

Runoff Variation of the Trunk Stream and Tributaries of the Yarkant River and Their Response Relationships from 1957 to 2017

1957–2017年葉爾羌河幹支流徑流變化及回應關係研究

FAN GAO

高 凡

College of Hydraulic and
Civil Engineering, Xinjiang
Agricultural University,
Urumqi,
Associate Professor

LAN ZOU*

鄒 蘭

School of River and Ocean
Engineering, Chongqing
Jiaotong University,
Chongqing,
Ph.D. Student

BING HE

何 兵

Key Laboratory of Northwest
Water Resources and
Environment Ecology of
MOE, Xi'an University of
Technology, Xi'an,
Ph.D. Student

DONGYONG SUN

孫 東 永

School of Environmental
Science and Engineering,
Chang'an University, Xi'an,
Associate Professor

ABSTRACT

Understanding the influence of climate change and human activities on hydrological process in the river system in an arid inland region is of vital significance for maintaining the eco-hydrological safety of the region and recognizing appropriate allocation of water resources. In this work, the monthly runoff and synchronous meteorological data from 1957 to 2017 of trunk stream of the Yarkant River and its two tributaries, the Taxkorgan River and the Tiznap River, in Xinjiang, China were analyzed. The analysis was carried out using the moving cut data-wavelet transformation (MC-WT) in conjunction with the Mann-Kendall test (a non-parametric test) and moving t-test. The Budyko hypothesis-based water balance method was employed to calculate the response and sensitivity of the runoff variations of the trunk stream with respect to those of its tributaries and to identify the driving factors, as well as their contribution rates, that affect the variations. The results showed that the annual precipitation and temperature series of the trunk stream and tributaries of the Yarkant River had a significant increasing trend; their annual runoff series also had an increasing trend, but the increase was insignificant. Additionally, the highest runoff variation year of the Taxkorgan River and the Tiznap River was in 1993 and 1984, respectively, while that of the trunk stream was in 1993. The results further showed that the runoff sequence of the trunk stream of the Yarkant River could be divided into two periods: the baseline period (1957-1993) and the variation period (1994-2017). The runoff variation in both periods had significantly high sensitivity to rainfall and potential evapotranspiration. Every 10% increase in precipitation of the Yarkant River basin, the runoff depth increased by about 0.2%, and for every 10% increase in potential evapotranspiration, the runoff depth decreased by approximately 0.03%. The climate sensitivity coefficients of the Yarkant River basin were spatially different, and

*Corresponding author: Ph.D. Student / School of River and Ocean Engineering, Chongqing Jiaotong University, Chongqing / 400074 / 1191490234@qq.com

the climate sensitivity coefficients of the tributaries were higher than that of the trunk stream. After the abrupt change, runoff variation was more sensitive to human activities compared to climate change. Human activities were also the primary driving factor influencing the runoff variation; their contribution rates in the trunk stream and the two tributaries were 72.3%, 67.9% and 72.8%, respectively.

Keywords: Moving cut data-wavelet transformation (MC-WT), runoff variation, climate change, human activities, hydrological response, Yarkant River.

摘 要

氣候變化和人類活動影響下，揭示乾旱內陸河流水資源系統的干支流水文情勢回應關係及敏感性特徵對於維護乾旱區生態水文安全及水資源合理配置具有重要意義。利用新疆葉爾羌河流域葉爾羌河幹流與其支流塔什庫爾幹河及提孜那甫河1957—2017年共61年逐月徑流資料與同步氣象資料，採用滑動移除小波分析法對葉爾羌河幹支流徑流進行變異診斷，並結合滑動核對總和Mann-Kendall非參數檢驗加以輔證，分析葉爾羌河幹支流徑流變化特徵；採用基於Budyko假設的水量平衡方法，分析葉爾羌河幹流徑流對支流徑流變化的回應及敏感性，定量識別葉爾羌河幹支流徑流變異的驅動因素及貢獻率。結果表明，（1）葉爾羌河流域幹支流年降水與氣溫序列均呈顯著增加趨勢，年徑流序列呈不顯著的增加趨勢。（2）塔什庫爾幹河與提孜那甫河徑流序列變異年份分別為1993年、1984年，葉爾羌河幹流徑流序列變異年份滯後，為1993年。將葉爾羌河幹流徑流序列劃分為2個時期，分別是基準期（1957—1993年）和改變期（1994—2017年）。（3）由基準期至改變期，徑流變化對降水和潛在蒸散發的敏感性顯著增加，葉爾羌河流域降水量每增加10%時，徑流深將增加約為0.2%，潛在蒸發量每增加10%時，徑流深將減少約為0.03%。葉爾羌河流域氣候敏感係數存在空間差異性，支流氣候敏感性係數高於幹流。（4）徑流突變後，徑流變化對人類活動的響應程度較高，是影響葉爾羌河徑流變異的主要驅動因素，葉爾羌河幹流及兩條支流塔什庫爾幹河與提孜那甫河的貢獻率分別為72.3%、67.9%和72.8%。

關鍵詞：滑動移除小波分析，徑流變異，氣候變化，人類活動，水文回應，葉爾羌河。

1. INTRODUCTION

Natural hydrological processes are extremely complex and constantly changing, and exhibiting different characteristics (non-linear, non-stationary, and multi-scale) depend on the impacts of physical factors such as climate and underlying surface (Zhang *et al.*, 2016a). While the changing environment affects regional water cycle and hydrological process to different degrees, it markedly affects the hydrological regimes, therefore poses a serious threat to water, ecological and food securities in the regimes (Zhang *et al.*, 2011; Milly *et al.*, 2005; Zhang *et al.*, 2016b; Vörösmarty *et al.*, 2010). The evolution law and response relationship of runoff under the influences of climate change and human activities is a key link in the hydrological

cycle that has attracted extensive attention from researchers and government departments (Zhan *et al.*, 2012). Therefore, it is of great significance to plan and manage water resources in arid inland river basin, as well as to diagnose the runoff sequence change under changing environment and to identify the driving forces that affect the change and understand their response relationships.

