Transformation process of five water in epikarst zone: a case study in subtropical karst area

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Abstract
Five water stands for five form existence models of water. In karst area, five water means precipitation, groundwater, evapotranspiration water, soil water, and overland flow. The complicated water-bearing hydrogeological media and the inhomogeneous water storage structure lead to low efficiency of water utilization. To reveal intricate water resources transformation in karst areas, a typical epikarst zone was selected. The five water and their conversion processes were studied and the transformation models were built based on the long-term positioning observations. The results show that (1) overland flow can be generated when precipitation reaches 6 mm and lasts for 6 h. Under light and moderate rainfall (LMR) conditions, less than 6% of the precipitation is converted to overland flow. Under heavy rainfall and rainstorm (HRR) conditions, the conversion of precipitation into overland flow in about 3.5–6%. (2) Under LMR conditions, the conversion rate of precipitation to vegetation water, soil water and groundwater was 2–3.5%, 40–60% and 25–35%, and the conversion rate under HRR conditions was 1.5–2.2%, 25–30% and 32–50%. (3) The proportion of different levels precipitation was transformed to soil water is 20–70%. (4) The conversion rate of groundwater and karst fissure water for LMR conditions are 8–15% and 10–15%, and that for HRR is 15–20% and 40–50%. (5) The proportions of different degrees of precipitation transformed into vegetation transpiration and evaporation water are 1.5–3.5% and 6–9%, respectively. (6) Generally, <4% of the precipitation is converted into overland flow, 20–70% into soil water, 25–50% into karst groundwater, and 1–10% into evaporative water.

Keywords Five water · Epikarst zone · Water resource transformation · Groundwater · Surface water

Introduction
Water is the critical factor that constrains human survival and socio-economic development in karst areas (Apollonio et al. 2018; Mesnil et al. 2020Castro 2020). The karst features such as pipes, caves, cavities, sink holes and grooves lead to frequent exchange of surface water and groundwater, which constructed an open system in epikarst zone. The difficulty of getting storage between surface water and groundwater is due to the complex and variable hydrological structure of open systems. In addition, the warm and humid climate of subtropic karst areas, abundant rainfall resources and large amount of carbonate rocks together form unique hydrological conditions (Fahad et al. 2021a, b). Due to recent economic development, land use patterns in karst areas have changed dramatically, and climatic conditions have been altered by human activities. The changes in land use and climate in karst areas can directly affect plant biodiversity and even alter the hydrological cycle at the small watershed scale (Sönmez et al. 2021a, b; Fahad et al. 2019, 2021a, b). The most direct manifestations of karst areas are severe soil erosion, droughts and floods. This is the main reason for the frequent occurrence of water resources problems in karst areas. (Zverev and Kostikova 2016).

Epikarst zone is a natural water storage medium for the surface part of the strongly karst envelope in karst mountainous
areas (Soglio et al. 2020; Fidelibus et al. 2017). Epikarst zone is an important critical zone for water resources transformation in the karst area (Khan et al. 2021; Valipour et al. 2021; Florea et al. 2021). And it is also an important carrier for water resources and ecological environment. In recent years, with the global climate change, the water resources problems in karst areas become more and more prominent. The transformation process of five water in epikarst zone of karst area refers to the mutual transformation process among precipitation, karst groundwater, evapotranspiration water, soil water and overland flow. Among them, karst groundwater includes surface karst water and groundwater. In addition, evaporation water includes surface evaporation water and vegetation transpiration water. In the transformation process of five water, part of the precipitation can be directly transformed into surface karst water, soil water, overland flow, groundwater, etc. (Qi et al. 2012). Precipitation can also be indirectly converted to groundwater indirectly through surface karst water (Jiang 2009). At the same time, precipitation can be absorbed by vegetation, and finally converted to precipitation again by surface evaporation and vegetation transpiration (Carrière et al. 2019).

The current research on water resources is focusing on the three waters transformation, i.e. including overland flow, groundwater and precipitation (Hartmann 2015). Wang (2006) proposed corresponding rational water resources utilization on measures in the study of the three waters transformation process in the southwest karst mountains. Zhao (2015) analyzed the influencing factors of water resources transformation processes in karst areas. Jiang (2009) conducted various studies on water resources transformation and hydrological dynamics of the epikarst zone. These related studies revolved the macroscopic laws of overland flow, groundwater and precipitation. However, overland flow, soil water and evapotranspiration in the epikarst zone are also important for water balance. The research on the epikarst zone focused on the monitoring study of hydrological and hydrodynamic processes and related research methods. However, the specific processes and laws of water resource transformation in different types of karst areas have rarely been studied by scholars.

