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The interactions between hydrological drought evolution and precipitation-streamflow relationship

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ABSTRACT

Hydrological drought evolution (development and recovery) is directly related to the amount of precipitation transformed into effective streamflow. However, how hydrological drought alters the precipitation-streamflow relationship, and how the precipitation-streamflow relationship affects the hydrological drought development and recovery require more in-depth research. We present a detailed assessment of the effects of hydrological drought propagation on the precipitation-streamflow relationship. We propose the concept of effective streamflow-precipitation ratio (ESPR), which is defined as the amount of precipitation in the current month that is converted to effective streamflow relative to that of the previous month, for hydrological drought propagation assessment. Long-term unregulated streamflow and precipitation data from six hydrometric stations in different countries (China, USA, and Australia) were used to investigate the proposed concept. The results show that hydrological drought causes a significant decrease in the precipitation-streamflow correlation and coefficient of determination. However, the changes in the precipitation-streamflow relationship are substantially different during the hydrological drought development and recovery stages. In our study areas, the precipitation-streamflow relationship was weakened by 60%, mainly during the hydrological drought development rather than recovery. The *ESPR* values during the hydrological drought development are substantially lower than those of the recovery period, suggesting insufficient precipitation leads to little to no streamflow especially during the drought development period. Additionally, the larger the *ESPR* during hydrological drought evolution, the faster the hydrological drought recovery will occur and vice versa. This study provides insights into the drivers of hydrological drought evolution by connecting with the changes in precipitation-streamflow relationship.

1. Introduction

Drought is a complex and recurrent climate phenomenon that occurs in all climatic regions (Wilhite and Glantz, 1985). Droughts are also called “the creeping natural hazard” and have far-reaching negative impacts on the economy, ecology, agriculture, and human life (AghaKouchak et al., 2021; Ashraf et al., 2017; Lake, 2006; Mehran et al., 2015). Hydrological drought refers to a lack of water resources in the hydrological system and is characterized by abnormally low flow in river channels or low levels in lakes, reservoirs, and groundwater (Tallaksen and Van Lanen, 2004). Hydrological drought evolves from meteorological drought (precipitation deficit), often develops slowly, and can last for months to years, with serious impacts on the ecosystem, environment, agricultural production, and water resources systems (Van Loon, 2015).

In previous studies, hydrological drought evolution was separated into two processes, namely, development and recovery (Parry et al., 2016a, 2016b). The former stage is regarded as the period from the beginning of the hydrological drought to its peak intensity (*PI*) (i.e., maximum intensity during the hydrological drought duration). The latter is defined as the period from the *PI* to the end of the hydrological drought and is called the drought recovery period (Wu et al., 2018a;

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Tallaksen and Van Lanen, 2004). A great deal of research has focused on hydrological drought evolution (e.g., Thomas et al., 2014; Zhang et al., 2016; Wu et al., 2018a) and its socio-environmental impacts (e.g., AghaKouchak et al., 2021; Madadgar et al., 2017; Mehran et al., 2015; Parry et al., 2016b; Van Loon, 2015). Other than meteorological conditions, basin hydrological properties, such as water storage capacity, groundwater-surface water interactions, snow condition, vegetation type, and land use/land cover are key factors affecting hydrological drought evolution (Tijdeman et al., 2018; Van Loon et al., 2014; Van Loon, 2015; Parry et al., 2016a, 2018; Zhao et al., 2018; Zhang et al., 2019a). Wu et al. (2018a) pointed out that factors that influence hydrological drought evolution are complex and include not only meteorological and basin properties, but also human activities and man-made infrastructure. Nevertheless, the most important factors in both hydrological drought development (*HDD*) and hydrological drought recovery (*HDR*) are the decrease and increase in precipitation relative to the long-term mean (Tallaksen and Van Lanen, 2004).

In addition, some previous studies investigated the evolution patterns of hydrological drought and found that the average *HDD* was longer than the average *HDR* and several explanations were given (Parry et al., 2016a; Wu et al., 2019). For instance, it was proposed that hydrological drought was caused by a shortage of precipitation over a long period, but heavy rainfall in a short period may terminate a hydrological drought (Tallaksen and Van Lanen, 2004; Wu et al., 2018a). However, there is a lack of quantitative indicators (or methods) to explain the reasons for the differences in the hydrological drought development and recovery patterns.

Hydrological drought occurrence and evolution are primarily influenced by meteorological (precipitation) conditions and the resulting streamflow (Tallaksen and Van Lanen, 2004; Van Loon, 2015). Consequently, it is necessary to recognize and track meteorological conditions from the onset to the recovery of hydrological drought and determine the corresponding interactions with land surface processes to understand hydrological drought (Zhang et al., 2019b).

The critical conditions for the occurrence of hydrological drought in response to meteorological drought and the influencing drivers were investigated by using linear (e.g., Pearson correlation analysis) (Lorenzo-Lacruz et al., 2013; Sun et al., 2016) and non-linear (e.g., logarithmic function) models (Wu et al., 2017) in earlier studies. The evolution of hydrological drought, including the onset and recovery times, was also investigated in recent studies (i.e., Parry et al., 2016a, 2016b; Wu et al., 2018a). These studies primarily focused on the meteorological conditions at the time of the onset of hydrological drought rather than hydrological and meteorological interactions throughout the drought onset, development, and recovery periods.

Given that changes in hydrological drought are a function of meteorological conditions, the precipitation-streamflow relationship is expected to change during the drought development and recovery process (Yang et al., 2017). Thus, the precipitation-streamflow relationship is commonly used to investigate the possible hydrologic responses to meteorological drought at the catchment scale. For example, Saft et al. (2015) analyzed the annual precipitation-streamflow relationship in southwest Australia and showed that the relationship weakened in 46% of the study region because of a long-term meteorological drought. Zhang et al. (2018) conducted a study in the Yellow River basin in China and found that the annual precipitation-streamflow relationships during the droughts were significantly different from those during non-drought periods. Investigating the Millennium drought in southeast Australia, Yang et al. (2017) studied the time lags between meteorological and hydrological drought recovery and concluded that the recovery was primarily influenced by precipitation, and other factors (e.g., catchment landscape and properties) had only a secondary or minor influence. While previous studies have broadly investigated the precipitation-streamflow relationship during drought and non-drought periods, we are not aware of any investigation on the precipitation-streamflow relationship during the hydrological drought development and recovery (i.e., change in the precipitation-streamflow relationship during *HDD* and *HDR*). Furthermore, we lack information on the feedback effects of shifts in the precipitation-streamflow relationship during the *HDD* and *HDR*.

