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An improved methodology for quantifying the impact of human activities on hydrological drought change

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A R T I C L E I N F O

Keywords:
Dry-wet hydrological changes
Climate change
Human activities
Quantifying

A B S T R A C T

Study region: Upper Shiyang River in the eastern Qilian Mountains, China.

Study focus: Quantifying the impacts of anthropogenic and climate change on wet and dry hydrological variability was done by improving the Slope Change Ratio of Cumulative Quantities (ISCRCQ) method.

New hydrological insights for the region: The scientific method is critical to quantify the driving factors of dry-wet hydrological changes. In this study, the slope change ratio of cumulative quantity (SCRCQ) method was improved to quantify the impacts of human activities and climate change on dry-wet hydrological changes. The results show a hydrological aridification trend at an annual scale from 1961 to 2016 in the upper reaches of the Shiyang River. However, the dry-wet hydrological change trends of the six tributaries differed: the hydrological humidification of the four western tributaries was apparent, while the remaining tributaries showed hydrological aridification. The influences of human activities and climate change on dry-wet hydrological changes were also evidently distinct in the different tributaries. Changing in climate is a vital factor triggering the dry-wet hydrological changes in the western tributaries, while human activities have completely changed the direction of the dry-wet hydrological changes and intensified the hydrological aridification in the eastern tributaries. Human activities have resulted in an increase both in the frequency of droughts and in the risk of socio-economic droughts. Thus, human activities in the region of eastern tributaries should be controlled within reasonable limits.

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1. Introduction

In the context of global change, the impacts of drought are becoming increasingly complicated (Zelenhasić and Salvai, 1987; Xiao et al., 2012; Ahmadi and Ahmadalipour, 2019) due to its broad impact and heavy losses, therefore, drought is recognized as one of the world's serious natural disasters (Zheng, 2000). Droughts can be divided into four categories (Richard and Heim, 2002). Among them, hydrological drought is defined as a specific period of time in which the runoff of a river is below the normal level or the water level of an aquifer decreases (Dong and Xie, 2014). Hydrological drought is the inheritance, continuation, and development of meteorological drought (Wu, 2017), and is also an intermediate link that leads to agricultural and socioeconomic drought (Richard and Heim, 2002). Numerous academics have verified that the hydrological drought situation in the world is severe (Zhang et al., 2020; Pi, 2019; Sun et al., 2018; Zhao et al., 2020). Therefore, it is necessary and urgent to clarify the process and the driving mechanism of dry-wet hydrological changes to provide a basis for making decisions that will allow for the wise use of local water resources and the development of plans for disaster mitigation and prevention. (Dai et al., 2019).

Dry-wet hydrological changes are the consequence of climate change and human activities. Quantitative assessment of the effects of human activities and climate change on hydrological variability in different areas is important for the rational allocation and prediction of water resources, which has become an issue of global concern (Meng, 2020; Van Loon et al., 2016; Wang et al., 2019). Currently, the key step in the quantitative assessment of the effects of anthropogenic and climate change on dry-wet hydrological variability is separating their effects on drought. The main research methods include the similar watershed comparison method (Van Loon and Van Lanen, 2013; Zhou et al., 2019; Wu et al., 2018; Wu et al., 2017a, 2017b, 2017c), the "upstream-downstream" method (Lin et al., 2017), hydrological model simulation (Chen et al., 2020a, 2020b; Wang et al., 2019), the tributary comparison (Li et al., 2020), and hydrological time series decomposition and statistical analysis (Zhu et al., 2019; Sadri et al., 2015).

Hydrological time series decomposition and statistical analysis methods have clear principles and strong operability. Among them, although previous statistical methods initially revealed the natural and unnatural contributions of runoff changes in individual tributaries, there were many problems, and some results might not be reliable (Wang et al., 2012). Wang et al. concluded that the cumulative anomaly method of runoff and precipitation is reliable in judging the turning year, and the correlation coefficient of the fitted relationship can be greatly improved by using the linear fitting method of year-cumulative volume curves with the turning point year as the boundary, and the method of the slope change ratio of cumulative quantity (SCRCQ) is proposed to quantify the contribution rate of the climate and human activities to runoff. And wang et al. applied the method in the Yellow River Basin several times

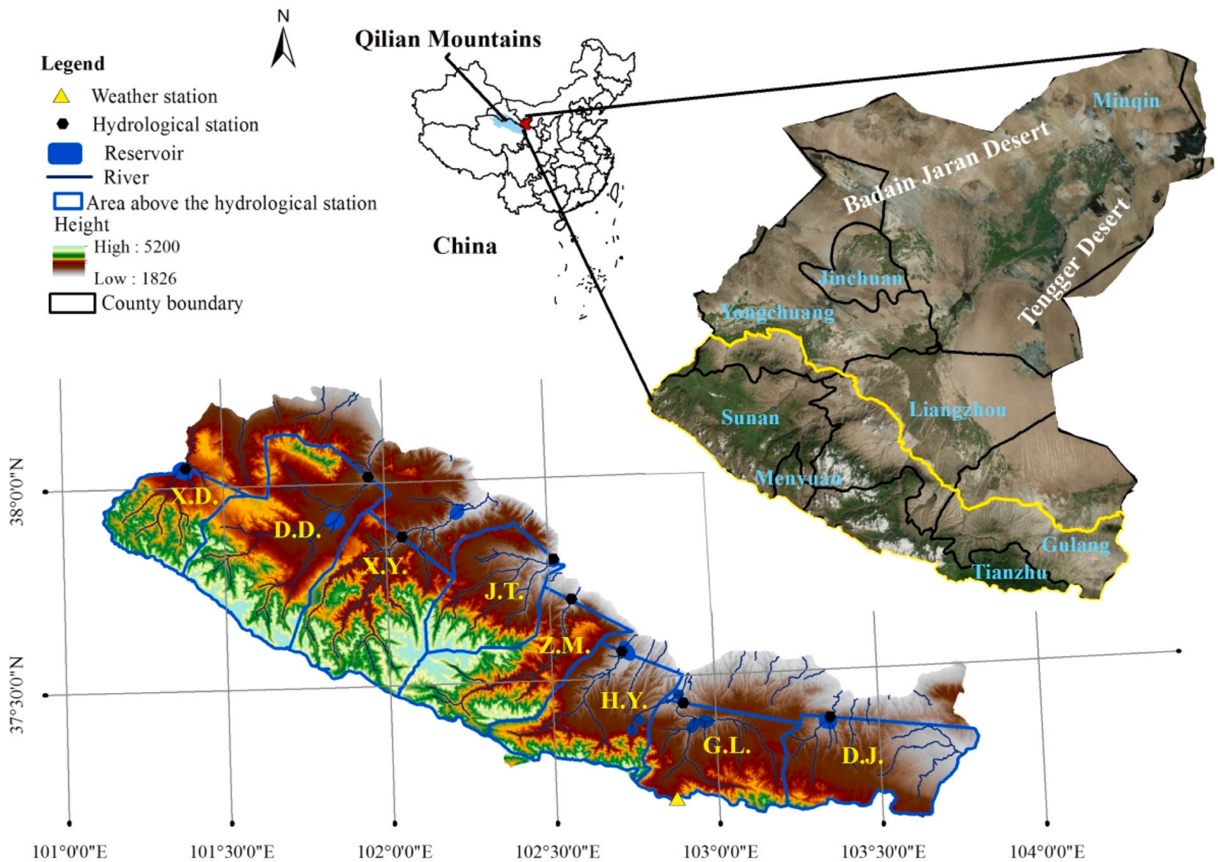

Fig. 1. Overview of the study area.

