Defining and Classifying the Formation, Characterization, and Significance of Karst Hyporheic Zones in a Karst Peak-Forest Plain in China

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Abstract

Groundwater (GW)-surface water (SW) interactions in karst areas may have a strong impact on the quantity and quality of the groundwater system. Although knowledge of karst hydrology has improved in recent decades, the interaction patterns of GW-SW, and understanding of the hyporheic zone (HZ) on improving or deteriorating groundwater remains very limited. Here, we document HZ in a karst basin through study of hydrological, hydrochemical, and biological processes. The depths of some sinkholes or karst windows in the karst plain are more than 100 m, which are dozens of meters lower than the river elevations. The HZ is not limited to the riverbed, but extends into aquifer along the karst conduits. And their interaction patterns are not limited to the mixing GW and SW, but also include mixing of groundwater with other water bodies. Due to the existence of karst conduits, the types of HZ and the dynamic process of hyporheic flow are unique within karst aquifers. We defined these generally in karst groundwater systems dominated by conduits as karst cave hyporheic zones (KCHZ), with the meaning of the place or area where conduit flow interacts with other types of water bodies. The KCHZ was further classified into four types. Research on the five springs in the study area showed the formation of KCHZ is related to the karst development and the hydrogeochemical gradient of water environment. Once the quality of one type of water deteriorates, or the amount of water decreases, the function of hyporheic zone will degenerate.

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Abstract: Groundwater (GW)-surface water (SW) interactions in karst areas may have a strong impact on the quantity and quality of the groundwater system. Although knowledge of karst hydrology has improved in recent decades, the interaction patterns of GW-SW, and understanding of the hyporheic zone (HZ) on improving or deteriorating groundwater remains very limited. Here, we document HZ in a karst basin through study of hydrological, hydrochemical, and biological processes. The depths of some sinkholes or karst windows in the karst plain are more than 100 m, which are dozens of meters lower than the river elevations. The HZ is not limited to the riverbed, but extends into aquifer along the karst conduits. And their interaction patterns are not limited to the mixing GW and SW, but also include mixing of groundwater with other water bodies. Due to the existence of karst conduits, the types of HZ and the dynamic process of hyporheic flow are unique within karst aquifers. We defined these generally in karst groundwater systems dominated by conduits as karst cave hyporheic zones (KCHZ), with the meaning of the place or area where conduit flow interacts with other types of water bodies. The KCHZ was further classified into four types. Research on the five springs in the study area showed the formation of KCHZ is related to the karst development and the hydrogeochemical gradient of water environment. Once the quality of one type of water deteriorates, or the amount of water decreases, the function of hyporheic zone will degenerate.

Key words: hyporheic zone, karst conduit, backflow, GW-SW interaction, water environment

1. Introduction

Groundwater (GW) and surface water (SW) cannot be exploited and managed separately in karst areas, due to their interconnectedness; while this is well recognized, it is not always adequately considered in management decisions (Smith et al., 2008). The reason is because studies and understanding of GW-SW interactions in a comprehensive and coordinated manner remains limited (Bailly-Comte et al. 2009; Winter 1995). GW-SW interactions may vary in space and time (Sophocleous, 2002; Rugel et al., 2016). Their interactions would not only change the hydrological processes within the respective systems, but also affect the water quality and aquatic ecosystems of both components (Dahm et al., 1998; Lapworth et al., 2011; Kurz et al., 2015).

GW-SW interactions in the riparian zone are well known and have been actively studied for decades (Jesper et al., 2006). The hyporheic zone is defined by ecologists as the zone below the river bed and both sides of the river, where GW and SW mix (White 1993). A general definition (in porous and fractured aquifers) of the GW-SW hyporheic zone is the shallow subsurface pathways through river beds and banks beginning and ending at the river (Cardenas, 2015); therefore, the significance of hyporheic zone is its function as the area where the interaction among surface water (river), groundwater (aquifer) and sediment occurs (Hancock 2002 Bianchin et al., 2011). In this definition, the river is the primary representation of the hyporheic zone, in which hydrodynamic conditions occur for the interaction of GW and SW (Triska et al. 1993; Valett et al. 1996; Brunke and Gonser 1997). Within the sediment and aquifer outlets is where hyporheic exchange often occurs, while groundwater creates the input for the interaction. However, the impact of GW-SW interactions within karst groundwater systems has been less widely examined.

In terms of the relationship between GW and SW, in karst areas groundwater often flows quickly through the aquifer to SW bodies and results in rapid mixing (Ford and Williams, 2007). The concept of a karst hyporheic zone (KHZ) was proposed by Wilson (2013) during a study on karst conduit-matrix interactions related to pollutant transport. The KHZ refers to an active zone hydrologic exchange between karst conduits and the matrix. The KHZ interface is also where solute exchange between the two sources occurs inside the aquifer, which is somewhat different from the interactions within a more traditional surface river hyporheic zone.

The significance of the karst hyporheic zone needs additional study to better understand the various interactions occurring within this transition zone. Even if the concept of a surface river hyporheic zone is applied in a karst area, there are still some unique characteristics different from porous or fractured aquifers that are not applicable. For example, the morphology of KHZ and the dynamic processes of hyporheic flow may be different from traditional surface water hyporheic flow due to the flow characteristics of karst conduits. Since karst conduits often discharge directly through base level springs and contribute directly to the KHZ, the input of water from these during varying flow conditions may generate distinctively different KHZ flow dynamics over time. In addition, the distribution of the hyporheic zone may exceed the river bed and extend to the phreatic zone along the karst conduit (Binet et al., 2017), or extend to the deep karst aquifer system (Hancock et al., 2005) and interfluve in rivers because of the development of karst in the river valley.

The main characteristics of the KHZ are:

- In karst areas dominated by conduit flow, the KHZ may extend into the aquifer along the karst conduit

- The interaction time of GW and SW is more rapid and frequent, and it is related closely to the hydrological dynamics of the river, especially during flood events
- Karst conduits can be large and allow for rich biological diversity in the KHZ
- The KHZ is sensitive to anthropogenic activities and environmental change, with high vulnerability to pollution and development

These characteristics make the hyporheic zones in karst water systems are diverse and special.