At present, water scientists have conducted a large number of research on quantitative analysis of hydrological responses of climate change and human activities. The common attribution analysis methods for hydrological changes of watershed can be classified into three categories: hydrological model method (Chiew *et al.*, 2008), mathematical statistics method (Ma *et al.*, 2008) and hydrological sensitivity analysis method (Zheng *et al.*, 2009; Xu

et al., 2014). Since its proposal by the meteorologist, Budyko, the method has been widely and presently used is the hydrological sensitivity analysis method (Budyko, 1948 and 1974). This method has more obvious physical significance compared with the traditional method that relies on mathematical statistics. Its calculation process is also relatively simple and the parameters can be more easily obtained compared with the hydrological model method, which makes it an ideal analysis method in terms of annual or multi-year time scale (Zheng *et al.*, 2009; Xu *et al.*, 2014). For example, Ghaffari *et al.* (2010) studied Zanjanrood basin in northwest Iran using SWAT model, and concluded that land use plays a leading role in the process of hydrological change in this area. Xu (2011) used linear regression method to evaluate the impact of climate change and human activities on annual runoff variation, and the results showed that climate change could explain 78.6% of the annual measured runoff and 72.9% of the natural runoff decrease. Yang *et al.* (2014) evaluated the impacts of climate change (e.g., precipitation and evapotranspiration) on runoff change in 210 sub-basins in China using the Budyko hypothesis-based hydrothermal coupling balance equation. Wu *et al.* (2017) employed the climate elasticity method developed eight Budyko-based methods in attribution analysis of runoff changes in 17 catchments across the Loess Plateau. They found that human activities were the dominant factor affecting the runoff changes during the wet season, while climate change was the controlling factor during the dry season. Xu *et al.* (2014) conducted attribution analysis based on Budyko hypothesis on 33 small watersheds in Haihe mountain area, showing that the contribution rates of climate change and land use/coverage change to runoff reduction in the Haihe River basin in the past 50 years were 26.9% and 73.1%, respectively.

The Yarkant River is one of the important sources of "four sources and one trunk" water system in the Tarim River basin, located in the

hinterland of the Eurasian continent. It belongs to the extreme arid region in the northwest of China and has low precipitation and strong evaporation; its runoff generation mechanism is over-infiltration. The hydrological process of the Yarkant River basin is highly complex, especially for surface runoff that is particularly sensitive to climate change and human activities. While there are a large number of studies on the variation characteristics of hydrological and meteorological elements sequences in the Yarkant River basin (Chen *et al.*, 2014; Wang *et al.*, 2018; Liu *et al.*, 2017), there are only a few studies on the variation and response characteristics of runoff in the trunk stream and tributaries of the basin. Studies on the contribution rates of climate change and human activities to runoff variation are also limited.

In this study, the Yarkant River basin was selected as the research area, and its trunk stream and two tributaries, the Taxkorgan River and the Tiznap River, were used as the research objects. The monthly 61-years runoff sequences and synchronous meteorological data from 1957 to 2017 were observed. The moving cut data-wavelet transformation analysis method, which is a non-linear dynamic time series variation diagnosis method, was adopted to identify the runoff variation points of the area, and moving t-test was used for verification. The Mann-Kendall test, which is a non-parametric test, was then employed to analyze the trend of hydro-meteorological elements of the area to reveal their runoff variation and response relationship characteristics. The Budyko hypothesis-based hydrological sensitivity analysis method was further employed to investigate the sensitivity of runoff change in the trunk and tributaries of the Yarkant River, to quantify the contribution rate of climate change and human activities on runoff variation, and to identify the dominant factors causing the variation. This study aims to provide a reference for the development and utilization of water resources to better manage and control risk of changing environments in arid inland river basin.

2. STUDY AREA AND DATA SOURCES

2.1. Study area

The Yarkant River basin is situated in the center of the Eurasian continent, in the southwestern part of the Xinjiang Uygur Autonomous Region, and in the southwest of the Tarim basin. Its geographical coordinates is between 74°27'-80°54'E and 34°50'-40°24'N (Figure 1). As one of the sources of "four sources and one trunk" of the Tarim River, the Yarkant River has a wide range of river basins and numerous tributaries. The Yarkant River has a total length of 1269 km and flows through ten counties into the Tarim River. The total area of the river basin is 85,800 km², of which 66.9% is the mountain area (57,400 km²) and 33.1% is the plain area (28,400 km²). The mountain area contains 3,059 modern glaciers covering a total area of 5,313 km², reserves with an area of 684.4 km², and annual glacial meltwater of about 3.824 billion m³ (Yin *et al.*,

2017). The Yarkant River belongs to the temperate and warm temperate arid zone with typical continental climate, sufficient sunshine, strong evaporation and scarce precipitation. The average annual river runoff in the basin, which is mainly supplied by meltwater and mountain precipitation, is about 6.725 billion m³, approximately 64% of which is glacial meltwater (Chen *et al.*, 2014; Yin *et al.*, 2017).

2.2. Data sources

The monthly runoff data observed from 1957-2017 of three control stations, including the Kaqun hydrologic station on the trunk stream of Yarkant River, the Yierliehei hydrologic station, and the Yuzimenleke hydrologic station on two tributaries (the Taxkorgan River and the Tiznap River), were obtained from the National Hydrologic Yearbook and the Hydrologic and Water Resources Bureau of Kashgar, Xinjiang. The runoff data for the Yierliehei hydrologic station and the Yuzimenleke hydrologic