(Wang et al., 2012, 2013a, 2013b). Subsequently, the method has been widely applied to major river basins around the world to explore the contribution of factors to runoff changes, such as the Daihai Lake Basin (Wang et al., 2021), Pearl River (Mo et al., 2023), Jinsha River (Zhang et al., 2021), Poyang Lake Basin (Wang et al., 2020a, 2020b) in China, the Iranian Minab River (Mikaeili and Shourian, 2023), and so on. The methodology has also been extended to explore other areas related to runoff change, for example, quantifying the impacts of climate change and human activities on streamflow and hydrological components (Shi et al., 2023), exploring the role of ecological restoration on groundwater restoration (Luan et al., 2023), determining which factors contribute most to the variability of Dissolved organic carbon loading in the watershed (Wu et al., 2023), exploring the relative contribution of climate change and ecological restoration to runoff change (Lian et al., 2020a, 2020b; Wu et al., 2017a, 2017b, 2017c) and other areas. The method of SCRCQ has relatively low data richness requirements and has been considered to be a more accurate way to isolate the impact of human activities and climate change on dry-wet hydrological changes. Therefore, this method has been generally applied in related studies of different river basins (Lian et al., 2020a, 2020b; Wang et al., 2019; Cheng et al., 2019a, 2019b; Wu et al., 2017a, 2017b, 2017c; Wang et al., 2015). However, we found that the traditional SCRCQ had obvious defects, and thus enhancing the method of SCRCQ (ISCRCQ) is proposed in this study, as well as the main innovation of this paper.

As a result, taking the existing research into account, in this study, we aim to (1) improve the method of SCRCQ and use the improved SCRCQ (ISCRCQ) to quantify the driving factors of dry-wet hydrological changes in the upper reaches of the Shiyang River (USR). (2) provide an in-depth verification of the scientific applicability of the method of ISCRCQ through empirical research.

2. Materials and methods

2.1. Study area

The USR originates from the eastern Qilian Mountains, with a runoff yield area of 11,550 km^2. The climate is alpine semihumid and semiarid. The upper reaches slope from west to east, while the western part is steep and tends to be low and flat towards the east (Fig. 1). The tributaries of the USR from west to east include the Xidai (X.D.), the Dongda (D.D.), the Xiyang (X.Y.), the Jinta (J.T.), the Zamu (Z.M.), the Huangyang (H.Y.), the Gulang (G.L.) and the Dajing (D.J.), the eight tributaries are an important source of water for the entire watershed. The average runoff of the eight tributaries in the recent 60 years has been 1.454 billion m^3, among them, the annual average runoff of X.Y. is the highest (371 million m^3) and that of the D.J is the lowest (12.7 million m^3). There are reservoirs above the hydrological stations in the tributaries except for Z.M. and H.Y. The most highly developed inland river basin in China as it is, however, and the contradiction between the water resource supply and demand is extremely prominent. Over the last few decades, under the dual influences of human activities and climate change, the natural ecological environment in the basin has gradually deteriorated, the shortage of water resources has become more apparent, hydrological drought has become more and more prominent, and the increase in the frequency of drought events significantly impacted on regional ecology and the social economy (Zhou et al., 2015).

2.2. Datasets

The datasets used in this paper include meteorological data, runoff, DEM, land use, soil, reservoir, and population data. The data content and sources are shown in Table 1.

In the monthly flow data of eight hydrological control stations upstream, G.L. and JT were not analyzed due to the lack of monthly runoff data for 15 years and older. Daily precipitation data from the Wushaoling Meteorological Station and monthly precipitation grid data from the USR were obtained from the China Meteorological Data Network (CMDN). Among them, the Wushaoling Meteorological Station has not migrated in 58 years, and the data coherence is great, with high reliability. The data were generated in real time using an optimal interpolation method based on the climatic background field to produce gridded daily precipitation data with a spatial resolution of $0.5^\circ \times 0.5^\circ$. Error analysis showed that the absolute error of approximately 91% of the data was less than 1.0 mm, and the gridded product had high accuracy (Shen et al., 2010).

Table 1
Data content and sources.

Data Type		Content
Meteorology	Grid data	Monthly precipitation, monthly temperature, daily minimum temperature, daily maximum temperature, and daily average temperature of 0.5×0.5 grid points, from 1961 to 2016
	Wushaoling station data	Daily average minimum temperature, daily average maximum temperature, daily average temperature, daily average relative humidity, sunshine hours, and daily average wind speed, from 1961 to 2016
Runoff		Monthly runoff data from 1961 to 2016 for six hydrologic stations
Land use		Manual visual interpretation data of remote sensing images in 1986–2016
Soil		Soil texture and effective soil depth with a resolution of 1000 m
Reservoir		Reservoir and beneficial reservoir capacity as of 2016
Population		Population data of towns and villages in the USR in 2000

2.3. Methods

2.3.1. Drought index

In this study, the Standardized Runoff Index (SRI) values at 12-month time scales were calculated according to the research results of Li et al. (2020). For specific calculation methods, please refer to the literature (Husak et al., 2007). The value of SRI in December of each year (SRI12) was taken as the SRI on the annual scale (Ye, 2014).

2.3.2. Improvement of the slope change ratio of cumulative quantity （ISCRCQ）

2.3.2.1. The Slope Change Ratio of Cumulative Quantity （SCRCQ） method. The method of SCRCQ is aimed at quantifying and separating the impacts of human activities and climate change on runoff change (Wang et al., 2013a, 2013b). The method is based on the following principle, which calculates the ratio of the rate of change of the slope of the cumulative climatic factor to the rate of change of the slope of the cumulative runoff, which is the rate of contribution of the climatic factor to the change in runoff. The contribution of human activities is equal to 1 minus the contribution of climate change to the change in runoff. The introduction of cumulative quantity eliminates the influence of the inter-annual fluctuation of the measured data to a certain extent (Searcy and Hardison, 1960). This method has been widely used since it was proposed (Lian et al., 2020a, 2020b; Zhang, 2020; Cheng et al., 2019a, 2019b; Wu et al., 2017a, 2017b, 2017c; Wang et al., 2013a, 2013b).

