elucidate the mechanism underlying karst geological structure's control of solute transport processes with groundwater flow in typical karst trough zone of western Hubei.

1 SITE DESCRIPTION

The selected perennial karst groundwater flow systems (YQD and MQG) are in Sixi valley in western Hubei, Central China, upstream of the Maoping River. This is also the first tributary of the Yangtze River, on the south bank of Three Gorges Reservoir, and it belongs to the karst trough zone of China (Liu et al., 2020). The regional geomorphology is characterized by deep-cut canyons combined with flat platforms on the top, while the Sixi valley comprises four main tributaries, namely Shunyangxi, Bajiaoxi, Xiaoxi and Daxi (Figure 1).

About 70% of the valley is covered by carbonates with complex and diverse karst geomorphology, from pre-Sinian to Silurian strata. Notably, the valley strata are monoclinic, tending to the southwest. The Loushanguan Formation (LSG, C_2O_1l) and Qinjiamiao Formation (QJM, C_2q) were two typical karstic water-bearing aquifers in Sixi valley, and QJM lies below LSG. Moreover, QJM is divided into three sections, with the upper and lower parts comprising argillaceous dolomite with low-permeability, while the middle layer made up of thick-bedded calcite dolomite. On the other hand, LSG mainly comprises pure thick-bedded dolomite with widely developed fissures and conduits. Although the valley does not have a large fold, numerous small-sized ones are present in the weak layers.

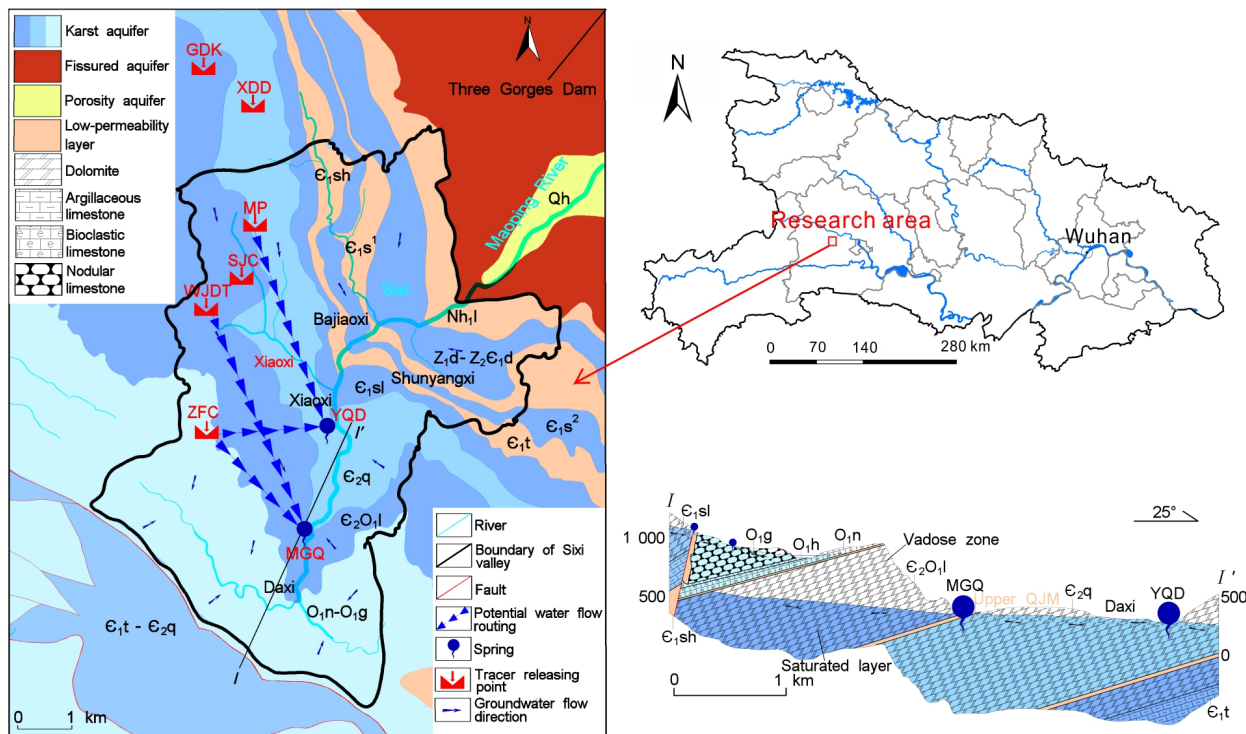


Figure 1. Location and hydrogeology of Sixi Valley. Nh_1l , Liantuo Formation (LT); Z_1d , Doushantuo Formation (DST); Z_2E_d , Dengying Formation (DY); E_{1s} , Shuijingtuo Formation (SJT); E_{1sh} , Shipai Formation (SP); E_{1t} , Tianheban Formation (THB); E_{1sl} , Shilongdong Formation (SLD); E_{2q} , Qinqiangmiao Formation (QJM); E_{2O_1l} , Loushanguan Formation (LSG); O_{1n} , Nanjinguan Formation (NJG); O_{1g} , Guniutan Formation (GNT).