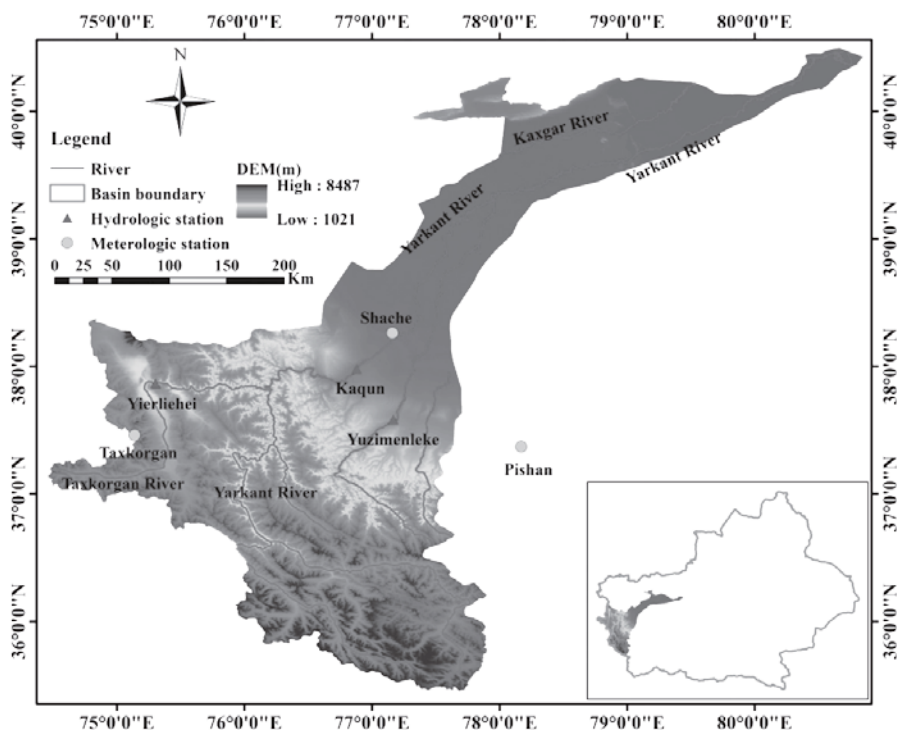


Fig. 1. Geographic location and elevation map of the Yarkant River basin.

station were incomplete; thereby, a linear regression model was employed to interpolate the missing data. The calculation showed that the data passed the consistency test.

Daily meteorological data (such as precipitation, temperature, humidity, radiation, wind speed and sunshine duration, etc.) of the study area and three nearby national meteorological stations (i.e., the Taxkorgan, the Shacha and the Pishan) from 1957 to 2017 were acquired from the National Meteorological Information Center of the China Meteorological Administration (<http://data.cma.cn/>). Because of the actual evaporation data in the meteorological data were missing, the inverse distance weighting method (IDW) was used to spatially interpolate the relevant meteorological data. The potential evapotranspiration data of the trunk stream and tributaries of the YR were estimated according to the Penman Equation (Penman, 1948), while their other meteorological elements were obtained by interpolation (Qiu *et al.*, 2016).

3. METHODOLOGY

3.1. Moving cut data wavelet transformation analysis

Moving cut data-wavelet transformation (MC-WT) method is an analysis that considers both immediateness and accuracy, and can detect the dynamic structure mutation points and mutation intervals of linear and non-linear time series (Sun *et al.*, 2017). The method has strong stability, anti-noise ability, and high calculation speed, thus, it is particularly useful for processing of large data.

The scale index γ is the core of MC-WT. Before processing with the moving cut data-wavelet transformation analysis, the estimation method of the scale index was selected. The wavelet-based analysis method proposed by Veitch and Abry (1999) was used to estimate the scale index. Its basic principle is an unbiased estimator calculated under a

Gaussian assumption, which are conceptually simple and can directly and effectively analyze oversized data sets. Steps in calculating the scale index are as follows:

- ① Assuming $x(t)$ is a time series, the decomposition scale M selected according to its length N was subjected to Mallat one-dimensional wavelet decomposition; after which, wavelet coefficients $d_{j,k}$ were calculated ($j=1, 2, \dots, M; k=1, 2, \dots, 2^j / N$);
- ② The intermediate variables η_j, s_j ($j=1, 2, \dots, M$) were calculated from the wavelet coefficients according to the following equation:

$$\eta_j = \log_2 \left[\frac{\sum_{k=1}^{N_j} d_{j,k}^2}{N_j} \right] \quad (1)$$

$$s_j = \frac{N \ln 2}{2^{j+1}} \quad (2)$$

- ③ The wavelet estimate $\gamma(j_1, j_2)$ of the scale index was calculated using the following equation:

$$\gamma(j_1, j_2) = \frac{1}{2} \left[\frac{\sum_{j=j_1}^{j_2} j s_j \eta_j - \sum_{j=j_1}^{j_2} j s_j \sum_{j=j_1}^{j_2} s_j \eta_j}{\sum_{j=j_1}^{j_2} s_j \sum_{j=j_1}^{j_2} j^2 s_j - \left(\sum_{j=j_1}^{j_2} j s_j \right)^2} + 1 \right] \quad (3)$$

where $1 \leq j_1 \leq j_2 \leq M$.

MC-WT analysis has the characteristic that the time series of data can randomly be removed with no obvious dynamic structural mutation and the correlation has negligible influence on the calculation of scale index. It can detect the mutation point or mutation interval by the contribution of the data in different time periods to the whole sequence scale index. Steps in MC-WT analysis are as follows:

- ① The removing window length L according to sequence length N was selected;
- ② The sliding step length was assigned as L , and the L data were continuously removed from the

t ($t=1, 2, \dots, N-L+1$) data in the sequence $x(t)$ to form the subsequent $\text{int}(N/L)$ with unit length $N-L$ (int stands for integer);

- ③ By estimating the scale index γ of each subsequence by wavelet estimate analysis, a scale index sequence of length $\text{int}(N/L)$ was obtained;
- ④ The scale index sequence was subjected to Variance analysis, and the mutation point or mutation interval of the original sequence was determined according to the magnitude of the variance contribution.

3.2. Moving t-test

Moving t-test detects abrupt change; it determines whether or not the difference between the mean values of the two groups of samples is significant (Zhang *et al.*, 2018). With the time series of x and the sample size N , a certain moment was set as the artificial reference point and continuous random variables was divided into two subsequences: x_1 and x_2 , with sample sizes n_1 and n_2 , respectively. Generally, the length of the selected subsequence should not be less than 3, and should not exceed 1/3 of the length of the entire time series; thus $n_1 = n_2$. The statistic can be expressed as follows:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}} \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (4)$$

where $\bar{x}_1$ and $\bar{x}_2$ are mean values, s_1^2 and s_2^2 are variances. The statistic obeys the t-distribution at a $n_1 + n_2 - 2$ degree of freedom.