2.3.2.2. Improvement of the SCRCQ method. In the process of using this method, scholars have been continuously adapting and improving the method of SCRCQ, mainly focusing on two aspects. First, some scholars suggest that precipitation and

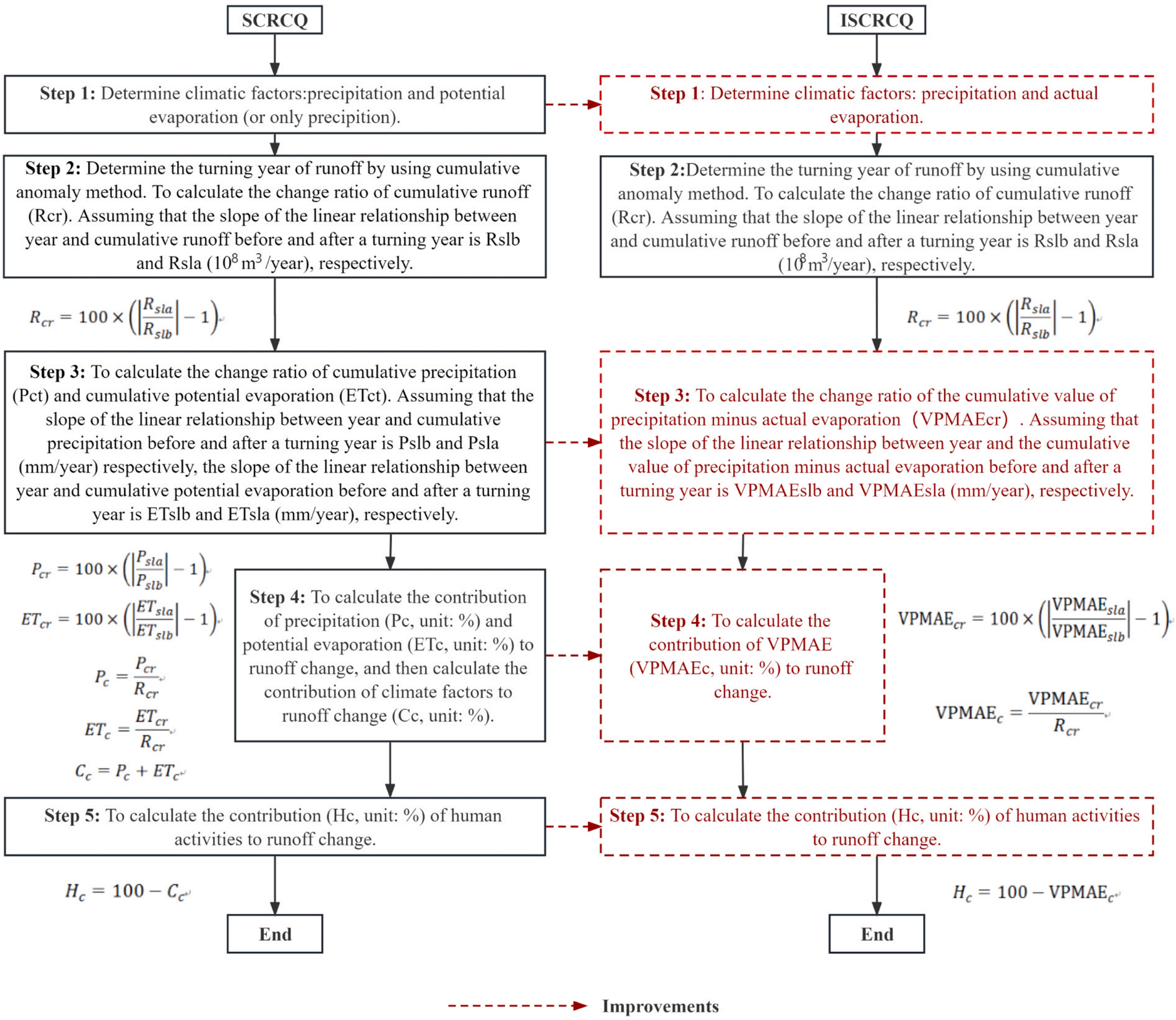

Fig. 2. Concrete calculation steps of the method of SCRCQ and improvement process of the ISCRCQ.

evapotranspiration should be considered simultaneously when analyzing the effect of climate on runoff variability (Lian et al., 2020a, 2020b; Cheng et al., 2019a, 2019b; Wu et al., 2017a, 2017b, 2017c; Wang et al., 2013a, 2013b). Second, how to integrate the contribution of precipitation and evapotranspiration to runoff changes? Scholars have proposed substituting the actual evapotranspiration with potential evapotranspiration, meanwhile, taking the negative value of the contribution of potential evapotranspiration to the change in runoff and adding it with the contribution of precipitation to the change in runoff to obtain the total contribution of climate factors to the change in runoff (Chen, 2016; Wang et al., 2013a, 2013b). The above improvements have optimized the scientific nature of the method, but there is still room for further improvement. The main reasons are as follows:

On the ground of the water balance principle, runoff is the result of a comprehensive balance between precipitation (income) and actual evapotranspiration (expenditure). When it comes to calculating the contribution rate of climate factors to runoff change, Precipitation, and actual evapotranspiration should be regarded as a whole, instead of being isolated from each other. Accordingly, our main process for improving this methodology is as follows. First, we calculate the value of precipitation minus actual evapotranspiration (VPMAE). Second, we calculate the contribution of VPMAE to the change in runoff, which is the total contribution of climate change to the change in runoff. In principle, this calculation process is more scientific, but the key to realizing this process is to calculate the actual evapotranspiration (see Section 2.3.3). See Fig. 2 for the specific improvement process of the method of SCRCQ.

There are three kinds of calculation results of VPMAEc (the contribution of VPMAE): when VPMAEc is between 0% and 100%, it indicates that climate change and human activities affect runoff in the same direction. When VPMAEc is negative, Hc (contribution of human activities) is positive and greater than 100%, which shows that human activities have utterly changed the runoff or dry-wet hydrological changes under natural conditions in the region. When VPMAEc is greater than 100%, it shows that climate conditions have a more positive impact on runoff change than human activities' negative effects.

The results of adding only the contributions of precipitation and evapotranspiration to the variability of runoff differ from the results of directly calculating the contribution of VPMAE to the variability of runoff, as shown below.