The main function of the HZ is its ability to exchange water, sustain biodiversity, and serve to reduce pollutants through filtration and creating geochemical gradient (Gandy et al., 2007). In a typical karst aquifer, allogenic water discharges to karst conduits through sinkhole in the upstream portion of the basin; therefore, sinkholes form a transition zone from sufficient light and heat on the surface to a cool and humid underground environment. When groundwater discharges from the aquifer by the way of a spring, another transition zone from a constant temperature, lightless, oligotrophic environment to a variable temperature, increased light, eutrophic environment occurs downstream. The aforementioned transition zones will appear repeatedly in karst discharge zones. It is unclear if any attenuation of contaminants occurs during these exchanges due to varying flow dynamics between the karst system inputs and outputs within the KHZ.

The objectives of the present study were to discuss the interaction patterns of GW-SW in karst areas based on the concept of hyporheic zone and to extend the knowledge of hyporheic zones in karst aquifers. Then the definition of hyporheic zone in karst aquifers dominated by conduit flow was defined and the types of KHZ were classified. For this study, the formation and the characteristics of five typical KHZ were examined in detail. The research results help to explain the mechanism of groundwater degradation in karst areas and provide an effective approach for managing complex, integrated groundwater and surface water systems.

2. Materials and methods

2. 1. Study area

Wuming Basin (WB) is located in the south of Guangxi Province, China. This drainage basin consists of 4536.3 km^2 mostly within the Wuming district. A total area of 3175.7 km^2 in the basin is covered by karst. The Wuming Basin is surrounded by mountains on three sides, low in the middle, and open to the southwest (Fig.1). Its topography is mostly a karst peak-forest plain (Fenglin) at 150 m.a.s.l. (meters above sea level). The peak and remnant hills are usually present in isolated sections, with the elevation less than 300 m.a.s.l. Soil cover in the plain varies from 3-20 m, with bare rock outcrops in some areas. Strata are exposed from Tertiary to Cambrian in age and carbonate rock exists from Tertiary Beisi Formation to the Devonian Donggangling Formation and is widely distributed being from Carboniferous to Devonian age strata.

The Wuming basin is well-known by Chinese karst scientists for its distinct karst development and features. Twelve mid-Pleistocene teeth from a gigantopothecus were found in a cave in the area in 1965, indicating the cave was formed before the Pleistocene (Zhang et al., 1973). A kind of blind fish, *Oreonectes anophthalmus* was found in 1977 in a cave in Wuming (Zhao 1983). The ancestor of *Oreonectes anophthalmus* was believed to have lived in river, lake, or pool outside the cave. Blind fish found in the cave indicates the karst water linked to a much larger water body outside the cave.

The climate is sub-tropical with average rainfall and potential evaporation of about 1,247 mm and 1,278 mm/year, respectively. The mean annual temperature is 21.9 °C. Rainfall is generally higher in the summer, with the highest average monthly rainfall occurring between May and August. Karst groundwater in the basin discharges in springs, karst windows, or sinkholes. Lingshui Spring is the biggest spring in the basin, providing the only drinking water source for 140,000 residents. Surface rivers in the basin include the Youjiang River and its tributary, the Wuming River, and the tributary of Wuming River, the Xiangshan River, and so on (Fig. 1). The elevations of the rivers vary from 95 to 100 m.a.s.l. Vertical depth of some karst windows or sinkholes can reach 60 to 100 meters, and sometimes more than 100 meters in certain area, which is several tens of meters deeper than the rivers.

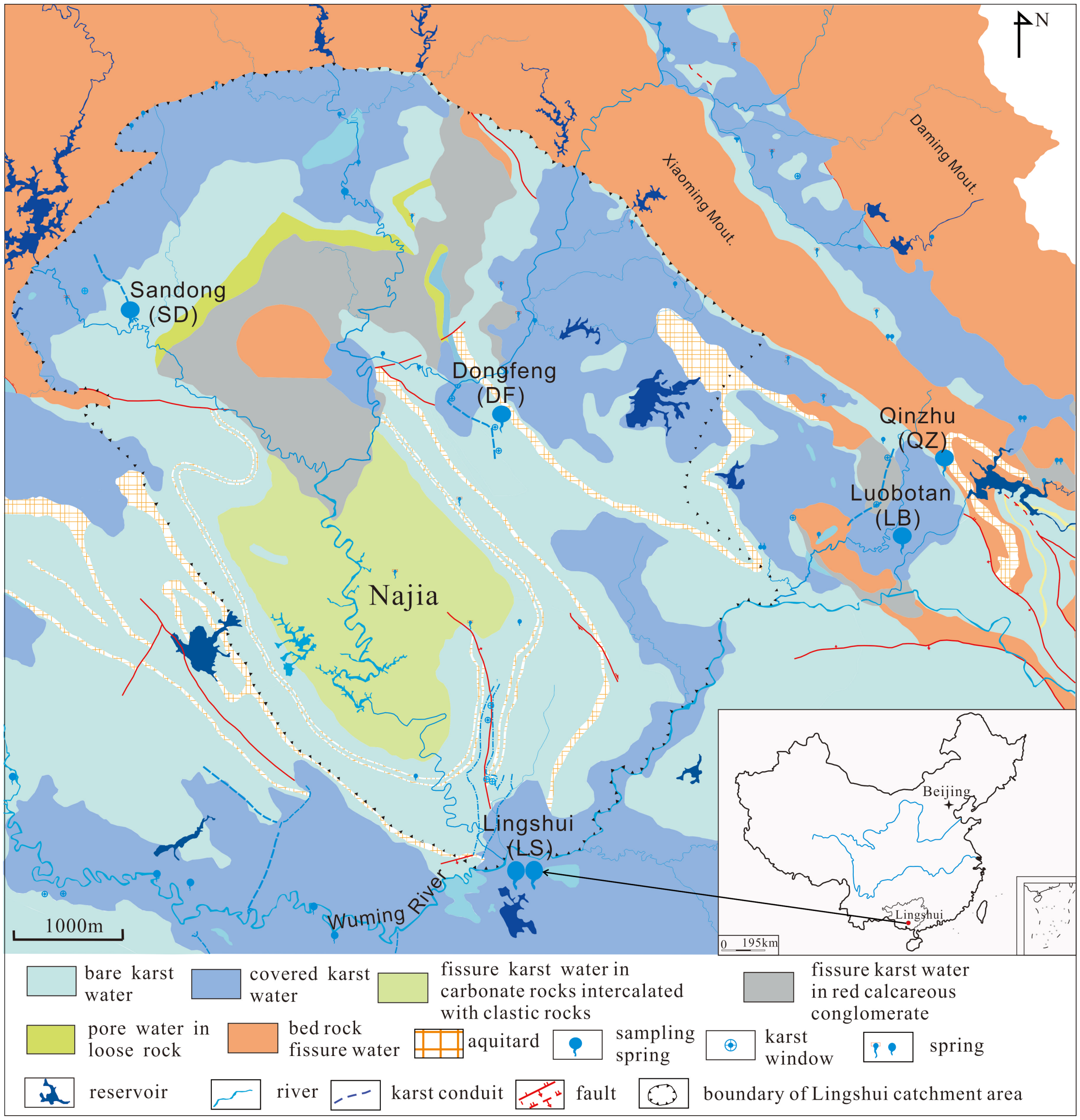

Fig.1 Simplified hydrogeological map of the basin (Revised from Guo et al., 2020)