The continuous calculation of sliding yielded the statistical sequence t_i ($i = 1, 2, \dots, n - (n_1 + n_2) + 1$). The critical value of t_α at a given significant level α (generally 0.05 or 0.01) was obtained from the t-distribution table. The mean value of the two subsequences was considered not significant when $|t_i| < t_\alpha$; otherwise, the time series was considered having an abrupt change at the reference point.

3.3. The Mann-Kendall test

The Mann-Kendall test (or MK test) is a non-parametric trend test widely used to detect abrupt change as recommended by the world meteorological organization. The sample sequence obtained from the test has many advantages, such as it does not obey a specific probability distribution, and it is unaffected by a few abnormal values, wide detection range, small artificial interference and high quantification degree, and so on (Mann, 1945; Kendall, 1975; Xu *et al.*, 2003). Therefore, the test is highly suitable for data with non-normal distribution of time series, such as hydro-meteorological data.

For independent random time series data ($x_1, x_2, \dots, x_n$), the test statistic S was calculated the following equation:

$$S = \sum_{i=1}^n \sum_{j=1}^{i-1} \text{sgn}(x_i - x_j) \quad (5)$$

where: n is the sample size; when $x_i - x_j > 0$, $\text{sgn}(x_i - x_j) = 1$; when $x_i - x_j = 0$, $\text{sgn}(x_i - x_j) = 0$; and when $x_i - x_j < 0$, $\text{sgn}(x_i - x_j) = -1$.

The MK test statistic Z was calculated as follows:

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (6)$$

$$Z = \begin{cases} \frac{S+1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S-1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases} \quad (7)$$

where $\text{Var}(S)$ is the variance of S .

$|Z| > Z_{1-\alpha/2}$ indicates that a trend of change of the time series is significant. $Z < -Z_{1-\alpha/2}$ indicates that declining trend of the time series is significant. $Z > Z_{1-\alpha/2}$ indicates that increasing trend of the time series is significant. The α value is the significant level, and the critical value of $\pm Z_{1-\alpha/2}$ can be obtained from the Standard Normal Distribution Table.

3.4. Hydrological sensitivity analysis

3.4.1. Analysis climate sensitivity based on Budyko hypothesis

Given that watershed is a closed system, water cycle in such system is a process of movement and transformation any forms of water from rivers, lakes, mountains, vegetation and soil, etc. to the atmosphere. And water balance is described by runoff, precipitation and actual evapotranspiration, and can be expressed as follows:

$$P = Q + E + \Delta S \quad (8)$$

where P represents the precipitation (mm), Q represents the runoff depth (mm), E represents the actual evapotranspiration (mm), and ΔS refers to the change of water storage within the basin, which was assumed to be zero ($\Delta S = 0$) over a long period of time, such as 5-10 years.

Budyko hypothesized that based on the coupled analysis of global water and energy balance, the long-term average evapotranspiration on the land surface can be determined by an equilibrium state between the water supply and energy supply on the land surface by the atmosphere (Budyko, 1948 and 1974). Zhang *et al.* (2001) studied a new curve equation by applying Budyko's hypothesis to analyze vegetation using average annual evapotranspiration, and the equation can be expressed as follows:

$$F(\Phi) = \frac{1 + \omega(E_0/P)}{1 + \omega(E_0/P) + (E_0/P)^{-1}} \quad (9)$$

where $\Phi = E_0/P$ is the drought index, E_0 is the potential evapotranspiration (mm), and ω is the water availability coefficient, which varies depending on vegetation type ($\omega = 0.2$, which can be calibrated with the actual evapotranspiration E , was used in this paper) (Zhang *et al.*, 2001; Dooge *et al.*, 1999; Wang *et al.*, 2018).

Based on the relationship between actual evapotranspiration and Budyko curve function, $E = P \times F(\Phi)$, proposed by Koster and Suarez (1999), the runoff variation caused by climate change without the impact of human activities can be expressed as:

$$\Delta Q_C = \alpha \Delta P + \beta \Delta E_0 \quad (10)$$

where ΔP (mm) and ΔE_0 (mm) are the changes of precipitation and potential evapotranspiration at a certain time period, respectively, α is the sensitivity coefficient of runoff change with respect to precipitation, and β is the sensitivity coefficient of runoff change with respect to potential evapotranspiration. Hydrological sensitivity is defined as the hydrological response of precipitation and potential evapotranspiration, namely runoff response. The equations for estimating the sensitivity coefficient proposed by Li *et al.* (2007) and Zhang *et al.* (2001) are shown in equations (11) and (12):

$$\alpha = \frac{1 + 2(E_0/P) + 3\omega(E_0/P)}{(1 + (E_0/P) + \omega(E_0/P)^2)^2} \quad (11)$$

$$\beta = -\frac{1 + 2\omega(E_0/P)}{(1 + (E_0/P) + \omega(E_0/P)^2)^2} \quad (12)$$

3.4.2. Contribution rate of runoff variations

To quantify the contribution rates of climate change and human activities to runoff changes, the following equation was used:

$$Q = f(C, H) \quad (13)$$

where C and H stand for the climate change and human activities, respectively, and f is the first-order function. Partial derivative of eq. (13) is shown in eq. (14):

$$\Delta Q = \frac{\partial Q}{\partial C} \Delta C + \frac{\partial Q}{\partial H} \Delta H = \Delta Q_C + \Delta Q_H \quad (14)$$

where ΔQ is the total amount of runoff changes calculated according to the observed runoff, and ΔQ_C and ΔQ_H are the runoff changes caused by climate change and human activities, respectively. To identify the driving factors of runoff variation, two variables in eq. (14) were assumed to be independent of each other, which have also been used by Wang *et al.* (2013). The assumption was applied to throughout runoff variations.

