Water Resour Manage (2016) 30:115–131
DOI 10.1007/s11269-015-1149-x

Impacts of Climatic Change on Hydrological Regime in the Three-River Headwaters Region, China, 1960-2009

Tianxu Mao [1,2] · Genxu Wang [1] · Tao Zhang [1,2]

Received: 21 March 2015 / Accepted: 17 September 2015 /
Published online: 24 September 2015

Abstract To identify the changing characteristics of runoff and climate change trends and their relationship in the Three-River Headwaters Region (TRHR), this study uses the runoff and meteorological data of three hydrological gauging stations and 12 meteorological stations across the TRHR for the period from January 1960 to December 2009 as the research subjects. The runoff coefficient (RC), ratio of monthly maximum/minimum runoff, and flow duration curves (FDCs) were calculated to identify spatio-temporal variations in runoff and reflect the change in hydrological regime. Results showed an insignificant decrease in annual runoff both in the Yellow River Headwater Region (YERHR) and the Lantsang River Headwater Region (LARHR), whereas it increased in the Yangtze River Headwater Region (YARHR). The RC of the three sub-regions showed a decreasing trend, the LARHR maintained a high mean value of 0.55, followed by a lower value in the YERHR (0.32), and that in the YARHR was the lowest at only 0.23. The variations in monthly maximum/minimum runoff were synchronized; their ratios were relatively steady in the study period. The flow duration analysis showed a remarkable decline in high runoff (at a frequency of 5–15%) in the three sub-regions after 1990. The runoff characteristics showed an overall decrease in the YERHR, the moderate runoff (at the frequency of 15–30% and 40–70%) of the YARHR showed an obviously increase, and the runoff of the LARHR was relatively steady. The relationship between precipitation, temperature and runoff illustrated that precipitation was the dominant factor in runoff generation, whereas the impacts of temperature on regional hydrological regime should not be neglected. Results of this study are of practical significance for water resources management and evaluation of the impacts of climatic change on the hydrological regime in a long-term consideration.

✉ Genxu Wang
wanggx@imde.ac.cn

[1] Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, People's Republic of China

[2] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

Keywords Climatic change · Hydrological regime · Mann-Kendall test · Three-River Headwaters Region

1 Introduction

Global warming is a non-disputed fact under the background of climate change, and its impacts have received widespread concern. The IPCC's Fifth Assessment Report (AR5) stated that 1983–2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, the globally averaged combined land and ocean surface temperature data show a warming of 0.85°C over the period from 1880 to 2012, and the total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78°C based on the single longest dataset available (IPCC 2013). Increasing temperature and changing atmospheric circulation inevitably accelerate the process of the water cycle and cause redistribution of water resources at spatial and temporal scales (Lan et al. 2010) as well as in precipitation amounts, intensities and patterns (Nijssen et al. 2001). These changes will in turn affect water availability and may affect the hydrological regime of rivers. In recent decades, researchers have been paying increasing attention to the changes in regional hydrological regime associated with climatic change and human activity (Abdul Aziz and Burn 2006; Li et al. 2012; Ma et al. 2003; Middelkoop et al. 2001; Mimikou et al. 1999; Xu 2011).

The Qinghai-Tibet Plateau (QTP) is considered to be more sensitive to climatic warming than other regions (Wang et al. 2009). Over the past three decades, the large area at an altitude above 4000 m has warmed 0.3°C per decade, which is twice the rate of observed global warming (Xu et al. 2009a). The Three-River Headwaters Region (TRHR) located in the hinterland of the QTP, is the source region of the Yangtze River, Yellow River and Lantsang River, known as "China's Water Tower". This region is divided into three sub-regions: the Yangtze River Headwater Region (YARHR), the Yellow River Headwater Region (YERHR) and the Lantsang River Headwater Region (LARHR). This region is not only an important ecological barrier of China and Eastern Asia but also a region with a sensitive and fragile ecological environment (Liu et al. 2014). A significant portion of the TRHR is underlain by permafrost, which is highly sensitive to the global climatic change. Permafrost as an impermeable layer that plays an important role in the process of runoff generation in cold regions (Woo et al. 2008). The degradation of permafrost is an indisputable fact accompanied by the sustained increase in temperature during the last several decades (Cheng and Wu 2007; Wu and Zhang 2008). The melting of permafrost with the rise of soil temperature, deepen the thickness of active layer, and so on. These then inevitably lead to significant alternations in hydrological regime in the TRHR. Related studies have been conducted in the Eurasian Arctic drainage basin (Shiklomanov et al. 2007; Yang et al. 2002, 2004), northern Canada (Déry and Wood 2005), and northwest China (Niu et al. 2011).

Because of the lack of human interventions (e.g., reservoirs, dams, agricultural irrigation), this region is considered to be an ideal place for hydrological research. In addition, the influence of snow melt water on runoff can be ignored due to relatively small snowfall and limited observation. Many studies have investigated the impacts of climate change on hydrological processes in different sub-regions of the TRHR. Zhang et al. (2011) reported that during the period 1965–2004 the temperature of the TRHR increased, the runoff of the three sub-regions decreased, and both had abrupt changes in 1994, whereas no significant changes occurred with precipitation. Analyzing hydrological and meteorological datasets from the past 50 years, Lan et al. (2010) found that runoff in the YERHR has been decreasing continually since the end of the 1980s. Xu et al. (2009b) simulated runoff under four scenarios using different GCMs during the future for the three benchmarks; the results suggested an overall decreasing trend in mean annual runoff in the YERHR. However, a clearly increasing trend was reported in the YARHR (Li et al. 2013). Obviously, the impacts of climatic change on runoff were not unified in the three sub-regions of the TRHR. Using wavelet correlative analysis, Qian et al. (2014) investigated the impacts of precipitation, air temperature and evapotranspiration on annual runoff in the YARHR during 1957–2009 and indicated that the correlation between runoff and climatic components depends on periods. Similarly, the IPCC (2013) noted that trends based on short records are very sensitive to beginning and ending dates and do not in general reflect long-term climate trends due to natural variability.

These studies provided a preliminary understanding of the effects of climatic change on runoff process in the YERHR, YARHR and LARHR, respectively. Because the effects of climatic change on the hydrological regime are not consistent in different regions, there has been little research on comparative analyses at the same time scale. In addition, the influence of climatic change on hydrological trends and regimes are slow and profound; more details of the changes from a holistic perspective are required in the three sub-regions of the TRHR. This present study utilized long-term (1960–2009) climatic records from 12 meteorological stations and river discharge records from three gauging stations distributed in the YERHR, YARHR and LARHR. The objectives of this study were to (1) compare the changes in evaluation indexes which reflect regional hydrological regime during the same historical periods in the YERHR, YARHR and LARHR; (2) investigate the trends and amplitudes of runoff, precipitation and temperature at annual and seasonal scales; and (3) clarify the relationship between runoff and meteorological variables in the three sub-regions of the TRHR. The results of this study can provide helpful information for understanding and assessing regional hydrological regimes and their changes under climatic warming in the TRHR.