SCRCQ method:

$$C1_c = \frac{P_{cr} - E_{cr}}{R_{cr}} = \frac{P_{sla} \bullet ET_{slb} - ET_{sla} \bullet P_{slb}}{P_{slb} \bullet ET_{slb} \bullet R_{cr}} \tag{1}$$

ISCRCQ method:

$$C2_c = \frac{VPMAE_{cr}}{R_{cr}} = \frac{P_{sla} - AET_{sla} - P_{slb} + AET_{sla}}{(P_{slb} - AET_{slb}) \bullet R_{cr}} \tag{2}$$

where Rcr is the slope changing ratio of cumulative runoff, Pcr is the slope changing ratio of cumulative precipitation, Ecr is the slope changing ratio of cumulative potential evapotranspiration, and VPMAEcr is the change ratio of the cumulative value of precipitation minus the actual evapotranspiration. The slope of the linear relationship between the year and cumulative precipitation before and after a turning year are Pslb and Psla (mm/year), respectively. The slope of the linear relationship between the year and cumulative potential evapotranspiration before and after a turning year are ETslb and ETsla (mm/year), respectively. The actual evapotranspiration before and after a turning year are AETslb and AETsla (mm/year), respectively.

Generally, $P_{sla} \neq ET_{sla}, P_{slb} \neq ET_{slb}$, which is, $C1_c \neq C2_c$. Therefore, from a statistical point of view, the results calculated by the two methods also differ. In this paper, the ISCRCQ method is used to quantitatively distinguish the driving factors of dry-wet hydrological changes in the USR, and the results are compared with those calculated by the SCRCQ method.

2.3.3. Calculation of actual evapotranspiration

2.3.3.1. Selection of the calculation method. Actual evapotranspiration refers to the amount of water actually entering the atmosphere from the underlying surface, which is an objective variable to measure the change in water (Liu et al., 2008; Donohue et al., 2012). At present, there are two main estimation methods for actual evapotranspiration: the direct measurement method and the estimation simulation method (Liu, 2021). As the direct measurement method is limited by the monitoring conditions, it is difficult to achieve long-time series measurements at the basin scale. Hydrological models based on physical processes and estimation simulation methods based on experience are widely used in the calculation of actual evapotranspiration, mainly the AA model, CRAE model, GG model based on evapotranspiration complementarity theory, and Budyko's water and heat balance theory (Zhang et al., 2016), especially Budyko's water and heat balance theory, which lays a theoretical foundation for the scientific evaluation of AET. On the basis of Budyko's theory of water and heat balance theory, a simple model framework was proposed to estimate long-term mean annual evapotranspiration based on potential evapotranspiration, rainfall, and a plant-available water coefficient (Zhang et al., 2001, 2004). This is calculated using the following formula:

$$\frac{\mathrm{AET(x)}}{\mathrm{P(x)}} = 1 + \frac{\mathrm{PET(x)}}{\mathrm{P(x)}} - \left[1 + \left(\frac{\mathrm{PET(x)}}{\mathrm{P(x)}}\right)^{\omega}\right]^{1/\omega} \tag{3}$$

where AET(x) is the actual evapotranspiration, P(x) is the precipitation, PET(x) is the potential evapotranspiration, and ω is a model parameter.

Potential evapotranspiration and runoff were taken into account for over 470 catchments around the world with long-standing precipitation records. The model has a slope of 1.00 through the origin and explains 89% of the variance, with a mean absolute error between observed and simulated evapotranspiration of 54 mm (Zhang et al., 2004). The calculation results are highly reliable.

Moreover, relevant studies have proven that Formula (3) can accurately estimate the actual evapotranspiration of inland river basins in arid areas of northwest China (Yao et al., 2017), and it has good applicability in the estimation of AET over a relatively long time scale in mountainous areas (Li et al., 2015a, 2015b). As a result, this paper chose Formula (3) to calculate the AET of the study area.

2.3.3.2. Parameter sensitivity. In Formula (3), the parameters affecting AET are precipitation (see Section 2.2), potential evapotranspiration (see Section 2.3.3.3), and ω. The parameter ω can be thought of as representing the integrated impacts of watershed characteristics on evapotranspiration ($1.7 < \omega < 5.0$). Donohue et al. (2012) proposed an empirical formula to calculate ω:

$$\omega(x) = Z\frac{AWC(x)}{P(x)} + 1.25 \tag{4}$$

where z is the Zhang coefficient, which is a parameter used to express regional precipitation characteristics. AWC(x) means effective soil water content in millimeters, the value is determined by the soil texture and effective depth (Donohue et al., 2012). Consequently, the value of ω is determined by the calibration of Z, and the calibration process is as follows: the premise and basis for determining the Z-value in this paper is that precipitation minus AET should be equal to runoff. Specifically, this paper first assigned a value to Z according to experience, then calculated AET by Formula (3), compared the difference between precipitation and AET with natural runoff, and further adjusted the Z value until the difference between the precipitation and AET was very close to the natural runoff After repeated calibration, the Z value was 4.1, the error was controlled within 4%, and the calculated actual evapotranspiration was highly reliable (Zhao et al., 2019).

2.3.3.3. Calculation of the potential evapotranspiration. Potential evapotranspiration (PET_0) is the greatest amount of evapotranspiration that the land surface may experience under specific meteorological conditions when the water supply is not limited (Zhao et al., 2013; Zhang, 2018). The penman-Monteith model is recommended by the European Union and the United States, and has become a general standard algorithm to estimate the latent heat flux and evapotranspiration of the surface (Allen et al., 1998; Penman, 1984). It is an ideal method to study the evapotranspiration of the underlying surface in an unsaturated state, and also easy to calculate and has high estimation accuracy (Li, 2003; Li et al., 2005; Jin, 1997; Hong et al., 2001; Wu, 2019), which has been widely used globally (Gao et al., 2006; Allen-Wardell et al., 1998; Zhang et al., 2009), the P-M model requires a large amount of meteorological data. For the calculation of the ET_0 with less meteorological data, the Food and Agriculture Organization of the United Nations (FAO) recommended the Hargreaves formula (H formula for short). However, the results of a number of studies have shown that there is a deviation in the calculation of the ET_0 by the H formula in different regions, necessitating the correction of the results when using this method (Liu, 1996; Hargreaves and Samina, 1985).

In the USR, only Wushaoling Station has relevant data, which meets the calculation of the P-M model (ET_0-P-M) and the potential evapotranspiration (ET_0-H) can only be calculated for other areas by using the monthly grid meteorological data and H formula. As a consequence, the ET_0-H in the USR from 1960 to 2016 can only be corrected by the regression models established by ET_0-PM and ET_0-H of the Wushaoling Meteorological Station. This paper adopted the regression model established by Zhao et al. in 2019 to correct the ET_0-H in the USR and its tributaries from 1961 to 2016. The regression model is as follows:

$$ET_{0-PM} = 0.404ET_{0-H} + 0.493 \tag{5}$$

where ET_0-PM is the ET_0 (mm) calculated by the P-M model, and ET_0-H is the ET_0 (mm) calculated by the H formula. The correlation coefficient R was 0.906. The relative deviation between the results calculated by Model (3) and the results calculated by the P-M model is between − 5.097% and 9.764%, and the simulation accuracy of the model is high, which can meet the needs of this research.