2 TRACER EXPERIMENTS

Based on analysis of the regional geological and hydrogeological information, as well as the site investigation, six depressions with sinkholes on northern upper platform of Sixi Valley were selected as tracer injection sites in this study (Figure 1), for subsequent confirmation of the north boundaries of YQD and MGQ groundwater flow systems. The injection points were Miaoping (MP), Sunjiacao (SJC), Wangjiadatang (WJDT), Zhufenchi (ZFC), Guodikeng (GDK) and Xiaodaodong (XDD). The flowthrough field fluorimeters, namely GGUN-FL20, GGUN-FL30, accuracy $0.01 \mu\text{g/L}$, previously developed by the Institute of Hydrogeology, Neuchatel University, Switzerland, were set up at the outlets of YQD, MGQ and Xiaoxi. Three fluorescent tracers, namely uranine, rhodamine B and tinopal (Behrens et al., 2001), for the experiments.

Briefly, the tracers were instantaneously injected into sinkholes during three rainfall events on June 4th, July 15th, and August 8th, 2017. On June 4th, 2 kg of rhodamine B was injected at ZFC and detected at both YQD and MGQ, 2 kg of uranine was injected at SJC and detected only at Xiaoxi, while 8 kg of tinopal was injected at WJDT and detected only at MGQ. In addition, 5 kg of tinopal was injected at MP on August 8th and detected only at YQD. Tracers injected at GDK and XDD were not detected at any of the three receiver sites.

3 DATA ANALYSIS AND MODELING

3.1 Parameter Calculations

The average tracer transport velocity and cross-sectional

area of karst conduit were estimated by the QTRACER2 program, while the initial injected tracer concentration (C_i) used as the boundary condition for CXTFIT 2.1 (Toride et al., 1999). Previous studies have shown that better fitting can be generated from calibration of experimental data, based on a known tracer mass (Vojtechovska et al., 2010; Goldscheider, 2008). Thus, here the injected tracer concentration for modeling was determined by fitting. The initial estimate of the injected tracer concentration C_i was assumed to be equal to $M/(Av)$ (where M is the injected tracer mass, A is the cross-sectional area of the conduit (L^2), and v is the average tracer velocity (L/T)). The QTRACER 2 (Field, 2002a) was applied to estimate the average tracer transport velocity (v) and the cross-section area of the karst conduit (A).

Additionally, the tracer recovery by zero-order distance, the average retention time and the average transport velocity by first-order moments, and the longitudinal dispersion coefficient by second-order moments based on the principle of moment analysis were calculated by QTRACER 2. The corresponding calculation equations were presented by Eqs. (1)–(4) (Field, 2002b).

The average tracer retention time is

$$\bar{t} = \frac{\int_0^\infty tC(t)Q(t)dt}{\int_0^\infty C(t)Q(t)dt} \quad (1)$$

Flow-channel volume is

$$V = \int_0^t Q dt \quad (2)$$

Flow-channel cross-section area is

$$A = \frac{V}{x_s} \quad (3)$$

Average tracer transport velocity is

$$\bar{v} = \frac{\int_0^\infty \frac{x_s}{t} C(t) Q(t) dt}{\int_0^\infty C(t) Q(t) dt} \quad (4)$$

where V is the volume of the underground water flow system (L^3); A is the cross-section area of the underground water flow (L^2); x_s is the corrected tracer transport distance (L) ($x_s = S_d x$, S_d is the conduit bending coefficient, which is taken as 1.5 in this test, and x is the straight-line distance from the injection point to the monitoring point (L)); $Q(t)$ is the discharge as a function of time (L^3); $C(t)$ is the concentration as a function of time (M/L^3).

The two-region nonequilibrium transport model in CXTFIT 2.1 (Toride et al., 1999) was implemented to analyze the BTCs. CXTFIT was based on the Levenberg-Marquardt algorithm and the nonlinear least-squares functional optimization method was used to fit the BTCs and solve for the model parameters.

