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A 602-year Reconstruction of July-June Streamflow in the Kuqa River, China, Reveals the Changing Hydrological Signals of the Tarim Basin

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Abstract: A regional tree-ring width chronology of Schrenk spruce (*Picea schrenkiana*) was used to determine the annual (previous July to current June) streamflow of the Kuqa River in Xinjiang, China, for the period of 1414–2015. A linear transformation of the tree-ring data accounted for 63.9% of the total variance when regressed against instrumental streamflow during 1957–2006. The model was validated by comparing the regression estimates against independent data. High streamflow periods with a streamflow above the 602-year mean occurred from 1430–1442, 1466–1492, 1557–1586, 1603–1615, 1687–1717, 1748–1767, 1795–1819, 1834–1856, 1888–1910 and 1989–2015. Low streamflow periods (streamflow below the mean) occurred from 1419–1429, 1443–1465, 1493–1556, 1587–1602, 1616–1686, 1720–1747, 1768–1794, 1820–1833, 1857–1887 and 1911–1988. The reconstruction compares well with the tree-ring-based streamflow series of the Tizinafu River from the Kunlun Mountains; both show well-known severe drought events. The streamflow reconstruction also shows highly synchronous upward trends since the 1980s, suggesting that streamflow is related to Central Asian warming and humidification. Thus, the influences of the extremes and the persistence of low streamflows on local society may be considerable. Climatic changes in the watershed may be responsible for the change in the hydrologic regime of the Tarim Basin observed during the late twentieth century.

Key words: tree rings, streamflow reconstruction, Kuqa River, Tarim Basin

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1 Introduction

Under the global warming background, the shortage and uneven distribution of water resources is becoming a bottleneck for development in drylands (Huang et al., 2016; Prăvălie, 2016). The Tarim Basin, known as drought, is the largest inland basin in China, and the Taklimakan Desert is located in the centre of the basin. Due to the low precipitation and high evaporation in the basin, rivers originating from the high-altitude mountainous area are extremely important to the oasis ecosystem and for regional sustainable development. Reasonable water resource management and plans are based on long-term hydrological variations. However, the gauge records from the Tarim Basin generally span less than 60 years, and this period is too short to properly examine the intensity, frequency and duration of low streamflow events and limits the estimation of future variability of water resources. Therefore, high-resolution, long-term streamflow reconstructions are critically important for revealing hydrological variation at different time scales because they can place current hydrological conditions in a long-term context (Jiang et al., 2016).

Tree-ring series are widely applied as reliable proxies for past hydrological variation in river basins and can be used to evaluate the long-term streamflow behaviour of rivers and their related water resource management efforts from different areas of the world (Meko and Woodhouse, 2011). In Asia, including China (Wang and Wan, 2000; Yuan et al., 2007; Gou et al., 2010; Liu et al., 2010; Yi et al., 2010; Yang et al., 2012; Sun et al., 2013), Mongolia (Davi et al., 2013), Pakistan (Cook et al., 2013), Turkey (Akkemik et al., 2008), Kyrgyzstan (Chen et al., 2017), Kazakhstan (Panyushkina et al., 2018), India (Shah et al., 2013) and Indonesia (D'Arrigo et al., 2011), tree rings have been applied extensively to demonstrate hydrological histories. Xinjiang is located in the hinterland of Eurasia with an extremely arid climate (Liu, et al., 1998; Su et al., 2007) and is a perfect area for dendrohydrological research. Since the 1980s, dendrologists have conducted dendrohydrological research on the northern slopes of the Tianshan Mountains (Yuan et al., 2007; Shang et al.,

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2014), the Tarim Basin (Li et al., 2000), and the Altay Mountains (Chen et al., 2016). Due to sparse tree-ring data, the streamflow reconstruction of only the Aksu River was developed based on tree rings of spruce trees from the southern slopes of the Tianshan Mountains (Zhang et al., 2016).

In this study, a 602-year streamflow reconstruction of the Kuqa River was developed based on tree-ring records from the southern slopes of the Tianshan Mountains. Due to the extreme arid climate, the tree-ring width data of Schrenk spruce (*Picea schrenkiana*) are sensitive to streamflow and precipitation. The sensitivity of tree-ring width to the environment also improves the robustness and reliability of the reconstruction model. Streamflow reconstruction provides a long-term hydrological record for water resource management. Furthermore, the reconstruction is compared with the streamflow reconstruction from the northern slopes of the Kunlun Mountains to reveal spatial and temporal coherence in the hydroclimate.

