



Changes in drought propagation under the regulation of reservoirs and water diversion

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Abstract

Drought propagation is very significant for short-term drought forecast and water resources management. However, the law of drought propagation is still unclear, especially with human activities. In this study, we calibrated and validated the SWAT model in the Luanhe River basin controlled by the Luanxian hydrological station, where there are three large reservoirs upstream and water diversion to Tianjin city. The variable threshold level (VTL) method was employed to identify meteorological and hydrological events both under natural and reservoir-influenced conditions. Drought occurred more frequently, drought duration became longer, and drought deficit became larger with the influence of reservoir regulation and water diversion to Tianjin city. The lag time of hydrological drought onset was shorter and termination longer, i.e., the drought period was more persistent. Multiple regression was used to establish the relations between hydrological drought and the driving factors both under natural and reservoir-influenced conditions. The coefficient of determination is high enough to explain drought propagation. The driving factors were different under the two conditions. The results could provide valuable information for water resource managers.

1 Introduction

Drought is a natural hazard that occurs not only in arid climate regions but also in semi-arid and semi-humid climate regions, even in humid area. It originates from a period of precipitation deficiency, which is classified as a meteorological drought. The precipitation deficit results in soil moisture and streamflow decrease, which is called agricultural and hydrological drought, respectively. The development from meteorological drought to agricultural and hydrological drought is defined as drought propagation.

The topic of drought propagation has been widely studied over the past years. The first step is to identify drought events of each drought type. Therefore, numerous drought indices

were proposed corresponding to each drought type over different study areas. Standardized precipitation index (SPI) is a well-known meteorological drought index which was presented by McKee et al. (1993). Analogous to SPI, some other standardized drought indices were developed, such as standardized hydrological index (SHI) (Sharma and Panu 2010), standardized runoff index (SRI) (Shukla and Wood 2008), standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010). The Palmer drought severity index is also a widely used drought index for addressing long-term drought (Guttman 1998; Wang et al. 2015). These indices are generally on monthly or longer timescales, and it is unsuitable for drought events with short duration, i.e., 1–29 days. The threshold level method (TL) could identify drought events on any timescales (Yevjevich 1967), which can be a fixed or variable threshold. The 70th–90th percentile for a hydrometeorological time series was recommended as the threshold (Van Loon 2015). Drought events are recognized when the precipitation/streamflow values are below a predefined threshold. Based on the identification of different types of drought events, the features of drought propagation could be summarized through pooling, attenuation, lag, and lengthening (Van Loon et al. 2014). The propagation of drought shows different patterns among different areas, since it is controlled by climate and catchment characteristics. Yang et al. (2017) examined the lags in hydrologic recovery from

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the Millennium meteorological drought in South Australia in 130 unimpaired catchments. They found that the recovery rate of meteorological drought was more significant than catchment landscape in the lags of hydrological recovery. Mo (2011) analyzed the drought onset and recovery over the USA, and the results showed most of the meteorological droughts were earlier than the agricultural droughts, but a few agricultural droughts occurred before the meteorological droughts in drought propagation.

The patterns of drought propagation in natural condition are not applicable in a disturbed watershed due to human activities (Van Loon et al. 2016). Reservoir construction is one of the significant control factors which can lead to changes in drought propagation through changes in the runoff process. Wu et al. (2017) studied the nonlinear relationship between hydrological and meteorological drought on a monthly timescale in the Jinjiang River basin of China and found that the relationship between hydrological and meteorological drought became stronger under the influence of a reservoir regulation. Under the same meteorological drought condition, the hydrological drought was somewhat alleviated with the impact of reservoir. Rangecroft et al. (2016) concluded that the Santa Juana dam in Chile could alleviate hydrological drought's downstream. Li et al. (2011) also found the regulation of reservoir mitigated the downstream hydrological drought. However, the regulation of reservoir does not affect the hydrological drought in the same way. Lopez-Moren et al. (2009) analyzed the effect of the Alcántara reservoir on the Tagus River and found that the downstream experienced more severe droughts than upstream part both in duration and magnitude. Zhang et al. (2015) took cascade reservoirs in the Huaihe River of China as an example and pointed out that the reservoirs reduced hydrological drought frequency and extended the duration.

Most previous studies about the reservoir's impact on drought propagation were conducted by a correlation analysis on monthly scale and could not reflect the mechanism of propagation. Therefore, this paper is aimed at analyzing the impact of a reservoir on drought propagation on a daily scale by a multi-regression analysis. The results could provide valuable information for water resource managers in drought condition.

2 Study area

The Luanhe River basin is located in the northeast part of China, which is between 115°30'E-119°15'E and 39°10'N-42°30'N (Fig. 1). The Luanhe River has a total drainage area of 44,600 km², including plain,

mountains, and plateaus with altitude ranging from 2 to 2205 m.

The basin belongs to a temperate semi-arid and semi-humid continental monsoon climate with cold winter and hot summer. Annual average temperature is -0.3~11 °C. Annual potential evaporation is 950~1150 mm. Average annual precipitation is 535 mm, with 70%~80% falling in the flood season (June–September).