The solute transport processes in this paper included advection, dispersion, mass transfer between mobile and immobile regions, and reversible interactions between the tracer and the rock surface, such as adsorption and tracer degradation. The corresponding equation for the one-dimensional two-region nonequilibrium model (2RNE) were presented by Eqs. (5)–(6) (Barberá et al., 2018; Lauber et al., 2014; Field and Pinsky, 2000). It divided the BTCs into two parts: mobile and immobile regions. The advection and dispersion of solutes mainly occurred in the mobile region and the tailings were in the immobile region.

$$\beta R \frac{\partial C_1}{\partial T} = \frac{1}{P} \frac{\partial^2 C_1}{\partial Z^2} - \frac{\partial C_1}{\partial Z} - \omega(C_1 - C_2) - \mu_1 C_1 + \gamma_1(Z) \quad (5)$$

$$(1 - \beta)R \frac{\partial C_2}{\partial T} = \omega(C_1 - C_2) - \mu_2 C_2 + \gamma_2(Z) \quad (6)$$

where $T = vt/L$; $Z = x/L$; x is the tracer transport distance; L is the characteristic length; P is the Peclet number, $P = vL/D$, D is the coefficient of dispersion, which is approximated here by the value of the longitudinal dispersion coefficient; C_1 represents the reduced solute concentration in the mobile region (ML^{-3}); C_2 represents the reduced solute concentration in the immobile region (ML^{-3}). t and Z represent the time and space variables, respectively. The coefficient of partitioning between mobile and immobile regions (β):

$$\beta = \frac{\theta_m + \rho f K_d}{\theta + \rho K_d} \quad (7)$$

where θ_m is the volumetric water content of the mobile

zone; f is the fraction of adsorption sites that equilibrates with the mobile liquid phase (T'); and K_d is the distribution coefficient for linear adsorption ($M^{-1}L^3$). ω denotes the rate of solute transfer in the mobile and immobile regions ($\omega > 0$)

$$\omega = \frac{\alpha L}{\theta v} \quad (8)$$

where α is a first-order mass transfer coefficient of the solute between the mobile and immobile regions (T').

Particularly, the tracer was injected with Dirac pulses indicating instantaneous injection, with the tracer injection time assumed to be negligible relative to the observed transport time. The mean flow velocity v was calculated by the tracer concentration BTCs using Qtracer 2 (Magal et al., 2013). Consequently, v was fixed in the CXTFIT and only the parameters D_L , ω , and β needed to be fitted. Therefore, the longitudinal dispersion coefficient in the mobile region ($D_m = D_L/\beta$) and the mean flow velocity in the mobile region ($v_m = v/\beta$) could be calculated.

3.2 Assumptions and Boundary Conditions

Parameter estimation was carried out under two assumptions: (1) existence of a uniform circular conduit; and (2) the correction length of the conduit is equal to the linear distance multiplied by the correction factor of 1.5.

The solute transport of karst conduit flow in a pressurized conduit flow condition, was viewed as a one-dimensional convective dispersion problem, in which dispersion in the flow direction was the most important.

4 RESULTS AND DISCUSSION

4.1 Profiles of BTCs after Tracer Experiments

Experimental results from tracer experiments, which were conducted during a period of intense rains, revealed five direct water paths between the injection sites and springs or stream. These were from: ZFC to both YQD and MGQ, WJDT to MGQ, MP to YQD; and SJC to Xiaoxi (Liu et al., 2020).

Most tracers could be flushed to groundwater table by heavy rainfall through large vertical conduits system immediately after injection (Lauber and Goldscheider, 2014), thus both the 2RNE model and the advection-dispersion model could be applied here, which assume that solute was transported in the saturated zone. Similarly, continued external water was applied to flush tracer into the saturated conduits system, and they were also simulated by both models (Geyer et al., 2007; Birk et al., 2005).

Furthermore, results from tracer experiments revealed a water flow path, from ZFC to YQD (Figure 2), while BTCs for ZFC-YQD exhibited multiple peaks (Figure 3a). These multiple peaks, which are attributable to presence of multiple flow paths (Wang et al., 2020; Lauber and Goldscheider, 2014), which indicated different flow regimes of the karst systems. For the BTC of ZFC-YQD, a combination with discharge curve analysis resulted in a shape and time of the first four peaks of the rho-