The current research on the mechanism and amount of transformation of pentahydrate still has certain difficulties and shortcomings. For example, the blurred boundaries of different types of water in karst areas, the complex structure of water storage and the complicated and variable transformation process of five waters. In this study, multiple hydrological monitoring devices and monitoring methods are used to elucidate the transformation process of water resources of five water. And the transformation process and response law of water resources in karst areas was also revealed. The efficiency of water use in karst areas can be effectively enhanced by the conclusions of this study.

Materials and methods

Study area

The research site is located in Huixian Town, South of China, where distributed most typical karstic peaks and forests landscape with unique hydrogeological conditions and strong karst development. The lithology of the experimental site is pure-strong carbonate and strong water-bearing rock group, and the stratum is Upper Devonian Rongxian Group (D3r) with light gray pure carbonate rocks (Fig. 1). The experimental site is surrounded by a large underground river system in the Huixian karst wetland. The study area has strong karst development and frequent exchange of groundwater and surface water. Because of the rapid response of overland flow and groundwater to precipitation, the study area is suitable for the study of the transformation process of five water and the response process of different types of water resources to precipitation. The experimental site is located near the northern part of the tectonic basin, which is the core area of Huixian karst wetlands. This tectonic type is the basis of strong karst action and facilitates the formation of different types of caves, karst pipes and karst fissures.

The geophysical exploration (high-density electrical method) was conducted in the experimental site to study the tectonic and karst development of the epikarst zone (Fig. 2). The results show that the surface (0–4 m) resistivity of the epikarst zone is low (<163 Ω), while the resistivity in the middle and lower part of the epikarst zone is high (1279–10,000 Ω). The resistivity data indicate that the surface layer (0–4 m) of the epikarst zone is covered by soil and the karst fissures filled by soil. In the Lower and middle parts of the epikarst zone (>4 m) are rocky or have karst fractures that are not filled with soil. It is a rainy and a typical of subtropical monsoon climate here. The total annual rainfall increased from 1987 to 2019, and the average annual temperature ranged of 18.5–19.5, high rainfall and temperature are the driving factor of karst action. In addition, the average annual temperature shows a small increasing trend ranged 1–2 (Fig. 3).

Vegetation growth in the epikarst zone of the study area is dense (Fig. 4). However, due to various factors such as pool soil, high temperature and complex topography, the vegetation is mainly shrubs and scrub with only a few dwarf trees, such as Celtis sinensis, Xylosma racemosum, Sapindus sebiferum. The main vegetation species include Sageretia thea, Bauhinia championii, Zanthoxylum, Pyracantha fortuneana, A. trewiioides, Vitex negundo, Albizia julibrissin, Rosa cymosa and Celtis sinensis, and the dominant species are Sageretia thea and championii (Table 1). Although the vegetation in the study area is relatively dwarfed, considering
the dense and abundant growth of shrubs, the transpiration is also a very important part of water conversion.

**Data collection**

Due to the complexity and variability of the transformation of different types of water resources in karst areas, the data in this study were mainly obtained by setting up hydrological
and meteorological stations as well as actual measurement data. Many different types of dynamic monitoring devices were established to achieve quantitative analysis of different types of water resources. The experimental devices include meteorological stations, overland flow dynamic observation station, soil water dynamic observation devices, vegetation transpiration water observation devices, cave drip water dynamic observation devices, etc.

Data analysis

Precipitation

Precipitation data were collected from meteorological stations in the study area. The different levels of precipitation

Table 1 Main vegetation types of the experimental sites

| Classification | Scientific Name                  | Distribution type |
|----------------|----------------------------------|-------------------|
| Shrub          | Sageretia thea (Osbeck) Johnst   | Dominant species  |
|                | Bauhinia championii (Benth.)     | Dominant species  |
|                | Pyracantha fortuneana (Maxim.)   | Common species    |
|                | Li                               | Common species    |
|                | Rosa cymosa Tratt                | Common species    |
|                | Paliurus ramosissimus (Lour.)     | Common species    |
| Dwarf tree     | Xylosma racemosum (Sieb. et Zucc.) Miq | Common species |
|                | Sapian sebiferum (L.) Roxb       | Common species    |
|                | Celtis sinensis Pers             | Common species    |
|                | Zanthoxylum bungeanum Maxim      | Common species    |
were classified and analyzed by the classification criteria of the China Meteorological Administration (Table 2).

