

Transformation Process of Five Water in Epikarst Zone: A Case Study in Subtropical Karst Area

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Abstract

Five water stand for five forms 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 leads to low efficiency of water utilization. To reveal intricated 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 was 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 rate is 3.5%-6%. (2) Under the condition of LMR, there are 2%-3.5%, 40%-60% and 25%-35% that transformed to vegetation water, soil water and groundwater respectively, while it is 1.5%-2.2%, 25%-30% and 32%-50% under the condition of HRR. (3) The proportion of 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 20%-35%. (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, about 0%-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.

Introduction

Water is the critical factor that constrain human survival and socio-economic development in karst areas (Apollonio et al., 2018; Mesnil et al.,2020; Castro, 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. 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 (Jiang and Yuan, 1999; Williams, 2008), and it is also an important carrier for water resources and ecological environment. 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 (Wang and Shi, 2006) proposed corresponding rational water resources utilization on measures in the study of the three waters transformation process in the southwest karst mountains. Zhao (Zhao and Dong, 2015) analyzed the influencing factors of water resources transformation processes in karst areas. Jiang (Jiang and Guo, 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, the 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 resources transformation in different types of karst areas have rarely been studied by scholars.

Although researchers had conducted studies on karst water resources, future researches are still needed to reveal the mechanism of Five water. 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 are the difficulties in the current research. The transformation process of water resources of Five water was elucidated. In this article, 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 article.

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). Experimental site is surrounded by a large underground river system in the Huixian karst wetland. This means that the experimental site has a high degree of rock water content and karst development, and at the same time, overland flow and groundwater are frequently exchanged. 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. 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.

In order to study the tectonic and karst development of the epikarst zone, geophysical exploration (High-density electrical method) was conducted in the experimental site (Fig. 2). The results show that the surface (0-4 m) resistivity of the epikarst zone is low (<163 ohm), while the resistivity in the middle and lower part of the epikarst zone is high (1279-10000 ohm). 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. High rainfall and temperature are benefit for karstification. The total annual rainfall increased from 1987 to 2019. And the average annual temperature ranged of 18.5-19.5. 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*, *Sapium sebiferum*. The main vegetations species include *Sageretia thea*, *Bauhinia championii*, *Zanthoxylum*, *Pyracantha fortuneana*, *A. trewioides*, *Vitex negundo*, *Albizia julibrissin*, *Rosa cymosa* and *Celtis sinensis*, and the dominant species are *Sageretia thea* and *championii* (Table 1). However, considering the dense and abundant growth of shrubs, the transpiration is also a very important part of water conversion.

Table 1
Main vegetation types of the experimental sites.

Classification	Scientific Name	Distribution type
Shrub	<i>Sageretia thea</i> (Osbeck) Johnst.	Dominant species
	<i>Bauhinia championii</i> (Benth.) Benth.	Dominant species
	<i>Pyracantha fortuneana</i> (Maxim.) Li	Common species
	<i>Rosa cymosa</i> Tratt.	Common species
	<i>Paliurus ramosissimus</i> (Lour.) Poir.	Common species
Dwarf tree	<i>Xylosma racemosum</i> (Sieb. et Zucc.) Miq.	Common species
	<i>Sapium sebiferum</i> (L.) Roxb.	Common species
	<i>Celtis sinensis</i> Pers.	Common species
	<i>Zanthoxylum bungeanum</i> Maxim.	Common species

Data collection

Due to the complexity and variability of the transformation of different types of water resources in karst areas, the data obtained in this study were mainly obtained by setting up hydrological and meteorological stations as well as actual measurement data. In order to achieve quantitative analysis of different types of water resources, many different types of dynamic monitoring devices

for water resources were established by this study. 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 were classified and analyzed by the classification criteria of the China Meteorological Administration (Table 2).

Table 2
Different levels of rainfall classification standards.

Degree of rainfall	Rainfall Abbreviation	Rainfall(mm/24h)
Light rain	LR	0-9.9
Moderate rain	MR	10.0-24.9
Heavy rain	HR	25.0-49.9
Rainstorm	RS	50.0-99.9
Above Rainstorm	RS	>100

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. Parameters such as the area of the study area, rock exposure rate, and average soil depth were measured in the field during the actual measurements, and the total soil volume was calculated from these parameters to obtain the soil water content. One of the soil volume calculation equations is as follows.

QS=MHC

where QS is the total soil volume (m³), M is the area of the study area (8507 m²), C is the soil cover (%), H is the average soil thickness (m).

2.3.3. 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 was calculated by the following formula (Li et al., 2006; Gao et al., 2018).

$$Q=Mb[(2g)^{0.2}H^{1.5}]$$

$$M=(0.45+0.027/H) [1+0.55H^2/(H+P)^2]$$

where b is the weir width, H is the head on the weir (m), P is the weir wall height (m), 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). 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 quantized 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. The dominant species in the study area were determined under field investigation.

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 1-4%. Although the conversion rate is low, the amount converted to overland flow is still significant when the rainfall extent is large or the precipitation duration is long. On the other hand, the overland flow can only be generated when the rainfall is greater than $350 m^3$ (Fig. 5). After calculation, when the rainfall time is 1h 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, and it is not enough to generate overland flow when the rainfall is small or continuous light rain.

Under the conditions of LMR, the vast majority of precipitation is 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 the conditions of HR, 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 rainfall

The increase (and attenuation) of overland flow for the three degrees of LMR, HR, RS is consistent with the change pattern of increase (and attenuation) of precipitation (Fig. 6). In the early stage of the three degrees of precipitation, overland flow and precipitation show a trend of non-synchronous changes, while in the late stage of precipitation, overland flow and precipitation show the trend of synchronous changes. The overland flow production time is shorter under HR condition than that of LMR conditions. 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, and the amount of overland flow production 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 certain 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 of this overland flow can last to 30 minutes (Fig. 6a). Under HR conditions, the duration of delay effect is lower than that of LMR, and the delay time is about 20 minutes (Fig. 6b). The delay time of RS is shorter compared with that of LMR and HR, and the delay time is about 10-20 minutes (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 m², and the average soil thickness was 42.4 m. At the same time, the total soil volume was 1731 m³ calculated by the calculation formula in the above research method.

The soil water at 20 cm depth in the case of light to MR showed a significant increasing trend with the increase of precipitation, while the soil water at 30 cm and 50 cm depth in a certain time period was basically unchanged (Fig. 7a). In the case of HR (Fig. 7b), soil water at 20 cm, 30 cm and 50 cm depth showed a certain increasing trend with the increase of precipitation. This trend of increasing soil moisture was obvious at a depth of 20 cm, but not at 30 cm and 50 cm depths. In the case of RS (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 has a certain prolongation, 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 the degree of LMR with the conversion rate of about 40-70% (Table 3). while the conversion soil water is lower for the degree of HRR than the degree of LMR with the conversion rate of about 20-30%. The conversion of soil water shows a decreasing trend with the increase of rainfall degree. It shows that in the case of LMR, most of the precipitation is mainly absorbed by soil and converted into soil water. In the case of HRR, 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., which 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.

Table 3
Soil water conversion in different degrees of rainfall.

Type	Rainfall(m ³)	Soil water(m ³)	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

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. However, due to their high density, transpiration cannot be ignored. 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 was: *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 the degree of LMR, about 2%-3.5%. While the proportion of rainfall transformed into whole transpiration water in the degree of HRR was lower than that of LMR, about 1.5%- 2.5%.