The objective of this study, therefore, is to establish an indicator to explain the differences in hydrological drought development and recovery patterns using the precipitation-streamflow relationships during *HDD* and *HDR*. This paper focuses on the following two aspects:

(i) Identify the hydrological drought development and recovery patterns, and determine whether the precipitation-streamflow relationship is different during *HDD* and *HDR*.
(ii) Develop an indicator for investigating the feedback mechanism of the shifts in the precipitation-streamflow relationship and the effects on hydrological drought development and recovery.

This paper presents a general framework for understanding the onset, development, and recovery of hydrological droughts and the underlying mechanisms. The remainder of the paper is organized as follows. Section 2 describes the framework and details of the analysis approaches. Section 3 presents the case study area and the data set used in this study. The key results and discussion are presented in Sections 4 and 5. We note that throughout the paper, we use the terms 'rainfall' and 'precipitation' and runoff' and 'streamflow' interchangeably.

2. Methodology

The proposed methodological framework includes four steps (see Fig. 1):

(i) The first step involves selecting a threshold for identifying hydrological droughts based on the historical monthly streamflow records.
(ii) The second is the identification of the hydrological drought characteristics, including duration (*D*), intensity (*I*), peak intensity (*PI*), and the development and recovery processes based on the drought threshold (determined in *step 1*) and the so-called run theory discussed in the following section. The definitions of these hydrological drought characteristics are described later.
(iii) The third step is to investigate the precipitation-streamflow relationship during different periods, i.e., non-drought, drought, drought development, and recovery periods. Following previous studies, we use a linear regression model and the coefficient of determination (R^2) to explore changes in the precipitation-streamflow relationship in different periods (Sankarasubramanian et al., 2001; Saft et al., 2015).
(iv) The fourth step is to calculate the effective streamflow-precipitation ratio (*ESPR*) during the non-drought, drought, development, and recovery periods. We define the *ESPR* as the amount of precipitation in the current month that is converted to effective streamflow relative to the previous month. We propose the *ESPR* as an indicator to reflect the interactions between the precipitation-streamflow relationships during different periods. Fig. 1 displays the flowchart of the proposed method.

2.1. Defining hydrological droughts based on a threshold (step 1)

Drought indices are commonly used to identify and characterize hydrological droughts (Mishra and Singh, 2010). Broadly, hydrological drought indices can be grouped into two types, namely, standardized indices and threshold-based indices. Standardized indices allow for consistent regional comparison of hydrological drought severity (Mishra and Singh, 2010). Examples include the Standardized Streamflow Index (*SSI*) (Vicente-Serrano et al., 2012) and Standardized Runoff Index (*SRI*) (Shukla and Wood, 2008), both of which are based on the Standardized

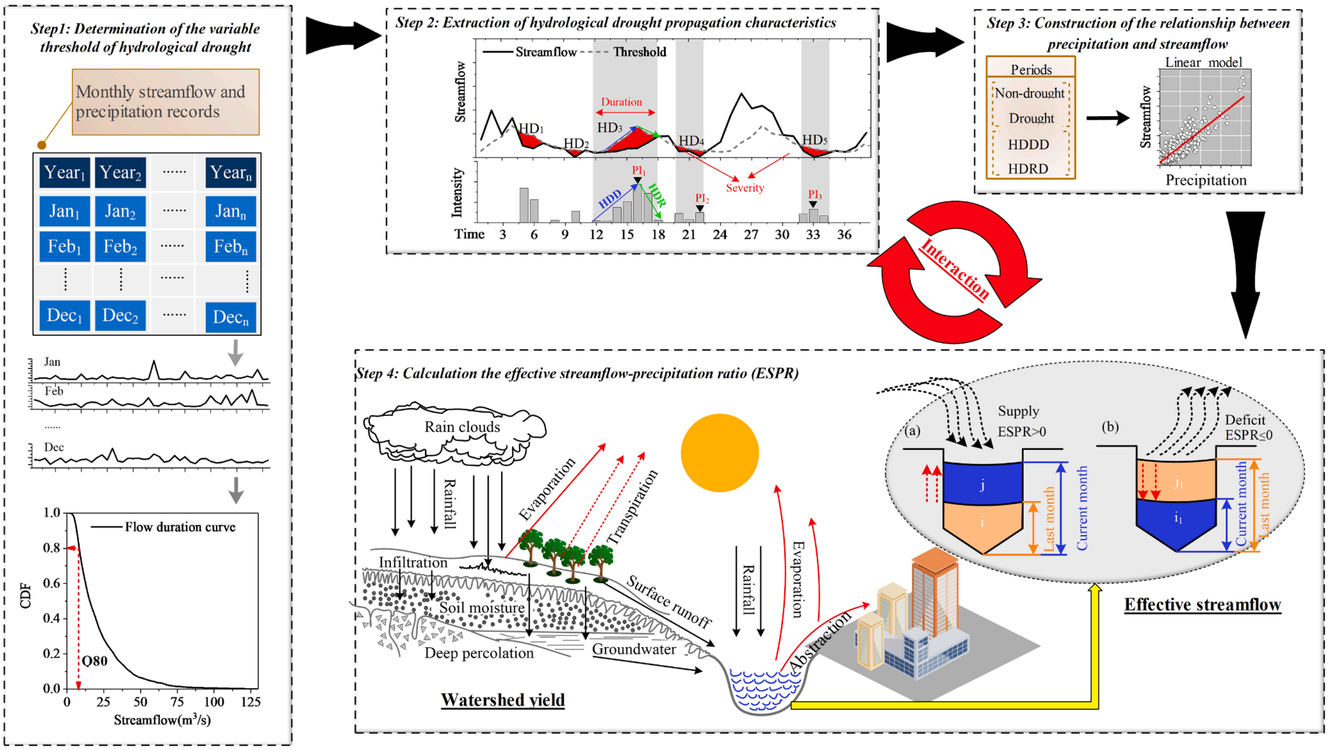

Fig. 1. Flowchart of the proposed framework; Q80 corresponds to the 80th percentiles of the flow duration curve (cumulative frequency of streamflow from high to low); the PI is the peak (or maximum) intensity during the hydrological drought (*HD*); *HDD* (*HDDD*) and *HDR* (*HDRD*) refer to the hydrological drought development and recovery stages (duration), respectively. The graph of the watershed yield was obtained from Chapter 20 'watershed yield' in the Hydrology National Engineering Handbook of the U.S. Department of Agriculture.