**Soil water**

Soil water data were collected from the soil water dynamic observation stations and actual measurements in the mountain and depression settings in the study area. The soil water content and variations at different soil depths were collected by the water dynamic observation stations. During the actual measurement, the area, rock exposure rate and average soil depth are measured and the total soil volume is calculated from these parameters to obtain the soil water content. One of the soil volume calculation equations is as follows:

$$\text{QS} = \text{MHC},$$

where QS is the total soil volume ($m^3$), $M$ is the area of the study area (8507 $m^2$), $C$ is the soil cover (%), and $H$ is the average soil thickness (m).

**Overland flow**

The data related to overland flow and dynamic changes under different rainfall levels were collected by the overland flow monitoring device. The overland flow data were calculated by the following formula (Li et al. 2006; Gao et al. 2018).

$$Q = M b \left[ \left( 2g^{0.2} \right) H^{1.5} \right],$$

$$M = \left( 0.45 + \frac{0.021}{H} \right) \left[ 1 + \frac{0.55H^2}{(H + P)^2} \right],$$

where $b$ is the weir width, $H$ is the head on the weir (m), $P$ is the weir wall height (m), and $Q$ is the flow rate ($m^3/s$).

**Karst groundwater**

Groundwater data were collected from groundwater observation stations (groundwater data monitoring stations are set at the entrance and exit of underground rivers). Karst fissure water data were obtained by cave drip observation stations and field surveys, which include fissure survey of the study area profile and fissure soil filling rate survey. Although there are some small pipes and fissures in the study area, groundwater entrances and exits are the most important channels for groundwater exchange. Because the missed water in pipes and fissures is small and negligible, the flow variation between the inlet and outlet was used to calculated the groundwater volume.

**Evaporated water**

Evaporated water data were collected from the meteorological stations. Specific evaporation data were obtained by the daily evaporation precipitation data and the conversion rate of evaporation to precipitation. Vegetation transpired water data were collected from the vegetation transpired water devices and field surveys, which included surveying the vegetation species and quantity. In addition, the dominant species in the study area were determined under field investigation.

**Source of error**

In the study, the sources of experimental errors were mainly from monitoring instrument errors and unavoidable errors. Among them, the monitoring instrument error mainly refers to the existence of certain limitations and errors in current hydrological monitoring methods and equipment, so it leads to a small degree of error in the data in this study. In addition, the unavoidable error refers to the complex structure of the Epikarst zone, and the current monitoring methods and research methods cannot be generalized, so the research methods used in this study have a small degree of error in order to ensure the scientificity and reliability of the five waters in this study.

**Results**

**Overland flow**

**Conditions for the generation of overland flow**

In this study, the overland flow data with different levels of precipitation were selected for analysis. As shown in Fig. 5, the precipitation and the overland flow show good linear relationship. When the precipitation increases, the overland flow gradually increases. Overland flow percentages of the selected several rainfalls are 0.005%, 0.89%, 1.44%, 2.29%, 3.8%, 3.34%, 3.81%, respectively. The amount of precipitation that is converted into overland flow volume for different levels of precipitation (MR, HR, and RS) is approximately between 1 and 4%. Although the conversion rate is low, the

| Degree of rainfall   | Rainfall abbreviation | Rainfall (24 h)  |
|----------------------|-----------------------|------------------|
| Light rain           | LR                    | 0–9.9 mm         |
| Moderate rain        | MR                    | 10.0–24.9 mm     |
| Heavy rain           | HR                    | 25.0–49.9 mm     |
| Rainstorm            | RS                    | 50.0–99.9 mm     |
| Above rainstorm      | RS                    | > 100 mm         |
amount converted to overland flow is still significant when the precipitation extent is high or the precipitation duration is long. In addition, the overland flow can only be generated when the precipitation is greater than 350 m$^3$ (Fig. 5). After calculation, when the rainfall time is 1 h and the precipitation amount is 6 mm or more, the condition of overland flow generation is satisfied. In other words, overland flow can be generated only under the condition of MR in general. A overland flow cannot be generated when the precipitation is small or persistent light rain.

Under LMR conditions, the most precipitation was converted into vegetation water, soil water and groundwater of 2–3.5%, 40–60% and 25–35%, respectively. The conversion rate of precipitation into overland flow is low, about 0–6%. Under HR conditions, the amount of overland flow generated increases, but the conversion rate is basically unchanged, between about 3.5–6%. However, the conversion rate for vegetation water, soil water and groundwater are 1.5–2.2%, 25–30% and 32–50%, respectively.