2 Study Area Description

The TRHR, as the headwaters of the Yellow River, Yangtze River, and Lantsang River, is located in the hinterland of the Tibetan Plateau (31°39′ N-36°12′ N; 89° 45′ E-102°23′ E), an area of 30.25×10^4 km^2, and accounts approximately for 12 % of the total land area of the Tibetan Plateau. The region is also known as the "Water Tower" in China. The total contribution rate of the YERHR to water volume of the Yellow River is approximately 49 %. The YARHR provides approximately 20 % of the water volume of the Yangtze River, and the contribution of the LARHR to the Lantsang River is approximately 15 %. The altitude in the TRHR ranges widely from 2610 to 6950 m, with an average elevation of 4500 m and higher mountains. The study area is a typical plateau continental monsoon region, the annual mean temperature ranges from -5.38 to 4.14°C, the annual precipitation ranges from 262.2 to 772.8 mm, and the annual evaporation ranges from 730 to 1700 mm (Cao and Pan 2014; Yi et al. 2012).

3 Materials and Methods

3.1 Data Set

There are 18 meteorological stations in the TRHR; most of them were not established until the 1960s. To establish a uniform, stable climate sequence, as well as to ensure the completeness and consistency of the meteorological data, 12 meteorological stations (Fig. 1) over the TRHR were ultimately selected in this study, and the time period considered is from January 1960 to December 2009. The monthly average temperature and precipitation data of 12 meteorological stations were provided by the China Meteorological Data Sharing Service System (available from http://cdc.cma.gov.cn). The individual missing data were interpolated by linear regression. Table 1 shows the detailed information of the 12 meteorological stations, such as location, WMO number, latitude, longitude, and altitude. Monthly runoff data were collected from the Tangnaihai, Zhimenda and Changdu hydrological stations that located at the outlet of the YERHR, YARHR and LARHR, respectively. Figure 1 and Table 2 show the detailed information of the three hydrological stations, such as location, latitude, longitude, altitude and drainage area.

In this study, the climatic and hydrological variables were analyzed at annual and seasonal scales, and December-February (next year), March-May, June-August and September-November correspond to winter, spring, summer, and autumn, respectively.

3.2 Trend Analysis

To analyze the long-term trends of hydrometeorological variables, the non-parametric Mann-Kendall test (Kendall 1975; Mann 1945) was used. Mann-Kendall test is a statistical test widely used for the analysis of trends in climatologic and hydrologic time series (Hamed 2008; Yue et al. 2002; Yue and Wang 2004). The MK test is based on the statistic S defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{1}$$

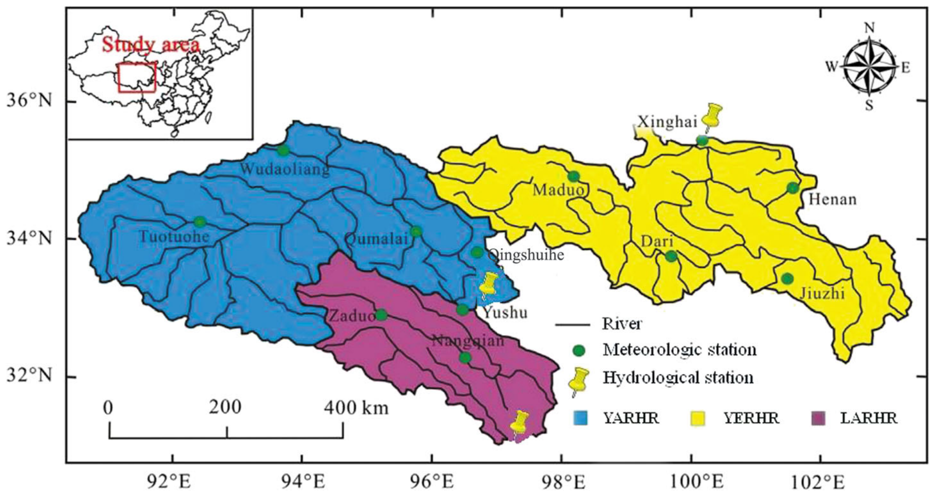

Fig. 1 Distribution of meteorological stations, hydrological stations and sub-regions in the Three-River Headwaters Region (based on (Cao and Pan 2014))

Table 1 Detailed information on the 12 meteorological stations in the Three-River Headwaters Region

Basin	WTO number	Station	Long.(E)	Lat.(N)	Altitude (m)	Data period
YERHR	56046	Henan	101°36′	34°44′	3529	1960–2013
	56065	Dari	99°39′	33°45′	3989	1956–2013
	56067	Jiuzhi	101°29′	33°25′	3631	1959–2013
	56033	Maduo	98°12′	34°54′	4272	1953–2013
	52943	Xinghai	99°59′	35°35′	3305	1960–2013
YARHR	56034	Qingshuihe	97°08′	33°48′	4422	1957–2013
	56021	Qumalai	95°47′	34°07′	4197	1957–2013
	56004	Tuotuohe	92°26′	34°12′	4542	1957–2013
	52908	Wudaoliang	93°04′	35°13′	4622	1957–2013
	56029	Yushu	97°05′	33°00′	3637	1956–2013
LARHR	56018	Zaduo	95°17′	32°53′	4074	1957–2013
	56125	Nangqian	96°29′	32°12′	3656	1957–2013

Where x_j is the sequential data values, n is the length of the data set, and

$$\mathrm{sgn}(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{2}$$

If the data set is independent and identically distributed, the statistic S is approximately normally distributed with the mean and variance as follows:

$$E(S) = 0 \tag{3}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \tag{4}$$

A normalized test statistic Z can be computed based on S as follows:

$$Zc = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \tag{5}$$

Table 2 Detailed information on the three hydrological stations in the Three-River Headwaters Region

Basin	Station	Long.(E)	Lat.(N)	Altitude (m)	Drainage area (km^2)	Data period
YERHR	Tangnaihai	100°08′	35°30′	2725	121,972	1956–2010
YARHR	Zhimenda	97°14′	33°00′	3536	137,704	1953–2010
LARHR	Changdu	97°11′	31°08′	3224	50,608	1960–2009

In a two-sided test for trends, the null hypothesis H_0 is accepted if $-Z_{1-\alpha/2} \le Z_c \le Z_{1-\alpha/2}$, where $\pm Z_{1-\alpha/2}$ is the standard normal variance and α is the significance level for the test.