Wuming Basin is an important fruit industry base in China. In 2018, Wuming District had an annual output of 1125,247 tons of fruit, which was the first among all counties in the province. In 2019, the fruit planting area in Wuming District reached 47,666 hectares. The main fruits are citrus, banana, grape, dragon fruit, etc. Eucalyptus grows rapidly in most of the hills since late 1990s and both the fruit and eucalyptus planting consume large quantity of groundwater.

2.2. Interactions between karst groundwater and surface water

In addition to the largest spring, Lingshui, there are other 147 springs or subterranean rivers in the basin. Using hydrologic monitoring tools, groundwater discharge measurements, the discharge patterns of springs, karst windows, and sinkholes, and the elevation relationship between karst groundwater and surface water were surveyed. A hydrogeological map at a scale of 1:50,000 was compiled in order to demonstrate the distribution and relationship between groundwater and surface water.

2.3. Typical karst groundwater-surface water hyporheic zone

Five springs were chosen for detailed study. They included: the largest spring-Lingshui (LS), Dongfeng (DF), Sandong (SD) spring in the catchment of Lingshui, the second largest spring-Luobotan (LB) (adjacent to Lingshui), and Qinzhu (QZ) spring located in the catchment of Luobotan (Tab.1).

Table1 Descriptive information for the five springs.

System	**Spring**	**Flow in dry season (l/s)**	**utilization**	**Aquatic pla**
Lingshui	LS	2215	Drinking water for 140,000 residents	None
	DF	77.3	Drinking water for a farm and a factory	None
	SD	-	Irrigation since 2017	Snapdragon
Luobotan	LB	207.6	Drinking water for 35000 residents	Tape grass
	QZ	27.8	Irrigation	Tape grass

Long-term monitoring: In Lingshui Spring, between 2010 and 2020, hydrological conditions were monitoring by a Solinst Levelogger at an interval of 15 minutes (Solinst Canada Ltd.), with precisions of 0.41 cm (level) and 0.1°C (temperature), respectively. Another Solinst instrument was also used for pressure correction. Water temperature (T, in °C), specific electrical conductivity (SEC, in S/cm), pH, and dissolved oxygen (DO, in mg/l) were measured every 15 minutes using a YSI multi-parameter water quality instrument (ProPlus), with precisions of 0.01°C, 0.1 s/cm, and 0.01 for pH, 0.01% air saturation for DO, respectively.

In-situ monitoring and measurement: Each water body in the springs was divided into a grid profile for sampling purposes (Guo et al., 2019). A YSI ProPlus was used to measure pH, SEC, DO, and water temperature *in situ*. Chl-a was measured by a ALGAE-Wader Pro, with a precision of 0.01 g/L.

A current meter made by Chongqing Huazheng Hydrological Instrument Co., Ltd. was used to measure the velocity of groundwater at the cross-section of the HZ every 3 months. The discharge of springs then was calculated based on the cross-sectional area and flow velocity.

Sampling and analysis: Regular water sampling campaigns were carried out every three to four months between 2010 and 2020 with a total of more than 150 samples. In particular sampling periods, such as flooding events, water samples were taken every day for more than one week. Water samples were analyzed for major ions and the abundance and species of plankton. Anions (Cl^-, NO_3^-, SO_4^{2-}) were analyzed by IC (Ion Chromatography) Dionex DX-320 and cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) were analyzed applying conductometric detection using an IC Dionex DX-500. The analytical error was estimated to be 8%.

The plankton was sampled four times in January, April, July, and October during 2016 to 2017. A plankton net (10- m mesh) was applied in a ∞ shape to collect samples from the water. Then, 150 mL of the collected samples were stored in a plastic bottle and sent to the laboratory for qualitative microscopic examination of the phytoplankton. Another 1,500 mL of water sample was collected in a bottle, fixed by 37-40% formaldehyde solution, and then stored in the laboratory for 48 h for quantitative phytoplankton analyses. Using a Sedgwick Rafter chamber, 1 mL of each concentrate was counted under a phase-contrast microscope at 400x magnification. The identification of phytoplankton was referenced to assure accurate species determination (Hu et al., 2006), which was done in the Key Laboratory for Information Systems of Mountainous Areas and the Protection of the Ecological Environment of Guizhou Province, Guizhou Normal University.

3. Results and discussion

3.1. Groundwater systems in the Wuming Basin

The basin is comprised of strata from Devonian to Cretaceous. The extensive development of strata from Devonian to upper Triassic is mainly composed of carbonate rocks. Sandstone is only distributed in upper Permian with a depth of 30 m, which is hard to constitute as a regional aquitard. Middle Triassic to Cretaceous period is mostly composed of clastic rocks, which have limited distribution area in the basin. The wide distribution of soluble rocks in the basin, combined with the influx of allogenic water from the surrounding mountainous areas, provides basic conditions for karst formation. The formation of karst groundwater systems is thus controlled together by topography, hydrodynamic conditions, geological structure, and karst development.

Topographically, the northern part of the basin is a peak-forest plain (Fenglin), the central part where the Najia syncline core located is dominated by gentle, sloping hills, and the rest are isolated peaks and hilly valleys (Fig.1). Except for a small number of karst peaks with steep terrain, most areas have flat terrain. Valleys and plains are mostly covered by Quaternary sediment. Due to the relatively flat terrain, the hydraulic gradient of groundwater is generally small, ranging from 1.5-3‰, and locally up to 5-6‰. Therefore, the groundwater hydrodynamic conditions are relatively slow, and there is no favorable condition for strong erosion, which is not conducive to the development of big karst conduits.