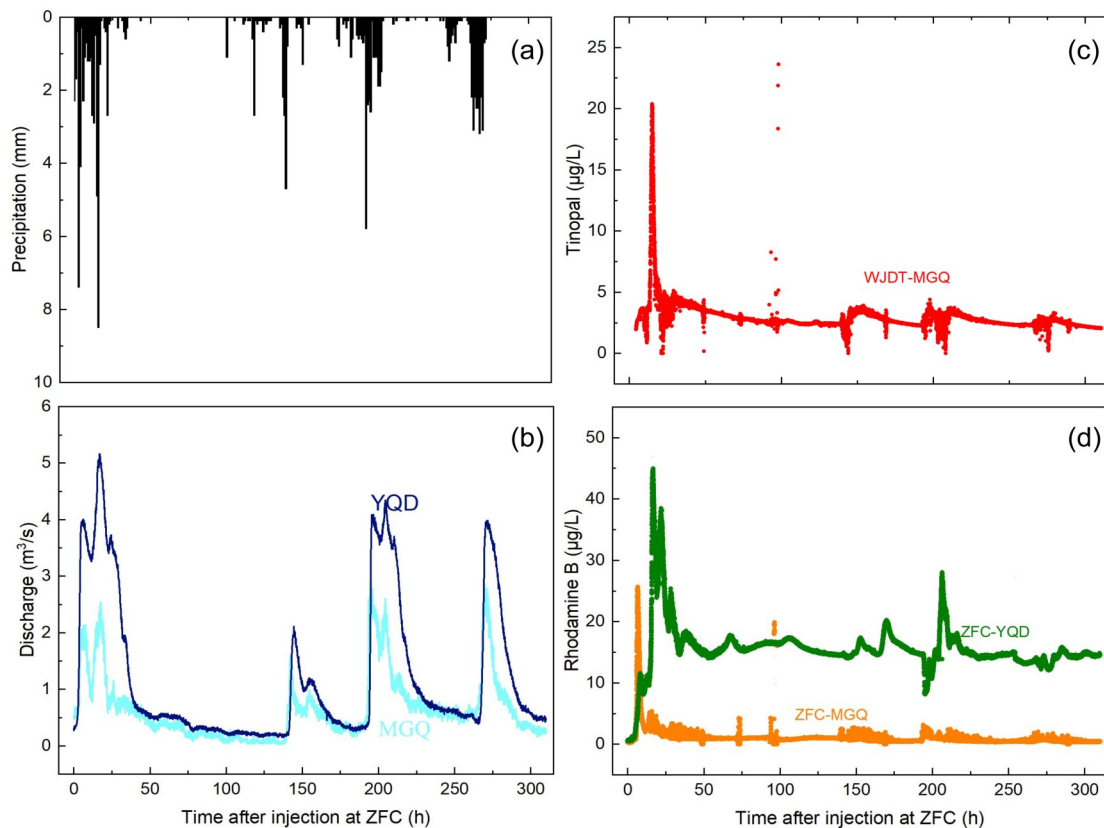


Figure 2. Precipitation (a), discharge (b), and BTCs at MGQ (c) and YQD(d) for the rain event on June 4, 2017.

Table 1 Parameters obtained by QTRACER2 and CXTFIT

Parameters	Programs	WJDT-MGQ	ZFC-MGQ	ZFC-YQD		
Tracer		Tinopal	Rhodamine B	Rhodamine B		
Tracer transport distance (m)		6 165	3 495	3 210		
Flow channel volume (m ³)		113 190	75 421	252 890		
Flow-channel cross-section area (m ²)	QTRACER2	18.36	14.39	78.78		
Based on an estimated conduit diameter (m)		4.84	4.28	10.02		
Reynolds number		31 032	30 277	32 750		
Peak number		1	1	1	2	3
v (m/h)		459.2	259.7	358.3	190.1	144.8
D_L (m ² /h)	CXTFIT	7 194	29 850	27 940	1 088	3 280
α (m)		15.67	114.94	77.98	5.72	22.65
Peclet number		393	30	41	561	42
R^2		0.988	0.947	0.928		

α . Dispersivity; R^2 . the coefficient of determination.

damine B concentration curve that were almost identical to the discharge peaks (Figure 2), indicative of different water flow pathways. Consequently, the first four peaks of the BTCs were chosen for fitting.

Tracer rhodamine B injected from ZFC, was detected at YQD with a 54.2% recovery. Notably, rhodamine B was first detected at 268 min, with a peak time of 1 012 min after injection. In addition, the average flow velocities, calculated from the four peak fits, were 358.3, 190.1, 144.8, 109.9 m/h, whereas the longitudinal disper-

sion coefficient calculated from the four peak fits were 27 940, 1 088, 3 280, 620 m²/h. Moreover, the tracer had a corrected transport distance of 3 210 m. With regards to calculated structural parameters of the karst conduit, it found a groundwater flow channel volume of 252 890 m³ and an average cross-sectional area of 78.8 m² (Table 1).

Furthermore, results from tracer experiments revealed presence of two groundwater flow paths from WJDT and ZFC to MGQ, respectively. The BTCs for both WJDT-MGQ and ZFC-MGQ had one main peak (with a