The magnitude of the slope of the trend is estimated using the approach of Thiel (1950) and Sen (1968). The slope is estimated by:

$$\beta = Median\left(\frac{x_i - x_j}{i = j}\right), \forall j < i \tag{6}$$

Where $1<j<i<n$, β is the estimate of the slope of the trend and x_i is the *i-th* observation. A positive (negative) value of β indicates an increasing (decreasing) trend.

The software used for performing the statistical Mann-Kendall test is Matlab2012.

3.3 Evaluation Indexes of Hydrological Regime

3.3.1 Runoff Coefficient

The runoff coefficient (RC) is the ratio between the depth of runoff and precipitation in a certain time and area, and it reflects the impacts of natural geographical factors on runoff. RC was widely used as a diagnostic variable for runoff generation in process studies, and as the important input parameter in hydrological design (Viglione et al. 2009; Wainwright and Parsons 2002; Wang et al. 2012, 2013).

3.3.2 The Ratio of Monthly Maximum/Minimum Runoff

To evaluate the variations in hydrological regime, it is essential to analyze the changes in extreme hydrological events, which include monthly maximum runoff and monthly minimum runoff in this study. Maximum runoff is usually associated with floods, while minimum runoff represents the base flow. Although future climate model projections suggest that the frequency and magnitude of extreme hydrological events will increase, they show no evidence of widespread trends in extreme runoff across the Russian Arctic drainage basin (Shiklomanov et al. 2007). Smith et al. (2007) analyzed daily discharge data for 111 northern rivers and found an overall pattern of increasing minimum daily flows with climate change throughout Russia. Ye et al. (2009) analyzed the relationship between runoff characteristics and basin permafrost coverage by using monthly runoff in the Lena River and found that the ratios of monthly maximum/minimum runoff directly reflect hydrological regimes. In this study, the same method will be used to assess the variations in hydrological regime in the three sub-regions of TRHR.

3.3.3 Flow Frequency Analysis

A flow duration curve (FDC) illustrates the relationship between the frequency and magnitude of runoff. Applications of FDC are of interest for many hydrological problems related to hydropower generation, river and reservoir sedimentation, water quality assessment, water-use assessment, water allocation and habitat suitability (Castellarin et al. 2004). FDC was considered to be an essential operative tool to understand runoff regime and widely used in hydrological research of ungauged river basins or short runoff records (Ganora et al. 2009; Li et al. 2010; Liucci et al. 2014; Mohamoud 2008; Viola et al. 2011; Waseem et al. 2015).

An empirical long-term FDC is the complement of the empirical cumulative distribution function of monthly runoff based on the complete runoff record (Castellarin et al. 2007). Empirical FDCs can be constructed as follows: (1) by ranking the observations of natural runoff in descending order and (2) plotting each ordered observation versus its corresponding duration. The p_i is calculated as follows:

$$p_i = P(Q > q_i) = \frac{i}{N+1} \tag{7}$$

Where i is the rank assigned to each runoff value; N is the length of the monthly runoff series; q_i,i=1,2,…N, are the ordered observations; and p_i is the frequency of the exceedance of q_i.

4 Results

4.1 The Variations and Trends in Annual Runoff

Figure 2 shows the annual runoff change and trends at the three outlet hydrological stations in the YERHR, YARHR and LARHR during 1960–2009. The overall runoff represents a decrease (4.5 km^3 or 20.2 % and 1.9 km^3 or 12.1 %, respectively) in the YERHR and LARHR, and a slight increase (1.5 km^3 or 13.1 %) in the YARHR.

Since the 1980s, the runoff of the YERHR has shown a continual decrease, and the runoff observed in 2002 was the lowest since the first hydrological records. On the contrary, the runoff of the YARHR declined in the first few years and sharply increased in the middle of the 1990s, reaching the highest value of 24.5 km^3 in 2009. In contrast with YERHE and YARHR, the runoff of LARHR was relatively stable, with a small fluctuation between 9.3 km^3 and 22.6 km^3 in the study period. The coefficient of variation (Cv) is used to estimate the degree of variation of the observed variable in a time-series. From the perspective of Cv, the variation in runoff is not high, ranging from 0.20 to 0.27, indicating moderate variability. The Cv of runoff in the LARHA is lowest, whereas it was almost equal in the YERHR and YARHR as 0.26 and 0.27, respectively.

4.2 The Variations in Runoff Coefficient

Figure 3 shows the changes in RC in the YERHR, YARHR and LARHR during 1960–2009. Obviously, the RC of the LARHR is highest, with a mean value up to 0.55, followed by that in the YERHR (0.32), and the YARHR had the lowest value at only 0.23.

A linear regression analysis was conducted to detect the trends in RC. The results showed that the RC significantly decreased at the 99 % confidence level both in the YERHR and the LARHR. A negligible decrease was found in the YARHR, while the statistical result was not significant. The results stated that the capacity of runoff generation decreased in the TRHR, especially in the YERHR and the LARHR.

4.3 The Variations in Monthly Maximum/Minimum Runoff

In this section, the variations and trends in monthly maximum/minimum runoff were described in the YERHR, YARHR and LARHR during 1960–2009 (Fig. 4). A decrease in monthly maximum and minimum runoff was observed both in the YERHR and the LARHR; however, the trend showed a slight increase in the YARHR. Interestingly, regardless of increase or