2 Data and Methods

2.1 Study region and tree-ring record

The Kuqa River, the tributary of the Tarim River, is located at the northern edge of the Tarim Basin near the southern slopes of the Tianshan Mountains (Fig. 1). The Tarim Basin is known to have an extremely arid climate due to its scarce precipitation and high evaporation. Vertical zonality is prominent in the Kuqa River basin: permanent glaciers are distributed in the basin at elevations above 3700 m a.s.l., alpine meadows are distributed at elevations of 2900–3700 m, spruce forests are distributed on shady slopes at elevations of 2000–2900 m a.s.l., drought-tolerant shrubs dominate at elevations under 2000 m a.s.l., and extensive forests of *Populus euphratica are* distributed along the Tarim River.

During the 2013–2015 summer field seasons, spruce trees with no obvious injury or disease were collected using increment borers with a diameter of 10 mm at the four sampling sites (Table 1). In total, 292 cores from 146 trees (usually 2 cores per tree) were collected. All the sampling sites were located on shady slopes with elevations of 2200–2800 m. The substrate of all four sampling sites is harsh, with steep slopes and thin soil layers. The pre-treatment of tree-ring core samples followed the standard techniques of dendrochronology (Stokes and Smiley, 1968; Fritts, 1976). Tree-ring widths were measured using the LINTAB 6 measuring system with 0.01 mm precision. All the samples were cross-dated using the software package TSAP (Rinn, 2003). The accuracy of cross-dating and ring-width measurement was checked using the computer programme COFECHA (Holmes, 1983). The computer programme ARSTAN (Cook and Kairiukstis, 1990) was then applied to develop the chronologies. To remove non-climate trends, tree-ring width data are detrended by fitting linear or negative exponential curves (Fritts, 1976). The final chronologies were established by a robust weighted mean method. For the period 1800–2013, the correlation coefficients were higher among the four site chronologies (Table 2), although the maximum elevation difference among all

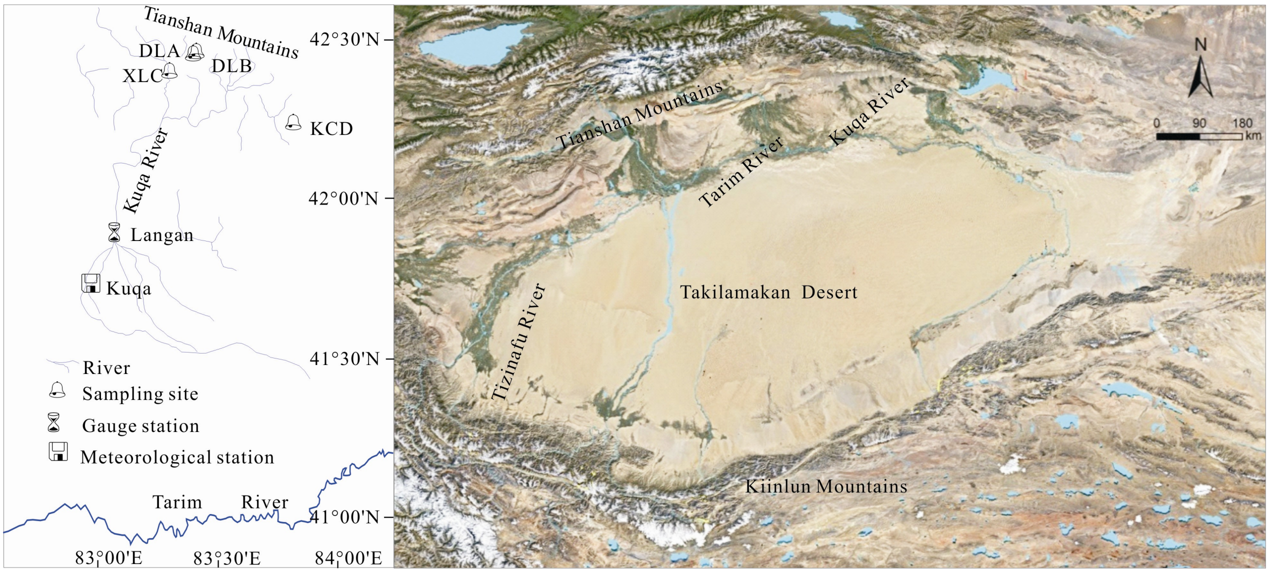

Fig. 1. Map of the study area. The location of the sampling sites (black triangle), hydrological station (flag) and meteorological station (star with circle) is illustrated in the map.