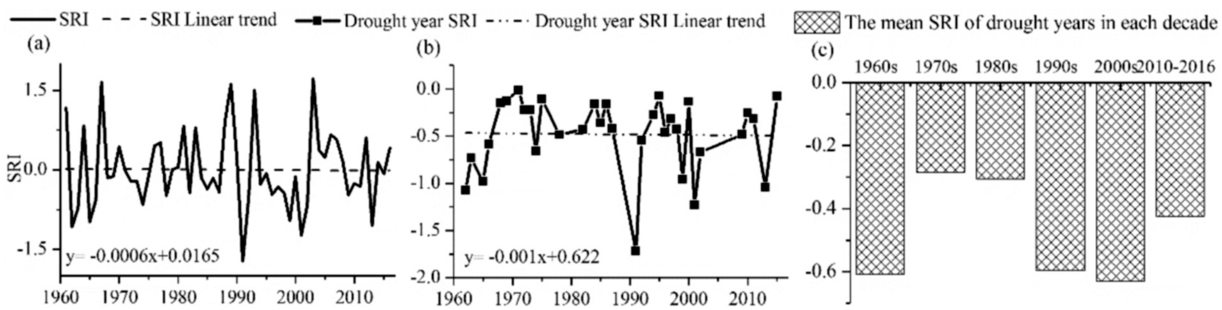

Fig. 3. (a) Annual standardized runoff index (SRI) variation characteristics in the USR from 1961 to 2016; (b) annual SRI variation characteristics in drought years; (c) means SRI of drought years in each decade.

3. Results

3.1. Dry-wet hydrological changes in the USR

3.1.1. Temporal variation of dry-wet hydrological changes

The annual dry-wet hydrological values in the USR from 1961 to 2016 were calculated, and their variation characteristics were analyzed.

Fig. 3a shows that the change tendency rate of the annual SRI in the USR from 1961 to 2016 is − 0.006/10 a, showing hydrological aridification, which was not significant according to the MK trend test ($p > 0.05$). From 1961–2016, there were more dry years (33) than wet years (23). The variation tendency rate of the annual SRI in dry years was − 0.01/10 a, which demonstrates that the drought degree in dry years was increasing (Fig. 3b); 1970 was the year with the weakest drought degree, and 2000 was the year with the strongest drought degree (Fig. 3c).

3.1.2. Spatial heterogeneity of dry-wet hydrological changes

As shown in Fig. 4, from 1961 to 2016, the tendency rate of the annual SRI of tributaries in the USR gradually changed from positive to negative from west to the east. The westernmost tributaries, X.D. and D.D., are hydrological humidification, while the rest of the tributaries are hydrological aridification, with H.Y. pointing out the most severe trend of hydrological aridity. The SRI of all tributaries increased gradually during the drought years from 1961 to 2016; that is, the drought degree decreased by degrees. Among them, the X. D.'s level of drought reduced the most notably, while that of the D.J. decreased the least by comparison. Though decreasing the drought degree was, the frequency of drought years in the eastern two tributaries (H.Y. and D.J.) was increasing, especially after 1995; there were 17 and 16 drought years in the H.Y. and D.J., respectively, accounting for 65% and 54% of the total number of drought years, while there was little change in the frequency of drought years in the western tributaries (X.D., D.D., X.Y., J.T., and Z.M.).

3.2. Contributions of human activities and climate change to dry-wet hydrological changes

3.2.1. Turning years

The turning years of SRI, runoff, and VPMAE of tributaries in the USR from 1960 to 2016 were calculated using the cumulative anomaly (CA) method.

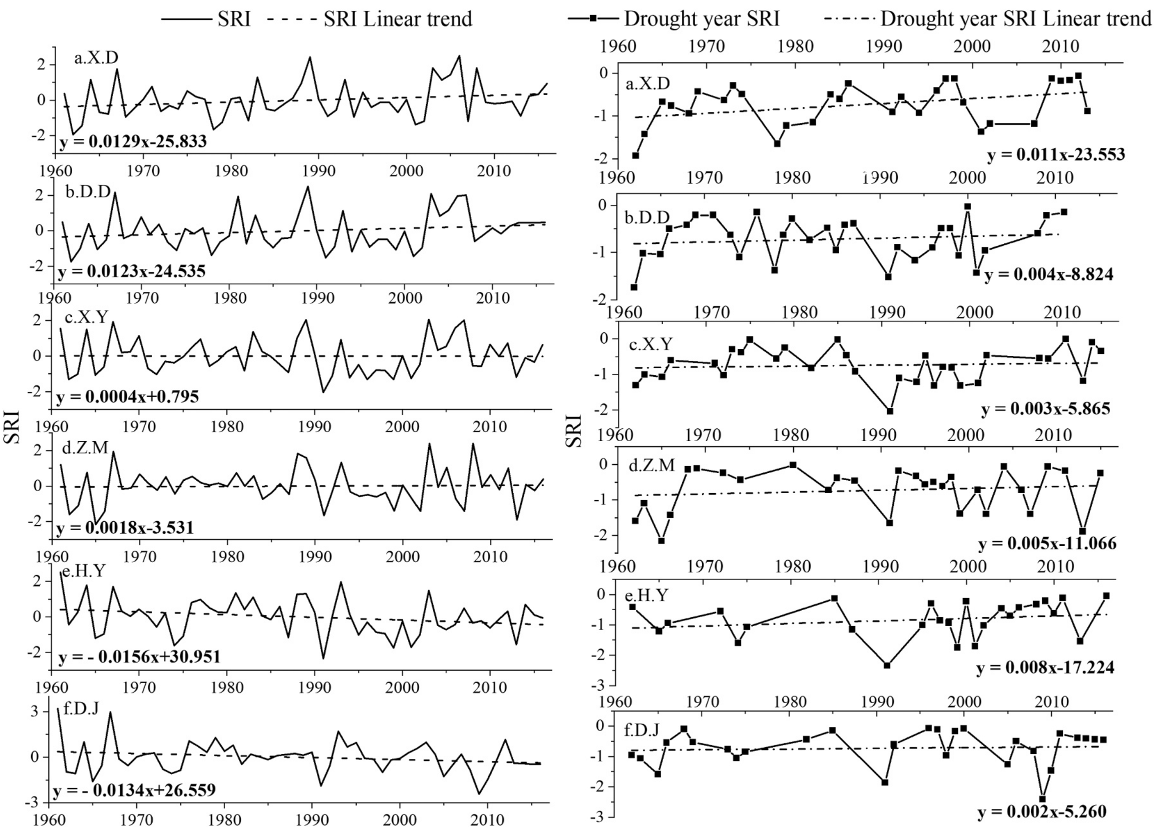

Fig. 4. Spatial differences in SRI changes each year and in dry years in each tributary from 1961 to 2016.