Table 4
Transpiration water conversion situation.

Type	Rainfall(m ³)	Vegetation transpiration(m ³)	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

This corroborates with the soil water conversion results. In the soil water conversion pattern, the conversion rate of soil water is high in LMR. Vegetation roots absorb surface soil water and thus convert it to their own transpiration and respiration consumption. In the case of HRR, although the conversion ratio of precipitation into soil water is low, the conversion amount is higher than that in the case of LMR. It indicates that the conversion of different the pattern of conversion of rainfall to soil water at different levels is basically similar to that of 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 ratio 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 ratios were negatively correlated with the mean temperature. As shown in the following table (Table 5), the ratios 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.

Table 5
Evaporation conversion situation.

Type	Rainfall(m ³)	Evaporation(m ³)	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

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). Combined with 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).

Table 6
Development of fractures in the study area.

Section number	volume(m ³)	Percentage of fissure volume(%)	Soil filling rate(%)
PM01	8	12.1%	7.5%
PM02	8	49.6%	0%
PM03	8	2.2%	0.5%
PM04	8	4.3%	5.7%
PM05	8	1.1%	0.1%
PM06	8	0.01%	0.05%
PM07	8	6.4%	2.1%
PM08	10	23.2%	0.7%
PM09	4	13.6%	1.2%
PM10	10	2.1%	7.8%

(2) Response process of karst fissure water to rainfall: 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 it is difficult for precise characterization of fissure development, it can be determined that these two groups of cave drips (drip-1 and drip-2) in the epikarst zone caves are the two main drip points for the conversion of fissure water into 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 intensities of rainfall. And the water volume of cave drip-2 was higher than that of cave drip 1 for all three different intensities of rainfall (Fig. 11). This result indicates that the fissure or conduit of cave drip-2 is larger than that of 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 rainfall in Cave Drip-2.

(3) Conversion amount of karst fissure water: In this study, the karst fissure water produced by different rainfall 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 rainfall 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%, while the conversion rate for HRR is about 40-50%.

Table 7
Conversion of karst fissure water.

Type	Rainfall(m ³)	Fissure water(m ³)	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

Groundwater response process and conversion volume

The trends of groundwater inlet and outlet flow increments under the three intensities of rainfall 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).

The amount of precipitation converted to groundwater over a period of time 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, with the percentage of groundwater conversion between 8% and 15% for LMR, and between 15% and 25% for HRR (Table 8).

Table 8
Conversion of groundwater.

Type	Rainfall(m ³)	Fissure water(m ³)	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

Five water conversion process and amount

As shown in the 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 of is complicated.

After summarizing the research, the water resources transformation process of the epikarst zone can be divided into several main processes:(1) The process of direct transformation of precipitation into slope overland flow, soil water, groundwater and karst fissure water. (2) The process of indirect transformation of precipitation into groundwater through soil water and karst, (3) The process of indirect conversion of precipitation into groundwater through soil water and karst fissure water. (4) The process 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 rainfall, precipitation is mainly converted into soil water and karst groundwater, and the conversion ratio can be more than 75%. In the case of LMR, the proportions of precipitation transformed into slope 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. In the case of HRR, precipitation transformed into slope overland flow, soil water, karst fracture water, groundwater, vegetation transpiration water and evaporation 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.

Discussion

Analysis of overland flow production law and response process

Overland flow production conditions

When the amount of rainfall is small or the rainfall time is short, overland flow will not be produced. The reason is that the slope is covered with soil and vegetation, and rainfall 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).

On the other hand, 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. And 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 flow 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 reason for the delaying effect of overland flow is caused by the combination of vegetation cover and soil interception. 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 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, part of the overland flow is transformed into soil water and stored in the soil within a period of time, forming the interflow.

On the other hand, 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 overland flow can also have an 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 (>30cm) to precipitation is faster than that of surface soil water (0-20cm), 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). Therefore, the dry or moist condition of surface soil is directly related to precipitation. 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 water. 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 rainfall starts, the surface soil rapidly absorbs water and the soil water content rises sharply. Under rainstorm conditions, the process of soil moisture saturation is accelerated. However, it takes some time for water to transfer from the top soil to the deep soil, which is an important reason for the delayed effect of deep soil water on the precipitation response process.

Vegetation transpiration water conversion law

Although the proportion of vegetation transpiration water to precipitation is small in different degrees of rainfall. 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 the case of heavy and major rainstorms. 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 rainfall 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

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 rainfall 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 is easily be saturated. 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.

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., 2003; Joseph et al., 2018). The process of precipitation in converting into overland flow, soil water, and groundwater occurs synchronously with the process of conversion of soil water and fissure water into groundwater, vegetation roots drawing water from the soil for transpiration, and surface evaporation.

We can find that in different degrees of rainfall, the proportion of precipitation transformed into soil water and karst fissure water and groundwater is larger. The proportion transformed into vegetation transpiration water, slope overland flow, and surface evaporation water is smaller. It is related to the structure of the epikarst zone, topography and geomorphology, vegetation type and quantity, and the degree of soil cover in karst areas. Chang and Jiang (Chang et al., 2010) found in their study on the flow production pattern of overland flow in karst areas that slope, soil type, and vegetation type all influenced the flow production of slope overland flow. And the flow production of overland flow accounted for about 3%-5% of precipitation, which corroborated with our findings. Aquilina (Aquilina et al., 2010) pointed out that groundwater recharge in karst areas is mainly from precipitation, which is overwhelmingly converted to groundwater during a rainfall periodicity. Although they classified karst fissure water and underground rivers as groundwater, it also still provides some reference value for our study.

The experimental site of this study is a typical superficial karst zone, and also a typical peak depression mountain. The stratigraphy of the epikarst zone is the Upper Devonian Rongxian Formation (D3r), and the lithology is light gray-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, we carry out other different topographic features or different hydrogeological conditions of Five water transformation with some universality. 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. Although there are some differences when studying water conversion patterns under other hydrogeological conditions and topographic features, the overall conversion patterns are similar.

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 slope overland flow, soil water, groundwater and karst fissure water. (2) The process of indirect transformation of precipitation into groundwater through soil water and karst. (3) The process of indirect conversion of precipitation into groundwater through soil water and karst fissure water. (4) The process of surface evaporation and vegetation transpiration water loss.

The proportion of different degrees of rainfall (complete rainfall process) transformed into overland flow, karst fissure water, groundwater and soil water were 0%-4%, 15%-50% and 8%-25%, 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.

Declarations

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Conflict of Interest

The author states that there is no conflict of interest.