The contribution rate of runoff change caused

by climate change and human activities was calculated by the following equation:

$$\eta_C = \frac{\Delta Q_C}{\Delta Q} \times 100\%, \eta_H = \frac{\Delta Q_H}{\Delta Q} \times 100\% \quad (15)$$

4. RESULTS AND ANALYSIS

4.1. Trend and characteristics of hydro-meteorological elements

The MK test was used to analyze the trends of meteorological data (e.g. precipitation, temperature, and potential evapotranspiration) of the trunk stream and tributaries of the Yarkant River basin from 1957 to 2017. As shown in Table 1, the average annual temperature of the trunk stream of the Yarkant River increased significantly ($Z = 6.35$) over the 61 years observed, its average annual precipitation showed a slow growth trend and its annual potential evapotranspiration decreased significantly ($Z = -3.67$); all of which had the significance level of 0.05. Additionally, the average annual of precipitation ($Z = 3.52$), temperature ($Z = 5.12$) and potential evapotranspiration ($Z = 3.57$) of the Taxkorgan River in the past 61 years showed significant increasing trends at the significance level of 0.05. Moreover, the average temperature of the Tiznap River in the 61 years observed showed a significant increasing trend ($Z = 6.12$), its average annual precipitation increased slowly, and its annual potential evapotranspiration showed insignificant decreasing

trend.

The trend of runoff series of 3 hydrological stations in the trunk stream and tributaries of the Yarkant River basin during 1957-2017 is shown in Figure 2. The runoff series of the trunk stream of the Yarkant River had an increasing trend but was not obvious. In addition, the runoff series of the Taxkorgan River and the Tiznap River also had an increasing trend, but the former was insignificant and the latter was slow and unobvious.

4.2. Diagnosis of runoff variation point in trunk stream and tributaries of the Yarkant River basin

In the calculation by MC-WT, $L = 12$ months with removed window length was selected and Mallat discrete wavelet transform method (Sun *et al.*, 2017) was used, from which the scale index of each sub-sequence was calculated; and sym8 was used as the filter group. The results from the calculation using sequence length $N = 732$, the decomposition scale $M = 4$, $j_1 = 1$ and $j_2 = M$ are shown in Figure 3. The abrupt change point of runoff sequence at the Kaqun hydrological station likely occurred in 1993, while that at the Yierliehei hydrological station and the Yuzimenleke hydrological station was likely in 1974 and 1993, and in 1984, respectively. The abrupt change point was also analyzed by moving t-test using annual scale analysis and the length of the sub-sequence of 13. The results illustrated in Figure 4 showed that the abrupt change point of runoff sequence at

Table 1. Results from the MK test of meteorological data of trunk stream and tributaries of the Yarkant River basin.

River	Precipitation (mm)			Temperature (°C)			Potential evapotranspiration (mm)		
	Z	Trend	Significance	Z	Trend	Significance	Z	Trend	Significance
Trunk stream of the Yarkant River	1.98	Increase	*	6.35	Increase	***	-3.67	Decrease	***
Taxkorgan River	3.52	Increase	***	5.12	Increase	***	3.57	Increase	***
Tiznap River	2.14	Increase	*	6.12	Increase	***	-1.26	Decrease	—

Note: *** indicates significance at $P = 0.001$, ** indicates significance at $P = 0.01$, * indicates significance at $P = 0.05$, — indicates insignificance.

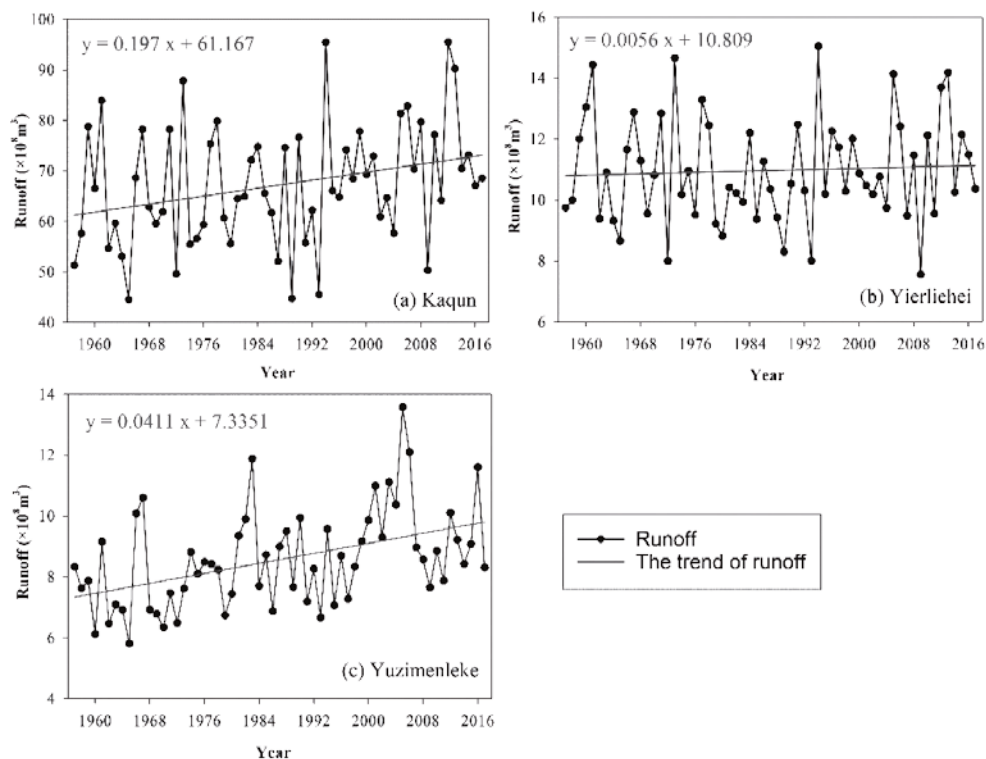


Fig. 2. Trends of runoff series in the Yarkant River hydrologic stations.