In the central part of the basin, the lithology varies complexity. Except for carbonate rock, shale intercalated with argillaceous limestone in middle Triassic is distributed in the core of the Najia syncline, followed by banded aquitard formed by tuff in lower Triassic and siliceous rock and coal bed in upper Permian. Due to the impure lithology of carbonate rocks or the existence of relatively aquitard, the development of karst is restricted; therefore, the karst development in this region is dominated by network-shaped caves and fissures and small-scale karst conduits are developed in local areas.

Within the Lingshui Spring catchment, the main geological structures are the Najia syncline and Wuming normal fault. Impure carbonate rocks in the Middle Triassic age at the axis of the Najia syncline are thick in the center and are relatively thin, or even partially missing, on both sides. The two wings of Najia syncline form a superimposed aquitard. The Wuming normal fault destroys the integrity of the Najia syncline, resulting in the groundwater appearing as concentrated runoff in the southeast of the syncline. Therefore, the Najia syncline water storage structure and Wuming normal fault control the formation of Lingshui Spring. On the whole, groundwater converges towards the middle of the Najia syncline from both sides, then flows southward. At the southeastern end of the syncline, groundwater collects together and finally meets with the fault at the southeast end of the Najia syncline, emerging to the surface in the form of karst springs.

3.2. Transformation patterns of groundwater and surface water

The karst groundwater in the basin is mainly recharged by rainfall, in addition to the recharge of fissure water from surrounding non-karst areas, and the lateral recharge of river water, etc. Groundwater generally flows from the north and south to the middle and the Youjiang river area flows to the west. Most of the karst groundwater is discharged to the surface by way of underground river outlets and karst springs, and a small part flows out of the surface through karst window, then flows into Wuming River and finally into Youjiang River.

The interaction of groundwater and surface occurs along the river valley. When groundwater is discharged into the river in a dispersed manner, the interaction takes place through small karst conduits. Under this circumstance, the interaction of GW-SW represents in the replenishment of groundwater to river water, and the short-term backflow of river water to the groundwater system (Guo et al., 2020). The landform of the Wuming Basin is flat. Except for some isolated peaks, the amplitude of the ground undulations in the rest of the region does not exceed 20 meters and the slope is very gentle. In addition, the horizontal permeability of the rock is high, and the speed of groundwater movement is basically determined by the hydraulic slope. Under a slight hydraulic gradient, the movement of groundwater near the valley is slow. And the alternation and cycle of groundwater occurs in area close to the water table, where the speed of the water circulation decreases rapidly as it goes down.

In the basin, the depth of river cut is generally between 10-20 meters, which is much smaller than the thickness of the aquifer. The amount of groundwater discharged into the river valley throughout the entire river reach may not be large. The lithology of the aquifer in the basin is uniform carbonates. Comparative studies of the region show the karst development of this type of river valley is generally strong, deep, and easy to develop, with often deep karst features. The saturated zones usually form integrated aquifers and may have intersecting karst conduits. In this case, groundwater mainly discharges to river valleys through the regional deep circulation conduits and enters under hydraulic pressure caused by depth or higher elevations.

Wuming River is the largest river in the basin, with the drainage area accounting for 90% of the total area. The river flows from east to west in the basin. Groundwater discharges into the river in the form of springs and comprise a major feature of the Wuming Basin. There are many karst conduit outlets along the river. The amount of groundwater recharge and the amount of spring water that each river receives is related to the recharge of the aquifer through which the river passes. In areas with high water abundance, rivers receive more groundwater recharge, and vice versa (Tab. 2).

Table 2 The quantity and flow of the river receiving spring water supply

Main stream	Tributary	Length of river (km)	Number of springs	Spring flow (l/s)
Xijiang	Jianjiang River	-	9	277.9
	Fucheng River	59	3	165.8
	Xianhu River	77	1	255
	Xijiang Main River	-	0	0
Xiangshan River	Luobo River	-	1	207.6
	Xiangshan River	71	1	350
Wuming River	Luoxu River	49	0	0
	Wuming main River	-	10	2801.9

In addition to the two main ways that the groundwater on both sides of the river recharges the river and the river seepage recharges the groundwater, there are also several other patterns of GW-SW interaction in this karst water system. In the recharge area, if allogenic water exits upstream in the system, SW and GW interaction will occur in sinkholes. In runoff areas, GW and SW may interact in sinkholes or karst windows during runoff periods of infiltration. In discharge areas, when karst groundwater emerges in the surface by way of a spring or resurging underground river, groundwater flows into river during low water conditions. However, in high water conditions when flooding occurs, the water level of the river rises rapidly, and the river can be elevated in level and reverse into the spring or groundwater outlet (Guo et al., 2019; Kipper 2019), and even enter the karst aquifer under hydraulic pressure through the conduits (Albéric, P., 2004).

3.3. Formation, concept, and classification of karst cave hyporheic zone

Considering common characteristics of conduit flow in southern China's karst areas, the hyporheic zone herein was then defined as karst cave hyporheic zone (KCHZ), which means the place or area where conduit flow interacts with other types of water bodies. Since there is frequent interaction of groundwater and surface water in karst regions and these interactions will improve/worsen the aquatic environment, there is a need to examine the uniqueness of these interactions as defined in the KCHZ. Groundwater in karst aquifers generally exhibits concentrated discharge through conduits or fractures. Karst springs are often located in river hyporheic zones. The hydrodynamic force in conduit flow changes dramatically from the low-flow period to the high-flow period. River flooding will result in flow interaction seasonally, especially during significant storms. In addition, the hyporheic zone may expand to include parts of the phreatic zone of the aquifer along conduit or expand towards the deeper aquifer and ripariann zone. In summary, the range of karst hyporheic zones is broader than that of non-karst hyporheic zones.

Karst groundwater-surface water interactions are not limited to river banks, but also occur along karst conduits in the watershed. In a typical karst groundwater system, in addition to the effects of interactions of GW/SW in the outlets of springs, allogenic water from upstream clastic regions are converted to karst conduit flow through sinkholes, and these sinkholes can also constitute an environmental gradient transition zone from surface regions with abundant heat and light to underground cool and dark regions. When groundwater is discharged in a concentrated manner as spring water, it forms a transition zone at the spring outlet from constant conditions of temperature, darkness, and a nutrient-deficient environment to a variable-temperature, bright, and nutrient-rich environment. Along the runoff paths, conduit flows may be exposed on the surface through karst windows. At the karst window, because the temperature, pH, and DO between the upper water layer and the lower water layer are different, a hyporheic zone may occur when upper and lower water layers interacts.