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Figures

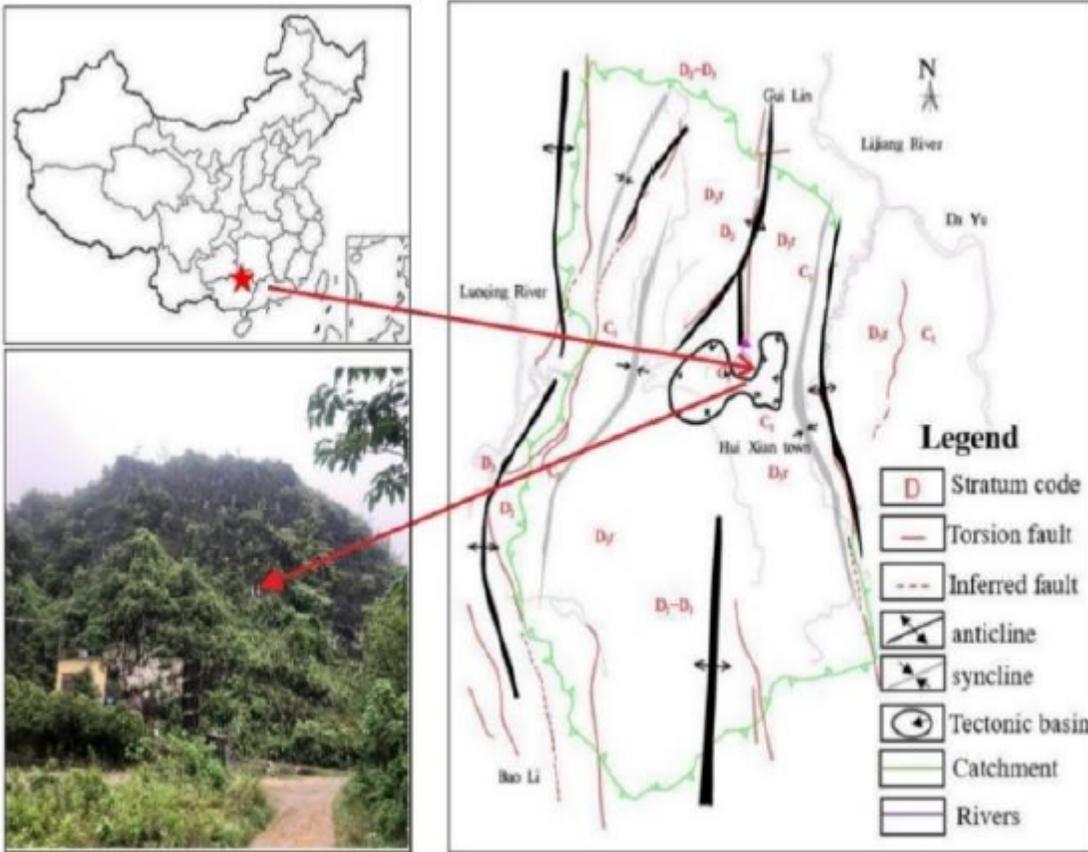


Figure 1

The location and hydrogeological conditions of the study area.

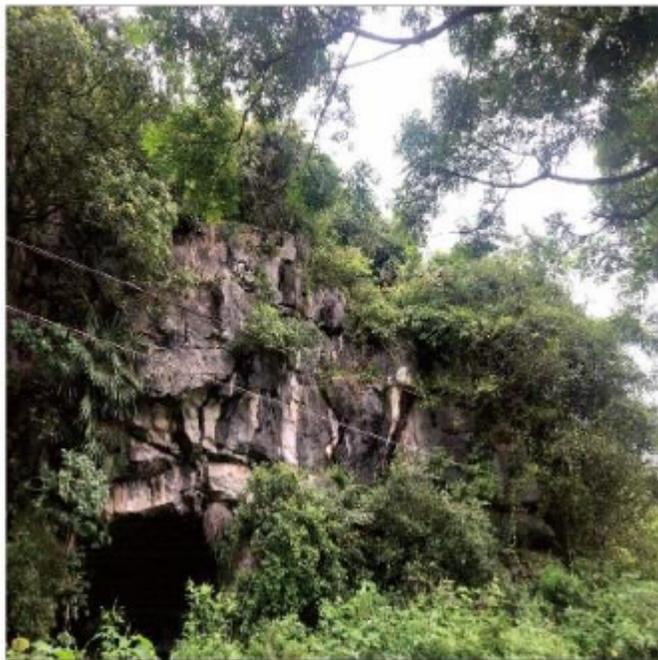
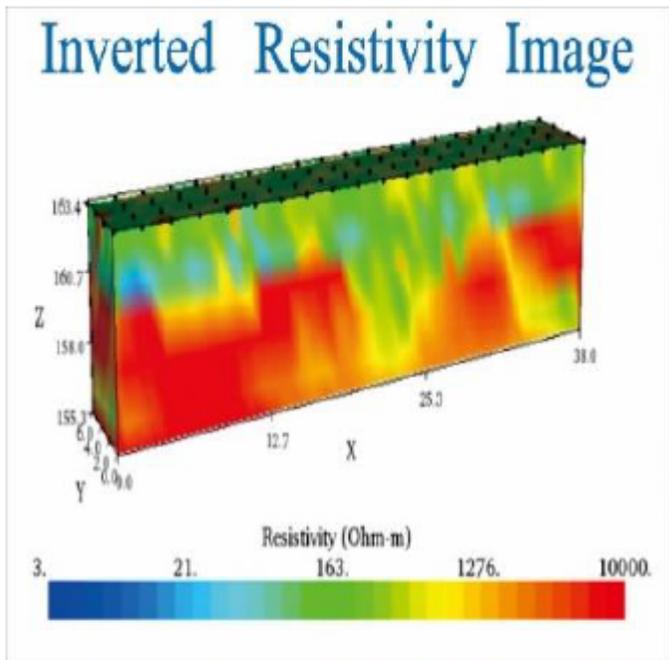


Figure 2

Geological strata and High-Density electrical map.