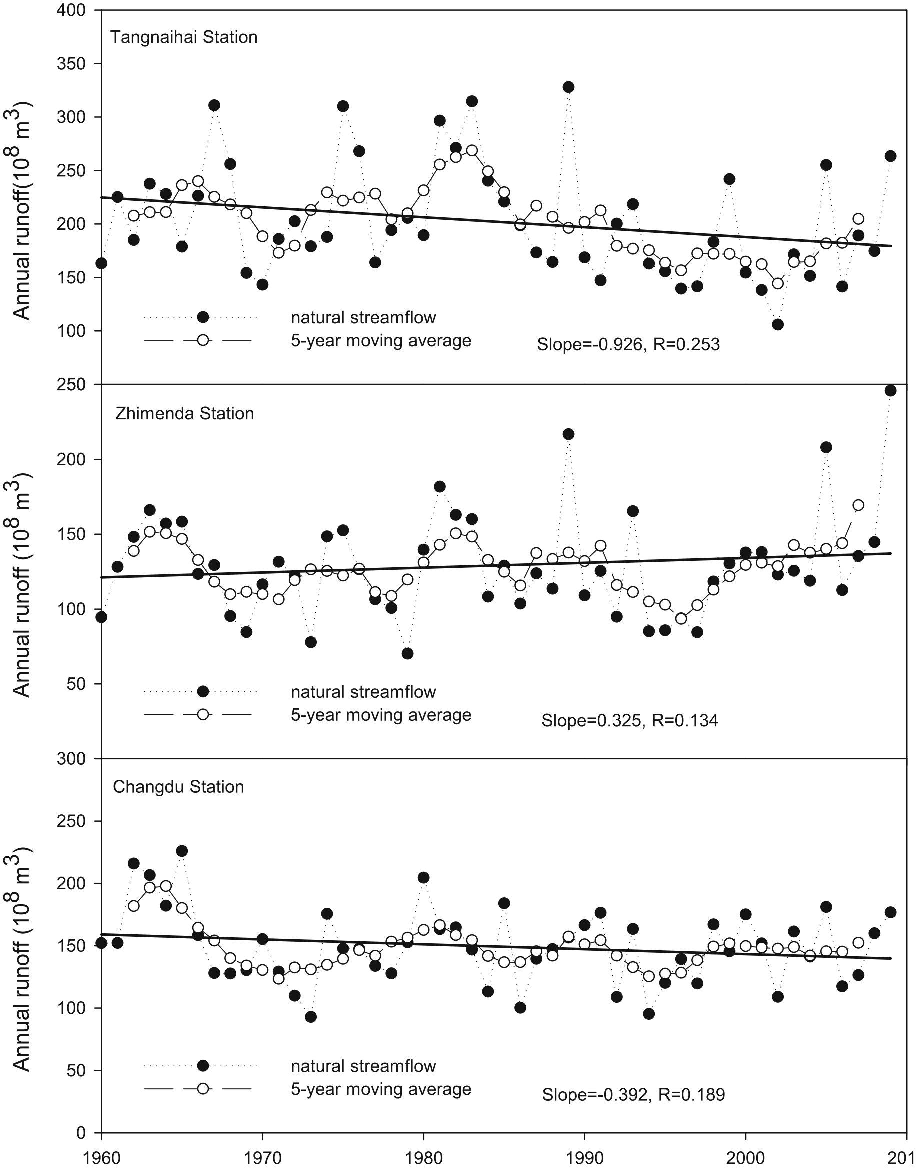

Fig. 2 Annual runoff observed at the outlet hydrological station during 1960–2009 in the YERHR, YARHR and LARHR

decrease, the trends or fluctuations of both monthly maximum runoff and monthly minimum runoff were consistent in the same region. The maximum monthly runoff occurred in the summer and was driven by precipitation, while the minimum monthly runoff happened in the winter and represented the runoff recession process. The consistency in fluctuation between monthly maximum runoff and monthly minimum runoff illustrated by the base flow in the runoff recession process depended on the summer runoff in the TRHR. The same results were reported in the Shule River, Hei River and Shiyang River (Niu et al. 2011), which were underlain by different levels of permafrost coverage.

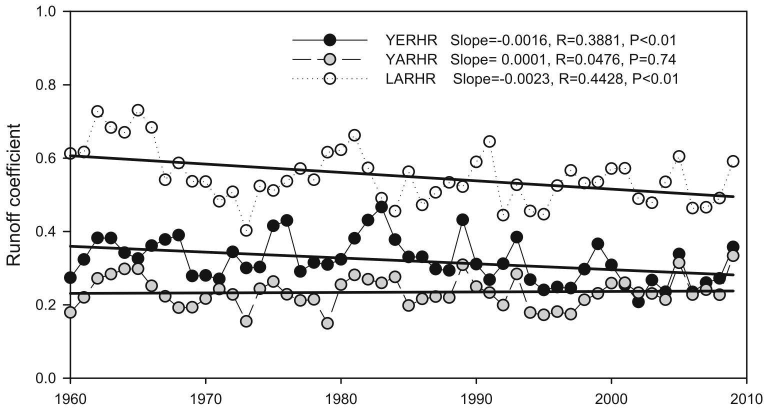

Fig. 3 The trend in runoff coefficient in the YERHR, YARHR and LARHR during 1960–2009

Figure 5 shows the change in the ratio of monthly maximum/minimum runoff in the YERHR, YARHR and LARHR. The ratio of Q_{max}/Q_{min} in the YARHR was significantly higher than in the YERHR and LARHR, with the average values of 19.7, 10.1 and 10.3, respectively. The trends in the ratio of Q_{max}/Q_{min} were slight and insignificant in the three sub-regions of the TRHR. From the perspective of Cv, the variation in the ratio of Q_{max}/Q_{min} is not high, ranging from 0.29 to 0.36, indicating moderate variability.

4.4 The Changes in Intra-Annual Runoff

To clarify the changes in distribution regime in intra-annual runoff in the TRHR, the monthly mean runoff was compared between two periods (1960–1989 versus 1990–2009) (Fig. 6). Obviously, the distribution type of the runoff of the YERHR was bimodal with peaks appearing in July and September in the period 1960–1989, weakening relatively in the period 1990–2009. A significant decrease appeared in the monthly runoff in 1990–2009 versus 1960–

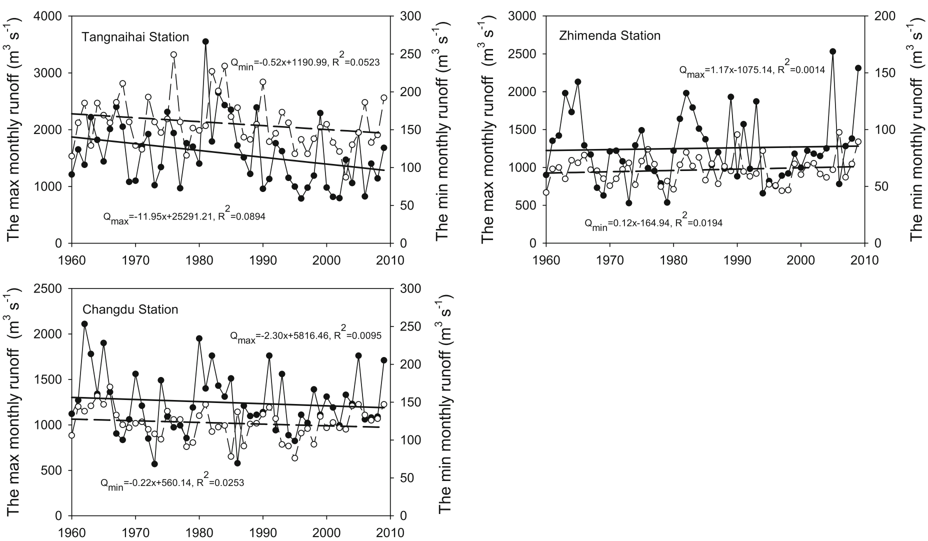

Fig. 4 The trend in monthly maximum/minimum runoff in the YERHR, YARHR and LARHR during 1960–2009