Generally speaking, the karst groundwater system contains relatively independent water catchment units, with clear inlets, windows that allow for overflow pressure regulation, and outlets with concentrated discharge. The inlet is usually the starting point at which allogenic water (rivers) enter the karst conduit via sinkholes. Particulate matter carried by allogenic streams is deposited in sinkholes and carbon dioxide degassing of the water results in abundant geochemical deposits. This forms a nutrient-rich cave environment in which multiple media co-exist. At these sinking streams, river water and karst groundwater mix in sinkholes. In addition, sinkholes themselves feature significantly large underground space and abundant sources of organic and detrital materials, which provide conditions for biogeochemical effects and biological activities, and promote nutrient migration and conversion. Therefore, regions in which surface water in the drainage basin enters cave conduits can be referred to as sinkhole hyporheic zones.

After the concentrated discharge of the groundwater system, groundwater is converted to surface water, which is accompanied by water temperature and hydrochemical changes. During discharge, significant amounts of dissolved carbon dioxide in the water are released, causing the pH and DO to increase. When spring water is discharged to lakes, rivers, reservoirs, wetlands, or other surface water, this surface water may affect the spring outlet environment to form a hyporheic zone, which is referred to as a spring outlet hyporheic zone.

In regions with developed karst conduits, their surfaces often contain windows, estevelles, blue holes, shafts, and other karst morphology. Although these water bodies have small areas, they have large depths ranging from several meters to several hundred meters. The sectional morphology of such vertically-developed caves is irregular and has protective effects on aquatic ecosystems. The lower sections of water bodies such as karst windows are connected to karst conduits, although the chemical characteristics of these water bodies differ from those of conduits. In karst windows and other microenvironments, nutrient and energy exchange at the water-air interface can cause hydrochemical changes. In addition, this environment is also suitable for the growth of organisms. Hence, karst windows connect the surface and underground environments to form a region where many different flow interactions occur, an area that is known as a karst window hyporheic zone.

Karst conduits feature irregular geometric morphology. Due to the influence of structural and lithological factors, this morphology exhibits significant dominance in the planar direction. Blue holes, underground karst lakes, and tortuous conduits are formed at fracture intersections. Conduits also form an inverted siphon at locations with large hydrodynamic gradients, i.e. a U-shaped conduit. These irregular morphologies will form many reservoir spaces around the conduit. When water flows through such reservoir spaces, flow velocity is decreased or sediment is intercepted (Bonacci, 1987). The area in which the main runoff inside the conduit interacts with the still water body caused by the irregular conduit morphology is termed the karst conduit hyporheic zone.

Common characteristic of the above four hyporheic zones was conduit flow. We propose the concept that the hyporheic zone of karst systems that is dominated by conduit flow is a karst cave hyporheic zone. These definitions were used to determine the types of hyporheic zones existing in distinct karst water bodies in the Wuming Basin. For example, Lingshui is a combination of the spring outlet hyporheic zone and river hyporheic zone; Luobo, Qinzhu, and Sandong are spring outlet hyporheic zones; and the karst window in Dongfeng Farm is a karst window hyporheic zone (Fig. 2).

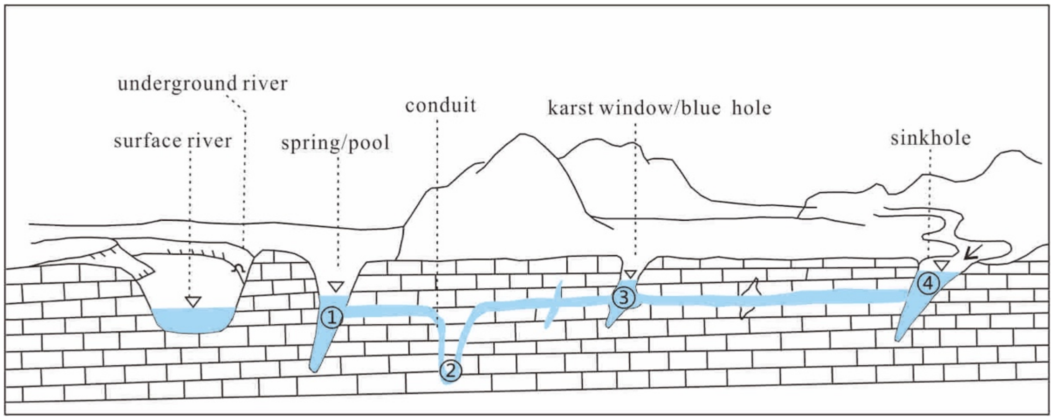

Fig. 2. Types of hyporheic zones in a karst groundwater system.

1. spring outlet hyporheic zone; karst conduit hyporheic zone; karst window hyporheic zone; sinkhole hyporheic zone

3.4. Water environment of the typical karst cave hyporheic zone

3.4.1. Spring outlet hyporheic zone

LB catchment is one of the biggest groundwater systems in the Wuming Basin. After LB Spring overflows to the surface, it runs for 50 m before converging into Luobo River (Fig. 3).

The LB spring is controlled by a compound syncline. The flowpath of the spring is 3.83 km, with two karst windows that intersect it. Water level in the dry season ranges from 3.7 to 10 meters. The water head difference is 20 m, with an average hydraulic slope of 5.2‰. The outlet of the spring is located in the middle of the valley, surrounded by isolated peaks, hills, and valleys, where the valley is relatively flat. After the groundwater is discharged, a 50-meters-long and 30-meter-wide lake is formed. The section of the spring outlet is funnel-shaped, reaching a depth of more than 100 m in some places. The outlet is a source of drinking water for the surrounding 35,000 residents.