The response process of overland flow to different degrees of precipitation

The increase (and attenuation) of overland flow of LMR, HR, RS is consistent with the change pattern of precipitation (Fig. 6). In the early stage of precipitation, overland flow and precipitation show a trend of non-synchronous changes. In the late stage of precipitation, overland flow and precipitation show the trend of synchronous changes. Under LMR conditions, when the amount of precipitation no longer increases significantly or tends to stabilize, the amount of overland flow production tends to 0. Under HRR conditions, the amount of precipitation is higher than that of LMR. However, when the amount of precipitation stabilizes or decreases, the overland flow also shows a trend of stabilization or decrease.

This indicates that there is a different degree of delaying effect in the response of overland flow to different degrees of precipitation. Meanwhile, there is a significant variability in the delayed effect time for different levels of precipitation. Under LMR conditions, the delay time can last to 30 min (Fig. 6a). Under HR conditions, the duration of delay effect is lower than that of LMR, and the delay time is about 20 min (Fig. 6b). The delay time of RS is shorter compared with that of LMR and HR, and the delay time is about 10–20 min (Fig. 6c).

Soil water

Response process of soil water to precipitation

In this study, the surface soil cover area and rock exposure rate were investigated. The results showed that the soil was brown limestone, and the rock exposure rate was about 52%. In the study area, the total soil cover area was 4083 m$^2$, and the average soil thickness was 42.4 m. At the same time, the total soil volume was 1731 m$^3$ calculated by the calculation formula in the above research method.

The soil water (at 20 cm depth) in LR and MR conditions showed a significant increasing trend with the increase of precipitation, while the soil water (at 30 cm and 50 cm depth) was basically unchanged (Fig. 7a). Under HR condition (Fig. 7b), soil water (at 20 cm, 30 cm and 50 cm depth) showed a increasing trend with the increase of precipitation. This trend was more pronounced in the 20 cm depth of the soil. Under RS conditions (Fig. 7c), soil water (at 20 cm, 30 cm and 50 cm depths) showed a trend of more substantial increase. This indicates that the response process of deep soil water (> 30 cm) to precipitation in the epikarst zone is significantly delayed, while the response process of surface soil water (0–20 cm) to precipitation is rapid.

Conversion of soil water

The conversion of soil water is higher for LMR condition with the conversion rate of 40–70% (Table 3). While the conversion of soil water is lower for HRR condition than LMR condition with the conversion rate of 20–30%. The conversion of soil water shows a decreasing trend with the increase of rainfall degree. It shows that in LMR condition, most of the precipitation is mainly absorbed by soil and converted into soil water. Under HRR condition, only a small part of precipitation is loaded into soil water, and most of the precipitation is converted into karst fissure water, groundwater and evaporated water, etc. It is determined by the specific hydrogeological conditions of karst area. Due to the high rate of rock exposure and the development of karst...
fissures and pipes, precipitation in RS conditions is directly converted to groundwater in the form of surface karst water, or surface karst springs are formed.

**Evapotranspiration water**

**Vegetation transpiration water**

1. Vegetation transpiration intensity: The dominant species in the study area have been summarized in the study area profile above. In general, the leaves and vegetation height of Dwarf trees such as *Xylosma racemosum*, *Celtis sinensis* and *Sapium sebiferum* were higher than those of shrubs such as *Bauhinia championii* and *Sageretia thea* in the study area. The transpiration intensity and water loss of the vegetation was measured by the vegetation saprophytic density. The results showed that the order of transpiration intensity of common species of vegetation is *Bauhinia championii* > *Sageretia thea* > *Sapium sebiferum* > *Paliurus ramosissimus* > *Pyracantha fortuneana* > *Xylosma racemosum* > *Celtis sinensis* (Fig. 8).

2. Water loss by vegetation transpiration: The results showed that the volume of different degrees of precipitation transformed into vegetation transpiration water was small (Table 4). The proportion of precipitation transformed into vegetation transpiration water was larger in LMR condition (about 2–3.5%). While the proportion of rainfall transformed into whole transpiration water in HRR condition was lower than that of LMR, about 1.5–2.5%.

This corroborates with the soil water conversion results. In the soil water conversion pattern, the conversion rate of soil water is higher in LMR condition. Vegetation roots can
absorb surface soil water and thus convert it to their own transpiration and respiration consumption. Although the conversion rate of precipitation into soil water is low in HRR condition, the conversion amount is higher than that in LMR condition. It shows that the pattern of conversion of different levels of precipitation to soil water is similar to the pattern of conversion to vegetation transpiration water.