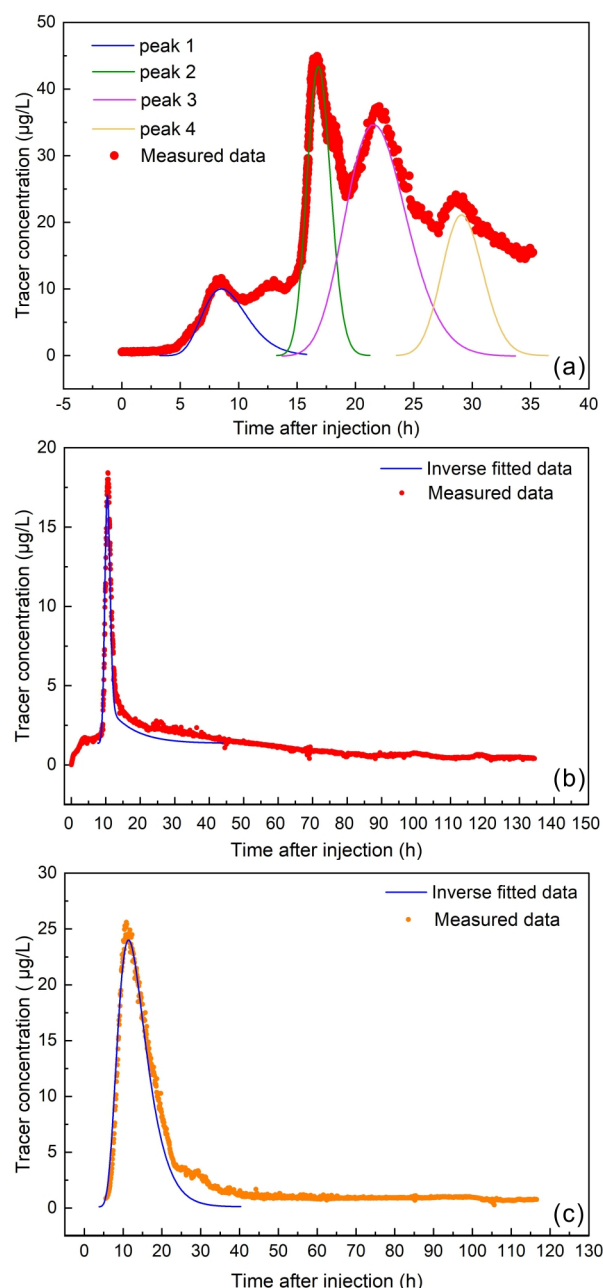


Figure 3. Measured BTCs compared to results from the calibrated models. (a) ZFC-YQD BTC and MDM; (b) WJDT-MGQ BTC and 2RNE model; (c) ZFC-MGQ BTC and 2RNE model.

high concentration), and numerous small peaks (Figure 2). When combined with the discharge curve, this finding indicated that the small peaks appeared almost synchronously with small peaks of the discharge peaks. In fact, subsequent small peaks originated from the residual tracer in fissures. Consequently, only the first main peak, with a higher concentration was fitted.

Tracer tinopal injected from WJDT, was detected at MGQ. This had recovery of 18.9%, and its BTC exhibited a single peak with a long tail (Figure 3b). Tracer was first detected at 540 min with a peak time of 638 min, after injection. The maximum concentration and corrected tracer transport distance were 18.42 μg/L and 6 165 m, respec-

tively. On the other hand, the maximum groundwater flow velocity was 685.0 m/h, with an average of 459.2 m/h. Other groundwater hydraulic parameters were calculated as follows: the groundwater longitudinal dispersion coefficient was 7 194 m²/h, longitudinal dispersivity was 15.67 m, the Peclet number was 393, and the Reynolds number was 31 032. In addition, structural parameters of the karst conduit were: groundwater flow channel volume of 113 190 m³, and with an average cross-sectional area of 18.36 m² for the karst conduit. The curve of WJDT-MGQ reached the best fit at β of 0.85, when ω was 3.047×10^{-4} .

Rhodamine B, injected from ZFC, was detected at MGQ (Figure 3c), with a recovery rate of 29.35%. Moreover, tracer was first detected at 260 min with a peak time of 807 min, after injection, while its maximum concentration was 25.31 μg/L. The corrected tracer transport distance was 3 495 m, while the maximum groundwater flow velocity was 806.5 m/h, (average 259.7 m/h). The other groundwater hydraulic parameters were as follows: groundwater longitudinal dispersion coefficient was 29 850 m²/h, longitudinal dispersivity was 114.94 m, Peclet number was 30, Reynolds number was 30 277. The calculated structural parameters of karst conduit included a groundwater flow channel volume of 75 421 m³, and an average cross-sectional area of 14.39 m² for the karst conduit. The ZFC-MGQ was best fitted at β of 0.8, when ω was 2.092×10^{-2} .

4.2 Sensitivity Analyses Based on the 2RNE Model

Parameters were adjusted by the 2RNE model in CXTFIT first, and then they were determined sensitivity by comparing with the variation of BTCs (Figure 4).

Taking the WJDT-MGQ fitted curve as an example, average flow velocity in the mobile region (v_m) (Figure 4a), longitudinal dispersion coefficient in the mobile region (D_m) (Figure 4b), the coefficient of partitioning between mobile and immobile regions (β) (Figure 4c), and the rate of solute transfer in the mobile and immobile regions (ω) (Figure 4d) exhibited a 5-fold increase or decrease in relation to the original fitted values, respectively (Figure 4). Generally, the range of β varied from 0 to 1, with an original fitted value of 0.8. However, it did not exhibit a 5-fold increase over 1, thus its expanded value was taken as 0.99. Overall, this indicated that v_m and β were more sensitive to influence by tracer transport model than D_L and ω (Figure 4). Notably, v_m mainly determined peak position and curve width of the BTCs, while β mainly affected the shape of the BTC tailing.