Fig. 5 shows that the SRI cumulative anomaly of each tributary was consistent with that of the runoff. Overall, the western tributaries (X.D., D.D., X.Y., J.T., and Z.M.) converted from hydrological aridification to hydrological humidification, while the eastern tributaries (H.Y. and D.J.) had the opposite hydrologic trend. The fluctuation of the runoff cumulative anomaly in the western tributaries (X.D., D.D., X.Y., J.T., and Z.M.) was basically consistent with that of VPMAE, though it was the opposite in the eastern tributaries (H.Y. and D.J.). Among them, the turning year of the four western tributaries (X.D., D.D., X.Y., J.T., and Z.M.) was 2002, and the turning year of the H.Y was 1994, as the turning process of the D.J was complicated, with two obvious turnings in 1975 and 2004. The turning was the result of the interaction of human activities and climate change factors, which can alter the dry-wet hydrological changes. Therefore, analysis of the influences and contributions of human activities and climate change factors on runoff after turning is very important to understand the driving mechanism of dry-wet hydrological changes.

3.2.2. Influences of human activities and climate change on dry-wet hydrological changes

The SRI was calculated from the runoff, and both the fluctuation and turning were exactly the same (Fig. 5). Therefore, to avoid the influence of positive and negative signs of the SRI on the cumulative process, we applied the cumulative quantity slope of runoff events of the SRI to quantify the influencing factors of dry-wet hydrological changes using the method of ISCRCQ.

From what has been shown above in Fig. 6, the effects of anthropogenic activities and climate change on the hydrological changes in the various tributaries of the USR are significantly different. The two influences in D.D. and X.D. are in the same direction for hydrologic drought. The climate change factor was dominant among them. In the X.Y. and Z.M., climate change had a positive influence and human activities had a negative impact on dry-wet hydrological changes, and the contribution of climate change factors was more than 100%. This manifests that in the process of runoff changing from "drying" to "wetting" after 2002, the low level of human activity failed to change the overall trend of dry-wet hydrological changes determined by climate change, among which human activity in the X.Y. had the least impact, with a contribution rate of only − 0.83%, which was consistent with the result of a study by Li et al. (2020), in which the X.Y. was chosen as a natural reference tributary. In the D.J. and H.Y., human activities had a positive influence on the hydrological aridification in absolute superiority, which entirely altered the influence of climate change on dry-wet hydrological changes. Moreover, the strong intervention of human activities occurred earlier in the H.Y., and the turning point of the SRI, runoff, and as well as the VPMAE of H.Y.

4. Discussion

4.1. Influence of climate change on dry-wet hydrological changes

All six of the USR's tributaries' yearly VPMAEs displayed an upward trend, with the rate of growth accelerating from west to east. Among them, the SRI of the four tributaries in the west was in accordance with the VPMAE, showing an increasing trend in the same direction, which indicates that the VPMAE had a significant influence on the dry-wet hydrological changes and was the leading factor, which is consistent with the results in Fig. 6. However, the VPMAE and SRI of the two eastern tributaries (H.Y. and D.J.) showed a reverse trend, which indicates that the hydrological aridification of the two eastern tributaries was influenced by more severe human activities (Fig. 7).

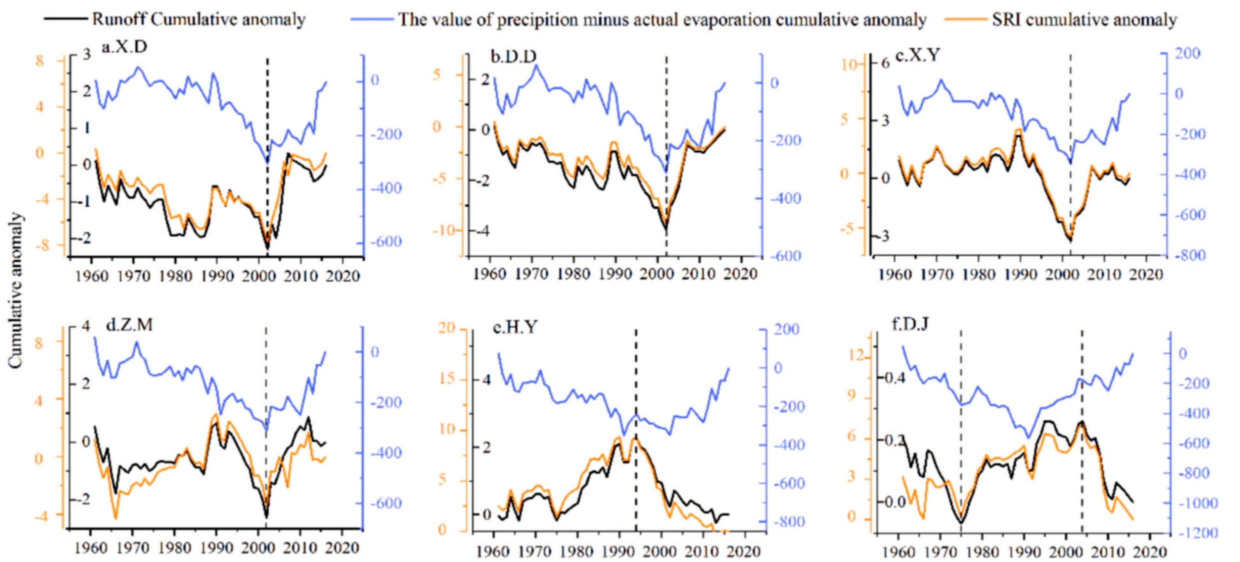

Fig. 5. Cumulative anomaly (CA) and turning years of the SRI, runoff, and VPMAE of each tributary from 1961 to 2016.

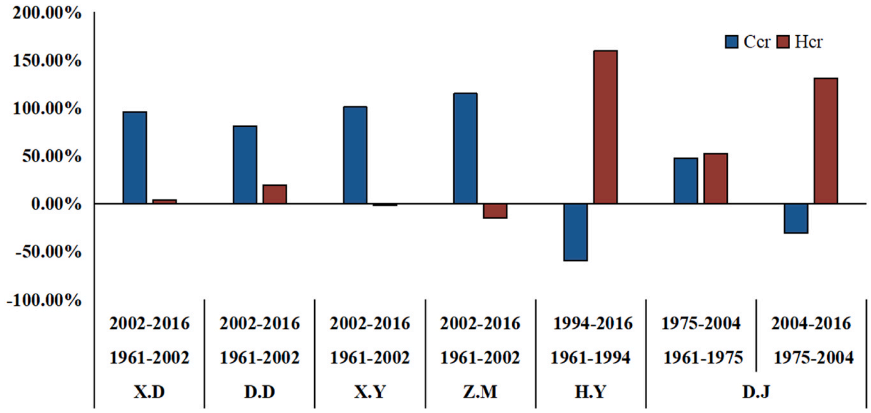

Fig. 6. Contributions of human activities and climate change to the dry-wet hydrological changes in different tributaries.