To alleviate the water crisis in Tianjin city, which is a significant city of China, a water transfer project from the Luanhe River basin to Tianjin was built, and the Panjiakou Reservoir, Daheiting Reservoir, and Taolinkou Reservoir were constructed. The Panjiakou Reservoir located in Tangshan city with a storage capacity of 29.3×10^8 m³, which was impounded in 1980. The Daheiting Reservoir located downstream 30 km away from the Panjiakou Reservoir, which was completed in 1982. The Taolinkou Reservoir located on a tributary (Qinglong River) of the main stream, with a storage capacity of 8.59×10^8 m³. The regulation of the three reservoirs and water transfer to Tianjin from the Daheiting Reservoir influenced the runoff at the Luanxian hydrological station, and therefore, influenced drought propagation from meteorological to hydrological drought.

The Luanhe River basin suffered from severe droughts in 1972, 1980–1984, and 1997–2005 (Ma et al. 2013). The annual runoff in this basin showed a significant decrease trend and resulted in a long hydrological drought during the last decade, which affected the water supply to Tianjin and Tangshan cities. Therefore, it is of great significance to select the Luanhe River basin as the study area to research drought propagation under the influence of reservoir regulations and water diversion.

3 Data and methods

3.1 Data

Daily precipitation data covering the period from 1963 to 2012 were available at 13 rain gauges and 5 weather stations. Daily streamflow data corresponding to the daily precipitation data at the Luanxian station were also available to analyze the simultaneous meteorological and hydrological droughts. Both the precipitation and runoff data were provided by the Hydrology and Water Resource Survey Bureau of Hebei province. Remotely sensed land use data of 1970 were used to simulate the natural streamflow at the Luanxian station, which was provided by the Chinese Academy of Sciences (Fig. 2).