4.3 Conceptual Model of Underground Waterflow and Solute Transport

Conceptual models of solute transport in YQD and MGQ water flow systems were generated, based on the hydrogeological conditions of Sixi Valley and the tracer experiment.

YQD was developed in the middle layer of QJM with calcite dolomite. The upper and lower parts comprised ar-

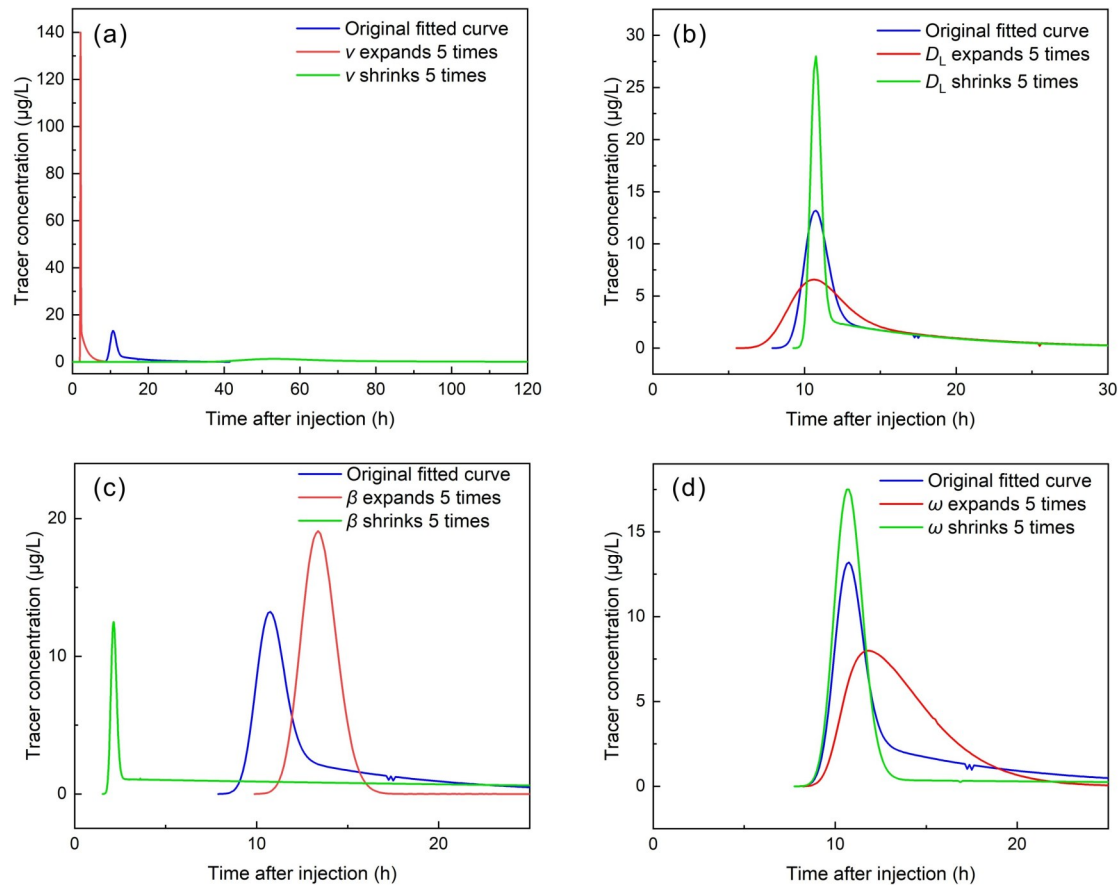


Figure 4. Results of sensitivity analysis of two region nonequilibrium model (with WJDT-MGQ as an example).

gillaceous dolomite and dolomitic mudstone, which can be considered boundaries of the YQD water flow system (Liu et al., 2020). Additionally, the tracer experiment is an efficient tool for confirming water flow paths, while its BTCs generally reflect the characteristics of the karst aquifer. The results revealed an obvious and sharp BTC peak, indicative of the rapid water flow and multiple peaks that imply different water flow paths. The BTCs of ZFC-YQD were divided into four peaks, each corresponding to a water flow path (Figure 2). When combined with fitting results (Table 1), the four flow patterns were generalized into overland flow, karst conduit flow, secondary conduit flow, and fissure flow, respectively (Figure 5).