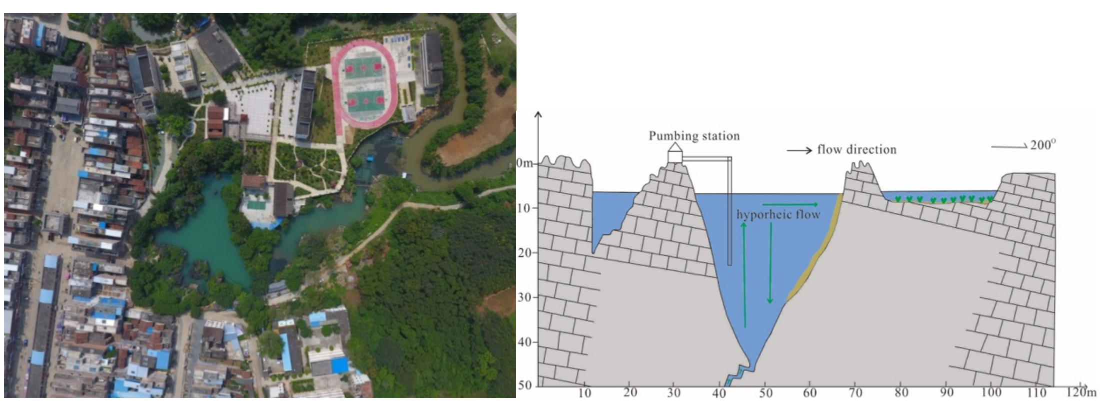

Fig. 3. View plan and cross-section of the Luobo Spring.

From the pathway of groundwater to river, water temperature decreases from 23.9 to 23.5°C at downstream, and DO decreases from 5.26 mg/l to 4.19 mg/l, and pH decreases from 7.29 to 7.24. The downstream trend of SEC is not consistent. Vertically in the water column, water temperature drops greatly from the surface to the bottom, and becomes stable at a depth of 10 m. SEC increases from the surface to the bottom. It rapidly increases at a depth of 20 m. At a depth of 100 m, SEC increases from 351 s/cm from the surface to 391 s/cm in the bottom (Fig. 4). This likely occurs from temperature effects as seen in Fig. 4.

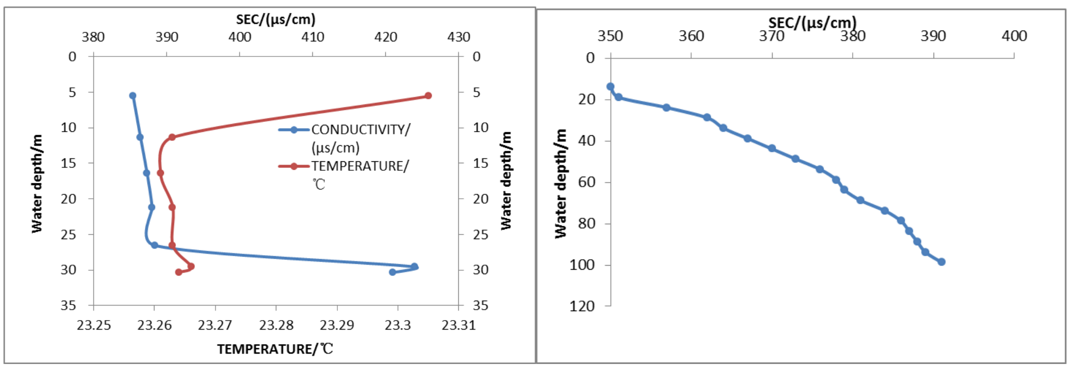

Fig. 4. Variation of SEC with water depth and temperature in LB.

There are 11 species of phytoplankton in the groundwater outlet (upstream) of LB, with a total abundance of 26.01 cells/0.1mL. The zooplankton has 12 species with abundance of 94.95 ind./L. While in the downstream area, the species of phytoplankton increase to 12, with an abundance of 35.21 cells/0.1mL, and species of zooplankton decrease to 10, with an abundance of 39.63 ind./L. This suggests that along the direction of water flow, both the species types and abundance of phytoplankton have an increasing trend, while the species types and abundance of zooplankton decrease.

Backflow of Luobo River into LB Spring never occurs, which means the surface river does not mix with the groundwater directly; however, the gradient of the system is represented at the spring outlet and it is found that fish or other aquatic organism can move between the two environments. Hence, LB Spring is classified as a typical spring outlet hyporheic zone.

Even the water column of QZ Spring and SD Spring are smaller than that of LB Spring, their karst development and hydrological conditions are similar. River backflow also never occurs in QZ and SD Spring. Therefore, they belong to the spring karst cave hyporheic zone. The difference lies in that the water depth of QZ Spring is only 0.5-1.5m, with no distinctly hydrochemical gradients in vertical direction. In addition, except for the conduit flow, surface runoff, overland flow, and interflow also exist in the QZ Spring, so the interaction of groundwater and other water is more complex. Most of water depth in SD Spring ranges from 1.0-1.5 m, but the deepest can be reached as 100 meters. The submerged plants in this spring are luxuriant, and the CO_2 degassing is remarkable, making it has a high hydrochemical gradients.

3.4.2. The combination of spring outlet hyporheic zone and river hyporheic zone

LS is the biggest spring in the Wuming Basin. LS is a spring group including 9 springs that outcrop at the south end of the syncline, forming a pool with an area of 29,300 m^2. The flow discharge is approximately 2–5 m^3/s. It flows downstream about 400 meters and joins Wuming River. One of the largest outlets, No.2, presents a conduit-like shape, with a length of 22 m and a width of 6 m (Fig.5).

At the spring outlets, groundwater is continuously drained from the aquifer, which is the nature of karst groundwater. After the groundwater is discharged by the spring group, it collects in the pool. Because of its large size and the spring run of about 400m before it flows into the Wuming River, a series of physical or chemical process occurs. During this process, CO_2 degases, and pH, water temperature, and dissolved oxygen rise, while SEC drops. Therefore, it is no longer pure groundwater, but begins to take on characteristics of surface water. The river that converges with the spring has very different physical-chemical properties and aquatic ecology from groundwater. Therefore, there is a transition zone between groundwater and river water that we classify as a spring outlet hyporheic zone.

Most of the year, groundwater replenishes the river water, but there are several floods every year that cause the Wuming River's water to flow back into Lingshui, and the water level of the pool rises by about 7-10 meters than usual. Although the time of river backflow is short, it not only changes the water chemical composition of the pool, but also brings a large amount of sediment to the pool, and the migration of aquatic organisms with the flood changes the water quality and ecosystem of the pool. It can be seen that LS also has the characteristic of river hyporheic zone. Therefore, LS is classified as a combined karst spring outlet and river hyporheic zone.