**Evaporated water**

In this study, evaporation data for one hydrological year from June 2019 to June 2020 in the study area were selected for analysis (Fig. 9). The results showed that the rate of evaporation to rainfall from June 2019 to June 2020 were 0.23, 0.19, 1.94, 5.3, 1.68, 3.22, 1.86, 0.58, 0.25, 0.40, 0.37, 0.37, and the rates were negatively correlated with the mean temperature. As shown in the following table (Table 5), the rates of precipitation to evapotranspiration for these six rainfall events were 11.57, 11.48, 13.66, 14.04, 14.92, and 17.86, respectively. The proportion of precipitation lost as surface evaporation was about 7–9% for the LMR cases, and 6–7.5% for the HRR cases.

**Karst groundwater**

**Karst fissure water**

1. Fissure development: After calculation, the average soil filling rate of the fissure is 1.89%, the average fissure percentage is 11.45%. For the epikarst zone, the total volume of is 301998 m³, and the volume of fissure-filled soil is 657 m³ (Table 6). Referring to the High-Density
physical sounding method, the development of these karst fissures is the key to the conversion of surface karst water into groundwater (Fig. 10).

2. Response process of karst fissure water to precipitation: karst fissure water is transformed into groundwater in the form of cave drips. The characteristics of the fissure include fissure length, direction, permeability, and the size and connectivity of the fissure.

Although karst fissures are difficult to be accurately depicted, these two sets of cave drips (drip-1 and drip-2) are the two main drip points where karst fissure water is converted to karst groundwater. The results showed that the response process of cave drip-2 to precipitation was more agile than that of cave drip-1 for three different degrees of precipitation. And the water volume of cave drip-2 was higher than that of cave drip 1 for all three different degrees of precipitation (Fig. 11). This result indicates that the karst fissure or conduit of cave drip-2 is larger than cave drip-1. On the other hand, the reason why the flow rate of cave drip-2 is greater than that of cave drip-1 is related to the size, connectivity and permeability of karst fissures. The karst fissures connected to Cave Drip-2 are larger and better connected, which results in a more rapid flow rate and response to precipitation in Cave Drip-2.

3. Conversion amount of karst fissure water: In this study, the karst fissure water produced by different degrees of precipitation was calculated, and the karst fissure water of six complete precipitation events with different intensities was selected for display (Table 7). With the increase of precipitation intensity, the conversion of precipitation into karst fissure water the conversion rate and the volume of water are larger. The conversion rate for LR is about 15–20%, and the conversion rate for HRR is about 40–50%.

Groundwater response process and conversion volume

The trends of groundwater inlet and outlet flow increments under the three intensities of precipitation were basically the same, all showed a gradual increase (Fig. 12). As the intensity of precipitation increases, the groundwater export and inlet flows increase (the groundwater outlet flow can reach up to 30 m³/h during HR condition).

The amount of precipitation converted to groundwater can be calculated based on the specific timing of the precipitation and the flow difference between the groundwater inlet and outlet flows. The results show that the amount of precipitation directly converted to groundwater increases with the intensity of precipitation. The conversion of precipitation to groundwater ranged from 8 to 15% for LMR conditions and from 15 to 25% for HRR conditions (Table 8).

Five water conversion process and amount

As shown in Fig. 13, due to the specificity of the structure of the epikarst zone and the heterogeneity of the intensity and time of precipitation, the five water transformation process were complicated. After summarizing the research, the

| Table 3  | Soil water conversion in different degrees of precipitation |
|---------|----------------------------------------------------------|
| Type    | Precipitation (m³) | Soil water (m³) | Percentage (%) |
| LR      | 487.5             | 319.5           | 65.5           |
| LR      | 600.0             | 361.8           | 60.3           |
| MR      | 1023.0            | 412.5           | 40.3           |
| HR      | 2573.6            | 766.4           | 29.8           |
| RS      | 4220.1            | 885.4           | 20.9           |
| RS      | 4867.5            | 972.5           | 20.0           |

| Table 4  | Transpiration water conversion situation |
|---------|------------------------------------------|
| Type    | Precipitation (m³) | Vegetation transpiration (m³) | Percentage (%) |
| LR      | 487.5             | 12.1                     | 2.5            |
| LR      | 600.0             | 18.7                     | 3.1            |
| MR      | 1023.0            | 22.2                     | 2.2            |
| HR      | 2573.6            | 54.8                     | 2.1            |
| RS      | 4220.1            | 83.9                     | 2.0            |
| RS      | 4867.5            | 85.7                     | 1.8            |