Table 1 Information about the sampling sites, meteorological and gauge stations in the Kuqa River basin

Name	Code	Time span	Longitude (E)	Latitude (N)	Elevation (m)	Aspect Slope*	Slope (%)	Trees/cores
Dalongchi A	DLA	1373–2014	83°23′	42°27′	2750	NEE	60.0	61/121
Dalongchi B	DLB	1353–2015	83°24′	42°27′	2550	N	40.0	33/69
Xiaolongchi	XLC	1588–2014	83°18′	42°24′	2228	N	45.0	26/51
East Kuqa	KCD	1532–2014	83°50′	42°15′	2620	NNE	38.0	26/51
Kuqa station	KC	1951–2013	83°04′	41°43′	1083			
Langan station	LG	1957–2006	83°04′	41°54′	1280			

* the aspect slope of NEE, N, and NNE represents the direction north east east, north, and north north east respectively.

four sites was approximately 500 m Considering the close distance, similar slope direction and high correlations, all ring-width data were combined together to develop a composite chronology (KCH) following the above method (Fig. 2).

The quality of the chronologies was described by several parameters, including the mean sensitivity (MS), standard deviation (SD), percentage of missing rings (PMR), average correlation between all series (RBAR), first-order autocorrelation (AC1), expressed population signal (EPS), and signal-to-noise ratio (SNR) of the chronologies (Table 3). The EPS and RBAR were evaluated using a 30-year moving window with a 25-year overlap. The value of 0.85 was generally suggested as the EPS threshold to identify the period of reliable chronology (Wigley et al., 1984). In this study, the reliable regional composite chronology spans 602 years, from 1414 to 2015 CE. Seven cores from four trees exist for the beginning year (1414 CE) of the reliable chronology.

2.2 Climate and streamflow data

The large altitudinal variation from 4505 m at the peak to ~1000 m at the plain area results in abrupt changes in the climate conditions in the Kuqa River basin. There are no long-term, continuous meteorological records in the mountainous area. Kuqa meteorological station (83°04′E, 41°43′N, 1083 m a.s.l.), with a record covering the period of 1951–2013, was selected for this study. The meteorological data (monthly total precipitation, monthly mean, maximum and minimum temperature) were obtained from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn). The average annual total precipitation is 70.9 mm, and the intra-annual distribution of precipitation is uneven, with 74.2% concentrated in May–September. The mean annual temperature is 11.3°C, with a higher daily range and annual range. The linear trend analysis of the mean annual total precipitation and mean temperature revealed an increasing trend for precipitation at the rate of 2.5 mm/10a and a decreasing trend for temperature at the rate of 0.3°C/10a (Fig. 3a,b,c).

Monthly streamflow data were obtained from Langan hydrological station (41°54'N, 83°04'E, 1280 m a.s.l.). The station, which was established in September 1956, is located at the outlet of the mountains of the Kuqa River basin. Data were available for the period 1957–2006. During this period, there were no dams in the upstream area of the hydrological station, and only a few herdsmen lived in the mountainous area. The streamflow data were assumed to record the natural hydrological variability. For the observation period (1957–2006), the mean annual streamflow was 12.0 m^3/s. The maximum and minimum annual streamflows were recorded in 1986 (24.1 m^3/s) and 2002 (6.4 m^3/s), respectively. A box plot was used to reflect the monthly hydrograph at Langan. It revealed the extreme seasonal distribution of streamflow, with 79.7% of the mean annual streamflow concentrated in the May–September period and only 10.9% concentrated in the November-March period (Fig. 3d,e). The seasonal distribution patterns of precipitation and streamflow were similar. The coefficient of variation (CV) of monthly streamflow was 64.2%, 49.5%, 40.6%, 43.3% and 47.3% in the months from May to September, respectively, and the annual streamflow was 28.0%, which was higher than the neighbouring Kaidu River and Aksu River around the southern slopes of the Tianshan Mountains. This result indicates that glacier meltwater is not the primary water source for the Kuqa River, although glaciers are distributed in the headwater area. According to Xie et al. (2004), the glacier area in the catchment is 24.23 km^2, and it is estimated that 7.4% of the total streamflow at the