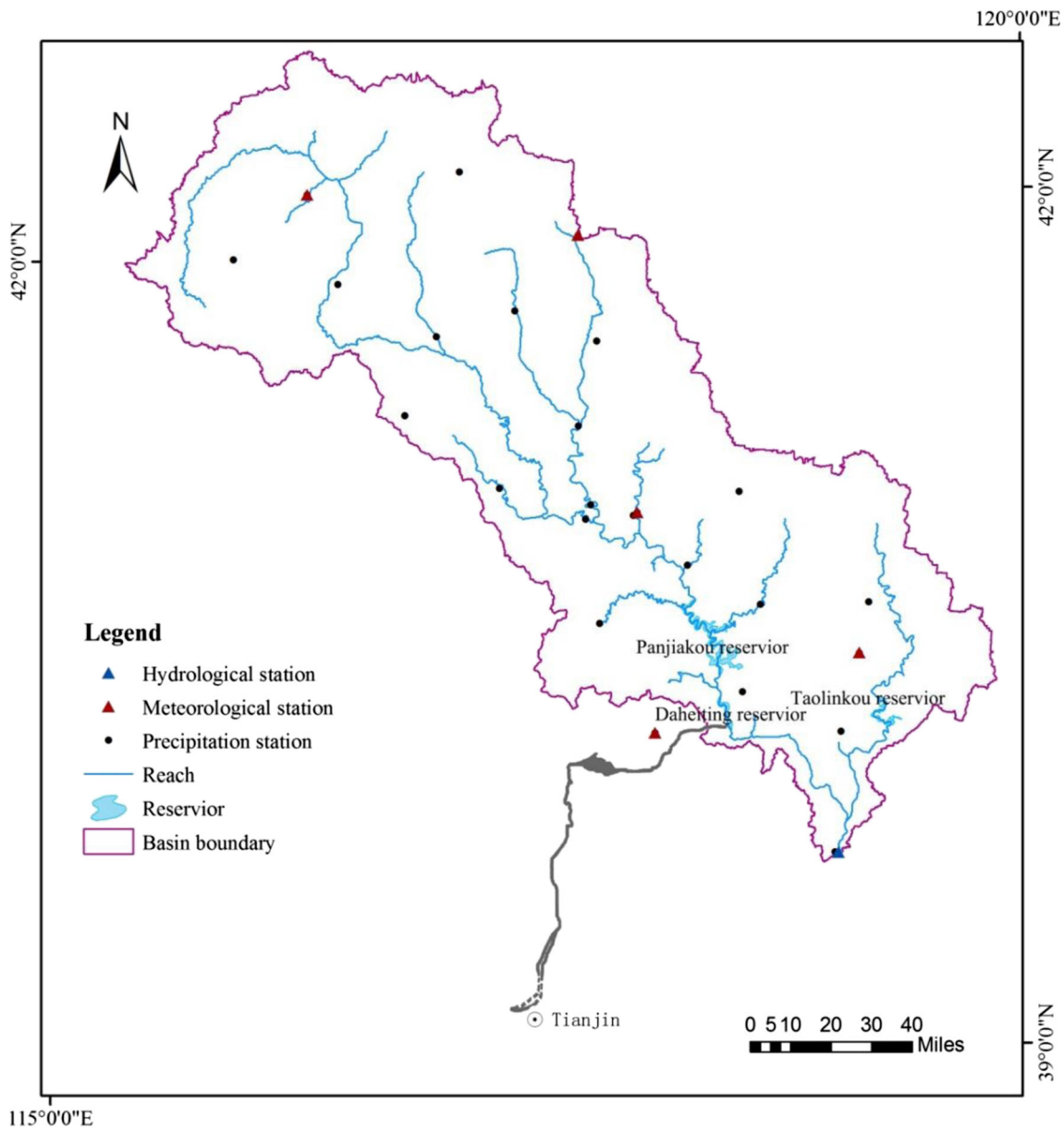


Fig. 1 Luanhe River basin and the reservoirs

4 Methods

4.1 Simulation of daily runoff in natural condition

The Soil and Water Assessment Tool (SWAT) was applied to simulate the daily runoff at the Luanxian hydrological station. The SWAT was widely used in water resource assessment, the impact of climate change and land use change on water resources and water pollution, etc. (Wang et al. 2014; Ahn and Merwade 2017). The daily precipitation and streamflow data from 1963 to 1979 were used for SWAT calibration and validation, because this

period was not influenced by human activities, and can be considered as a natural condition (Li et al. 2016), and the period of 1980–2012 was influenced by reservoirs.

The model performance is assessed by the Nash-Sutcliffe model efficiency coefficient (Ens) and the coefficient of determination (R^2), calculated as

$$ENS = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (1)$$

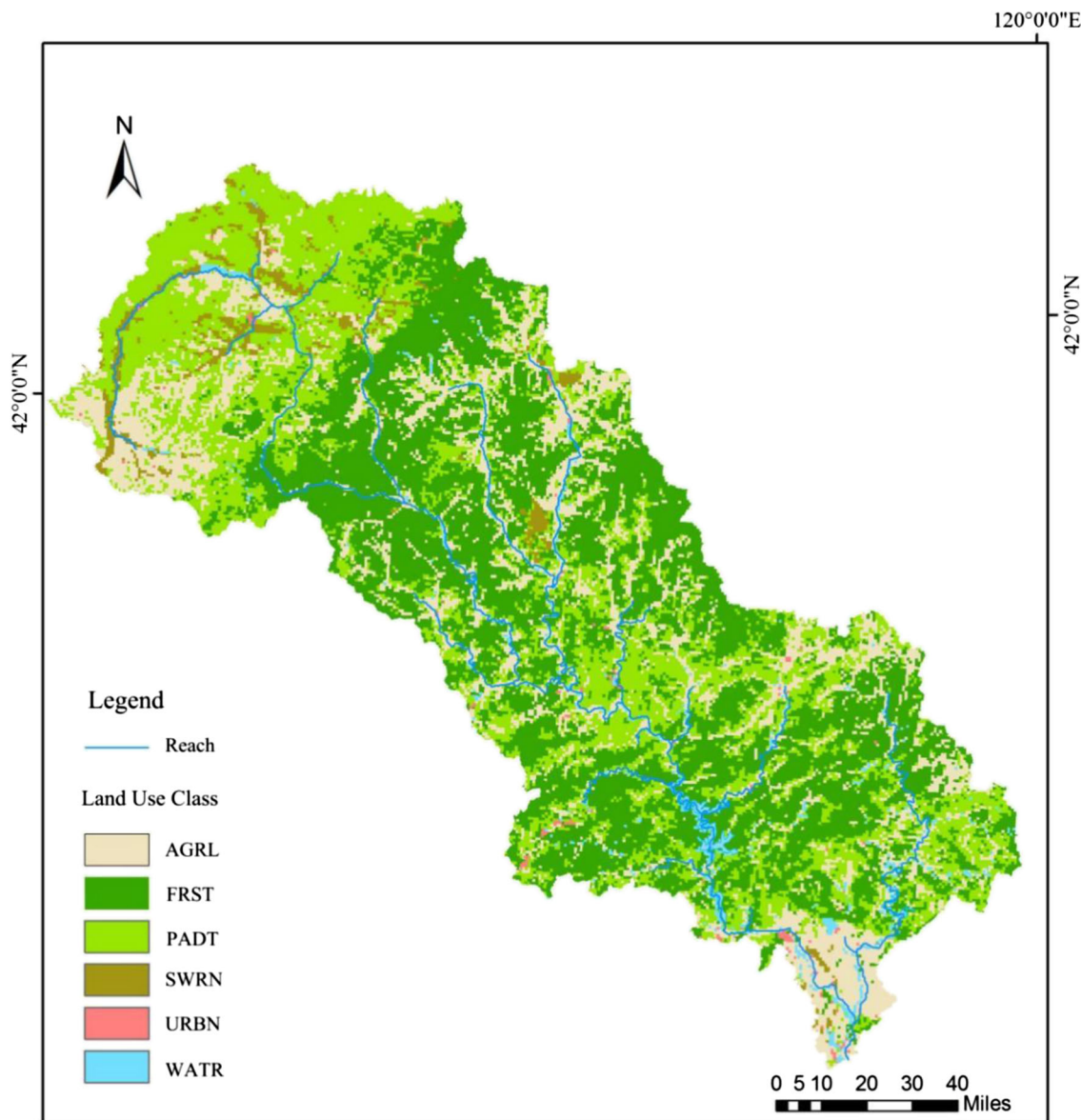


Fig. 2 Remotely sensed 1970 land use

$$R^2 = \frac{\left[\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S}) \right]^2}{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (S_i - \bar{S})^2} \tag{2}$$

where S_i and O_i are simulated and observed discharge, respectively. \bar{O} is the average of the observed discharge. In general, the performance of the model is acceptable if $Ens > 0.5$ (Moriassi et al. 2007).