Precipitation Index (*SPI*) (Mckee et al., 1993). However, the severity of hydrological drought events identified from standardized indices is expressed only in relative terms, i.e., using a non-dimensional standardized value, which does not provide any information on the volume of water deficit during hydrological droughts (Van Loon and Van Lanen, 2013). However, for water resource applications, the absolute deficit relative to the 'normal' condition is fundamental to risk assessment and decision making (Van Loon, 2015).

The alternative to standardized indices is a threshold-based approach for identifying droughts. In this approach, a hydrological drought is identified when the value of the streamflow drops below a certain threshold. The main advantage of the threshold-based methods is that they provide information on the volume of water deficit during hydrological droughts (Van Loon, 2015; Rangecroft et al., 2019). Two types of threshold-based approaches have been used in the literature: fixed and variable. The fixed threshold is more suitable for areas with less variability throughout the year, whereas the variable threshold method is more practical for locations with considerable seasonal variability (Van Loon, 2015). A comprehensive review of different hydrological drought indices can be found in Mishra and Singh (2010).

The framework presented in Fig. 1 can be used with both fixed and variable thresholds. The procedures for determining the variable threshold is shown in *step 1* of Fig. 1. First, the monthly streamflow records are ranked separately for each month (from January to December). Then the corresponding threshold level (e.g., Q80) for each month is determined based on a particular percentile of the flow duration curve (i.e., twelve thresholds corresponding to the January to December records), as suggested by Van Loon (2015).

2.2. Extract the hydrological drought evolution using the run theory (step 2)

Here the evolution pattern of hydrological drought refers only to the temporal component of drought evolution (i.e., development and recovery processes) (Parry et al., 2016a, Wu et al., 2018a). In this step, hydrological drought characteristics, such as *D*, *S*, *I*, *PI*, *HDD*, and *HDR* of all historical hydrological droughts, are identified. In this study, we extract the hydrological drought characteristics based on the run theory (Yevjevich 1967) and the threshold obtained in the previous step.

According to the rules of the run theory, if the streamflow series in a certain month is below the threshold (e.g., the dotted line in Fig. 1, *step 2*), the month is regarded as a drought month (e.g., HD_1 and HD_2 in the Fig. 1 *step 2*). If the streamflow series in a certain period of time remains below the threshold, this period is regarded as a hydrological drought event (e.g., HD_3, HD_4, and HD_5) (Linsley et al., 1982). The drought *D* is defined as the period from the beginning of the drought to the time of drought termination. Correspondingly, the hydrological drought development duration (*HDDD*) is defined as the period from the beginning of the drought to the time of *PI* and the hydrological drought recovery duration (*HDRD*) is defined as the period from the time of *PI* to the time of drought termination. The negative value for the difference between the streamflow and drought threshold at each time point is called the drought intensity of each month (the histogram in Fig. 1, *Step 2*). The integration of the difference between the streamflow and the drought threshold during *D* is defined as *S*. The average *S* during *D* is regarded as the drought intensity (*I*). The maximum drought *I* during the *D* is defined as the *PI* (e.g., PI_1, PI_2, and PI_3) (see Fig. 1, *step 2* in the flowchart). Here, hydrological drought events with a minimum duration of 3 months were extracted. The *HDDD* and *HDRD* cannot be obtained when *D* is less than 3 months (Parry et al., 2016a, 2016b; Wu et al., 2018a).

2.3. Quantifying the shifts in the precipitation-streamflow relationship (step 3)

Although the precipitation-streamflow relationship is complex at different spatial and temporal scales, in catchments with low human activities, a simple linear statistical model may be sufficient to represent the changes of relationship between precipitation and streamflow (Sankarasubramanian et al., 2001; Saft et al., 2015). In this study, we compared the linear relationship between precipitation and streamflow during the non-drought, drought, *HDD*, and *HDR* periods (*step 3* in Fig. 1) to determine changes in the precipitation-streamflow relationship during hydrological droughts (i.e., whether hydrologic drought substantially changes the precipitation-streamflow relationship).

We then compared the precipitation-streamflow relationship during the drought, *HDD,* and *HDR* periods to determine shifts in the relationship. Here, R^2 is used to describe the changes in the linear relationships during different periods. R^2 represents the part of the variance in the dependent variable that is predictable from the independent variable (Spiess and Neumeyer, 2010). The percent change in R^2 in a drought period compared to a non-drought period is described as follows:

$$Cp = \frac{\lambda_1 - \lambda_2}{\lambda_2} \times 100 \tag{1}$$

where the *Cp* is the contribution percentage to the shifts in the precipitation-streamflow relationship in a drought period compared to a non-drought period. λ_1 and λ_2 represent the R^2 of precipitation-streamflow relationship during the drought and non-drought, respectively. Similarly, if we want to obtain the contribution percentage to the shifts in the precipitation-streamflow relationship by the hydrological development and recovery periods (*HDDD* and *HDRD*), we can use their corresponding R^2 values in Eq. (1). This allows optaining the relative change of the precipitation-streamflow relationship during the development and recovery period.

2.4. Effective streamflow-precipitation ratio (ESPR – Step 4)

In this paper, *ESPR* is proposed to determine the feedback effects of the shifts in the precipitation-streamflow relationship during hydrological drought development and recovery. The effective streamflow is defined as the portion of rainfall that generates direct or indirect streamflow in the river channel, as mentioned above. The effective streamflow includes rainfall entering the river directly and the fraction of rainfall in the basin that is drained by the river; it does not exclude the inflow from other watersheds.

