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 (Talakkens 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;
commonly used to investigate the possible hydrologic responses to throughout the drought onset, development, and recovery periods. These studies primarily focused on the times, was also investigated in recent studies (i.e., Parry et al., 2016a, 2016b; Wu et al., 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, 2016b; 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 (R²) to explore changes in the precipitation-streamflow relationship in different periods (Sanakasubramanian 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
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 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 during the hydrological drought period (Van Loon, 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 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).

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, D, and D 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, HD, and HD) (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).

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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.

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:

$$C_p = \frac{\lambda_1 - \lambda_2}{\lambda_2} \times 100$$

(1)

where the $C_p$ is the contribution percentage to the shifts in the precipitation-streamflow relationship in a drought period compared to a non-drought period. $\lambda_1$ and $\lambda_2$ 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 HHRD), we can use their corresponding $R^2$ values in Eq. (1). This allows obtaining 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., m³/s), calculating the ESPR requires a third variable, that is, the runoff depth (RD). Hence, the ESPR is defined as follows:

$$ESPR = \frac{\Delta RD}{P_f} \times 100 = \left( \frac{1}{P_f} \times \frac{W}{1000F} \right) \times 100$$

(2)

where $\Delta RD$ is the absolute value of the increase in RD in the current month compared to the last month. $P_f$, $W$, 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 (m³/s), total runoff volume in a certain period (e.g., $\Delta t_j$) (unit: m³), and catchment area (km²), respectively. It should be noted that the $\Delta RD$ and actual RD are different; the actual RD is calculated from the actual flow in the current month and the $\Delta RD$ 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 Jiazhou, 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 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 humidity 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...
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
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 02361000, 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 HDDDs 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 HDRDs 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 HDRD 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...
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 hydrologically 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-streamflow relationship were examined using the runoff coefficient and runoff ratio. The ESPR was used to analyze the feedback effect of the precipitation-streamflow relationship on hydrological drought evolution. The proposed framework provides a useful tool for understanding the dynamics of precipitation-streamflow relationship during hydrological drought.

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).

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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

![Fig. 5. The effective streamflow-precipitation ratio (ESPR) during non-drought, drought, drought development, and drought recovery periods.](image1)

![Fig. 6. The average annual runoff coefficient at the six hydrometric stations.](image2)

![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.](image3)
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 HDD, 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 shown 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 regulations) (Chang et al., 2019; Tijdenman 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. Yuxia 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

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References


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