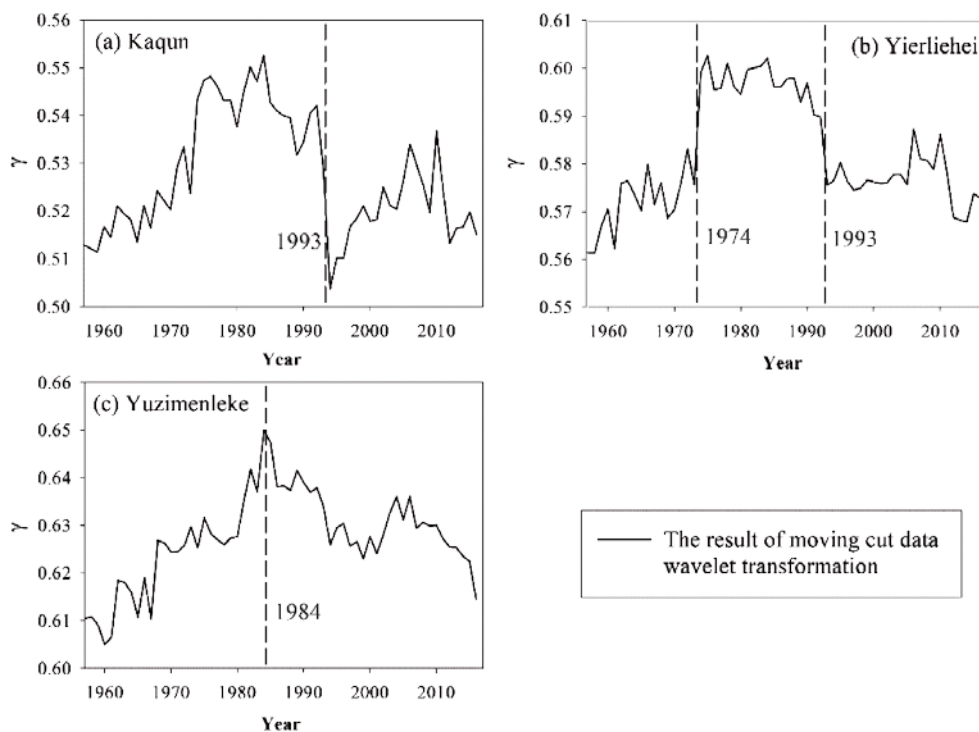


Fig. 3. Results from MC-WT analysis of runoff variations at different hydrological stations in the Yarkant River.

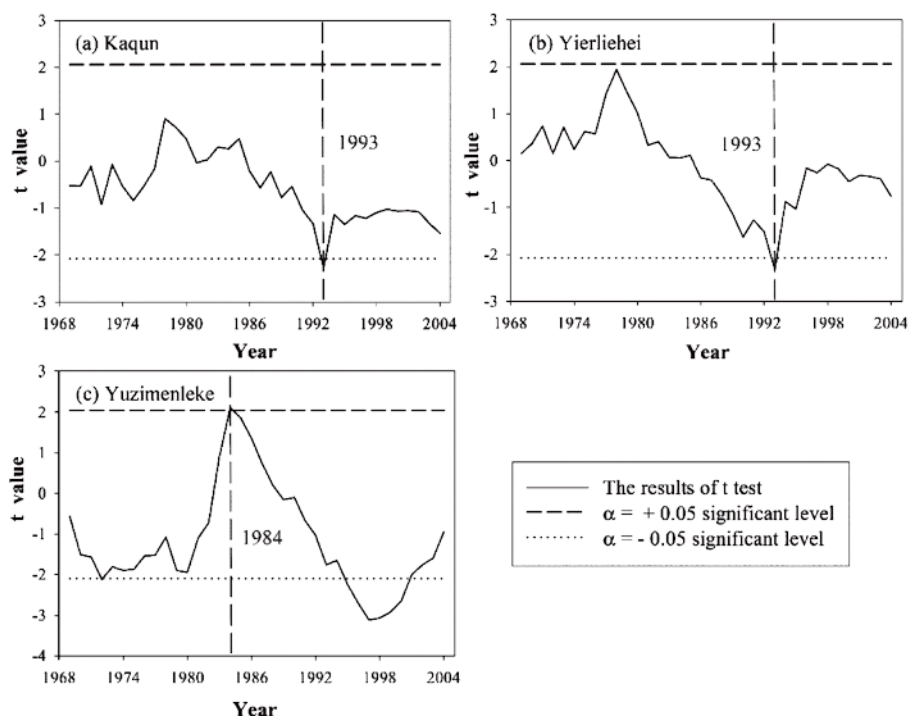


Fig. 4. Results of moving t-test of different hydrological stations at the Yarkant River.

the Kaqun station was in 1993, whereas the runoff variation years of two tributaries, the Taxkorgan River and the Tiznap River, were in 1993 and 1984, respectively. Comparative analysis of the variation diagnosis of the two methods showed that the MC-WT is reliable and rational. These data indicate that the runoff variation points of the trunk stream and tributaries of the Yarkant River at the Kaqun station, the Yierliehei station and the Yuzimenleke station were in 1993, 1993 and 1984, respectively.

According to the spatial location of trunk and tributaries water systems in the Yarkant River basin shown in Figure 1, the runoff variation points of adjacent hydrological stations (the Kaqun station and the Yierliehei station) at the same water system are consistent. Due to their different geographical locations, the upper reaches of the Tiznap River and the main stream of the Yarkant River are blocked by mountains, causing the runoff variation year to be inconsistent with the main stream, which shows that there is a lag of variability of the main stream.

4.3. Sensitivity characteristics of trunk and tributaries

To analyze the sensitivity characteristics of runoff variations in the trunk stream and tributaries of the Yarkant River caused by climate factors, the data were divided into two periods: Period 1—1957-1993, which was set as the baseline period and was assumed to be in the natural state, and Period 2—1994-2017, which was set as the variation period that was highly affected by climate change and human activities.

The sensitivity analysis was carried out based on Budyko hypothesis to investigate the sensitivity of runoff variation caused by climate factors (e.g., precipitation and potential evapotranspiration) in different periods. The results depicted in Table 2 showed that the sensitivity coefficients of the trunk stream and the two tributaries of the Yarkant River increased significantly during the variation period compared with that during the baseline period, in which the sensitivity coefficient of runoff variation

Table 2. Climate sensitivity coefficients of the trunk stream and tributaries of the Yarkant River.