Fig. 8 Vegetation sap flow density
Fig. 9 Hydrological annual evaporation and precipitation

Table 5 Evaporation from different precipitation

| Type | Precipitation (m³) | Evaporation (m³) | Percentage (%) |
|------|--------------------|------------------|----------------|
| LR   | 487.5              | 32.5             | 6.7            |
| LR   | 600.0              | 40.3             | 6.7            |
| MR   | 1023.0             | 60.6             | 6.0            |
| HR   | 2573.6             | 144.1            | 5.6            |
| RS   | 4220.1             | 216.1            | 5.1            |
| RS   | 4867.5             | 253.1            | 5.2            |

Fig. 10 Development status of cross-sectional fractures

water resources transformation process of the epikarst zone can be divided into several main processes: (1) The process of direct transformation of precipitation into overland flow, soil water, groundwater and karst fissure water. (2) The process of indirect conversion of precipitation into groundwater through soil water and karst fissure water. (3) The process

Table 6 Development of fractures in the study area

| Section number | Percentage of fissure volume (%) | Soil filling rate (%) |
|----------------|----------------------------------|-----------------------|
| PM01           | 12.1                             | 7.5                   |
| PM02           | 49.6                             | 0                     |
| PM03           | 2.2                              | 0.5                   |
| PM04           | 4.3                              | 5.7                   |
| PM05           | 1.1                              | 0.1                   |
| PM06           | 0.01                             | 0.05                  |
| PM07           | 6.4                              | 2.1                   |
| PM08           | 23.2                             | 0.7                   |
| PM09           | 13.6                             | 1.2                   |
| PM10           | 2.1                              | 7.8                   |

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of surface evaporation and vegetation transpiration water loss, etc. The precipitation will eventually be converted into groundwater or returned to the atmosphere in the form of vegetation transpiration and surface evaporation, thus constituting the regional water cycle of the epikarst zone.

In different degrees of precipitation, precipitation is mainly converted into soil water and karst groundwater, and the conversion ratio can be more than 75%. Under LMR condition, the proportions of precipitation transformed into overland flow, soil water, karst fracture water, groundwater, vegetation transpiration water and evaporation water are 0–6%, 40–70%, 15–20%, 8–15%, 2–3.5%, 7–9%, respectively. Under HRR condition, precipitation transformed into overland flow, soil water, karst fracture water, groundwater, vegetation transpiration water and evaporation water are 3.5–6%, 20–30%, 40–50%, 15–25%, 1.5–2.5%, and 6–7.5%, respectively.

Fig. 11  Response of cave dripping water to precipitation
Discussion

Analysis of overland flow production law and response process

Overland flow production conditions

When the amount of precipitation is small or the precipitation time is short, overland flow will not be produced. The reason is that the slope is covered with soil and vegetation, and precipitation in these cases can be directly retained and absorbed by the soil or vegetation. Therefore, overland flow will not be produced effectively. (Pielke et al. 2010; Roels, 2010).

The degree of vegetation and soil cover, soil type, and slope gradient have some influence on the generation of overland flow. For example, high vegetation and soil cover, sandy soils, and low slope gradient are not conducive to the generation of overland flow. Precipitation under such conditions will be preferentially absorbed and retained by soil and vegetation (Bugnion et al. 2012; XY et al. 2018). The overland flow is easily formed when vegetation is sparse. When the precipitation reaches a certain level or a certain amount of precipitation in a short period of time, the soil water will be saturated (reaches the soil field holding capacity). When precipitation cannot be completely absorbed by vegetation and soil in a short period of time, overland flow can be generated effectively. Based on this production law of overland flow, certain overland flow collection devices can be selected for mountain slopes with higher rock exposure rate and less vegetation cover to collect overland flow for reuse. It will enhance the sustainable use of overland flow in karst areas.

Delay effect of overland flow

The combination of vegetation cover and soil interception affects the retarding effect of overland flow. Vegetation cover can increase the resistance and reduce the flow rate of overland flow. Therefore, the speed of overland flow generation depends to some extent on the vegetation cover (Zhang et al. 2018; Li et al. 2007). Crompton (Crompton et al. 2020) found that the average shift flow velocity of overland flow is closely related to the vegetation cover, and the greater the vegetation cover, the slower the average flow velocity of overland flow. It corroborates with the results of our study. Soil properties and thickness is another important condition for the delay effect of overland flow. When the overland flow is generated, it is accompanied by the joint movement of water and sediment. Meanwhile, after a period of time part of the slope flow will exist in the soil and form the interflow. In addition, the strength of delay effect is also related to the nature of soil. For example, the rate of conversion of overland flow to sandy soil is faster than that to clay. Therefore, the strength of delay effect of sandy soil may be higher than that of clay soil (Ng and Pang, 2000; Wang et al. 2016). The roughness of the slope can also have an important effect on this retarding effect. Theoretically, the rougher the overland flow, the greater the retention effect and the longer the retarding time.