Table 2 Cross correlations among all the ring width chronologies for the common interval 1800–2014 CE

	DLA	DLB	XLC	KCD
DLB	0.937			
XLC	0.830	0.822		
KCD	0.666	0.683	0.801	
KCH	0.976	0.957	0.910	0.786

Table 3 The features of tree-ring width standard chronologies and analysis on common interval (1800-2010 CE)

Code	MS	SD	AC1	PMR (%)	EPS	Rbar	SNR
DLA	0.393	0.379	0.399	3.33	0.982	0.574	53.40
DLB	0.395	0.393	0.431	2.39	0.945	0.502	17.25
XLC	0.560	0.578	0.511	6.50	0.916	0.659	10.90
KCD	0.593	0.520	0.441	6.10	0.922	0.645	11.81
KCH	0.398	0.387	0.423	4.26	0.987	0.514	74.33

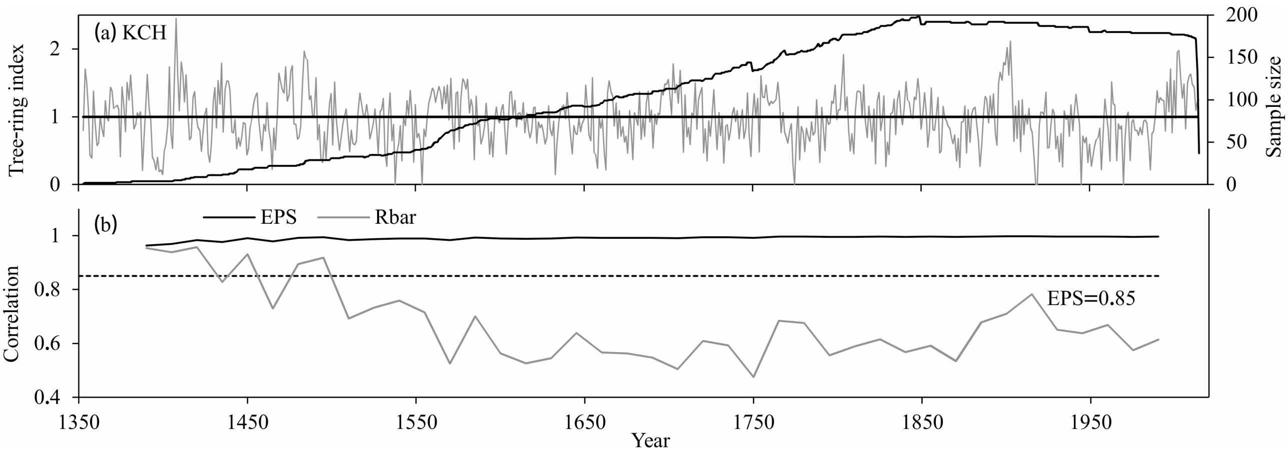

Fig. 2. (a) The composite tree-ring width chronology (KCH) and its sample depth from the Kuqa River basin; (b) EPS and Rbar values of the composite chronology. The dashed line is the EPS threshold value of 0.85.