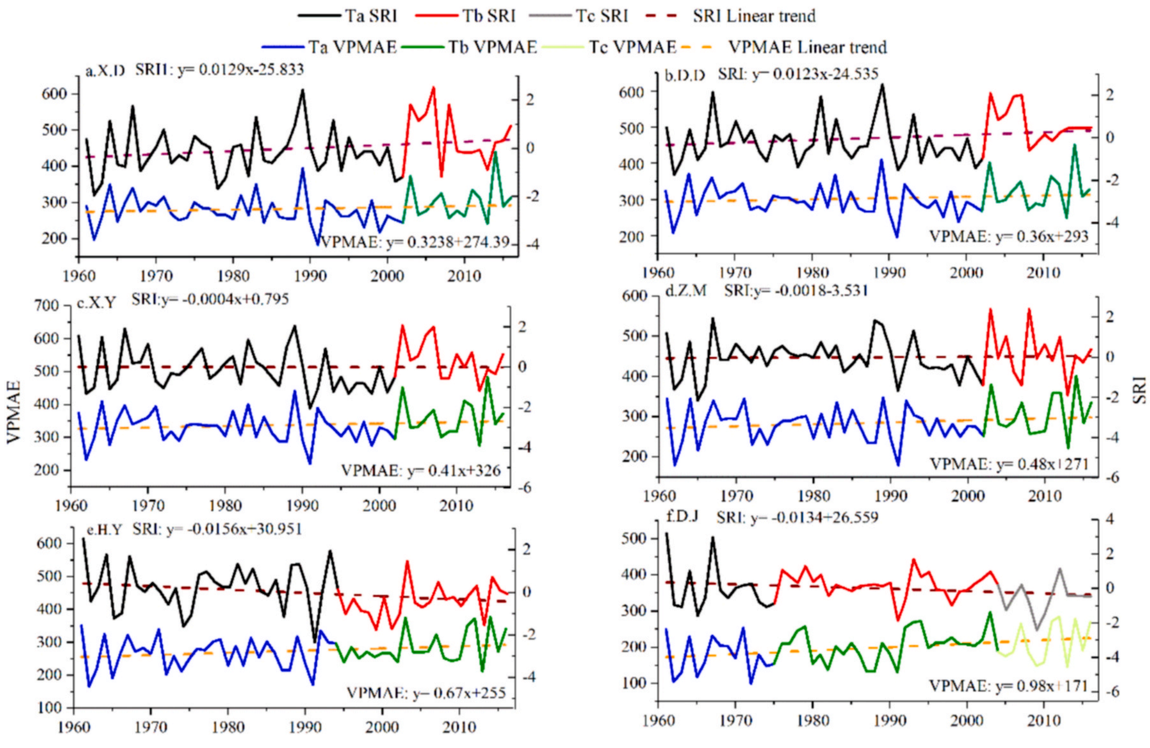

Fig. 7. Change trends of the VPMAE and SRI at an annual scale from 1960 to 2016 for each tributary (different colors were used before and after turning; Ta indicates before turning, Tb and Tc indicate after turning).

4.2. Differences in human activities between the eastern and western tributaries

In this study, three influencing factors, namely, the proportion of cultivated and constructed land (PCC), the reservoir capacity coefficient (CRSC), and the population density (PD), which can adequately reflect human activities, were selected to further study the

Table 2
The population density (PD), reservoir capacity coefficient (CRSC), and the proportion of cultivated and constructed land (PCC) of each tributary.

	X.D.	D.D.	X.Y.	Z.M.	H.Y.	D.J.
PCC (%)	0.645	3.827	0.641	3.936	30.2	30.914
PD (person/km^2)	9	3	13	1	55	35
Year of reservoir construction	1974	1985	None	None	1960	1960
CRSC	0.344	0.198	None	None	0.222	0.399

influence of human activities factors on dry-wet hydrological changes.

There were obvious differences in the land use structure and population density among different tributaries, and the proportion of cultivated and constructed land and population density of the two tributaries in the east were far greater than those of the four tributaries in the west (Table 2). The proportion of cultivated and constructed land and population density of the four western tributaries (X.D., D.D., X.Y., J.T., and Z.M.) were very small, and human activities had little influence on runoff or dry-wet hydrological changes. In the western tributaries, the X.Y. has no reservoir above the hydrological station, the proportion of cultivated and constructed land was the minimum among the eight tributaries, which was closest to the natural state, and the contribution of the climate change factor to dry-wet hydrological changes was close to 100%. The reservoir of the D.D. is above the hydrological station, and the dry-wet hydrological changes were influenced, to a certain extent, by reservoir regulation. Human activities were more intense in the eastern tributaries, especially in the H.Y. and D.J.

The population density of the H.Y. ranks first among the eight tributaries, and the proportion of cultivated and constructed land is only slightly less than that of the D.J., accounting for 30.2%. A larger population density and proportion of cultivated and constructed land mean that the underlying surface is more drastically reformed and more water resources are consumed. In the D.J. basin, the reservoir capacity coefficient and proportion of cultivated and constructed land were the largest, the population density was second only to that of the H.Y., and human activities were also greater. The analysis of the impacts of human activities on dry-wet hydrological in the H.Y. and D.J. was carried out in the following section.

Table 3 shows that the area of cultivated land and construction land increased in the H.Y. before 2000, with enhanced water lifting and diversion capacity brought about by the continuous improvement of water conservancy facilities and the continuous increase in irrigation area, which are the fundamental reasons for the continuous strengthening of hydrological drought in this basin. The Zhangyi irrigation district, located above the Huangyang Reservoir, was built in 1950, the Huangyang Reservoir Project was built in 1960, and the backbone projects were mostly built in the 1970 s and 1980 s. By the 1990 s, a water conservancy project system with simultaneous storage and introduction was formed. During the "Ninth Five-Year Plan" (1995–2000) and "Tenth Five-Year Plan" (2000–2005) of the Five-Year Plan for National Economic and Social Development of the People's Republic of China, irrigation districts actively strived to enact projects, raised funds from various sources, carried out farmland water conservancy construction, and constantly consolidated irrigation water conservancy construction facilities, and the cultivated land area and irrigated area increased continuously. By the end of the 1990 s, the cultivated land area had reached 260 km^2, which may be the fundamental reason for the turning of the dry-wet hydrological changes and the increase in the frequency of dry years in the H.Y. (Liangzhou District Water Resources Bureau, 2006).