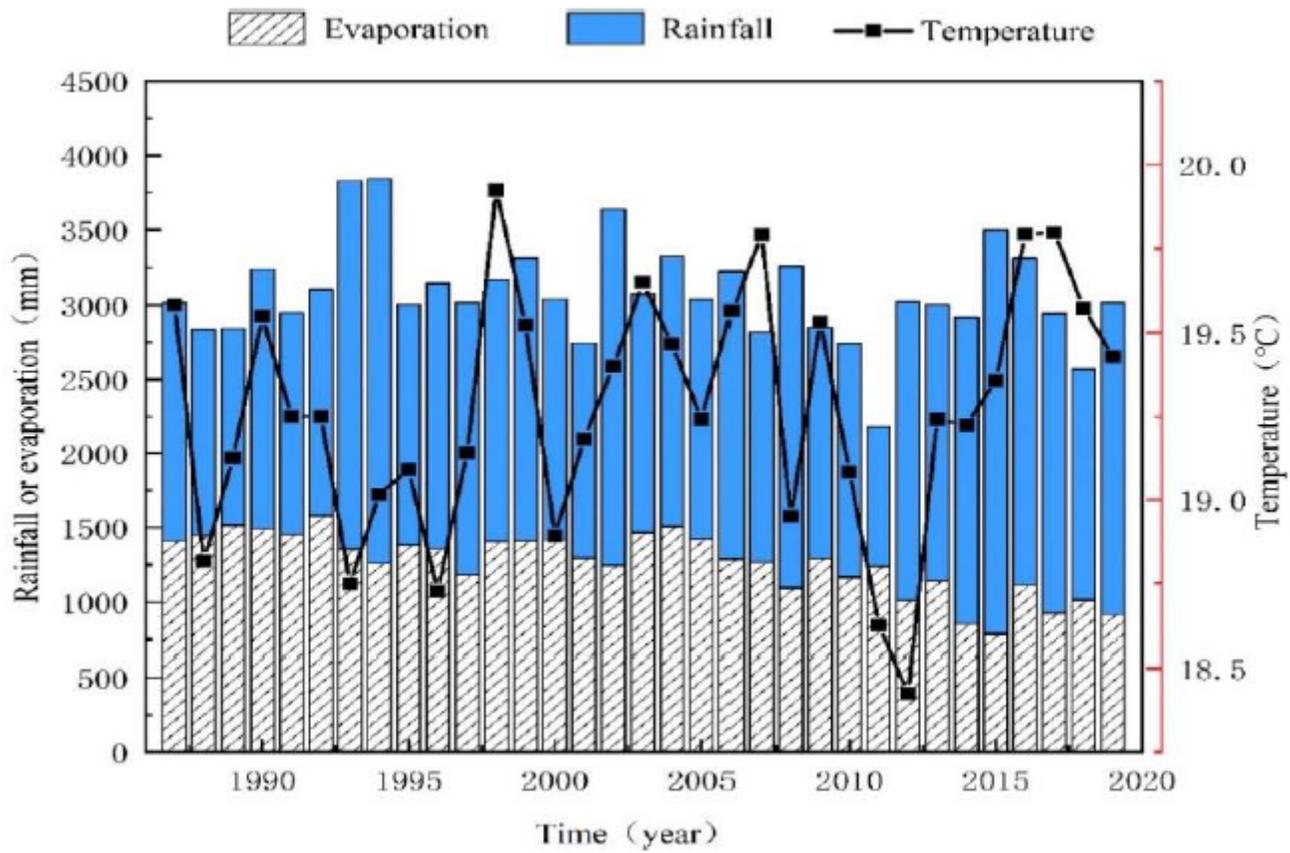


Figure 3

Annual rainfall, annual evaporation and average annual temperature in the study area.



Figure 4

Vegetation in the study area.

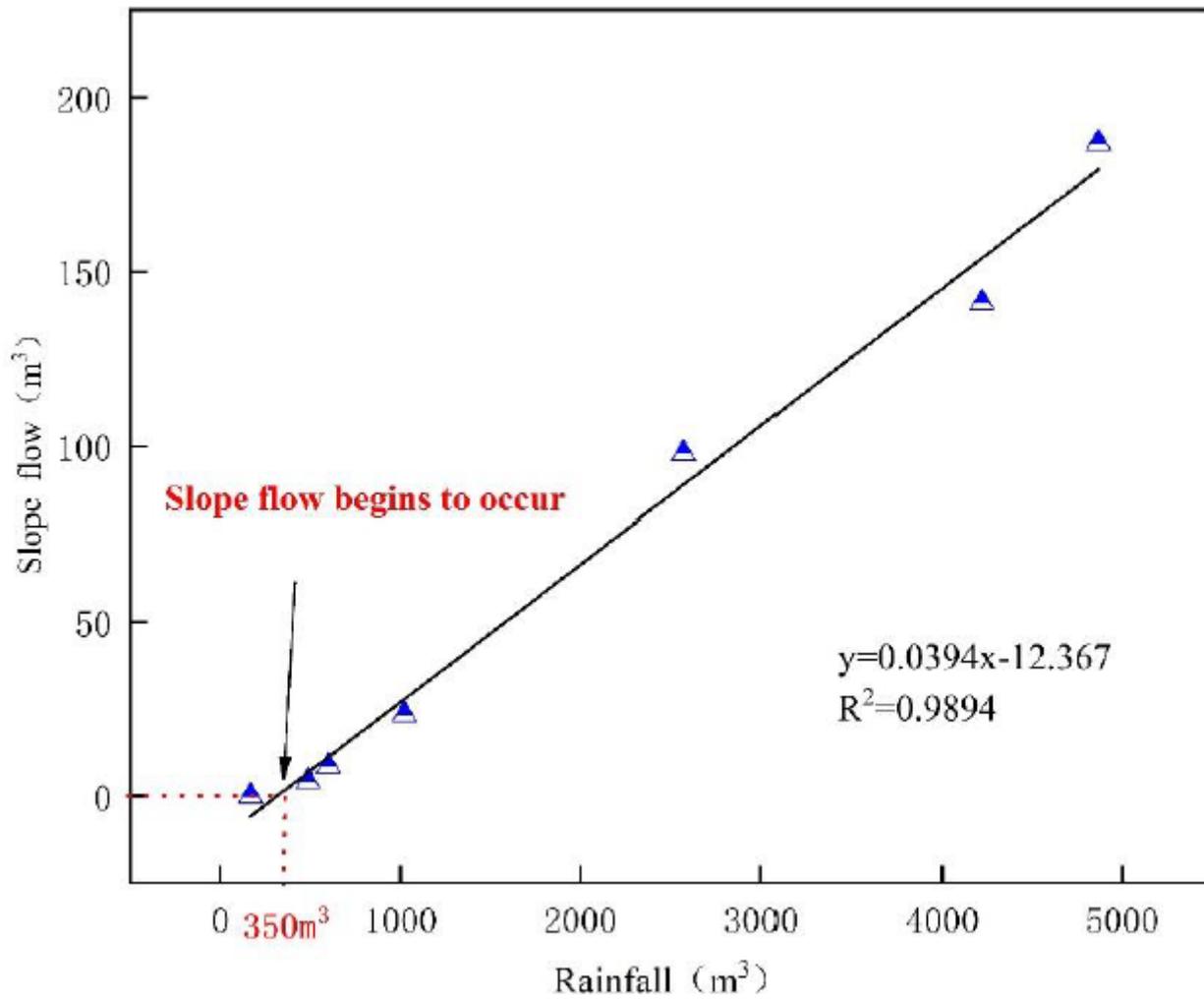


Figure 5

Linear relationship between rainfall and overland flow.