Analysis of the response process of soil water to precipitation

The response rate of deep soil water (>30 cm) to precipitation is faster than that of surface soil water (0–20 cm), which is related to the infiltration process of precipitation and the nature of soil at different depths. The surface soil water is the active zone of moisture exchange with the atmosphere (Chen et al. 2017). This is an important reason why surface soil water has an effective and agile response process to precipitation.

The agility of surface soils to precipitation is influenced by the nature of the surface soil and the state of vegetation development directly (Yizhaq et al. 2015; Zhao et al. 2017). Low vegetation cover leads to high sensitivity of surface soil

Table 7 Conversion of karst fissure water

| Type | Precipitation (m³) | Fissure water (m³) | Percentage (%) |
|------|-------------------|-------------------|---------------|
| LR   | 487.5             | 71.2              | 14.6          |
| LR   | 600.0             | 115.2             | 19.2          |
| MR   | 1023.0            | 364.2             | 35.6          |
| HR   | 2573.6            | 1041.0            | 40.4          |
| RS   | 4220.1            | 1924.4            | 45.6          |
| RS   | 4867.5            | 2351.0            | 48.3          |

Fig. 12 Response of groundwater outlet and inlet to precipitation
In contrast, the response of deep soil water (> 30 cm) to precipitation has a certain delay caused by the infiltration process of precipitation. In the early stage of precipitation, the surface soil water content is low. When the precipitation starts, the surface soil rapidly absorbs precipitation and the soil water content rises sharply. Under RS conditions, the process of soil moisture saturation is accelerated. However, the transfer of surface soil water to deeper soils takes some time, which is an important reason for the delayed effect of deep soil water on the precipitation response process.

### Table 8 Conversion of groundwater

| Type | Precipitation (m³) | Groundwater (m³) | Percentage (%) |
|------|--------------------|------------------|----------------|
| LR   | 487.5              | 60.5             | 8.6            |
| LR   | 600.0              | 85.8             | 9.8            |
| MR   | 1023.0             | 186.2            | 14.5           |
| HR   | 2573.6             | 630.5            | 18.3           |
| RS   | 4220.1             | 1553.0           | 20.3           |
| RS   | 4867.5             | 1962.0           | 22.6           |

Fig. 13 The transformation process of pentahydrate in epikarst zone and analysis of transformation amount
Vegetation transpiration water conversion law

Although the proportion of vegetation transpiration water to precipitation is small in different degrees of precipitation. Vegetation can support its own life activities by absorbing precipitation through its root system, such as photosynthesis and transpiration (Wang et al. 2015).

Although the percentage of transpired water conversion was higher for LMR than for HRR, the amount of transpired water was higher for HRR than for LMR. This indicates that most of the precipitation is converted into other water resources in HR and RS conditions. Wang (Wang et al. 2018) found that most vegetation water resources are originated from the epikarst zone soil. It symbolizes that vegetation transpiration water is an important way that absorb and transform precipitation in a short time. Vegetation transpiration has a relationship with precipitation, and vegetation transpiration increases with precipitation increasing (Dralle et al. 2019). When the precipitation is small, the vegetation will absorb more water for its own life activities. When the rainfall is large, the soil moisture content is near or far above the WHC. The root uptake rate of the vegetation is reduced when the vegetation is in a water deficit condition (Tenorio et al. 2006; Wu et al. 2018). This is one of the reasons for the higher transpiration water loss of vegetation in this study under small and moderate rainfall conditions.