The first peak of YQD was basically consistent with the overland flow, and exhibited a high average flow velocity ($v_m = 358.3$ m/h), which was diluted by surface water flow before the peak. The injection site 'ZFC' located on the edge of cliff, where vertical fissures were well-developed, and water with tracer converged into sinkhole and flew out just beneath the cliff as overland flow into a trough. This is because the karst trough zone is more likely to catch water and had more sloping land. The overburden layer on the slope easily reached saturation due to its small thickness. When a strong rain fell, the rainfall intensity was greater than the infiltration capacity, and the water mixed with tracer flowed over the surface, thereby forming overland flow. Its tracer transport was obtained by fitting calculation as 9.37% (Figure 3a).

The second peak was characterized by higher average flow velocity and lower longitudinal dispersion coefficient ($v_m = 190.1$ m/h), which corresponded to the rapid discharge of karst conduit flow. The tracer, which was transported through the water-resisting layer by the slope surface flow, entered the conduit along the fissure and was rapidly discharged through the conduit during strong rainfall. Notably, 29.25% of tracer mass was discharged with this peak (Figure 3a).

The third peak was characterized by slightly lower average flow velocity and higher longitudinal dispersion coefficient ($v_m = 144.8$ m/h), which represented water flows in secondary conduits. Notably, 47.02 % of tracer was discharged here (Figure 3a). This flow path may require activation of a certain amount of recharge, while karst features are extensively developed between ZFC and YQD, from which surface water flow is recharged to activate this flow channel.

The fourth peak was characterized by low flow velocity and low longitudinal dispersion coefficient ($v_m = 109.9$ m/h), which corresponded to the flow path in fractured medium. This peak was accentuated because of reduced rainfall and slower conduit flow, and the proportion of tracer transport was 14.36% (Figure 3a). The conduit and fissure were fully wetted, owing to abundant and continuous rainfall before and after tracer injection. Moreover, the smaller fissure was filled with water, and the tracer trapped by the fissure was carried into the karst conduit

by the continuous rainfall water, which resulted in high average flow velocity and small dispersion coefficient.

Therefore, solute transport in the YQD system was mainly dominated by karst conduit (76.27%), with a fracture medium transport of 14.36%, and an overland flow transport of 9.37%, during the intense rain event on June 4th, 2017, in Sixi Valley.

Both paths from WJDT and ZFC to MGQ were in the LSG Formation, indicating that they had similar control mechanisms on the solute transport by geological structure. The generalized conceptual model of solute transport of WJDT-MGQ is shown in Figure 6.

The BTC of WJDT-MGQ exhibited a single-peaked (Figure 2c), which was attributed to the fact that the layer on the path was LSG, its lithology was thick-bedded pure dolomite large fissures and the corresponding karst conduits were well-developed. Additionally, numerous small peaks were also presented at the tails of BTCs. It indicated that the conduit flow could be dominant here with a

small percentage of fracture flow (Liu et al., 2020). The WJDT-MGQ flow path exhibited a high average flow velocity with a low longitudinal dispersion coefficient, indicating that tracers were transported with conduit flow. Consequently, the number of water pools on the path increased the length of the BTC tail, and dispersion, but reduced the flow velocity of the model (Zhao et al., 2017). Thus, the higher longitudinal dispersion coefficient observed in 'ZFC', compared to 'WJDT', was presumably due to presence of pools in the path of ZFC-MGQ, which slowed down the tracer transport velocity, and it was also supported by the lower β and higher ω in the fitted results (Table 1). Additionally, the several followed smaller peaks on the BTC of WJDT-MGQ are the residual tracer washed out from fissures slowly by rainfall (Figure 2). The estimated diameter of karst conduits from ZFC and WJDT to MGQ, were similar, while the larger flow channel volume of WJDT-MGQ was due to its longer distance from MGQ.