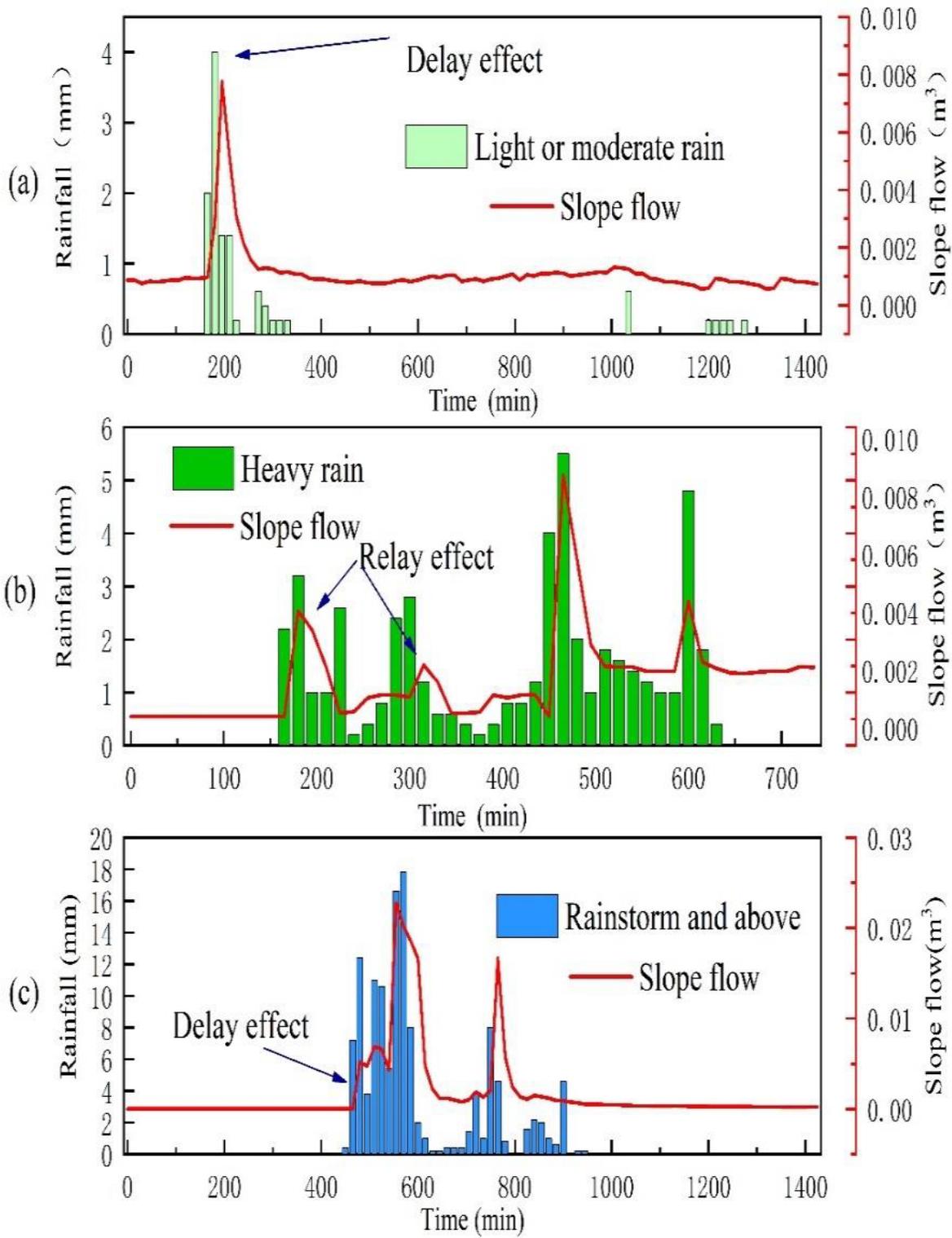


Figure 6

Response of slope surface flow to different levels of precipitation.