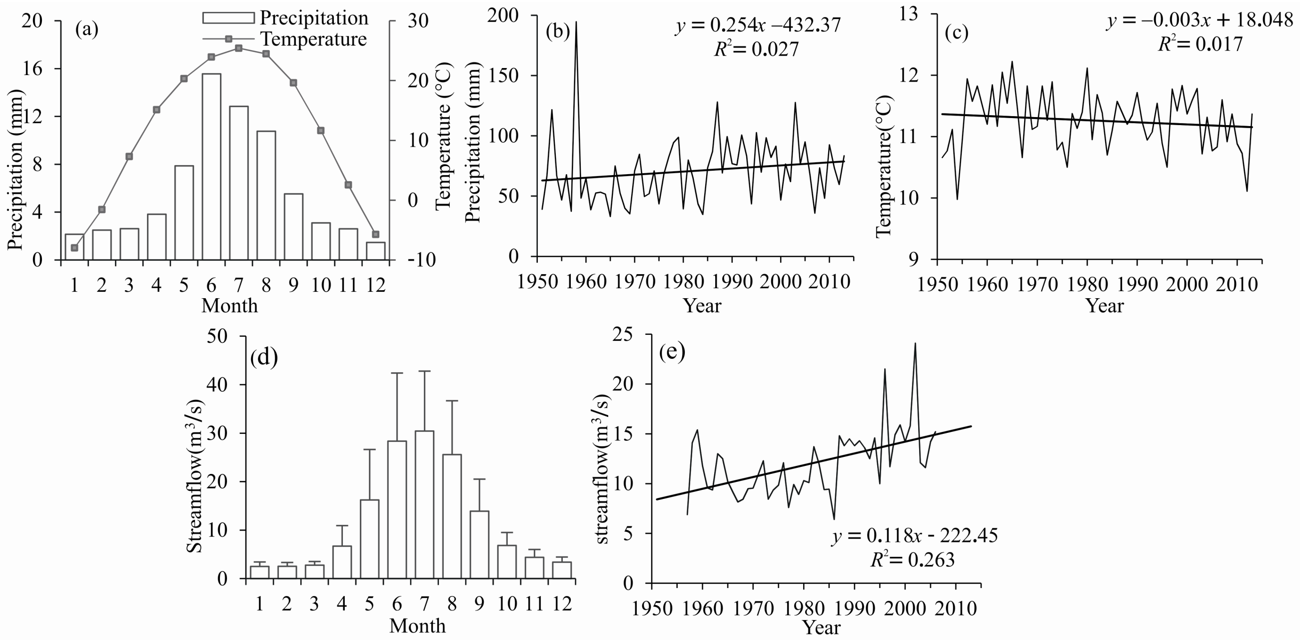

Fig. 3. (a) Monthly total precipitation and mean temperature of Kuqa meteorological station (1951–2013). Annual total precitation (b) and mean temperature (c) of Kuqa meteorological station (1951–2013). Mean monthly streamflow with standard error bars of the Kuqa River at the Langan station (1957–2006)(d). Annual streamflow at the Langan station (1957–2006) (e).

Langan station is attributed to glacier meltwater. To evaluate the linkages between tree growth and hydroclimate, Pearson correlation analysis was conducted for the common period between the standard chronology and mean monthly climate (1951–2013) and streamflow data (1957–2006) from previous May to current October. Split-sample calibration-verification tests were used to assess how the reconstructed streamflow tracked the independent instrumental streamflow data in the verification period (Meko and Graybill, 1995).

3 Results

3.1 The relationships between hydroclimate and radial growth

The monthly precipitation from previous May to current February was positively correlated with the composite chronology, and the correlations were significant (P < 0.05) for previous July and current January. Correlation analysis between the composite chronology and temperature showed that the correlations were negative for most months, with significant negative correlations (P < 0.05) appearing in previous July to September and current May and July. Streamflow showed a continuous and positive correlation with the composite chronology, and significant positive correlations (P < 0.01) were found in previous August to current March and current June (Fig. 4). High correlations were found between the hydroclimate combination and tree-ring width, i.e., the total precipitation from previous May to current February (r = 0.404, n = 62, P < 0.01) and the mean streamflow from previous July to current June (r = 0.800, n = 49, P < 0.01).