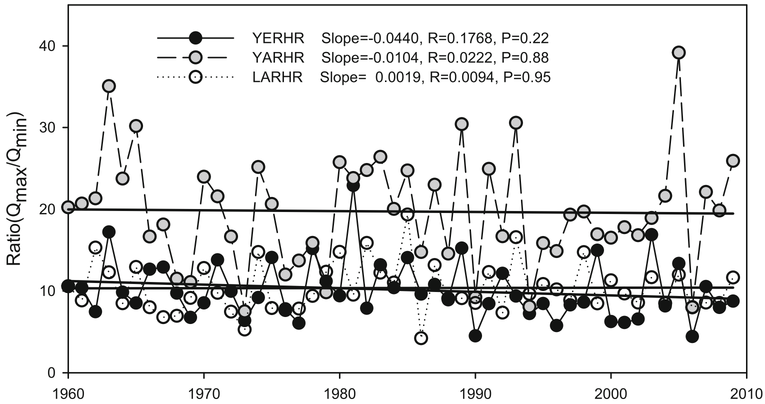

Fig. 5 Changes in the ratio between monthly maximum/minimum runoff (Q_{max}/Q_{min}) in the YERHR, YARHR and LARHR during 1960–2009

1989, especially in July (25 %), September (33 %) and October (25 %). In the YARHR, the runoff of cold seasons (October-next April) showed a slight increase (2.5–7.3 %), and decreased in July (12 %) but increased in August (11 %), representing a delayed-peak from July to August in 1990–2009 versus in 1960–1989. In the LARHR, the runoff increased in April-June but decreased in other months with inconspicuous changes; the most obvious change was the decrease in runoff peak by 11 % in July in the latter period. The unimodal pattern became smoother in both the YARHR and the LARHR in the period 1990–2009.

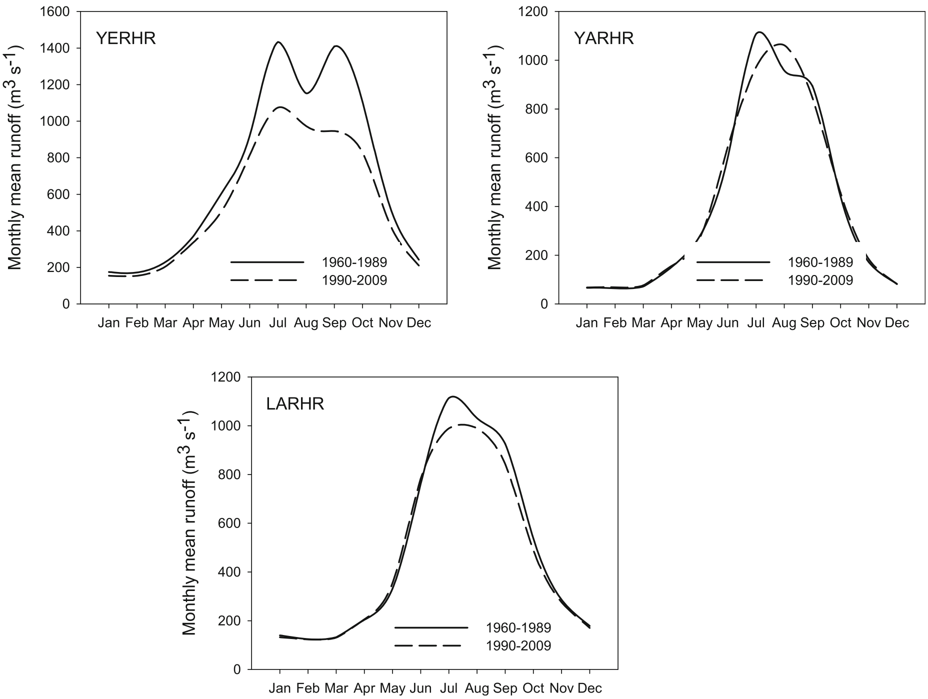

Fig. 6 Comparison of the monthly mean runoff between two periods (1960–1989 versus 1990–2009) in the YERHR, YARHR and LARHR

4.5 The Changes in Runoff Characteristics

To identify the changes in runoff characteristics historically, we compared the FDCs between two periods (1960–1989 versus 1990–2009) in the three sub-regions of the TRHR (Fig. 7). The change in the YERHR was consistent at all frequencies, with a decreasing trend. Interestingly, the degree of reduction weakened with the increase in frequency. The results indicated that the low and moderate runoff (frequency more than 40 %) was relatively stable compared with high runoff (frequency less than 40 %). In the YARHR, high runoff with a frequency of 5–15 % declined, but the higher runoff (frequency less than 5 %) and the moderate runoff (frequency of 20–30 % and 40–80 %) increased. An increase of 5 % in the lowest runoff (frequency of 100 %) was also observed in the YARHR. The changes in runoff characteristics were not remarkable in the LARHR, except in high runoff with a frequency of 5–15 %. In summary, the runoff characteristics are different in the three sub-regions of the TRHR; the most significant change was the decrease in high runoff with a frequency of 5–15 %.

5 Discussion

5.1 The Annual and Seasonal Variations of Precipitation and Temperature

To some extent, the impacts of climatic change on hydrological regime were driven by related meteorological factors, such as precipitation, temperature, and evapotranspiration. However, evapotranspiration is a complicated process that depends highly on both precipitation and

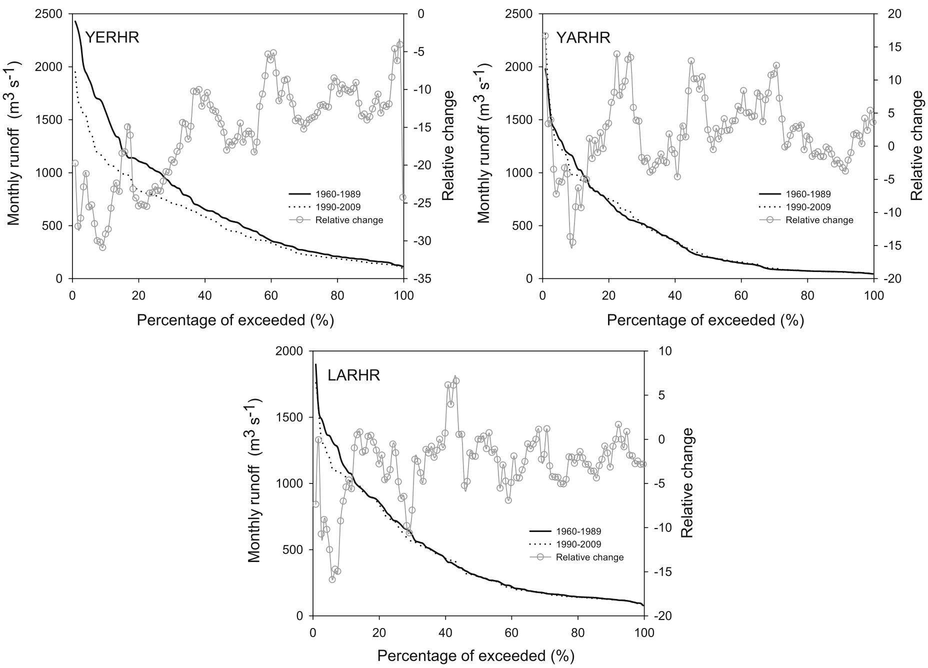

Fig. 7 Comparison of flow duration curves (FDCs) between two periods (1960–1989 versus 1990–2009) in the YERHR, YARHR and LARHR

temperature and is estimated differently at a regional scale (Qian et al. 2014). Xue et al. (2013) estimated evapotranspiration with the water balance method in the YERHR and the YARHR and found that basin-scale evapotranspiration can be reliably estimated by the difference between precipitation and runoff.