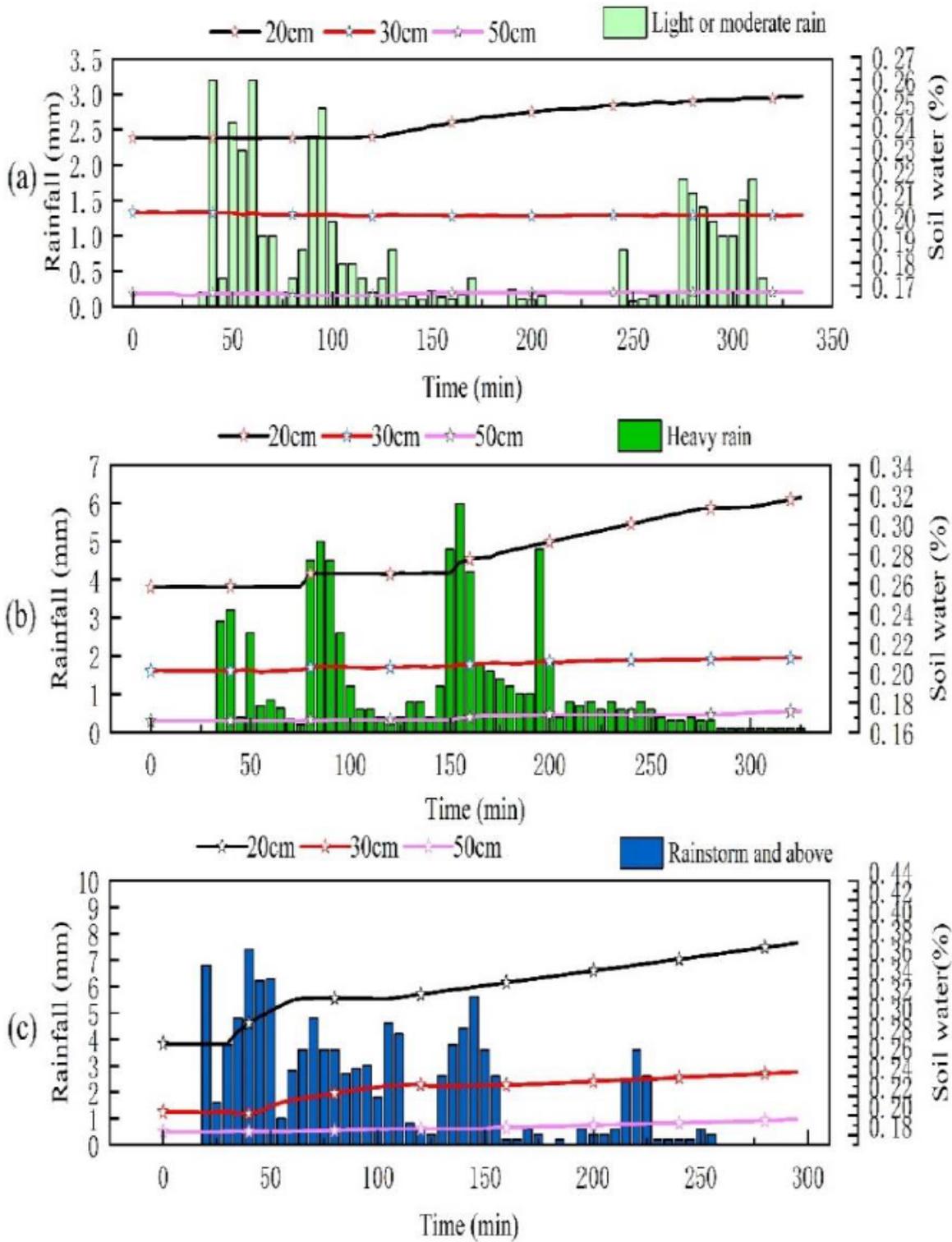


Figure 7

Response of soil water to different degrees of precipitation

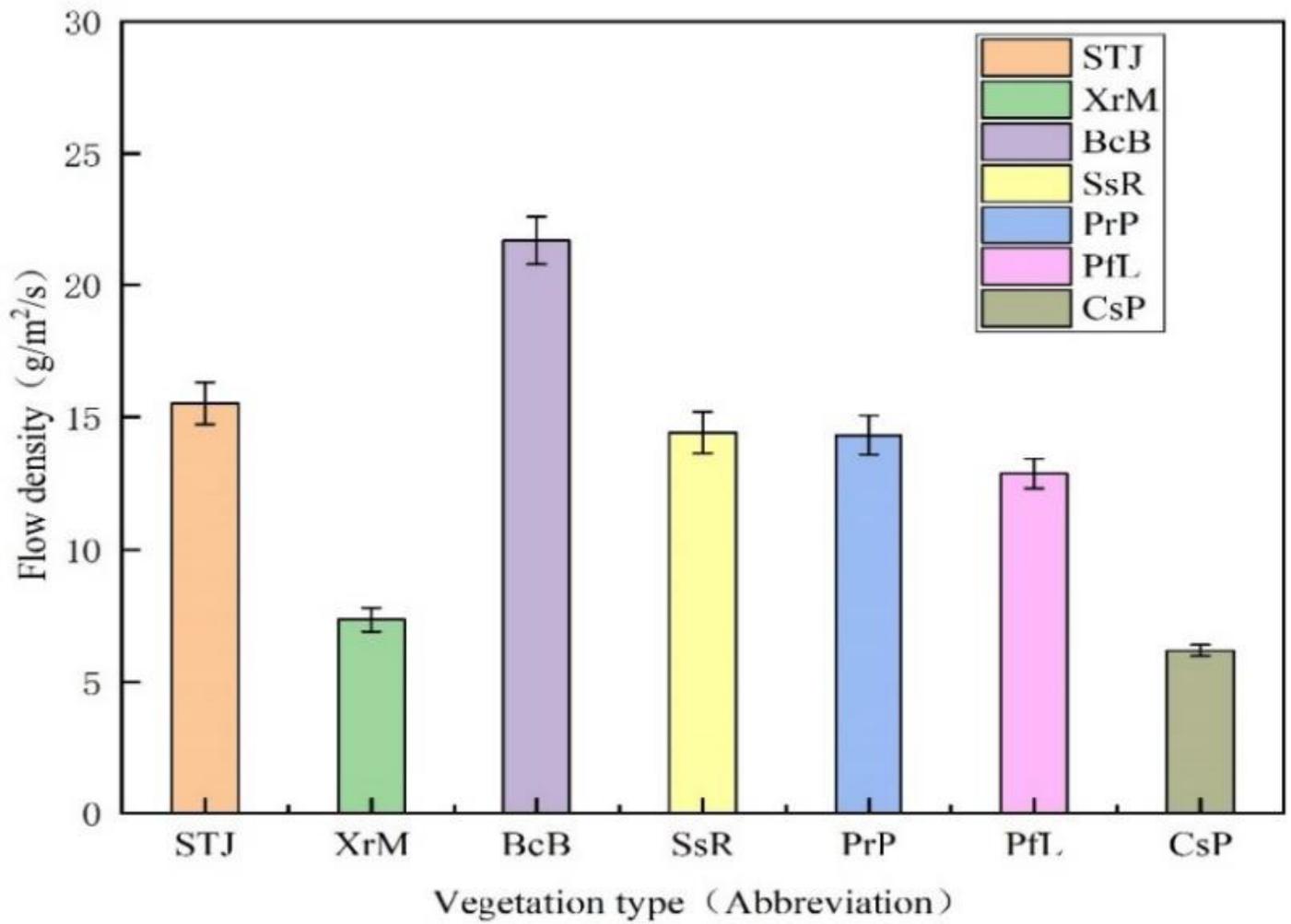


Figure 8

Vegetation sap flow density.

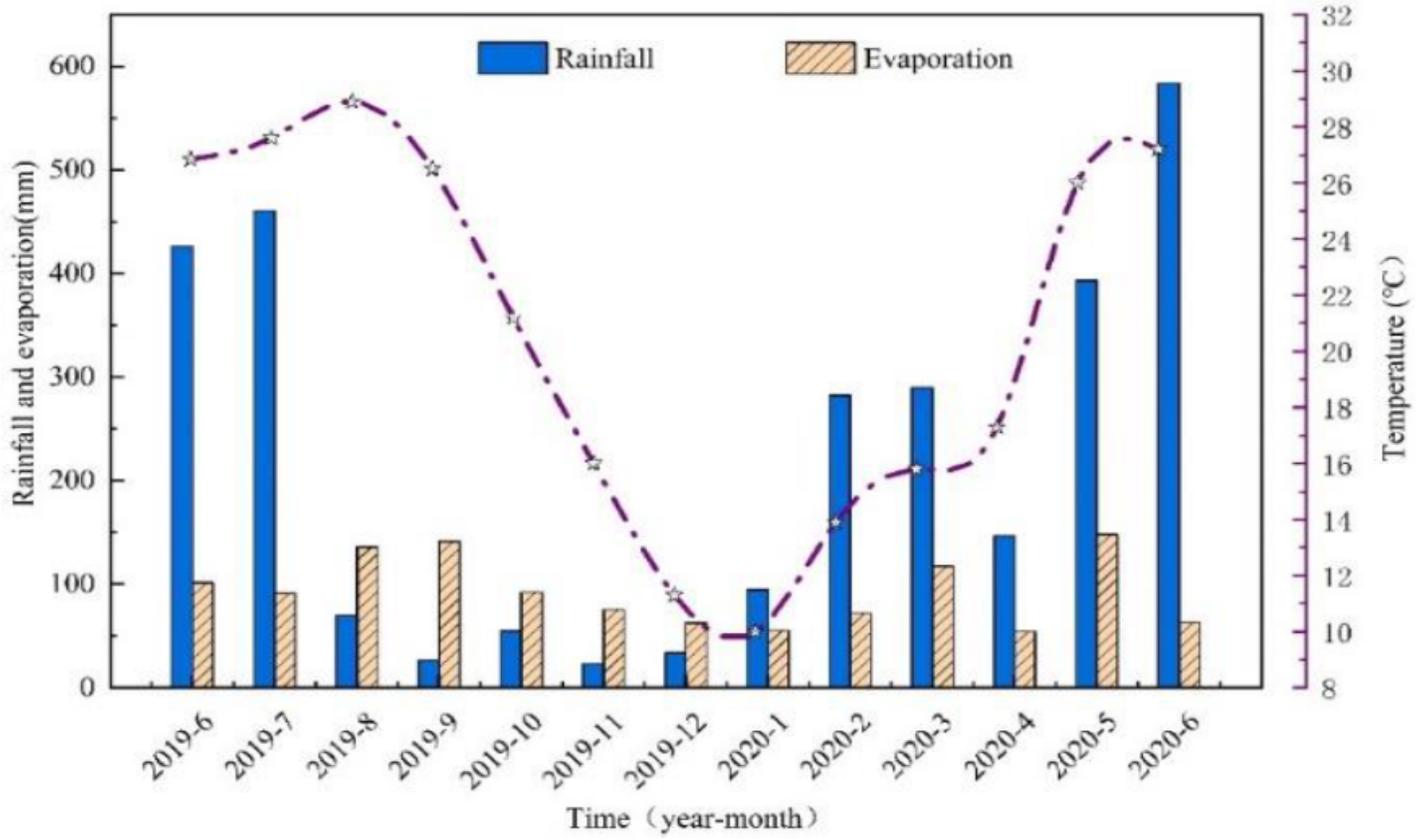


Figure 9

Hydrological annual evaporation and precipitation.