Period	Trunk stream of the Yarkant River		Taxkorgan River		Tiznap River	
	α	β	α	β	α	β
Baseline period	0.0135	-0.0024	0.0224	-0.0041	0.0135	-0.0024
Variation period	0.0222	-0.0041	0.0426	-0.0082	0.0231	-0.0042
1957-2017	0.0167	-0.0030	0.0297	-0.0055	0.0170	-0.0030

to precipitation increased by 64.4%-90.2%, and that to potential evapotranspiration increased by 70.8%-100%. Considering the entire period (1957-2017), the sensitivity coefficient of runoff in the trunk stream of the Yarkant River to precipitation was 0.0167, suggesting that the runoff depth will likely increase by 0.167% for every 10% increase of precipitation. The sensitivity coefficient of runoff to potential evapotranspiration was -0.0030, indicating that the runoff depth will decrease by 0.03% for every 10% increase of potential evapotranspiration. Moreover, the sensitivity coefficient of the tributary Taxkorgan River runoff to precipitation was 0.0297, which is 1.8 times higher than the sensitivity coefficient of the main stream; its sensitivity coefficient for potential evapotranspiration was -0.0055, which is 83.3% higher than that of the trunk stream. The sensitivity coefficient of runoff to precipitation of the Tiznap River was slightly higher than that of the main stream. The trunk stream and the two tributaries of the Yarkant River basin were sensitive to climate during the variation period, and

the tributaries were more sensitive to climate change than the main stream.

4.4. Attribution analysis of runoff variation in trunk stream and tributaries

Hydrological sensitivity analysis was employed to identify the driving factors of runoff variation and to quantitatively analyze their contribution rates (Table 3 and Figure 5). As shown in Table 3, the average annual precipitation of the trunk stream of the Yarkant River and two tributaries, the Taxkorgan River and the Tiznap River increased by 11.87, 22.59 and 13.11 mm respectively in the variation period compared with that in the baseline period. During the variation period, the perennial average potential evapotranspiration of the trunk stream of the Yarkant River decreased by 2.66 mm, whereas that of the Taxkorgan River increased by 1.98 mm and that of the Tiznap River decreased by 0.68 mm. Analysis of the geographical location of the Yarkant River basin shown in Figure 1 and the results tabulated in Table 3 showed that runoff variations

Table 3. Impacts of climate change and human activities on runoff in the Yarkant River basin.

River	Period	P (mm)	E_0 (mm)	ΔQ (mm)	ΔQ_C (mm)	η_C (%)	ΔQ_H (mm)	η_H (%)
Trunk stream of the Yarkant River	Baseline period	51.82	708.15	—	—	—	—	—
	Variation period	63.69	705.49	0.743	0.206	27.7	0.537	72.3
Taxkorgan River	Baseline period	67.02	740.06	—	—	—	—	—
	Variation period	89.61	742.04	2.057	0.660	32.1	1.397	67.9
Tiznap River	Baseline period	51.85	708.73	—	—	—	—	—
	Variation period	64.96	708.05	0.825	0.224	27.2	0.601	72.8

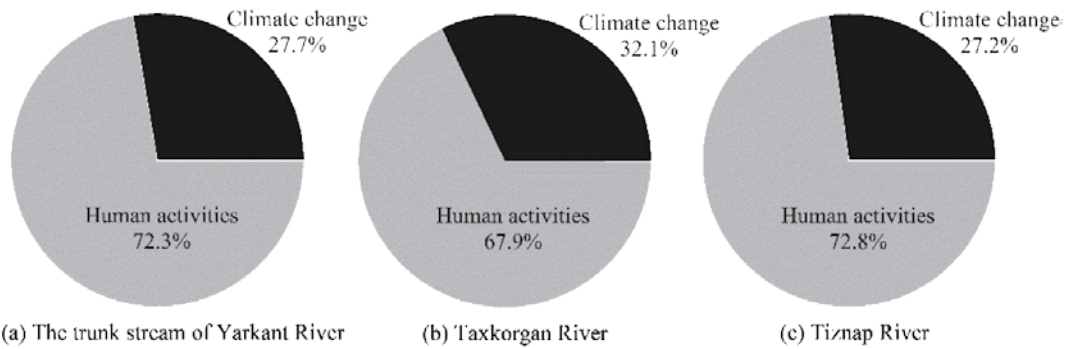


Fig. 5. Rates of contribution of climate change and human activities to runoff variation in trunk stream and tributaries of the Yarkant River during the variation period.

caused by different factors were spatially different. The total runoff variation of the trunk stream of the Yarkant River was smallest with a value of 0.743 mm. The increase of total runoff of the tributary (ΔQ) was 2.882 mm, which is 3.88 times higher than that of the main stream.

The data in Table 3 and Figure 5 showed that the responses of runoff changes to climate change and human activities in different rivers were spatially different according to the spatial location analysis of the river system in the Yarkant River basin. Compared with the trunk stream of the Yarkant River, the runoff changes of the two tributaries were more responsive to climate change, and contribution rate of the climate factors of the Taxkorgan River, which is located in the upstream, was largest with a value of 32.1%. This may be due to that the tributary originates from a glacier and is located in the mountain valley with higher terrain and denser vegetation coverage (Liu *et al.*, 2016). Runoff changes in the trunk stream of the Yarkant River were more responsive to human activities, with a contribution rate of 72.3%, and this may be related to geographical location and population distribution (Xu *et al.*, 2013). Moreover, considering the runoff abrupt change, human activities were the main factors leading to runoff variation. The runoff variation in response to climate change of the tributaries were larger than that of the trunk stream,

and that of high-altitude areas was larger than that of low-altitude areas with contribution rates ranging from 27.2% to 32.1%. However, human activities were the main factor contributing to the runoff abrupt change in the trunk and two tributaries of the Yarkant River basin, with contribution rates of 72.3%, 67.9% and 72.8%, respectively.