In Fig. 1, *step 4* shows a simple example of the watershed yield (left part of Fig. 1 – *step 4*). The right part of Fig. 1 (*step 4*) shows a simple diagram indicating the rising (a) and falling (b) of the river flow in the any given month (e.g., current) relative to the previous month. As shown the river flow is expected to rise when there is additional discharge (*j*) added to the water level of the previous month '*i*' (i.e., the total flow in the current month would be '$i + j$' with the actual water supply of '*j*' in the current month). Based on this perspective, the actual amount of river flow '*j*' can be defined as the effective streamflow in the current month relative to the previous month. In contrast, when the river flow in the current month is lower than the previous month, there is a deficit and hence, the *ESPR* (Equation 4) would be equal to or less than 0. Because the unit of precipitation (i.e., mm) is different from the unit of streamflow (i.e., m^3/s), calculating the *ESPR* requires a third variable, that is, the runoff depth (*RD*). Hence, the *ESPR* is defined as follows:

$$ESPR = \frac{\Delta RD_j}{P_j} \times 100 = \left[\frac{1}{P_j} \times \frac{W}{1000{*}F}\right] \times 100 \tag{2}$$

$$\mathrm{W} = \mathrm{Q} \times \Delta \mathrm{t_j} \tag{3}$$

where $\triangle RD_j$ is the absolute value of the increase in *RD* in the current month compared to the last month. P_j, *Q*, *W*, and *F* are the precipitation (unit: mm) in the current month, absolute value of changes in streamflow in the current month relative to the last month (m^3/s), total runoff volume in a certain period (e.g., $\triangle t_j$) (unit: m^3), and catchment area (km^2), respectively. It should be noted that the $\triangle RD_j$ and actual *RD* are different; the actual *RD* is calculated from the actual flow in the current month and the $\triangle RD_j$ is calculated using the absolute value of the increase in the flow in the current month relative to the previous month.

3. Study areas and data resources

3.1. Study areas

We present results from three case studies selected from different countries (China, United States, and Australia) for six hydrometric stations (two stations per study area) (Fig. 2). The stations are located in the upstream catchment (unregulated) with little human activity, and at least 30 years of monthly observed streamflow and corresponding precipitation records are used to evaluate the performance of the proposed framework. Limited human activities in the study basins have been confirmed in previous studies (Lin et al., 2014; Pena-Gallardo et al., 2018; Van Loon et al., 2019). In addition to the two hydrometric stations located in China (Yuecheng and Jiuzhou, hereafter referred to as China stations), we selected two hydrometric stations in the Southeast United States (USGS number: 02,372,250 and 02361000, referred to as the USA stations) and two stations in southeastern Australia (ID number: 419,005 and 419016, referred to as Australian stations). The climate in the first two regions (Chinese and USA stations) is a subtropical wet monsoon climate with abundant heat and precipitation in the same seasons (Blum et al., 2017; Wu et al., 2018b). The climate in the third region (Australia) is a semi-arid savanna climate (Van Loon et al., 2019).

3.2. Data

The monthly streamflow and precipitation records of the Chinese stations were obtained from the Water Conservancy and Electric Bureau in Guangdong Province. Monthly streamflow records for the USA stations were downloaded from U.S. Geological Survey (https://waterdata.usgs.gov/nwis/rt). The corresponding monthly precipitation for the USA stations was obtained from the PRISM Climate Group (http://prism.oregonstate.edu/). The streamflow data for the Australian stations were obtained from WaterNSW of Australia (https://www.waternsw.com.au/). We obtained the corresponding monthly precipitation for the Australian station from the Australia Bureau of Meteorology (http://www.bom.gov.au/?ref = logo) based on the location of the hydrometric stations.

These hydrometric stations were chosen because they also have been used as unregulated stations for hydrological process and drought identification analysis in previous studies (Blum et al., 2017; Lin et al., 2014; Tu et al., 2018; Van Loon et al., 2019; Wu et al., 2018b; Yang et al., 2017). Only a few months of streamflow data were missing in the datasets of these hydrometric stations. The missing data were filled by using the average of the month in the same period in history (≥30 years). There were no missing data in the monthly precipitation records. The detailed information on the hydro-meteorological data is given in Table 1.

To further investigate other drought-related variables (e.g., potential evapotranspiration, soil moisture, groundwater and etc.) during the drought and non-drought periods, we collected additional data from the two China stations. Thus, monthly weather data such as temperature, wind speed, and relative humanity during 1960–2006 were obtained from the National Meteorological Information Center of the China Meteorological Administration (http://www.nmic.gov.cn). These weather data were used to calculate the potential evapotranspiration (PET) using the Penman-Monteith equation (Penman, 1948; Monteith, 1965). Monthly groundwater and soil moisture (soil surface to 10 cm depth) data from 2002 to 2010 were also used in this study. The processed groundwater and soil moisture data were downloaded from the Google Earth Engine website; the former was derived from the Gravity