To better reveal and elaborate the changes in hydrological regimes of the TRHR, the Mann-Kendall test can be used to detect the trends of hydrometeorological elements. The trends in annual precipitation in the three sub-regions of the TRHR were compared in Table 3. The annual precipitation of the three sub-regions showed an increasing trend in the study period. In the YARHR and the LARHR, the annual precipitation showed an increase of 4.67 and 9.85 mm/decade, respectively, whereas the increasing magnitude was lowest (only 1.096 mm/decade) in the YERHR. The trends in precipitation were complex at the seasonal scale. The most obvious change occurred in the spring, when the precipitation increased significantly with a rate of 2.748, 2.440 and 8.500 mm/decade in the YERHR, YARHR and LARHR, respectively. Summer precipitation showed a similar increase with a magnitude between 0.729 and 1.017 mm/decade over the period 1960–2009. Autumn precipitation decreased insignificantly at the rates of -2.125 and -0.833 mm/decade in the YERHR and the LARHR, respectively, whereas it increased negligibly with the rate of 0.073 mm/decade in the YARHR. In winter, the precipitation showed a significant decrease in the YERHR, but it increased in the YARHR and the LARHR, where the regional difference was very obvious.

Temperature patterns are consistent with warming at a statistically significant level ($p<0.01$), at both annual and seasonal scales in the TRHR over the study period (Table 4). Due to the topographical complexity of the TRHR, it was easy to form a micro-climate. At the regional scale, the largest warming amplitude (0.355°C/decade) of the annual temperature occurred in the LARHR, whereas the lowest warming amplitude (0.227°C/decade) occurred in the YERHR, and the temperature variation was moderate with the rate of 0.334°C/decade in the YARHR during the period 1960–2009. Interestingly, the changes in temperature in different seasons were surprisingly similar to the changes in annual temperature, following the YERHR, the YARHR and the LARHR in the order of low to high (Table 4). In the same sub-region of the TRHR, the variation in temperature exhibited significantly seasonal differences. The increasing amplitude (0.383–0.483°C/decade) in temperature was largest in winter, followed by autumn, summer, and spring, for which the lowest increase occurred at a rate of 0.109–0.240°C/decade (Table 4). The same results were reported by Yang et al. (2010) and Xiong et al. (2013) over the Tibet Plateau.

The details of climate change in response to global warming were widely discussed in this region (Yi et al. 2012, 2013), some small differences in the trend and amplitude of the variations in precipitation and temperature exist. A possible reason was that the method used

Table 3 Trend in annual and seasonal precipitation (mm/decade) in the Three-River Headwaters Region

Region	β (mm/decade)				
	Annual	Spring	Summer	Autumn	Winter
YERHR	1.096	2.748*	0.729	−2.125	−2.125*
YARHR	4.670	2.440*	1.017	0.073	0.483
LARHR	9.85	8.500**	0.938	−0.833	1.216*

Note: Values significant at the 5 and 1 % level are indicated by "*" and "**", respectively

Table 4 Trend in annual and seasonal temperature (°C/decade) in the Three-River Headwaters Region

Region	β (°C/decade)				
	Annual	Spring	Summer	Autumn	Winter
YERHR	0.227**	0.109	0.215**	0.258**	0.383**
YARHR	0.334**	0.236**	0.276**	0.356**	0.442**
LARHR	0.355**	0.240**	0.269**	0.344**	0.483**

Note: Values significant at the 5 and 1 % level are indicated by "*" and "**", respectively

was different; the previous study was based on linear correlation, whereas the MK trend analysis was employed in this study. In addition, the study period was different.

5.2 The Relationship Between Precipitation, Temperature and Runoff

Table 5 shows the trends of annual and seasonal runoff in the three sub-regions of the TRHR. The results showed a decreasing trend at both the annual and seasonal scales in the YERHR, whereas the trend showed an insignificant increase in the YARHR. The runoff of the LARHR insignificantly decreased except in spring. The overall statistical results were consistent among the regions, as shown in Fig. 2. Whether increasing or decreasing, the largest change in runoff took place in summer and autumn in the same regions, but it occurred in spring for precipitation and in winter for temperature (Table 3 and Table 4). The results indicated that the variations between runoff and meteorological elements were not synchronous. The variations in winter runoff (low runoff) were slight during the period 1960–2009; the same results are shown in Fig. 7.

To better understand the impacts of precipitation and temperature on the runoff process in the three sub-regions of the TRHR, the relationship between precipitation, temperature and runoff were described in Fig. 8. Obviously, the impacts of precipitation on runoff were positive and significant ($p<0.01$) over the TRHR. This can sufficiently showed that the variations in runoff were mainly dependent on the variations in precipitation. Compared with the relationship between precipitation and runoff, the relationship between temperature and runoff was more complicated and showed remarkable regional differences. The impacts of temperature on runoff were negative in both the YERHR and the LARHR, whereas it was positive in the YARHR. The widespread view in the literature is that more infiltration and potential evapotranspiration occurs with increasing temperature, and these changes inevitably lead to decrease in runoff. In contrast, the runoff of YARHR showed an insignificant increase. We noted that

Table 5 Trend in annual and seasonal runoff (10^8 m^3 a^{-1}) in the Three-River Headwaters Region

Region	β (10^8 m^3 a^{-1})				
	Annual	Spring	Summer	Autumn	Winter
YERHR	−1.050*	−0.138	−0.367	−0.474	−0.047
YARHR	0.099	0.019	0.061	0.091	0.003
LARHR	−0.235	0.005	−0.164	−0.125	−0.021

Note: Values significant at the 5 and 1 % level are indicated by "*" and "**", respectively