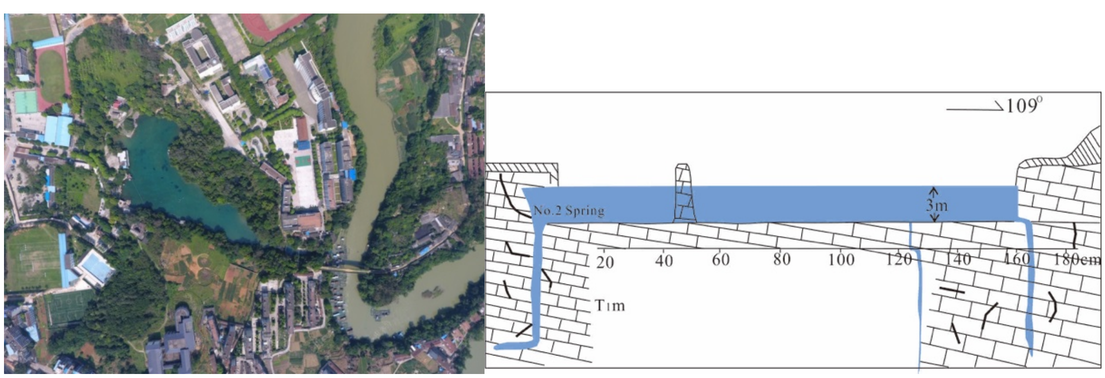

Fig.5. View plan and cross-section of the Lingshui Spring

Even though the water depth of LS ranges only from 1 to 3 m, there are still a certain physiochemical gradients vertical within the water column. Water temperature generally decreases from 0.2 m. The changes of SEC and DO with water depth both vary greatly (Guo and Jiang 2020). Changes of phytoplankton and zooplankton in LS similar to those in LB, but once the river reverses, the water chemistry will fluctuate for a short time, so the influence of river input is much greater than the water chemistry change of the spring itself.

3.4.3. Karst window hyporheic zone

DF is a rare underground water system dominated by large karst conduits in the Wuming Basin. The underground river has a length of 3.7 km with three karst windows along the flowpath. The groundwater level ranges from 3 to 11 m in dry seasons. The biggest karst window, which is the study objective herein, is located at the foot of an isolated peak. The karst window has a total length of 50 m and width ranges from 4 to 10 m (Fig.6). The funnel-shape section of the karst window has a detectable depth of 70 m and an annual variation of water level of about 3 m, with a cave at the bottom extending southward. The karst window provides drinking water for the surrounding 2,800 residents.

The karst window is about 1 km far away from the river. At the bottom, the karst window is directly recharged by the underground river, and its water level changes are mainly controlled by the underground river. Because the karst window is close to the river, and the drainage of the underground river is affected by the water level of the river, the water level change of the karst window is also related to the river. Although the direct interaction of karst window and river rarely happens, it does not rule out that fish and other aquatic organisms can migrate between the two environments.

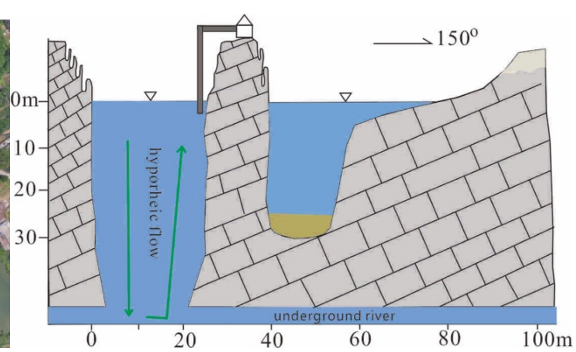

Fig. 6. View plan and cross-section of the Dongfeng Spring.

Observations found that the water flow in the karst window has obvious stratification, with poor fluidity in the surface and strong flow in the bottom. Once the water is pumped, there will be an interaction between the upper water and the lower water. The physiochemical monitoring shows water temperature, pH, and DO all decrease continuously and significantly with the increase of water depth, while the SEC increases with the water depth (Fig.7).

The phytoplankton and zooplankton in the upper, middle, and lower layer of the karst window hyporheic zone of DF show a trend of decreasing species and abundance from the surface to lower depths (Tab.3).

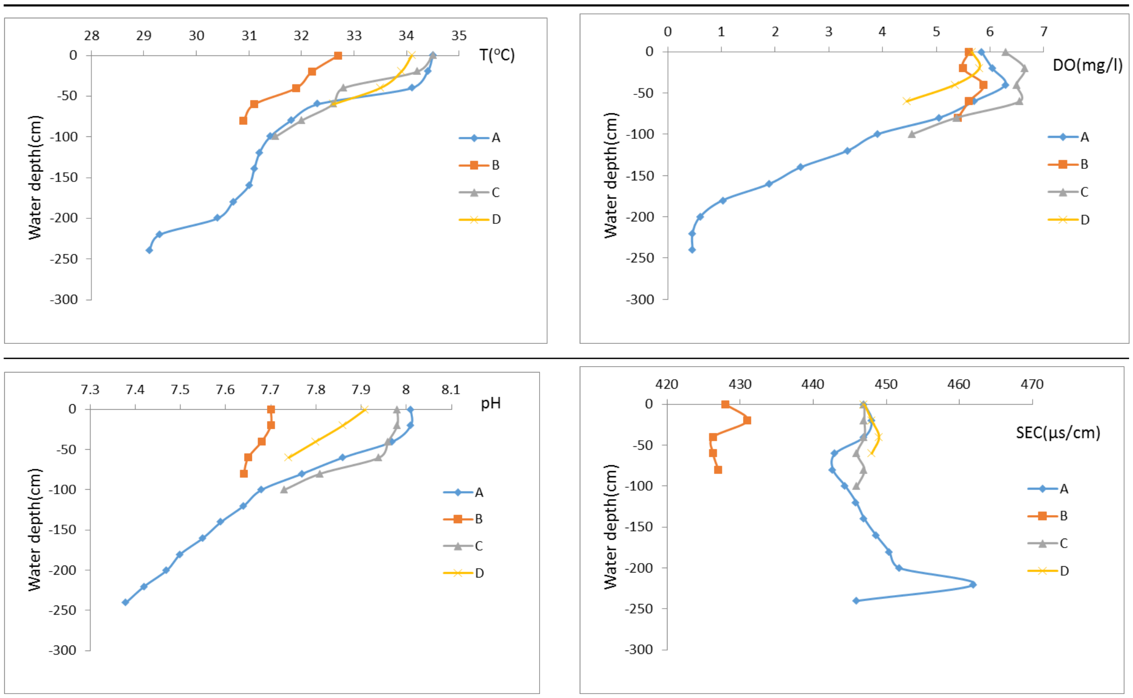

Fig. 7. Physiochemical parameters of water in DF Spring.