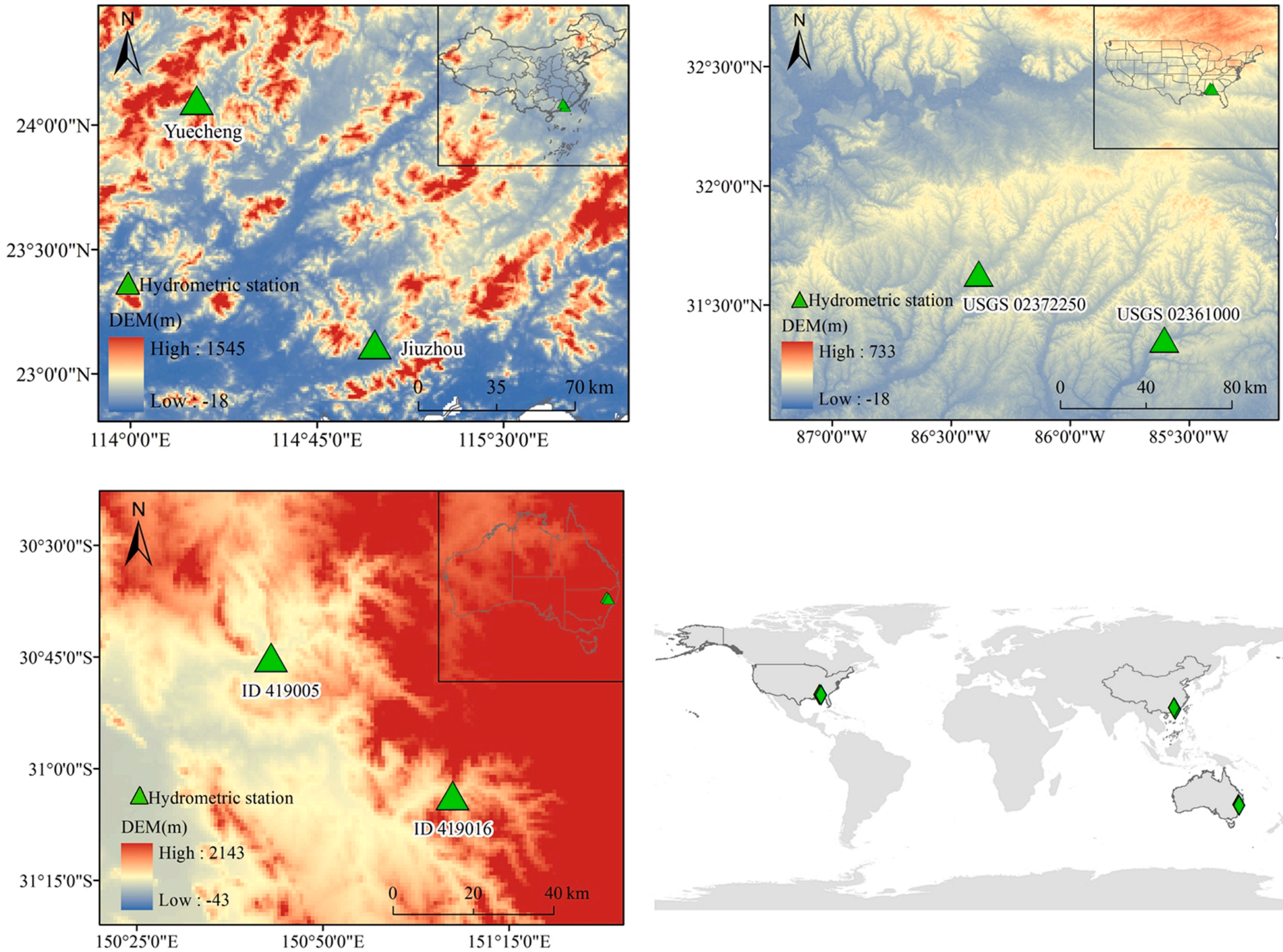

Fig. 2. Study areas and the location of the selected hydrometric stations.

Table 1
Study area and data used in this study.

Type	Location	Station	Catchment area (km^2)	Time series	Latitude	Longitude	Sources
Hydrometric	China	Yuecheng	531	1960–2006	24°03′35″N	114°09′36″E	Water Conservancy and Electric Power Bureau,
		Jiuzhou	385	1960–2006	23°04′12″N	114°35′24″E	Guangdong Province, China
	USA	USGS 02,372,250	1144	1974–2018	31°35′46″N	86°24′20″W	U.S. Geological Survey, USA
		USGS 02,361,000	1776	1936–2017	31°20′34″N	85°36′38″W	
	Australia	ID 419,005	2510	1931–2014	30°40′44″S	150°46′40″E	WaterNSW, Australia
		ID 419,016	907	1958–2015	31°03′37″S	151°07′34″E	
Meteorological	China	Yuecheng	Null	1960–2006	24°03′35″N	114°09′36″E	Water Conservancy and Electric Power Bureau,
		Jiuzhou		1960–2006	23°04′12″N	114°35′24″E	Guangdong Province, China
	USA	Crenshaw County		1895–2019	31°43′53″N	86°18′48″W	PRISM Climate Group,Oregon State University, USA
		Dale County		1895–2019	31°25′54″N	85°36′39″W	
	Australia	ID 55,031		1883–2016	30°45′00″S	150°43′12″E	Australia Bureau of Meteorology
		ID 55,143		1958–2015	31°01′12″S	151°04′12″E	

Recovery and Climate Experiment (GRACE) Monthly Mass Grids-Land (https://developers.google/com/earth-engine/datasets/catalog/NASA MASS GRIDS LAND) and the latter was obtained from the Global Land Data Assimilation System (GLDAS-2.1) (https://developers.google.com/earth-engine/datasets/catalog/NASA GLDAS V021 NOAH G025 T3H). These data were used to determine the possible correlations between the variation in streamflow (hydrological drought characterization index) and these drought-related variables. The GRACE groundwater and GLDAS-2.1 soil moisture were used here because they have been widely employed to examine the evolution of global and regional water cycle (e.g., Famiglietti, 2014; Rodell and Famiglietti, 2001; Rodell et al., 2004).

4. Results and discussion

4.1. Hydrological drought development and recovery patterns

By combining the Q_{80} threshold (i.e. a threshold above which 80% of the data falls) level with the run theory, as mentioned in *step 2*, the hydrological drought events and evolution properties, including the development and recovery information, for each hydrologic station in the study area were identified. The time series of hydrological drought intensity is provided in Fig. S1 (Supporting Information), and the boxplots of the development and recovery time for the six hydrometric stations are shown in Fig. 3. The average *HDDDs* for the Yuecheng, Jiuzhou, USGS 02372250, USGS 02361000, ID 419005, and ID 419,016 stations are 2.56, 2.85, 2.60, 3.73, 2.74, and 2.69 months, respectively. The average *HDRD*s for the same stations are 1.69, 2.08, 2.40, 1.64, 1.91, and 2.31 months, respectively. The average *HDRD* is considerably shorter than the average *HDDD* at each hydrologic station. These results are consistent with previous studies (Parry et al., 2016b; Wu et al., 2018a). The reasons for the different patterns of hydrological drought development and recovery are explained below.

4.2. Precipitation-streamflow relationship and hydrological drought evolution

4.2.1. Impact of hydrological drought on the precipitation-streamflow relationship

Fig. 4 shows the R^2 of the linear relationship between precipitation and streamflow during the non-drought, drought, drought development, and recovery periods (Fig. 4(a)) and the corresponding percent changes during hydrological droughts (Fig. 4(b)). The following observations are made:

(i) The R^2 of the precipitation-streamflow relationship during the non-drought period differs from that of the drought period. Overall, the R^2 for the precipitation-streamflow relationship is significantly larger during the non-drought period (all the *p*-values are less than 0.05). The R^2 of the drought period is 30.56%, 47.83%, 66.78%, 76.24%, 86.66%, and 96.64% lower than that of the non-drought period (Equation (1)) at the Yuecheng, Jiuzhou, USGS 02372250, USGS 0236100, ID 419005, and ID 419,016 stations, respectively (Fig. 4(b)).

(ii) The R^2 values exhibit considerable differences during drought development, and recovery periods. The R^2 of precipitation-streamflow relationship during the *HDRD* is often higher than that during the *HDDD*, which is reasonable because more precipitation may occur during the recovery period. During the hydrological drought studied here, the relative changes in R^2 of the precipitation-streamflow relationship during the *HDDD*s at the six hydrologic stations are 68.63%, 69.23%, 62.93%, 65.20%, 61.35%, and 64.46%, respectively. The corresponding changes in precipitation-streamflow R^2 values during the *HDRD*s at the six hydrologic stations are decreased by 31.37%, 30.77%, 37.07%, 34.80%, 38.65%, and 35.54%, respectively (Fig. 4(b)).