Analysis of karst groundwater response process and conversion amount

The karst groundwater in this study has spatial and temporal variability in response to precipitation (Taylor et al. 2013). This is directly related to the presence of a large number of karst fissures and pipes in the Epikarst zone, as well as their size and roughness (Xu et al. 2019). When the number of fissures and pipes in the Epikarst zone is large and large, precipitation can be easily converted into karst groundwater directly through the fissures and pipes (Arnaud et al. 2018). Under LMR conditions, most of the precipitation cannot generate runoff or ponding effectively, so most of the precipitation is absorbed by the soil or distributed as surface evaporation. When the precipitation gradually increases, the amount of soil water infiltration is much smaller than the amount of precipitation, and runoff is easily formed at the surface of the Epikarst zone, thus leading to the conversion of most of the rainfall into groundwater. This is the main reason why the proportion of rainfall converted into karst groundwater is larger under HRR conditions. Although the karst development in the Epikarst zone of the karst area varies, at the macro level, this study can be a reference for most of the karst development in the superficial karst zone.

As the intensity of precipitation increases, the proportion of water transformed into karst fissure water will increase. In addition, the amount of karst fissure water that is indirectly converted to groundwater will increase. Soil water gradually decreases as the intensity of precipitation increases and the amount of precipitation converted to soil water. This proves that in the case of LMR, most of the precipitation is converted to soil water. Part of the soil water is absorbed and used by the vegetation and lost through evaporation (Lu et al. 2019). However, under HR conditions, Soil water quickly reaches saturation and forms surface runoff or otherwise flows away. Soil water then will be converted into karst fissure water which will become groundwater ultimately (Zhang et al. 2016). Karst fracture water is converted to groundwater through fissure or through soil water converted to fissure water and then to groundwater. At the same time, the conversion of karst fissure water into groundwater takes a certain time. And this time is related to the length and size of the fissure, soil filling and permeability (Li et al. 2020). Therefore, it should be distinguished from karst fissure water when defining this part of water resources.

In addition, cave dripping is the most important process of precipitation conversion to karst groundwater (Tadros et al. 2019). The response of cave dripping to precipitation in this study was more agile in HRR conditions than in LMR conditions. Cave dripping is influenced by factors such as soil overburden, bedrock thickness, drip transport mode and time scale of water–soil–rock interaction, especially in areas where karst is strongly developed (Baker et al. 2020; Bian et al. 2019). Under HRR conditions, the aquifers in the Epikarst zone are easily saturated, the head pressure is high, the volume of cave dripping is high, and the response rate of cave dripping to precipitation is faster. However, under LMR conditions, it is difficult for precipitation to transfer directly into karst aquifers, resulting in water shortage in karst aquifers and a longer lag time of cave drip response to precipitation. On the other hand, precipitation must satisfy the water deficit in soil and Epikarst zone before it can cause drip response, which is also the reason for the small amount of cave drip under LMR conditions. Therefore, finding the threshold value of cave drip generation, especially the threshold effect under arid climate conditions, is the focus of future research work that should be done. This is of great significance to enhance the efficiency of water use in karst areas in arid climates and the hydrological storage in surface karst zones.

Comprehensive analysis of five water transformation process

The five water conversion process water in a typical epikarst zone is synchronous and non-independent (Luo et al. 2013).
resources exploitation and utilization in karst areas as well as the water resources problems such as low efficiency of water resources in karst areas has made some achievements, difficulty for the current research. Although the research on media and the unconfined watershed conditions form a great the multiplicity and heterogeneity of karst water-bearing formation (D3r), and the lithology is light gray–white pure carbonate rocks. The size and structure of the epikarst zone are different. In addition, the internal factors that affect the transformation of water resources are mainly topography and geomorphology, soil type and cover, karst fissure development, vegetation development, lithology when dissected from its structure. Therefore, it is general to conduct other five water studies under different topographic features or different hydrogeological conditions based on this study. Our experimental site is a typical epikarst zone, and the soil cover, karst development, and vegetation development are all consistent with the development pattern and conditions. At the same time, we have refined the water resources of the epikarst zone to improve the efficiency of water resources utilization in karst areas. In addition, improving the accuracy and effectiveness of current hydrological monitoring in karst areas is also a research priority.

Conclusions

The five water transformations in a typical epikarst zone can be divided into several main processes: (1) The process of direct transformation of precipitation into overland flow, soil water, groundwater, and karst fissure water. (2) The process of indirect conversion of precipitation into groundwater through soil water and karst fissure water. (3) The process of water loss by surface evaporation and vegetation transpiration.

The proportion of different degrees of precipitation (complete rainfall process) transformed into overland flow, karst fissure water, groundwater and soil water were 0–6%, 15–50%, and 8–25%, and 20–70%, respectively. In addition, the proportions of water returned to the atmosphere in the form of vegetation transpiration and evaporation are 1.5–3.5% and 6–9%, respectively.

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Declarations

Conflict of interest The author states that there is no conflict of interest.

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