4.2 Variable threshold level method

Drought event can be considered a period during which the precipitation/streamflow values are below a certain threshold.

The variable threshold level (VTL) method, which was proposed by Van Loon et al. (2014), was proven to be reasonable. The 80th percentile is frequently applied as the threshold, and this method has been used in the Luanhe River basin to identify the spatial and temporal distribution of droughts (Zhou 2015).

A drought event is defined as the following equations (Heudorfer and Stahl 2017):

$$\delta(t) = \begin{cases} 1 & \text{if } x(t) < \tau(t) \\ 0 & \text{if } x(t) \geq \tau(t) \end{cases} \tag{3}$$

Where x is the precipitation/streamflow series; τ is the predefined threshold value; t is the time; δ refers to the binary variable, which is used to identify if the variable x lies in a drought situation on day t .

The duration of a drought event i (Δ_i) can be calculated as

$$\Delta_i = \sum_{t=1}^T \delta(t) \cdot \Delta t \quad (4)$$

The deficit volume is viewed as the most appropriate characteristic to measure the severity of drought.

$$d(t) = \begin{cases} \tau(t) - x(t) & \text{if } x(t) < \tau(t) \\ 0 & \text{if } x(t) \geq \tau(t) \end{cases} \quad (5)$$

where $d(t)$ is the deviation from the threshold value τ on the day t .

$$D_i = \sum_{t=1}^T d(t) \cdot \Delta t \quad (6)$$

where D_i refers to the deficit volume of drought i .

4.3 The influence of reservoir on drought propagation

The relation of hydrological drought with the meteorological drought and other contributing factors will be established to illustrate the propagation from the meteorological to hydrological drought in both natural and reservoir-influenced conditions. In order to analyze the influence of reservoir regulation and water diversion on drought propagation, the following steps should be followed.

1. The natural daily streamflow during the period of 1980–2012 should be simulated first by the calibrated SWAT model.
2. By applying the same VTL values to the observed daily streamflow at the Luanxian hydrological station, the hydrological drought events will be identified under the influence of reservoir regulations and water diversion. Further, the impact of reservoir on drought characteristics will be investigated.
3. Change of drought propagation types and lag time affected by reservoir regulation will be investigated.
4. The potential contributing factors for drought propagation will be found to build the relation between hydrological drought and the contributing factors. Comparing the propagation equation in both natural and reservoir-influenced conditions, the differences in the contributing factors could be identified to analyze the impact of reservoir regulations and water diversion on drought propagation.

5 Results

5.1 Calibration and validation of SWAT model

The period before 1979 is undisturbed by human activities, especially without reservoirs in the Luanhe River basin.

Therefore, the years of 1963–1979 are considered undisturbed periods for model calibration and validation based on daily precipitation and discharges. Streamflow data from the Luanxian hydrological station are selected to calibrate and validate the SWAT model in the undisturbed period (1963–1979). The results are listed in Table 1. In the calibration period of 1963–1975, Ens and R^2 are greater than 0.65 and 0.65, respectively. Especially in monthly simulation, they are both 0.89. In the validation period (1976–1979), both Ens and R^2 of monthly simulation exceed 0.90 and the values of daily simulation is greater than 0.74. According to Moriasi et al. (2007), if the value of Ens is greater than 0.50, the SWAT model performs well.

Figure 3 depicts the simulated and observed runoff values on a daily scale at the Luanxian hydrological station, and it can be seen that the peak of simulated runoff is lower than the measured values, especially in 1964. The main reasons are that the underestimate of snowmelt runoff in the arid and semi-arid areas where the precipitation is scarce and the snowmelt runoff is an important source of supply during the spring flood. Figure 4 shows the scatter plot of observed and simulated daily discharge. The low flow is very close to 1:1-line, which agrees well with the observation in the undisturbed period. Compared with high flow, the model has a good performance to simulate low flow. Hence, this model can be used to simulate discharge without human influences during 1980–2012.

5.2 Impact of reservoir on drought characteristics

The same threshold levels for both natural and reservoir-influenced conditions were used to identify hydrological droughts, and the characteristics are listed in Table 2. The number of hydrological drought events with the influence of reservoirs and water diversion becomes less from 60 to 44, which seems that the hydrological droughts were mitigated. However, in terms of other characteristics (such as maximum and mean duration, maximum and mean deficit volume), the hydrological droughts were amplified. The maximum and mean durations are much longer from 250 to 688 days and from 50 to 180 days, respectively. The minimum duration keeps unchanged. The maximum and mean deficit volume becomes much higher from 11.20 to 71.57 mm and from 1.72 to 16.90 mm, respectively, while the minimum deficit volume is invariant. As to the total hydrological drought duration, they are 3000 and 7920 days for natural and reservoir-influenced conditions. And total hydrological drought deficit volume of all drought events during 1980–2012 were 103.2 and 743.6 mm under natural and reservoir-influenced conditions, respectively.