From Fig. 4 we can conclude that the occurrence of hydrological drought significantly alters the precipitation-streamflow relationship, and the changes during the *HDDD* period are larger than those in the *HDRD* period. Although the intensity of the changes in the precipitation-streamflow relationship due to drought is different, general behavior of changes during to precipitation-streamflow relationship during *HDDD* and *HDRD* are similar in different hydrometric stations.

4.2.2. Responses of hydrological drought evolution patterns to different precipitation-streamflow relationships

Fig. 5 shows that the *ESPR* values are considerably larger during non-drought periods than drought periods at the six hydrologic stations. This indicates that the amount of precipitation converted to effective streamflow was significantly greater during non-drought periods than drought periods. This is believed to be the primary cause of hydrological droughts: when precipitation decreases, the amount of effective streamflow generated from precipitation reduces substantially leading to hydrologic drought.

A comparison of *ESPR* values during the *HDDD* and *HDRD* periods indicates that the *ESPR* values during the *HDDD* are substantially lower than those of the *HDRD* period or are close to 0 during the *HDDD* (e.g., see the Australian station). In other words, insufficient precipitation leads to little to no streamflow especially during the drought development period (that is, during *HDDD,* the *ESPR* decreases whereas during *HDRD,* the *ESPR* increases). This explains why the average of the development time of hydrological drought is usually longer than the recovery time.

4.3. Discussion

It is well-known that the occurrence of hydrological drought changes the precipitation-streamflow relationship (Zhang et al., 2018; Saft et al., 2015). The reason is that the amount of precipitation that turns into discharge changes significantly throughout hydrological drought evolution (Lake, 2006; Yang et al., 2017). Most previous studies, however, focused on this issue at the annual scale, investigating the annual precipitation-streamflow relationships during drought and non-drought. In this study, we investigated this issue at monthly scale. In addition to drought and non-drought periods, the precipitation-streamflow relationship was also investigated during drought development and recovery periods. Our results confirm earlier findings that hydrologic

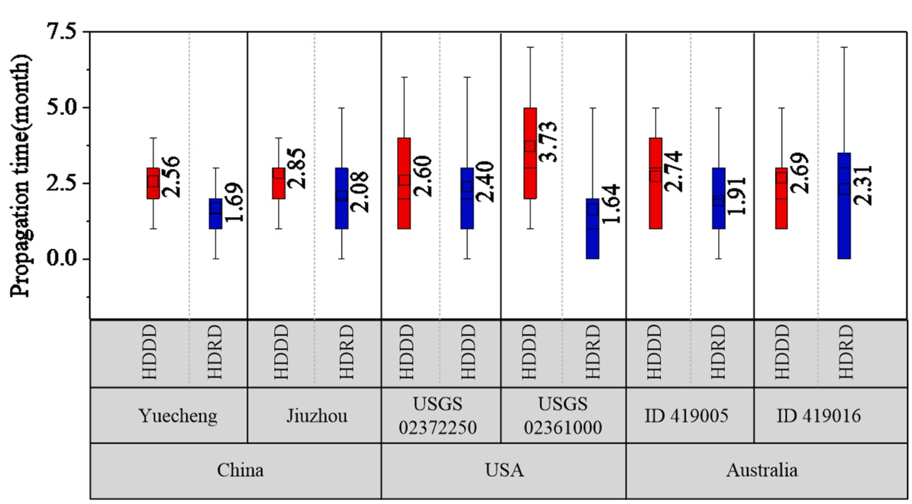

Fig. 3. Hydrological drought development and recovery characteristics based on the Q_{80} threshold level and run theory.