Overall, the contributions of climate change and human activities to runoff changes in the trunk and tributaries of the Yarkant River were different, while human activities were the dominant driving factor. Since the 1990s, growth of population and acceleration of industrial and agricultural development in Xinjiang has caused increased demand for water resources (Liu and Chen, 2006). The growth of human activities not only affect the middle and lower reaches of the Yarkant River basin, but also its upstream and other flow areas. For example, in the middle and lower reaches of the plain area, the impacts of human activities, such as oasis, irrigation agriculture and water diversion and water transfer were more prominent, and the runoff dissipation also increased. In the upstream areas, human relies on the construction of reservoirs, channels, dams and other water conservancy projects to regulate the downstream discharge, which has affected the hydrological process in the middle and lower reaches.

5. DISCUSSION

5.1. The response relationships of runoff variation in the Yarkant River basin

Based on the above analysis and previously published results, this paper discusses the response relationships of runoff variation in the Yarkant River. As illustrated in Table 1 and Figure 2, the annual runoff in the entire Yarkant River basin insignificantly increased, while its average annual runoff both before and after the abrupt change significantly increased. Before the abrupt change of runoff, runoff change was only affected by climate change. In the past decades, the influence of global climate change has caused the climate in Xinjiang to change from warm and dry to warm and wet (Wang *et al.*, 2018). Therefore, runoff change in response to climate change was reflected by higher water circulation in the source area and dramatic increase of river runoff due to temperature rise caused by various activities such as increasing precipitation in mountainous areas and melting of glacial snow.

By contrast, after the abrupt change of runoff, hydrological change process was affected by both climate change and human activities. The source area of the Yarkant River is located in the extreme arid area of northwest China, at which climate has high impacts on the river runoff in mountainous areas. However, with increasing human activities, the response of the middle reaches of the Yarkant River to the runoff variation in the upper reaches was gradually increased; that is, the response of the trunk runoff of the Yarkant River to the tributaries

was gradually increased, as manifested by change of underlying surface conditions, such as the increase of vegetation in the middle reaches, the decrease of vegetation in the upper reaches, and the increase of water consumption in the middle reaches. According to Yu *et al.* (2019) (see Table 4), since the 1990s, the vegetation coverage increased with elevation at a range of 1,500 to 3,500 mm, and the vegetation landscape exhibited the desert-shrub-forest-grass distribution state, which is the vertical zonal characteristic. At elevations of above 3,500 mm, the vegetation coverage tended to decrease with the increase of elevation. Li and Xia (2018) have described that dissipation of water resources is low in areas with low vegetation coverage while is high in areas with high vegetation coverage and large runoff consumption. Consequently, the increase in runoff caused by climate change should be greater than the decrease in runoff caused by human activities. This way, the amount of water in the upper and middle reaches of the Yarkant River can maintain its balance or slowly increase.

5.2. Uncertainty analysis

According to the above analysis, the change of hydrological process in the Yarkant River basin before the abrupt change was mainly affected by climate change, and that after the abrupt change was significantly affected by human activities. In the calculation of hydrological sensitivity analysis based on Budyko hypothesis, there may be errors due to the following uncertainties. Firstly, in the attribution analysis of runoff variation due to climate change, the influence of melted glacial snow and

Table 4. Variation of vegetation coverage with elevation in the middle and upper reaches of the Yarkant River.

Elevation (m)	Vegetation coverage	Area ratio (%)	Grade	Vegetation coverage (FVC)
1,500 - 2,500	Medium	14.17	Low	$FVC < 0.1$
2,500 - 3,500	High	17.52	Lower	$0.1 \leq FVC < 0.3$
3,500 - 4,500	Medium	22.9	Medium	$0.3 \leq FVC < 0.5$
4,500 - 5,500	Lower	36.36	Higher	$0.5 \leq FVC < 0.7$
> 5,500	Low	9.02	High	$FVC > 0.7$

land surface evapotranspiration were not taken into consideration because there are a large number of mountain glaciers distributed in the Yarkant River watershed (Yin *et al.*, 2017). Secondly, the overall impact of human activities on runoff variations was considered as precise underlying surface conditions and parameters, such as terrain, vegetation, soil and other factors were not considered. Finally, the study area is located in a mountainous area, which has complex topographical and geomorphic features, high and low altitude variation, and a small number with sparse distribution of hydro-meteorological platforms in the basin. This can lead to mutual interference between the hydro-meteorological data interpolation results, thus makes it impossible to accurately evaluate the spatial difference between hydrologic changes caused by climate change (Hubbard, 1994; Xu *et al.*, 2015).

6. CONCLUSIONS

To reveal the variation trend, abrupt change and response mechanism of the hydrological process in the Yarkant River, long-term hydrological and meteorological data of the Yarkant River from 1957 to 2017 were analyzed by the MC-WT, moving t-test and the MK test. The sensitivity and attribution of the runoff in the trunk stream and tributaries was also investigated by hydrologic sensitivity analysis method based on Budyko hypothesis. The following conclusions were drawn:

- (1) In different rivers, the change rate of runoff is not uniform and the increase trend is not significant. According to the MK test, the temperature and precipitation sequences of the trunk and tributaries were significantly increased. The abrupt change analysis showed that the runoff variation point of Yarkant River basin occurred at around the 1990s. When the baseline period (1957-1993) was assumed as the period with natural state, the variation period (1994-2017) was found affected by both climate

change and human activities.

- (2) In all periods, the sensitivity coefficients of runoff with respect to precipitation and potential evapotranspiration were significantly increased, and spatial differences in climate sensitivity coefficients in the Yarkant River basin were observed. The runoff in the tributary was more sensitive to climate change than that in the trunk stream, and the runoff in high-altitude areas was more sensitive to climate change than that in the low-altitude areas.
- (3) In the upper and middle reaches of the Yarkant River, the contribution rates of climate change on runoff variation were 27.2%-32.1%, and those of human activities to runoff variation were 67.9%-72.8%. The degrees of runoff changes in the trunk stream and two tributaries of the Yarkant River in response to climate change and human activities were different. Before the abrupt change of runoff, climate change was the dominant factors affecting hydrological process; but after the runoff abrupt change, human activities were the dominant factor.

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