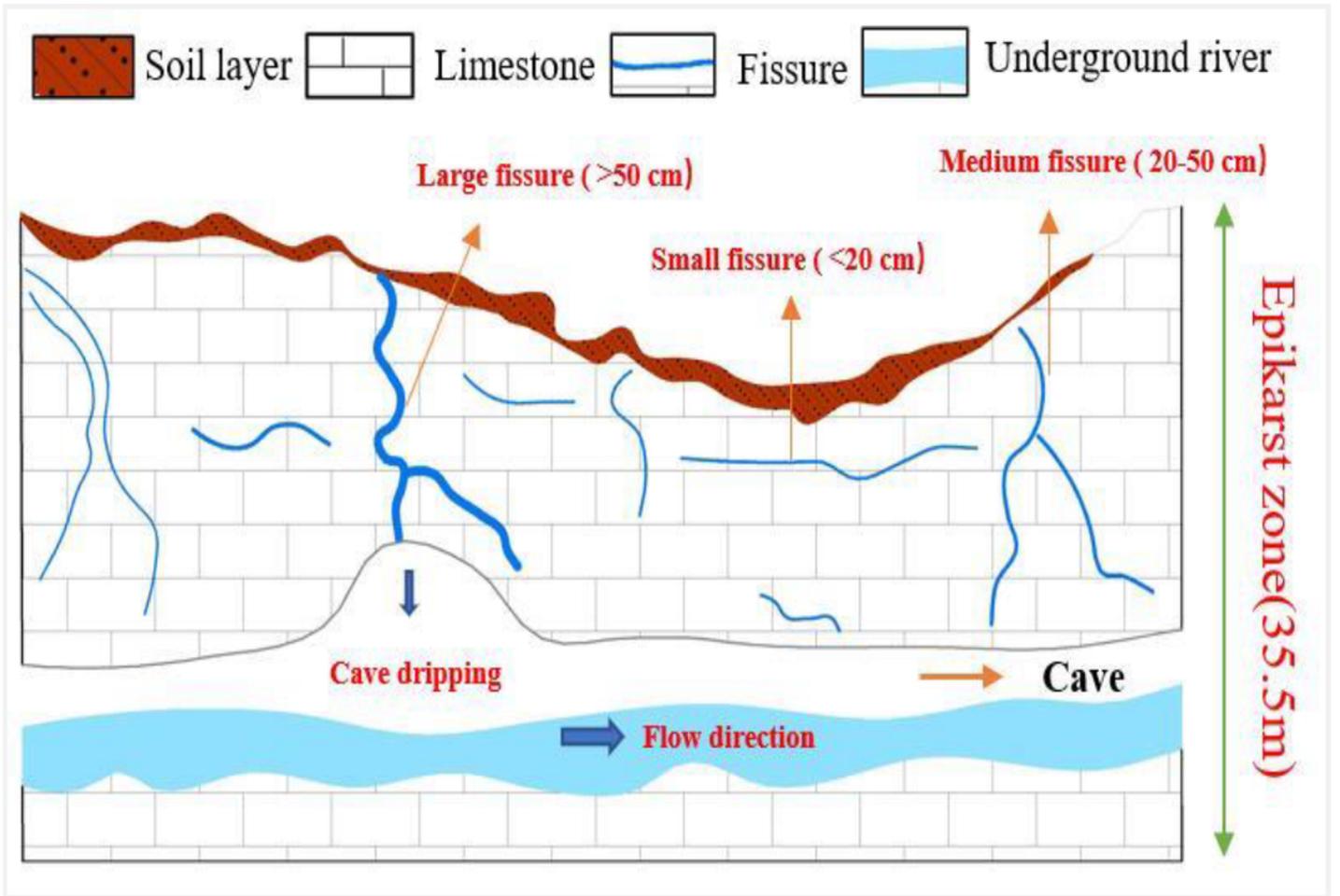


Figure 10

Development status of cross-section fractures.

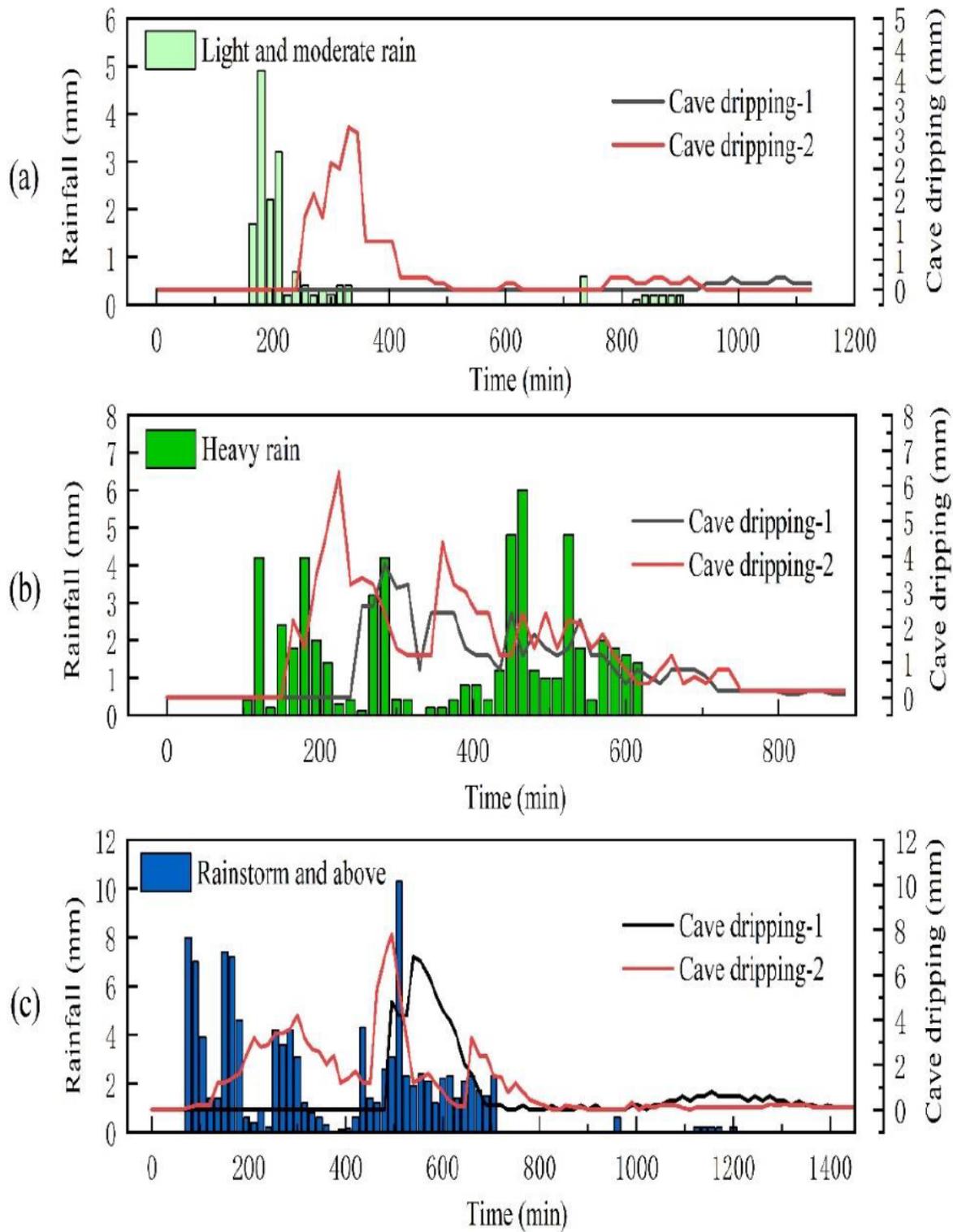


Figure 11

Response of cave dripping water to precipitation.