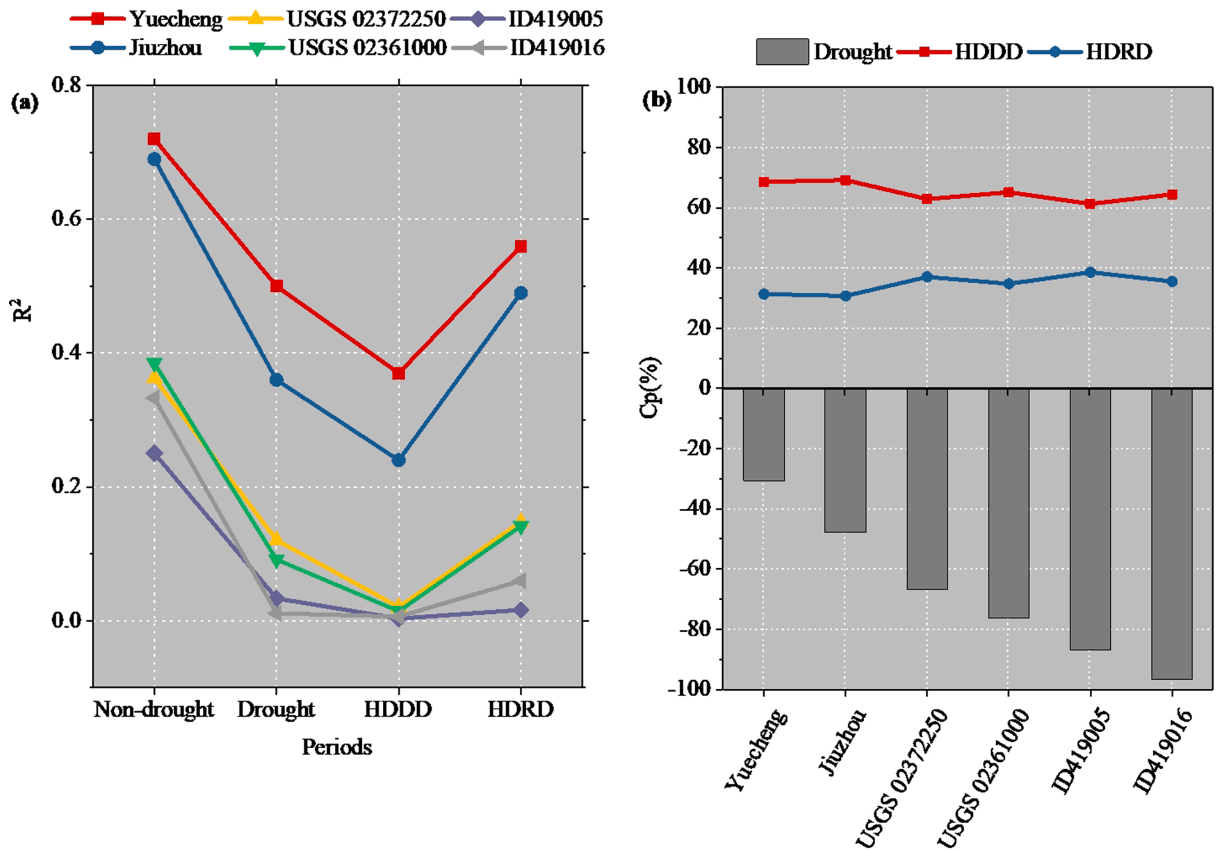

Fig. 4. The precipitation-streamflow relationships during the non-drought, drought, hydrological drought development (HDDD), and recovery (HDRD) periods (a); percentage change (Cp) in precipitation-streamflow relationship during hydrological drought development and recovery periods (Fig. 4(b) top); and percentage change (Cp) in the shifts in the precipitation-streamflow relationship driven by hydrologic droughts (Fig. 4(b) bottom).

droughts change the precipitation-streamflow relationship (Zhang et al., 2018; Saft et al., 2015). However, we investigated this relationship in greater details during the *HDD* and *HDR*. We found that the changes in the precipitation-streamflow relationship were more apparent during *HDD* periods than during *HDR*. In addition, hydrological drought has different impacts on the precipitation-streamflow relationship in different locations, which may be related to the differences in the climate and catchment characteristics (Saft et al., 2015; Van Loon et al., 2014; Van Loon, 2015; Yang et al., 2017; Zhang et al., 2018). For example, there were significant differences in the multi-year average runoff coefficients (Fig. 6) in the six study areas. The overall behavior of the multi-year average runoff coefficients (Fig. 6) was consistent with the percent changes in the precipitation-streamflow relationships (Fig. 4 (b)). In other words, the smaller the runoff coefficient, the more significant the change in the precipitation-streamflow relationship is expected during droughts.

Additionally, the proposed *ESPR* was used to analyze the feedback effect of the precipitation-streamflow relationship on hydrological drought evolution. As shown in the *ESPR* results (Section 4.2), this indicator appears to work well in describing the changes in hydrologic condition throughout the drought development and recovery. Previous studies have concluded that hydrological drought is caused by meteorological drought (Linsley et al., 1982; Van Loon, 2015; Liu et al., 2020) and several studies have investigated the response of hydrological drought to meteorological drought (Lorenzo-Lacruz et al., 2013; Pena-Gallardo et al., 2018; Wu et al., 2017, 2018b). Here, by investigating the precipitation-streamflow relationship throughout hydrologic drought, we strive to understand how this relationship changes and how it can be described using a generalized indicator. Fig. 7 shows the correlation between streamflow and other drought-related variables (i.e., precipitation, PET, soil moisture, and groundwater) during the drought and non-drought periods in two China hydrological stations. The figure shows that the correlations are significantly different between the drought and non-drought periods and across different variables. Fig. 7 highlights that while hydrological droughts are originated by deficit in precipitation, other variable such as PET and SM can also influence the process (Shao et al., 2019; Zhang et al., 2020). For simplicity, however, here we focused on an indicator between the two main drivers namely precipitation and streamflow.

Moreover, it is undeniable that the precipitation-streamflow relationship can be affected by non-climatic factors such as land use/cover change, change in irrigation pattern/intensity, groundwater withdrawal, surface water diversion and catchment characteristics (see *step 4* in Fig. 1) (AghaKouchak et al., 2015; Haslinger et al., 2014; López-Moreno et al., 2009; Mehran et al., 2015; Van Loon et al., 2014; Van Loon, 2015; Yuan et al., 2017; Zhang and Zhang, 2019). However, such changes occur often slowly and over a long period of time. We did not consider such external factors with the hope to develop a more generalized approach. For this reason, we focused on upstream basins with limited human impacts. Unraveling anthropogenic impacts on precipitation-streamflow relationship is more complex and warrants more in-depth research in the future (AghaKouchak et al., 2021).

5. Conclusions

We proposed a framework to analyze the interaction between hydrologic drought evolution and the precipitation-streamflow relationship. Hydrological drought evolution (i.e., development and recovery) was investigated using the variable threshold level and the run theory. Subsequently, the effects of hydrological droughts on the precipitation-