Therefore, the hydrological drought at the Luanxian station was amplified with the regulation of reservoirs and water diversion. It also can be seen from the change in median values

Table 1 Results of calibration and validation at Luanxian Station

| Luanxian station | Calibration period (1963–1975) | | Validation period (1976–1979) | |
|-------------------|--------------------------------|-------|-------------------------------|-------|
| | Ens | R^2 | Ens | R^2 |
| Monthly discharge | 0.89 | 0.89 | 0.96 | 0.95 |
| Daily discharge | 0.66 | 0.67 | 0.74 | 0.76 |

of duration and deficit volume, which become much higher from 28 to 206 days, and from 0.90 to 10.14 mm, respectively. In a natural watershed, the median values are lower than the mean, but higher than the mean with the reservoir regulations.

The relationship between deficit volume and duration was also examined under natural and reservoir-influenced conditions, which is shown in Fig. 5. The drought deficit volume is positively related to the duration. The plots were fitted using a linear equation, and the coefficient of determination was 0.59 and 0.95 under natural and reservoir-influenced conditions, respectively.

5.3 Impacts of reservoir regulation on drought propagation

5.3.1 Change in drought propagation types

Under the influence of reservoir regulation and water diversion, the propagation types (M, M-H, and NM-H) from meteorological drought to hydrological drought did not change, but the proportion of M events increased, the proportion of meteorological drought events that occurred in drought evolution decreased, and the average duration and average defect of NM-H events significantly increased. As can be seen from Table 3, compared with the case without considering the influence of a reservoir, the average duration of the meteorological drought of M-H event increased by 1.43 times, and the average deficit increased by 1.23 times. The average duration of the evolution of a hydrological drought increased by 4.4 times, and the average defect increased by 13.7 times. The average duration and average defect of the evolution of

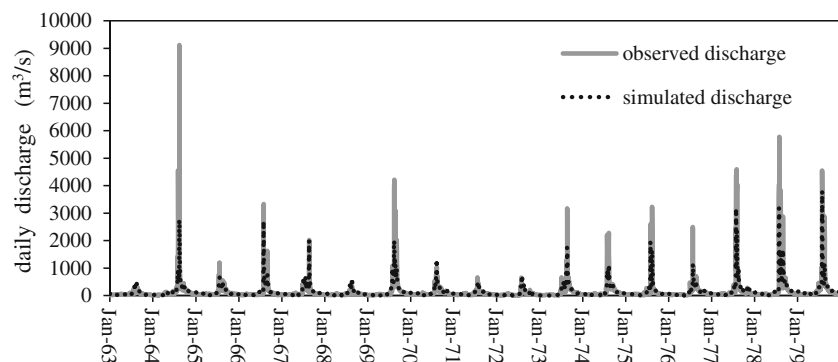
meteorological drought and hydrological drought evolving from meteorological drought is about 2 to 12 times as big as the case without considering the influence of the reservoir, which is related to the increase of the hydrologic drought duration and the reduction of drought frequency.

5.3.2 Change in lag time of hydrological droughts

Under the natural condition, 45 out of 60 hydrological drought events were developed from meteorological droughts during 1980–2012, which accounts for 75% of the total hydrological droughts. The average lag time of drought onset and end time from meteorological to hydrological droughts is 26.9 days and 47.7 days, respectively.

With the influence of the reservoirs, 16 out of 44 hydrological drought events were developed from meteorological droughts, which accounts for 36% of the total hydrological drought events. That means reservoir regulations influenced the occurrence of hydrological drought at the Luanxian station. Each of these 16 hydrological droughts was developed from the combination of several consecutive meteorological drought events and was characterized by a long hydrological drought duration from 159 to 688 days. The rainfall between the consecutive meteorological droughts recovered meteorological drought, but did not attenuate the hydrological drought because of the regulation of the reservoirs. The lag time from meteorological to hydrological droughts are listed in Table 4.

As to the lag time of hydrological drought onset, the maximum was longer with the regulation of the reservoirs, while the mean, median, and the minimum were shorter. For the lag time of drought end, all the maximum, mean, median, and

Fig. 3 The observed and simulated daily discharges during the undisturbed period (1963–1979)

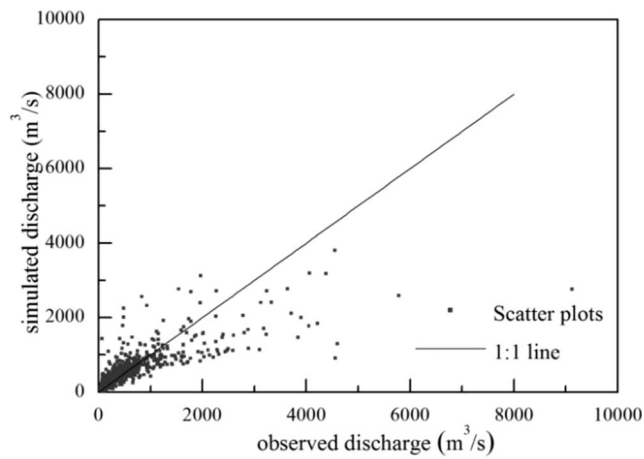


Fig. 4 Scatter plots of the daily simulated vs. observed discharge during 1963–1979 at the Luanxian station

minimum were longer with the influence of the reservoirs. Both the earlier lag time of drought onset and the delayed lag time of drought end resulted in the longer hydrological drought duration with the regulation of the reservoirs.