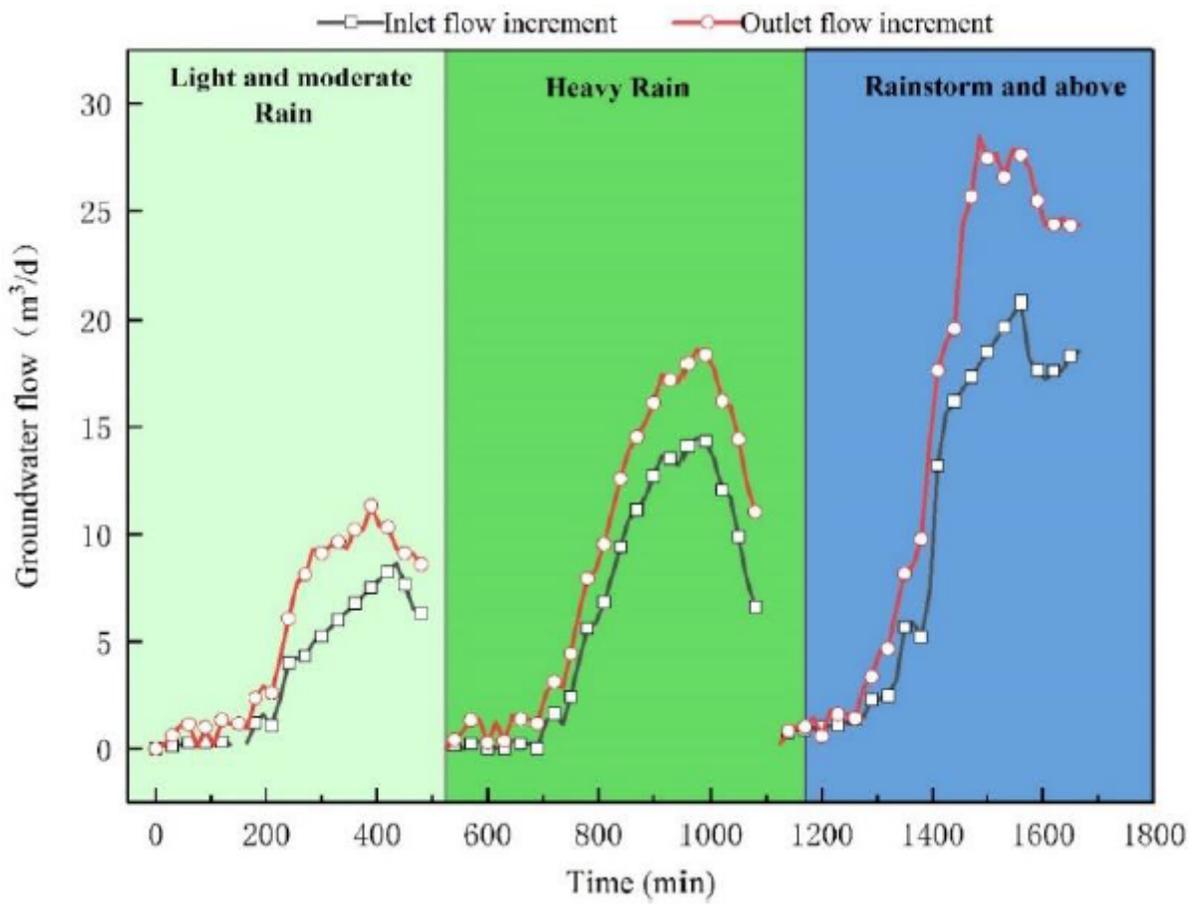


Figure 12

Response of groundwater outlet and inlet to precipitation.

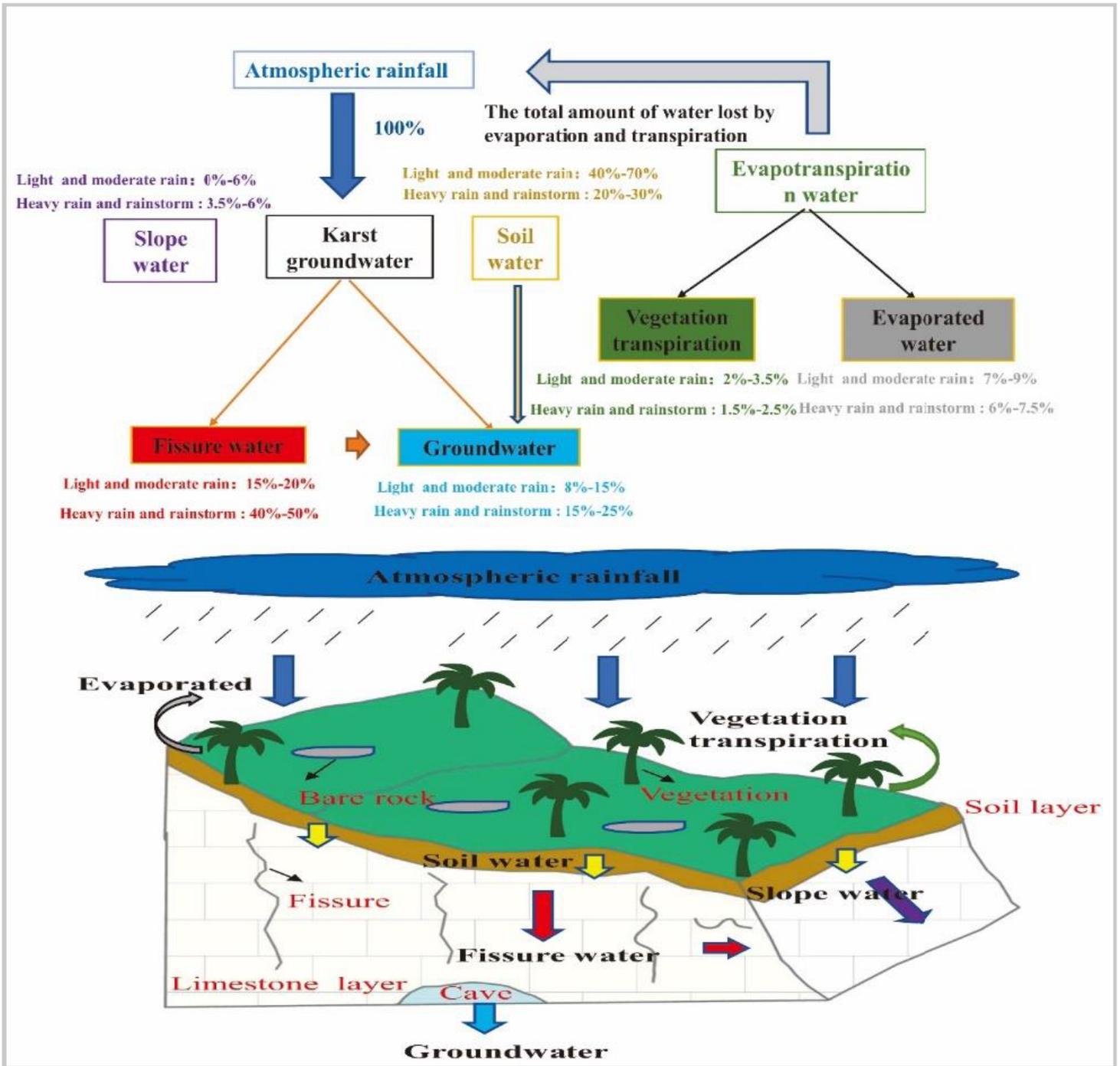


Figure 13

The transformation process of pentahydrate in epikarst zone and analysis of transformation amount.