Table 3 Comparison of plankton in different layer of the karst window in DF.

Location		Species	Abundance (cells/0.1mL, ind./L)
Upper layer	phytoplankton	23	257.96
	zooplankton	12	330.59
Middle layer	phytoplankton	15	131.70
	zooplankton	12	213.57
Lower layer	phytoplankton	17	130.13
	zooplankton	8	155.95

Because the physiochemical properties and biology of the upper, middle, and lower layer waters in the karst window are quite different, when the water flow changes, such as pumping period, it will cause the hydrological exchange between the upper and lower layer of water. This is the water interactive characteristic of the karst window hyporheic zone.

3.5. Function of karst cave hyporheic zone and the affecting factors

The effects and processes occurring in the hyporheic zone play an important role in maintaining the ecosystem of the water body and improving the water environment. The significance of hypoheic zone lies in the active environment constructed by the biogeochemical gradient and its pollutant attenuation function (Gandy et al., 2007). Similarly, the meaning of karst cave hyporheic zone refers to the effect that its environmental function plays. Research shows that environmental functions include many aspects, among which hydrological functions, hydrochemical functions, and aquatic biological functions are the most basic and the basis for other functions (Science Report, 2005).

Hydrological function refers to the ability of hydrological exchange, including physical effect such as dilution, mixing, scouring, and deposition caused by hydrodynamic forces (Boulton et al., 1998; Environment Agency, 2005). The stronger the hydrodynamic force, the more obvious these physical effects, and the stronger the hydrological function. The hydrodynamic forces of the cave hyporheic zone mainly refer to groundwater flow characterized by conduit flow and the fluctuations of rivers and pools. In aquifers, the hydrodynamic force of groundwater is influenced by the rainfall recharge. The hydrodynamic force of the spring is not only affected by the aquifer, but also related to river dynamics. The performance is most obvious when the spring outlet hyporheic zone and the river hyporheic zone are combined.

Affected by groundwater exploitation and land use change, springs in the aquifer have a tendency of decreasing flow. The current flow of Lingshui Spring has decreased by 25-50% compared with the 1980s. Most of the other springs in the basin have similar conditions. Among the surveyed 45 springs, 37 have a decrease in flow, with decrease rates of 3% to 97% (Guo et al., 2015). Observations of the four springs (LB, DF, QZ, and SD) show that, in comparing the two phases of 2010-2013 and 2015-2017, the flow velocity in the dry or normal water period has a tendency to decrease and slow down. Therefore, the hydrological function of spring outlet hyporheic zone has a tendency to weaken.

Hydrochemical function refers to the ability to promote the degradation and transformation of pollutants and the ability to provide nutrients for aquatic organisms by hyporheic flow (Environment Agency, 2005; 2009). The function of hydrochemistry is represented by the spatial variations of water chemistry in the cave hyporheic zone. Although the pollution load carried by the karst water system has an increasing trend, comparing the hydrochemistry data of spring outlet and the hyporheic zone, it is found that the NO_3^-, SO_4^{2-}, and Cl^- concentrations have decreased by 6.5%-90.9%, 2.1%-18.1%, and 0.3%-4.05%, respectively, indicating that the hydrochemistry function of the hyporheic zone is still working (Guo 2017).

Ecological function in the karst cave hyporheic zone refers to the role of organisms in maintaining the health of water bodies (Environment Agency, 2009; Hayashi and Rosenberry, 2002), which is mainly reflected by the relationship between the community structure of aquatic ecosystems and the water environment. The community structure and richness index of plankton and microorganisms in the five hyporheic zones were compared and suggest that the functions of aquatic organisms in the hyporheic zones are degrading. The weakening of hydrological function is responsible for the degeneration of environmental function in the hyporheic zone.

In the past ten years, followed by the increase of groundwater extraction in the basin, the flow of springs has been decreasing. Changes in land use types, such as eucalyptus planting and developing fruit and economic crops on wasteland and sloping farmland, greatly increase the amount of groundwater extraction. The decrease in the flow of karst springs and the slowing of the flow velocity increase the frequency of river water flowing back into springs, resulting in surface water intrusion into groundwater. In addition, the slowing of the flow rate will also cause the enhancement of sedimentation, which is manifested as the thickening of the sediments at the spring outlet and the expansion of the distribution of sediments. Large-scale planting of eucalyptus, fruits, and economic crops has caused the increased application of pesticides and fertilizers, so the load of pollutants in the watershed is also increasing. These factors will significantly change or destroy the function of the hyporheic zone and degrade the environmental function of the hyporheic zone. The superposition of climate change will also cause unpredictable changes to the environmental functions of the hyporheic zone.

4. Conclusions and implications

The river hyporheic zone refers to the mixing zone of surface water and groundwater in the river bed. In this case, the surface water is the center, where groundwater accounts for less than 10%. However, in karst areas, the hyporheic zone is not limited to the river bed and banks. At spring outlets, karst windows, and sinkholes, due to the mixing of groundwater and other types of water, hyporheic zones may exist. Under this circumstance, groundwater is primary, while the percentage of surface water and other types of water is small. Once the backflow of a surface river into the spring happens, the mixing of groundwater and surface water is short but violent, and a special spring outlet hyporheic zone is formed.

The formation of a cave hyporheic zone is related to the degree of karst development. Defined by common characteristics of conduit flow in China Southern karst areas, the hyporheic zone in this area is defined as a karst cave hyporheic zone, which means the place or area where conduit flow interacts with other types of water bodies. According to the interaction pattern of groundwater and other types of water, the KCHZ is divided into the spring outlet hyporheic zone, karst conduit hyporheic zone, karst window hyporheic zone, and sinkhole hyporheic zone. There are at least two types of flow in the KCHZ. Except for karst conduit flow, the other types of flow include allogenic water in the upstream, rivers in the downstream, surface runoff, interflow, water in the conduit transition zone, and the water in upper layer of a blue hole or karst window.

Affected by the increased intensity of human interference, the environmental functions of the karst cave hyporheic zone are easily degraded. The decrease of groundwater replenishment and the increase of other types of water bodies are the main reasons for the degradation of the hyporheic zone. It is manifested as the disappearance of submerged plants, the increase of plankton, and the phenomenon that special microorganisms occupy the dominant species. The problem of environmental degradation of karst spring environments should be solved by concurrent management of groundwater and other types of water bodies, especially surface rivers. The solution to this problem requires attention to the concept of the karst hyporheic zone types and their functions as defined in this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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