In the D.J., under the background of an increase in the cultivated land area (Table 3), the continuous improvement of water conservancy facilities and the continuous strengthening of irrigation capacity resulted in the increasing trend of hydrological drought and mutation in 1994 and 2004, respectively. The water conservancy construction of the D.J. developed at a rapid speed in the 1950 s and 1960 s, however, a host of patent quality problems appeared in many water conservancy projects built during this period. Since 1974, the government has discovered problems, learned lessons, and taken measures to rebuild the headwork, i.e., the east and west trunk canals of the D.J. At the same time, the government has paid attention to drought relief by drilling deep wells to fight drought, improving the surface hydrological conditions in the basin. As a result, with the influence of meteorological humidification, a turning from "dry" to "wet" has occurred (Fig. 5) (Gulang County Water Affairs Bureau, 1990). With the continuous increase in human activities, the reconstruction project of the east-west trunk canal of the D.J. began in 2004. Although there was meteorological humidification at this stage, it still failed to change the second turning of the hydrological changes in the basin from "wet" to "dry" (Gulang County Water Affairs Bureau, 2008).

4.3. Comparison of method of ISCRCQ and SCRCQ results

The results calculated by the method of SCRCQ were apparently inconsistent with the actual situation, especially for the four tributaries in the west. This mainly manifested in the following aspects:

First of all, through the analysis in 4.1 and 4.2, it is known that proportion of cultivated and constructed land and population density of X.D., D.D, X.Y. and Z.M. were small, indicating that the intervention degree of human activities in these areas was very small, but the contribution rate of human activities calculated by the method of SCRCQ was more than 53%, even as high as 80%, which seriously deviated from the actual situation (Table 4).

Secondly, for the H.Y. and D.J. in the east, the calculated contribution rate of human activities was relatively large. On the surface, this result corresponded with the situation that human activities in these two rivers were relatively considerable in Section 4.2, but the contribution rate of human activities in these two rivers was exceedingly close to 100%, and the influence of climate factors (precipitation and evapotranspiration) on dry-wet hydrological changes was particularly small, even less than − 5%, and this result was caused by the opposite direction of precipitation and evapotranspiration and the simple addition of numbers. This result weakened the

Table 3
The proportion of main land use area of the H.Y. and D.J. (Unit: %) (Con. L: construction land, Cul. L: cultivated land, Nat. V: natural vegetation).

Tributaries	H.Y.			D.J.		
Land Use	Con. L	Cul. L	Nat. V	Con. L	Cul. L	Nat. V
1986	0.4	28.1	65	0.5	26.1	73
2000	0.9	28.3	63	0.6	31	65
2016	1.5	25.9	69	0.9	23.3	72

Table 4
The contributions of climate change and human activities to dry-wet hydrological changes in each tributary calculated by the method of SCRCQ.

Tributary	Baseline Period	Change Period	PC_{cr}	ET_{cr}	C_{cr}	H_{cr}
X.D.	$T_{1961–2002}$	$T_{2002–2016}$	70.14%	-42.76%	27.38%	72.62%
D.D.	$T_{1961–2002}$	$T_{2002–2016}$	65.59%	-46.13%	19.46%	80.54%
X.Y.	$T_{1961–2002}$	$T_{2002–2016}$	89.21%	-42.81%	46.40%	53.61%
Z.M.	$T_{1961–2002}$	$T_{2002–2016}$	91.43%	-56.83%	34.60%	65.40%
H.Y.	$T_{1961–1994}$	$T_{1994–2016}$	-40.50%	32.83%	-7.68%	107.68%
D.J.	$T_{1961–1975}$	$T_{1975–2004}$	34.95%	2.64%	37.59%	62.41%
	$T_{1975–2004}$	$T_{2004–2016}$	-17.49%	13.27%	-4.22%	104.22%

effects of climate and was also inconsistent with the actual situation because the dry-wet hydrological changes of runoff were firstly the result of the balance between precipitation and evapotranspiration in the basin, and on this basis, the influence of human activities was superimposed. Although the influence of human activities on dry-wet hydrological changes was dominant, climate change still played an vital role during this process.

To sum up, the results calculated by the method of ISCRCQ were very consistent with the actual situation (Fig. 6 and Table 2), The method of ISCRCQ solved the problems and shortcomings of the method of SCRCQ, further certified the quantitative method, and was more scientific and applicable.

5. Conclusions

In this study, the Slope Change Ratio of Cumulative Quantity (SCRCQ) method was improved, and the improved SCRCQ (ISCRCQ) method was applied to quantify the drivers of dry-wet hydrological changes in the upper Shiyang River from 1961 to 2016, and the results show that the ISCRCQ method can quantify the contribution of climate and human activities to dry-wet hydrological changes more scientifically. The innovative improvement in the method will contribute to the related research in the future.

From 1961–2016, the USR showed hydrological aridification at an annual scale. The influences of human activities and climate change on the dry-wet hydrological changes in different tributaries were evidently different. Among them, climate change was the dominant factor of hydrological humidification in the four western tributaries (X.D., D.D., X.Y., J.T., and Z.M.) (the contribution rate was more than 80%), while human activities in the two eastern tributaries (H.Y and D.J) utterly converted the direction of the dry-wet hydrological changes and intensified the hydrological aridification, resulting in a significant increase in the frequency of drought years, threatening the water safety and increasing the risk of socioeconomic drought. Accordingly, the impact and intervention of human activities on hydrological processes should be moderately reduced in basins where human activities have a enormous impact, respecting the natural laws of the water cycle, and truly realizing the conservation goal of "green mountains are golden mountains".

CRediT authorship contribution statement

Junju Zhou: Conceptualization, Methodology, Writing – review & editing, Supervision. **Qiaoqiao Li**: Methodology, Software, Validation, Writing – original draft, Visualization. **Aizhong Ye:** Writing – review & editing. **Shizhen Xu:** Writing – review & editing. **Yunhan Yuan:** Writing – review & editing. **Shiqin Xu:** Writing – review & editing. **Dongxia Zhang:** Resources. **Xi Zhao:** Data curation. **Yanbing Zhu:** Data curation. **Yaru Zhao:** Data curation. **Dongxiang Xue:** Data curation. **Jiao Dou:** Data curation. **Chunfang Liu:** Funding acquisition. **Wei Shi:** Funding acquisition. **Wei Wei:** Funding acquisition. **Xuemei Yang:** Funding acquisition.

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.

Data availability

Meteorological data: including grid data (Monthly precipitation, monthly temperature, daily maximum temperature, daily minimum temperature, and daily average temperature of 0.5 × 0.5 grid points, from 1961 to 2016) and Wushaoling station data from China Meteorological Data Network are publicly available at (http://101.200.76.197/site/index.html); Landsat/TM remote sensing image data in 1986–2016 are publicly available at https://www.usgs.gov/; Soil texture and effective soil depth with a resolution of 30 arc-second from Harmonized World Soil Database are publicly available at (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/); Population data of towns and villages in the USR in 2000 from Data of the Fifth Population Census of China are publicly available at (http://www.stats.gov.cn/tjsj/pcsj/rkpc/5rp/index.htm); Runoff data are accessible from Zenodo repository (Zhou et al., 2022).

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