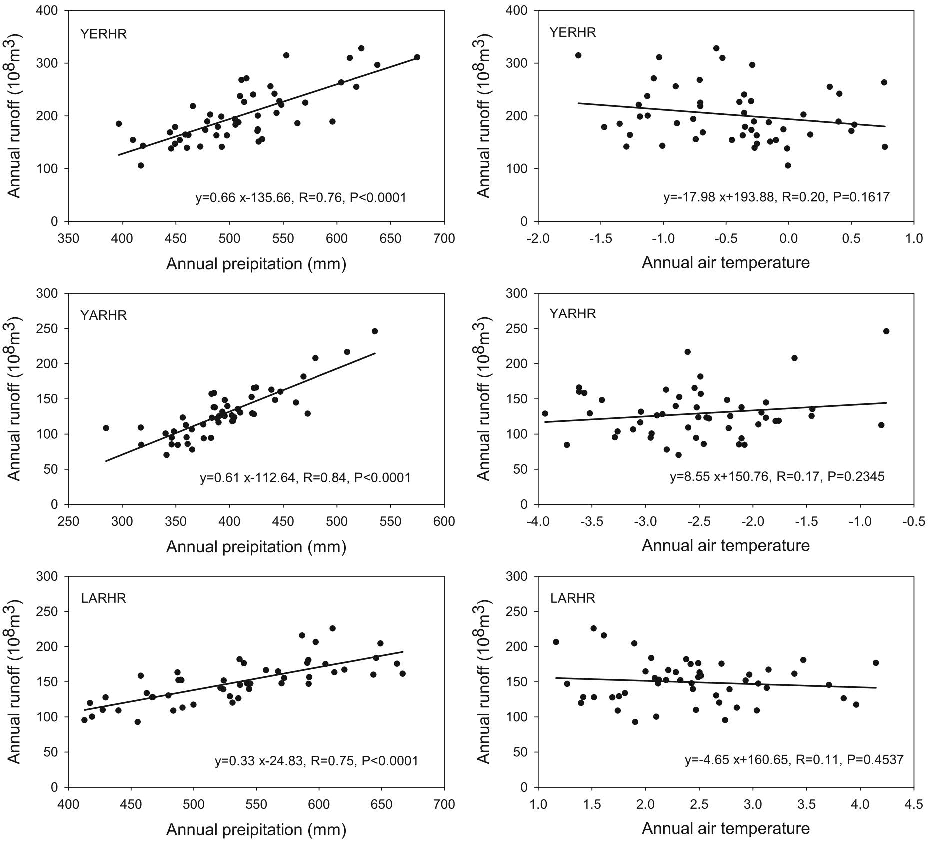

Fig. 8 The relationship between precipitation, temperature and runoff in the three sub-regions of the TRHR during the period 1960–2009

the precipitation of YARHR increased in annual and seasonal scales (Table 3), and it played a dominant role in the process of runoff generation. In addition, Yao et al. (2013) analyzed the changes in glacier area in the YARHR and found that the glacier melt runoff from 1986 to 2009 was 2.02×10^8 m^3/decade (accounting for 17.5 % of the total runoff changes), which is non-ignorable. In the YERHR, the increase in precipitation (1.096 mm/decade) can be negligible; the significant decrease in runoff was mainly caused by the continual increase in temperature (Liang et al. 2013). The increase in precipitation was most significant in the LARHR, corresponding with its amplitude of temperature increase which was also the largest. The cumulative influence on runoff was negative. The results indicated that the influences on the hydrological regime from increasing temperature were strong, which can be assumed to be a result of increasing precipitation in the LARHR.

6 Conclusion

This study investigated the impacts of climatic components on the hydrological regime in the three sub-regions of the TRHR, China. The Mann-Kendall test was employed to detect the trends in hydrometeorological components, and the runoff coefficient, the ratio of Q_{max}/Q_{min}

and the FDCs were used to reflect the variations in the hydrological regime. The significant findings of this work can be summarized as follows:

(1) The annual and seasonal runoff showed a decreasing trend in the YERHR and the LARHR, whereas it increased slightly in the YARHR. The variations in runoff indicated moderate variability in the period 1960–2009.
(2) The runoff coefficients (RC) presented an obvious decrease in the YERHR, YARHR and LARHR. The RC of the LARHR was the largest, followed by those of the YERHR and the YARHR.
(3) The fluctuations between monthly maximum runoff and monthly minimum runoff were consistent, and the ratios of Q_{max}/Q_{min} were basically stable in the same region.
(4) From the perspective of the FDCs, the most prominent change was the decrease in high runoff (at the frequency of 5–15 %) in the TRHR. In the YERHR, the runoff characteristics showed an overall decrease, the moderate runoff (at the frequency of 15–30 % and 40–70 %) of the YARHR showed an obviously increase, and the runoff of the LARHR was relatively stable.
(5) The obvious change in runoff occurred in the summer and autumn, but it occurred in the spring for precipitation and in the winter for temperature in the same region during the study period.
(6) Precipitation was the dominant factor during the process of runoff generation, but the influence on hydrological regimes caused by continual temperature increase should not be neglected for long-term considerations.

Acknowledgments We would like to thank the China Meteorological Administration for providing the meteorological data. This study was funded by the National Basic Research Program of China (973 Program) (Grant No.2013CBA01807). The authors are grateful to the anonymous reviewers and the editors for their constructive comments and suggestions which have substantially improved the presentation.

References

Abdul Aziz OI, Burn DH (2006) Trends and variability in the hydrological regime of the Mackenzie River Basin. J Hydrol 319:282–294
Cao L, Pan S (2014) Changes in precipitation extremes over the “Three-River Headwaters” region, hinterland of the Tibetan Plateau, during 1960–2012. Quat Int 321:105–115
Castellarin A, Galeati G, Brandimarte L, Montanari A, Brath A (2004) Regional flow-duration curves: reliability for ungauged basins. Adv Water Resour 27:953–965
Castellarin A, Camorani G, Brath A (2007) Predicting annual and long-term flow-duration curves in ungauged basins. Adv Water Resour 30:937–953
Cheng G, Wu T (2007) Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. J Geophys Res-Earth (2003–2012) 112
Déry SJ, Wood E (2005) Decreasing river discharge in northern Canada. Geophys Res Lett 32
Ganora D, Claps P, Laio F, Viglione A (2009) An approach to estimate nonparametric flow duration curves in ungauged basins. Water Resour Res 45
Hamed KH (2008) Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. J Hydrol 349:350–363
IPCC (2013) Climate cahange 2013: the physical science basis. contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York
Kendall M (1975) Rank correlation methods. Charles Griffin, London