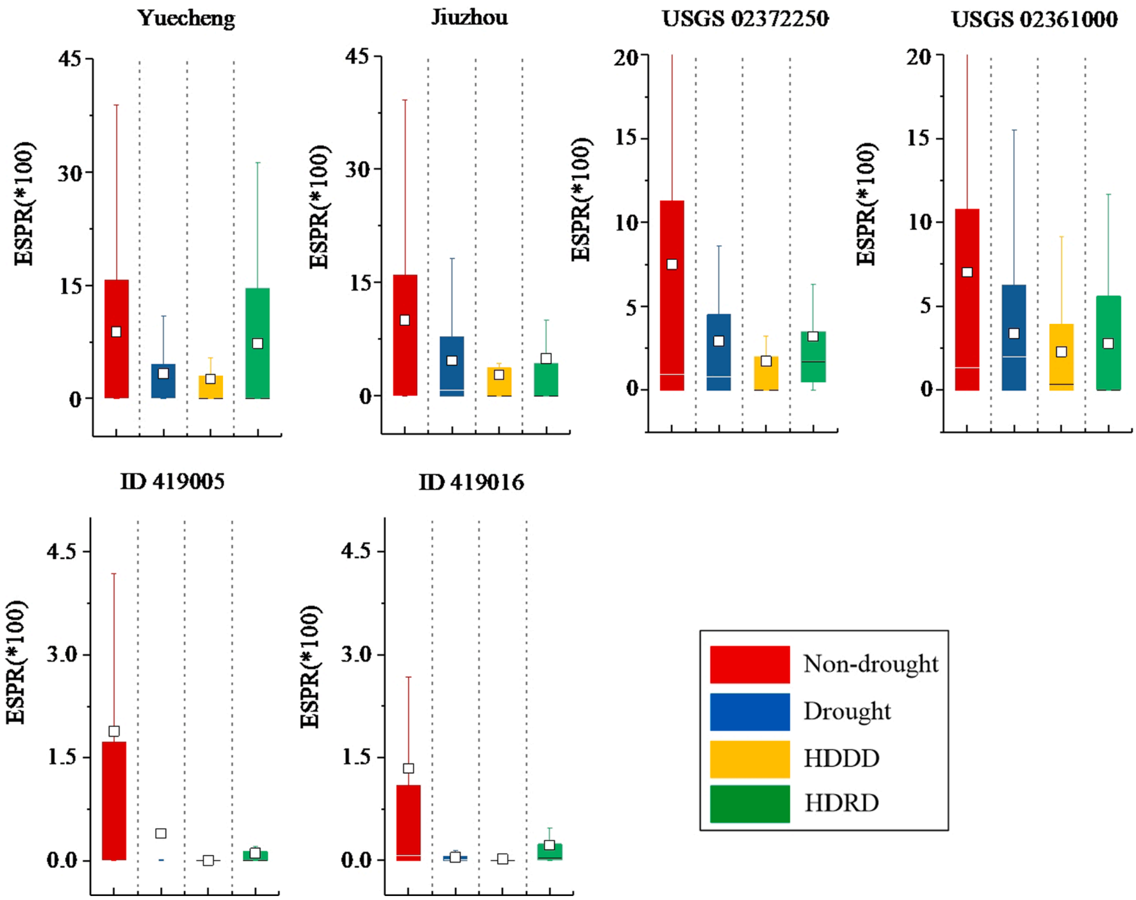

Fig. 5. The effective streamflow-precipitation ratio (*ESPR*) during non-drought, drought, drought development, and drought recovery periods.

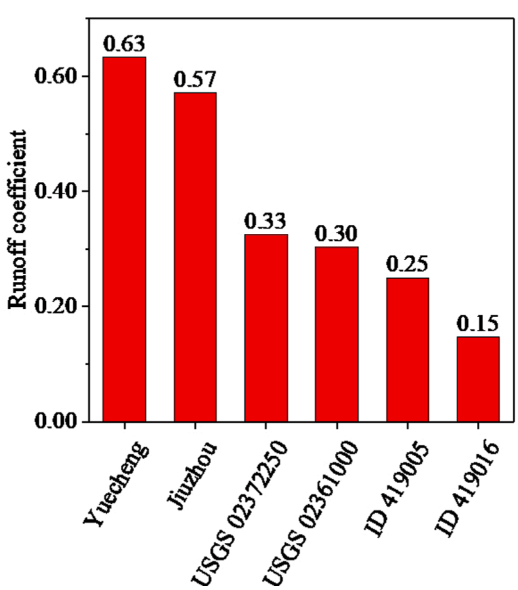

Fig. 6. The average annual runoff coefficient at the six hydrometric stations.

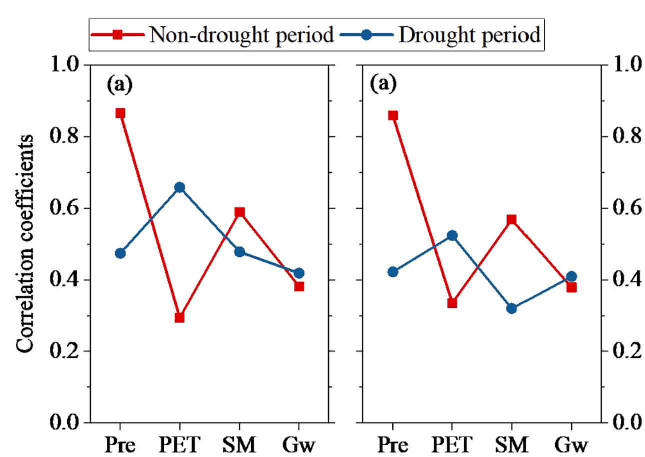

Fig. 7. The correlations between streamflow and drought-related variables (i.e., Pre, precipitation; PET, potential evapotranspiration; SM, soil moisture; GW, groundwater) in the China hydrological stations (a) Yuecheng, (b) Jiuzhou.

streamflow relationship were analyzed during hydrological drought development (*HDD*) and hydrological drought recovery (*HDR*). We also analyzed the feedback effect of shifts in the precipitation-streamflow relationship on hydrological drought evolution based on the effective streamflow-precipitation ratio (*ESPR*) indicator. The proposed framework was used to analyze drought conditions at six unregulated hydrologic stations in China, the USA, and Australia. The main conclusions are as follows:

(i) The average *HDD* period was longer than the average *HDR* period because the amount of effective streamflow generated by precipitation was lower during the *HDD* periods relative to the *HDR* periods.
(ii) The occurrence of hydrological droughts de-linearized the precipitation-streamflow relationship significantly, and the changes in the precipitation-streamflow relationship were

substantially different during the hydrological drought development and recovery. The observed changes in precipitation-streamflow relationship were more pronounced during the *HDD* periods.
(iii) The *ESPR* can be regarded as a suitable indicator to evaluated changes during hydrological drought evolution (development and recovery) at the watershed scale. The hydrological drought worsens as the *ESPR* approaches 0 during *HDD* periods. Generally, the larger the *ESPR* during the *HDR*, the faster the recovery occurs, and vice versa.

Drought-related variables typically exhibit some level of relationship. However, the underlying relationships are often complex and variable in different locations. For instance, many studies have showed that PET (Teuling et al., 2013), geology (Stoelzle et al., 2014), groundwater (Haslinger et al., 2014; Parry et al., 2018), land surface (Liu et al., 2017), and various human activities (e.g. reservoir regulation) (Chang et al., 2019; Tijdeman et al., 2018; Yuan et al., 2017) influence hydrological drought evolution in a variety of ways (directly or indirectly). The anthropogenic component cannot be generalized and requires case-by-case analysis. In general, the precipitation-streamflow relationship is more pronounced than other variables. Hence, in this study we focused on describing hydrologic droughts and their changes using an indicator based on precipitation and streamflow. We are not considering the impact of different streamflow generation mechanisms on the hydrological drought development and recovery patterns. We believe that in most cases, the effects of soil moisture, groundwater, and land surface condition are somewhat captured in streamflow. Anthropogenic changes can also alter the precipitation-streamflow relationship in complex ways. More research should focus on how anthropogenic impacts change the precipitation-streamflow relationship and hence, hydrologic droughts.

CRediT authorship contribution statement

Jiefeng Wu: Conceptualization, Methodology, Writing - original draft, Funding acquisition. **Xiaohong Chen:** Supervision, Project administration, Data curation. **Xing Yuan:** . **Huaxia Yao:** Writing - review & editing. **Yunxia Zhao:** Data curation. **Amir AghaKouchak:** Writing - review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2021.126210.

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