5.3.3 Change in the relations between hydrological droughts and the driving factors

The relations under natural condition The following factors are chosen as the driving factors for hydrological drought severity (DS_H): (1) simulated daily evapotranspiration during hydrological drought (E), (2) meteorological drought severity (DS_M), (3) simulated mean soil moisture deficit (SD), and (4) the summation of the difference between the daily precipitation and the long-term average daily precipitation 10 (PD_{10}), 20 (PD_{20}), 30 (PD_{30}), and 40 (PD_{40}) days before the hydrological drought. Then, the stepwise multiple regression method was used to establish the relation between hydrological drought severity (DS_H) and the driving factors, which is expressed as Eq. (7).

$$DS_H = 0.011^* \text{EXP}(1.130DS_M + 0.540E + 0.012SD - 0.035PD_{10}) - 0.008 \quad (7)$$

The coefficient of determination (R^2) for Eq. (7) is 0.656. The calculated DS_H and observed DS_H are plotted in Fig. 6. The plots are scattered symmetrically along the 1:1 line. Therefore, the equation can reflect the comprehensive impacts of the selected driving factors on the hydrological drought.

The relations under reservoir-influenced condition To test the applicability of Eq. (7) with the influence of the reservoirs, the values of the driving factors in Eq. (1) with the influence of the reservoirs are used to calculate the hydrological drought severity. The calculated hydrological drought severity by Eq. (7) and the observed values under the influence of the reservoirs are plotted in Fig. 7. Most of the plots are higher than the 1:1 line, which means the simulated values of the hydrological drought severity are larger than the observed ones. It confirms the results that the regulation of reservoirs amplified the downstream hydrological drought in section 4.1 in another way. Therefore, the development of the hydrological drought from meteorological drought under natural condition is not applicable in the reservoir-influenced condition, and the drought propagation mechanism has changed. It is necessary to find the new possible driving factors under the influence of the reservoirs.

Since hydrological drought is affected by the reservoirs through the regulation of the outflows and water diversion to Tianjin city, on the basis of driving factors under natural condition, regulated flow deviation (RFD) is proposed as a new driven factor, expressed as Eq. (8).

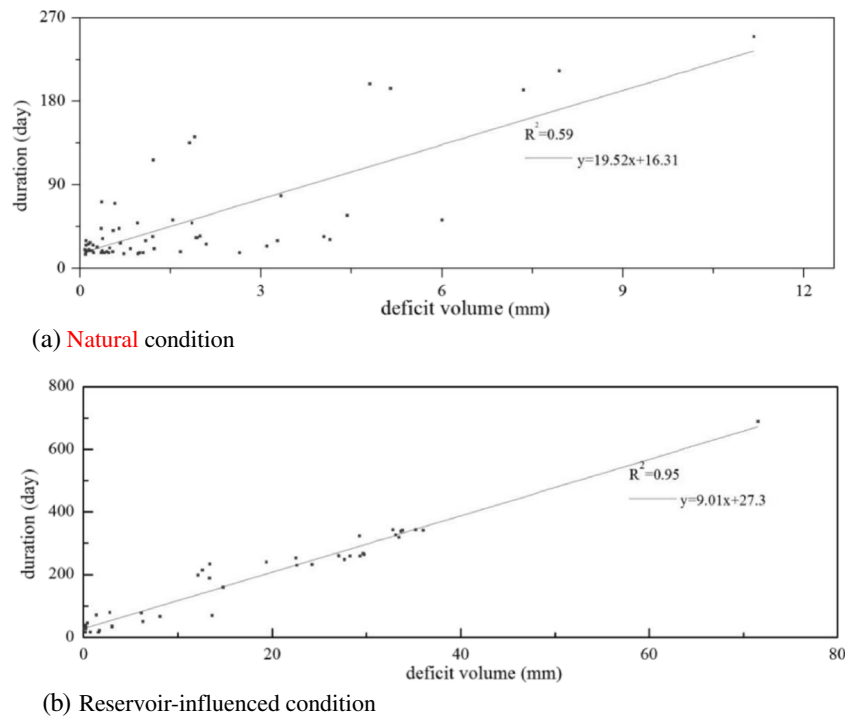
$$RFD = Q_{1i} - \overline{Q_{0i}} \quad (8)$$

where Q_{1i} is the observed discharge in the i th day with the influence of the reservoirs, $\overline{Q_{0i}}$ is the simulated mean discharge in the i th day of each year.