Lan Y, Zhao G, Zhang Y, Wen J, Liu J, Hu X (2010) Response of runoff in the source region of the Yellow River to climate warming. Quat Int 226:60–65
Li M, Shao Q, Zhang L, Chiew FH (2010) A new regionalization approach and its application to predict flow duration curve in ungauged basins. J Hydrol 389:137–145
Li B, Chen Y, Chen Z, Li W (2012) Trends in runoff versus climate change in typical rivers in the arid region of northwest China. Quat Int 282:87–95
Li L, Shen H, Dai S, Li H, Xiao J (2013) Response of water resources to climate change and its future trend in the source region of the Yangtze River. J Geogr Sci 23:208–218
Liang L, Li L, Liu C, Cuo L (2013) Climate change in the Tibetan Plateau Three Rivers Source Region: 1960–2009. Int J Climatol 33:2900–2916
Liu X, Zhang J, Zhu X, Pan Y, Liu Y, Zhang D, Lin Z (2014) Spatiotemporal changes in vegetation coverage and its driving factors in the Three-River Headwaters Region during 2000–2011. J Geogr Sci 24:288–302
Liucci L, Valigi D, Casadei S (2014) A new application of Flow Duration Curve (FDC) in designing run-of-river power plants. Water Resour Manag 28:881–895
Ma X, Yasunari T, Ohata T, Natsagdorj L, Davaa G, Oyunbaatar D (2003) Hydrological regime analysis of the Selenge River basin, Mongolia. Hydrol Process 17:2929–2945
Mann HB (1945) Nonparametric tests against trend. Econometrica: J Econometric Soc 245–259
Middelkoop H et al (2001) Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Clim Chang 49:105–128
Mimikou M, Kanellopoulou S, Baltas E (1999) Human implication of changes in the hydrological regime due to climate change in Northern Greece. Global Environ Chang 9:139–156
Mohamoud YM (2008) Prediction of daily flow duration curves and streamflow for ungauged catchments using regional flow duration curves. Hydrol Sci J 53:706–724
Nijssen B, O'Donnell GM, Hamlet AF, Lettenmaier DP (2001) Hydrologic sensitivity of global rivers to climate change. Clim Chang 50:143–175
Niu L, Ye B, Li J, Sheng Y (2011) Effect of permafrost degradation on hydrological processes in typical basins with various permafrost coverage in Western China. Sci China Ser D 54:615–624
Qian K, Wang XS, Lv J, Wan L (2014) The wavelet correlative analysis of climatic impacts on runoff in the source region of Yangtze River, in China. Int J Climatol 34:2019–2032
Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. J Am Stat Assoc 63:1379–1389
Shiklomanov A, Lammers R, Rawlins M, Smith L, Pavelsky T (2007) Temporal and spatial variations in maximum river discharge from a new Russian data set. J Geophys Res-Biogeo 2005–2012:112
Smith LC, Pavelsky TM, MacDonald GM, Shiklomanov AI, Lammers RB (2007) Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle. J Geophys Res-Biogeo (2005–2012) 112
Theil H (1950) A rank invariant method of linear and polynomial regression analysis, part 3. Neth Akad Wet Proc 53:1397–1412
Viglione A, Merz R, Blöschl G (2009) On the role of the runoff coefficient in the mapping of rainfall to flood return periods. Hydrol Earth Syst Sci 13:577–593
Viola F, Noto L, Cannarozzo M, Loggia GL (2011) Regional flow duration curves for ungauged sites in Sicily. Hydrol Earth Syst Sci 15:323–331
Wainwright J, Parsons AJ (2002) The effect of temporal variations in rainfall on scale dependency in runoff coefficients. Water Resour Res 38:7-1–7-10
Wang G, Hu H, Li T (2009) The influence of freeze–thaw cycles of active soil layer on surface runoff in a permafrost watershed. J Hydrol 375:438–449
Wang G, Liu G, La L (2012) Spatial scale effect on seasonal streamflows in permafrost catchments on the Qinghai–Tibet Plateau. Hydrol Process 26:973–984
Wang Y, Ding Y, Ye B, Liu F, Wang J (2013) Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. Sci China Ser D 56:1398–1412
Waseem M, J-y S, Kim T-W (2015) Comparing spatial interpolation schemes for constructing a flow duration curve in an ungauged basin. Water Resour Manag 29:2249–2265
Woo MK, Kane DL, Carey SK, Yang D (2008) Progress in permafrost hydrology in the new millennium. Permafrost Periglac 19:237–254
Wu Q, Zhang T (2008) Recent permafrost warming on the Qinghai-Tibetan Plateau. J Geophys Res-Atmos 1984–2012:113
Xiong L, Yu K, Zhang H, Zhang L (2013) Annual runoff change in the headstream of Yangtze River and its relation to precipitation and air temperature. Hydrol Res 44:850–874
Xu J (2011) Variation in annual runoff of the Wudinghe River as influenced by climate change and human activity. Quat Int 244:230–237
Xu B et al (2009a) Black soot and the survival of Tibetan glaciers. Proc Natl Acad Sci U S A 106:22114–22118

Xu Z, Zhao F, Li J (2009b) Response of streamflow to climate change in the headwater catchment of the Yellow River basin. Quat Int 208:62–75

Xue B-L, Wang L, Li X, Yang K, Chen D, Sun L (2013) Evaluation of evapotranspiration estimates for two river basins on the Tibetan Plateau by a water balance method. J Hydrol 492:290–297

Yang D, Kane DL, Hinzman LD, Zhang X, Zhang T, Ye H (2002) Siberian Lena River hydrologic regime and recent change. J Geophys Res-Atmos (1984–2012) 107:ACL 14-11-ACL 14-10

Yang D, Ye B, Shiklomanov A (2004) Discharge characteristics and changes over the Ob River watershed in Siberia. J Hydrometeorol 5:595–610

Yang M, Nelson FE, Shiklomanov NI, Guo D, Wan G (2010) Permafrost degradation and its environmental effects on the Tibetan Plateau: a review of recent research. Earth-Sci Rev 103:31–44

Yao Z, Liu Z, Huang H, Liu G, Wu S (2013) Statistical estimation of the impacts of glaciers and climate change on river runoff in the headwaters of the Yangtze River. Quat Int 336:89–97

Ye B, Yang D, Zhang Z, Kane DL (2009) Variation of hydrological regime with permafrost coverage over Lena Basin in Siberia. J Geophys Res-Atmos (1984–2012) 114

Yi X, Li G, Yin Y (2012) Temperature variation and abrupt change analysis in the Three-River Headwaters Region during 1961–2010. J Geogr Sci 22:451–469

Yi X, Li G, Yin Y (2013) Spatio-temporal variation of precipitation in the Three-River Headwater Region from 1961 to 2010. J Geogr Sci 23:447–464

Yue S, Wang C (2004) The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour Manag 18:201–218

Yue S, Pilon P, Cavadias G (2002) Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. J Hydrol 259:254–271

Zhang S, Hua D, Meng X, Zhang Y (2011) Climate change and its driving effect on the runoff in the "Three-River Headwaters" region. J Geogr Sci 21:963–978