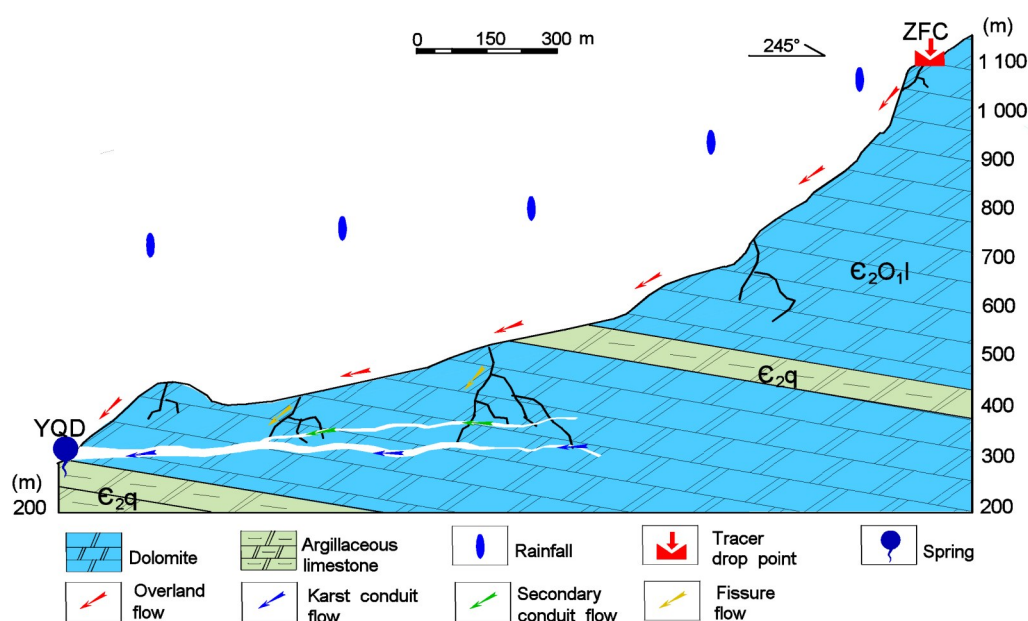


Figure 5. ZFC-YQD solute transport conceptual model.

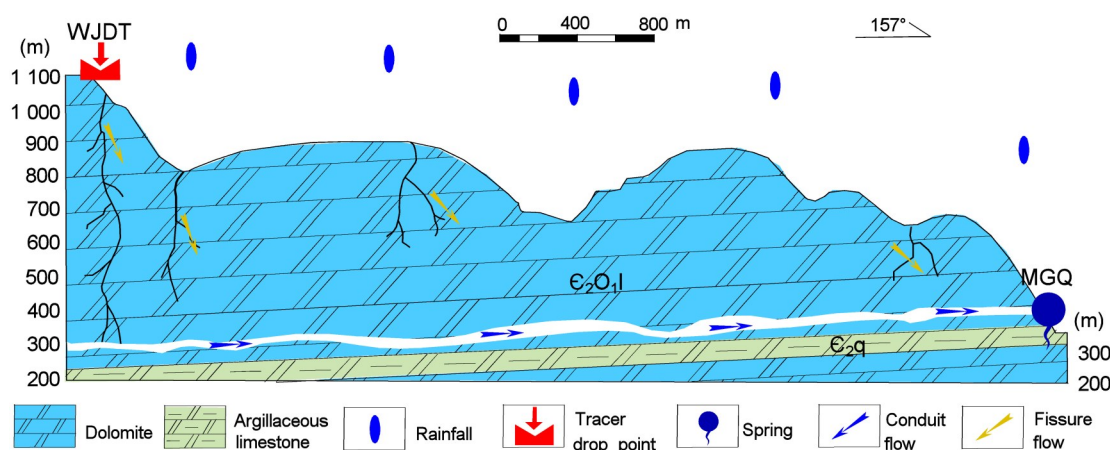


Figure 6. WJDT-MGQ solute transport conceptual model.

5 CONCLUSIONS

In this paper, two typical adjacent karst groundwater flow systems, namely YQD and MGQ, in Sixi Valley were studied and then elucidated the mechanism underlying karst geological structure control of waterflow and solute transport processes in typical karst trough zone of western Hubei. Based on the high precision field tracer experiments, the MDM and 2RNE model, were applied to describe the variation among BTCs, then introduced two conceptual modes were introduced to explain the solute transport processes. The following conclusions are drawn.

(1) BTCs analysis revealed that the hydraulic and structural parameters of karst conduits of three groundwater runoff paths, namely WJDT-MGQ, ZFC-MGQ and ZFC-YQD. All three flow paths exist with conduits and open fissures, as evidenced by the large average transport velocities. The BTC for ZFC-YQD is multi-peaked indicating different water flow paths. ZFC-YQD has the most developed karst, as evidenced by the largest average cross-sectional area. On the other hand, BTCs for both WJDT-MGQ and ZFC-MGQ are single-peaked with fast flow velocity. Both groundwater flow paths were single conduits as turbulent flow with large Reynolds number.

(2) Results of the parametric sensitivity analysis, performed on the results of the two-region nonequilibrium model fit, revealed that model results of tracer transport were most sensitive to the v_m and β , while D_m and ω were less influential. v_m mainly determined peak position and curve width of the BTCs, while β mainly affected the shape of the BTCs tailing. Therefore, MDM and 2RNE model could better fit the BTCs obtained from tracer tests in the karst trough zone, and also provided a relatively reasonable explanation of their physical significance. However, their definitions remain unclear.

(3) Conceptual models for solute transportation in YQD and MGQ groundwater flow systems was generalized. Specially, solute transport paths corresponding to BTCs peaks, then proportion of solute transport in each path was calculated. Solute transport in MGQ system was dominated by conduit flow, which was similar to that observed in the YQD system. However, surface flow in the YQD system also markedly contribute during intense rains. For example, 76.27% of tracer mass was discharged by conduit flow, during the rain event on June 4th, 2017, with 14.36% and 9.37% attributed to fissure media and slope surface flow, respectively.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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