Table 2 The characteristics of the hydrological drought at the Luanxian station

| Hydrological drought | Times | | Duration (d) | Drought deficit (mm) |
|--------------------------------|-------|---------|------------------|----------------------|
| Reservoir-influenced condition | 44 | Maximum | 688 | 71.57 |
| | | Mean | 180 | 16.90 |
| | | Median | 206 | 10.14 |
| | | Minimum | 15 | 0.10 |
| | | Total | 7920 | 743.6 |
| Natural condition | 60 | Maximum | 250 | 11.20 |
| | | Mean | 50 | 1.72 |
| | | Median | 28 | 0.90 |
| | | Minimum | 15 | 0.10 |
| | | Total | 3000 | 103.2 |

Fig. 5 The relationship between hydrological drought duration and deficit volume under natural and reservoir-influenced conditions. **a** Natural condition. **b** Reservoir-influenced condition



A stepwise multiple regression analysis was conducted to establish the relation between hydrological drought severity and the driving factors under reservoir-influenced condition. Only DS_M and RFD were included in the equation, as Eq. (9).

$$DS_H = \text{EXP}(0.017DS_M - 0.001RFD) - 1.007 \quad (9)$$

The coefficient of determination (R^2) for Eq. (9) is 0.854. The calculated DS_H and observed DS_H are plotted in Fig. 8, and we can see that the plots are scattered along the 1:1 line. Therefore, the equation can explain the hydrological drought development from meteorological drought and the regulation of the reservoirs. Evapotranspiration and soil moisture have little impact on hydrological drought with the influence of the reservoirs.

6 Discussion

The regulation of hydraulic structures has impacts on streamflow downstream; therefore, the propagation from meteorological to hydrological drought will change compared with the propagation under natural condition. Drought propagation with the influence of a reservoir could provide significant information for drought forecast and water resource management.

To study the impact of a reservoir on hydrological drought downstream, the ideal method is to compare the results in a pair of similar experiment watersheds with and without the reservoirs. However, the real similar watershed is not easy to find in terms of geography, climate, and land surface. Under this background, hydrological modeling is another effective

Table 3 Comparison of drought propagation characteristics between 1980 and 2012 under natural and reservoir-influenced conditions

| Drought types | Drought propagation | Proportion of drought events (%) | | Average duration (d) | | Average deficit (mm) | |
|------------------------|---------------------|----------------------------------|-------|--------------------------|-------|----------------------|-------|
| | | N | R | N | R | N | R |
| Meteorological drought | M (-NH) | 42.20 | 70.10 | 24.4 | 21.2 | 2.71 | 3.52 |
| | M-H | 57.80 | 29.90 | 23.7 | 57.7 | 7.96 | 17.76 |
| Hydrological drought | NM-H | 28.80 | 47.40 | 34.2 | 172.3 | 0.97 | 16.78 |
| | M-H | 71.20 | 52.60 | 46.9 | 229.9 | 1.72 | 22.02 |

M means meteorological drought only, M-A/M-H means meteorological drought develops into agricultural and hydrological droughts, NM-A/NM-H means no meteorological drought but agricultural and hydrological droughts occur; N means natural condition; and R means reservoir-influenced condition

Table 4 The lag time of hydrological drought from meteorological drought

| | | Lag time (d) | |
|---------------------|---------|-------------------|--------------------------------|
| | | Natural condition | Reservoir-influenced condition |
| Drought onset | Maximum | 66 | 74 |
| | Mean | 26.9 | 23 |
| | Median | 26 | 21.5 |
| | Minimum | 10 | 0 |
| Drought termination | Maximum | 226 | 210 |
| | Mean | 47.7 | 87.4 |
| | Median | 32 | 71 |
| | Minimum | 19 | 5 |

way (Wan et al. 2017). In this study, we modeled the natural streamflow under natural condition during the reservoir-regulated period by using the calibrated SWAT model. Although there existed an error and uncertainty in the model, the modeling results could provide reliable hydrological drought.

The observed streamflow was influenced by three large reservoir regulations, and also by water diversion from the Luanhe River to Tianjin city, which exacerbated hydrological drought downstream. Therefore, the effect of a reservoir regulation on the hydrological drought downstream in real condition was smaller than the results in this study. But the daily flow from the Luanhe River to Tianjin city cannot be collected, we have to analyze the comprehensive effect of reservoir and water diversion on hydrological drought downstream. The results in this study was opposite with the previous studies in the influence of a reservoir on the hydrological drought (Rangecroft et al.

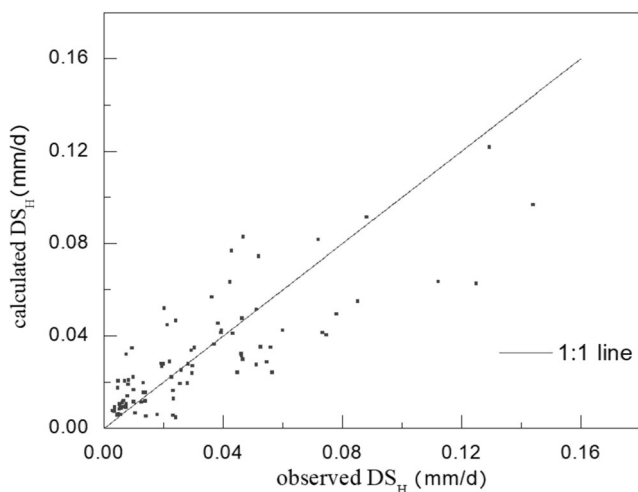


Fig. 6 Scatter plots between calculated and observed DS_H

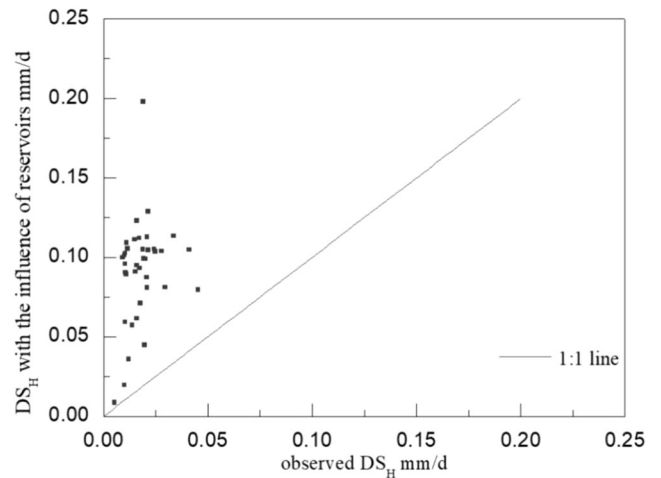


Fig. 7 The calculated DS_H using Eq. (7) under reservoir-influenced condition vs. the observed DS_H

2016; Li et al. 2011). Intuitively, in the case of reservoirs, one would assume that rainy season water fills the reservoirs, then smoothing the ups and downs of streamflow, when the water is then released from the reservoirs at more or less constant rates. But the regulation of the three reservoirs and water transfer to Tianjin from the Daheiting Reservoir influenced the runoff at the Luanxian hydrological station; therefore, it influenced drought propagation from meteorological to hydrological drought. The annual runoff in this basin showed a significant decrease trend, and resulted in a long hydrological drought during the last decade, which affected the water supply to Tianjin and Tangshan cities. Therefore, the reservoir regulation and water diversion aggravated the hydrological drought in the Luanhe River basin.

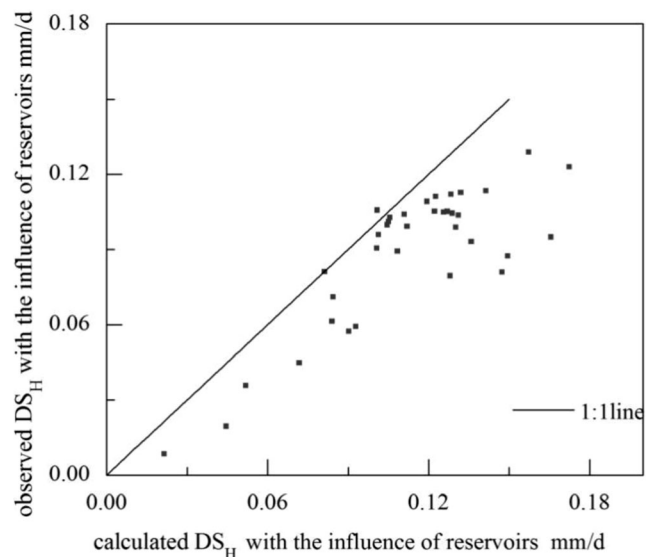


Fig. 8 The calculated and observed DS_H with the influence of reservoirs

The procedure in drought propagation in previous studies is pooling, attenuation, lag, and lengthening (Van Loon 2013). On the basis of the procedure, we further analyzed the driving factors of drought propagation under natural and reservoir-influenced conditions. The regression equation could reflect drought propagation under natural condition; however, the equation under reservoir-influenced condition was not accurate enough. This implies that there might be other potential driving factors except for the meteorological drought and reservoir regulation. We need to further analyze the water diversion project from the Luanhe River to Tianjin city in the future work.

7 Conclusions

The regulation of reservoirs had affected the hydrological drought at the Luanxian station significantly. Compared with the drought propagation under natural condition with reservoir-influenced condition, we could get the following conclusions.

1. The SWAT model was calibrated and validated at the Luanxian station using daily meteorological and streamflow data during the undisturbed period (1963–1979), and then, the daily streamflow under natural condition was simulated during the reservoir-influenced period (1980–2012). On the basis of streamflow simulation, hydrological drought characteristics were identified under natural and reservoir-influenced conditions. With the regulation of the reservoirs and water diversion, the hydrological drought duration became longer, and drought deficit became larger.
2. The impact of reservoir regulation and water diversion on drought propagation was significant. Under the influence of the reservoir, three drought propagation types did not change, but the drought characteristics of each type changed. Most of the meteorological drought did not transform into a hydrological drought under the influence of the reservoir. The lag time from the meteorological to hydrological drought was shorter for onset and longer for termination. The driving factors of the hydrological drought under natural condition were E , DS_M , SD , and PD_{10} , but under reservoir-influenced conditions they were DS_M and RFD . The relationship between hydrological drought and the driving factors which we built could provide a tool for drought propagation research.
3. Further research should be conducted to study the amplification mechanism of the hydrological drought under the influence of reservoir regulations and to find coping strategy to minimize the negative effects of reservoir regulation.

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