3.2 Streamflow reconstruction of the Kuqa River

Based on the results of the growth-climate response, the linear regression model was used to assess the annual (July-June) streamflow for the Kuqa River: KCR = 6.713×KCH + 5.239, where KCR is the annual (previous

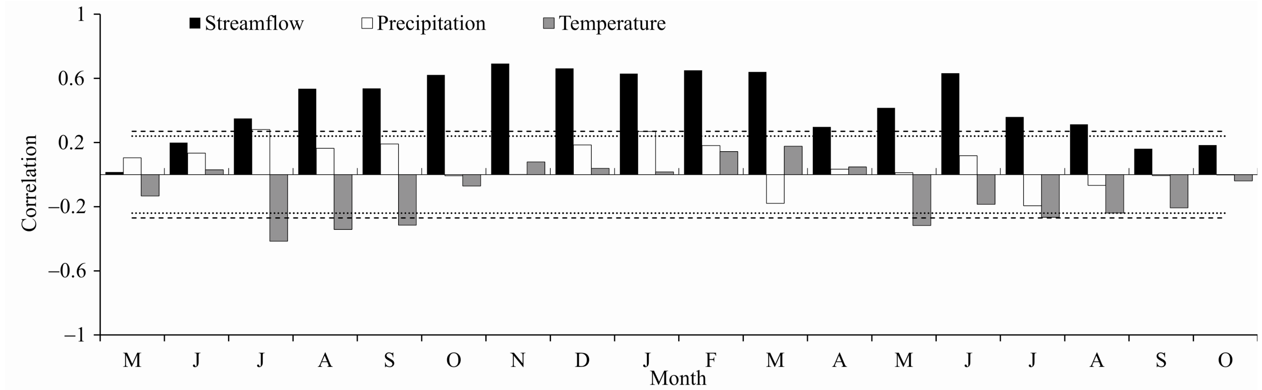

Fig. 4. Correlation coefficients between tree-ring widths and the climate/streamflow records. Dotted lines and dashed lines reveal the 0.05 significance level for runoff and climate respectively. For the abscissa letters, M, J, J, A, S, O, N and D represents May to December in the prior year, and J, F, M, A, M, J, J, A, S and O represents January to October in the current year respectively.

July to current June) streamflow series of the Kuqa River and KCH is the tree-ring index. The model accounts for 63.9% of the instrumental streamflow variance during the period 1957–2006 (Table 2), and the adjusted explained variance is 63.2%, with an F value of 83.3 ($P < 0.001$).

The common period between the instrumental streamflow record and the composite chronology (1957–2006) was split into two periods for the calibration-verification tests to assess the reliability of the streamflow reconstruction model (Table 4). The testing parameters included the Pearson correlation coefficient (r), coefficient of efficiency (CE), reduction of error (RE) and sign test. The high and positive RE and CE values indicated the skill of the regression model. For the calibration period 1982–2006, the result of the sign test reached the 0.05 significance level. All other statistics, including r, showed that the reconstruction was robust and reliable. As shown in Fig. 5a, the reconstructed and observed streamflows were consistent; however, the year with the largest difference between the observed and reconstructed streamflows was 2002, which was also the year with the highest observed streamflow. As shown in Fig. 5, the reconstructed values and measured values were in good agreement, except for high water years such as 1959 and 2002.

A correlation between the first-order differences of the observed and reconstructed streamflow was further computed to test the consistency in high frequency. Fig. 5b and the significant coefficient value ($r = 0.722$, $n = 48$, $P < 0.001$) indicated there was consistency in high frequency.

3.3 Reconstructed July-June streamflow since 1414 CE

The June-July streamflow for the Kuqa River was reconstructed from 1414 to 2015 CE (Fig. 6). The streamflow reconstruction spanned 602 years; the mean streamflow (mean) was 11.7 m^3/s, and the standard deviation (σ) was 2.50 m^3/s. The thick line is the 25-year low-pass filtered streamflow reconstruction. The streamflow reconstruction includes ten low streamflow periods (streamflow < 11.7 m^3/s), including 1419 to 1429 CE, 1443 to 1465 CE, 1493 to 1556 CE, 1587 to 1602 CE, 1616 to 1686 CE, 1720 to 1747 CE, 1768 to 1794 CE, 1820 to 1833 CE, 1857 to 1887 CE and 1911 to 1988 CE, and ten high streamflow periods (streamflow > 11.7 m^3/s), including 1430 to 1442 CE, 1466 to 1492 CE, 1557 to 1586 CE, 1603 to 1615 CE, 1687 to 1719 CE, 1748−1767 CE, 1795 to 1819 CE, 1834 to 1856 CE, 1888 to 1910 CE and 1989 to 2015 CE. We defined an extremely high streamflow year as having streamflow higher than the mean + 2σ (16.7 m^3/s) and an extremely low streamflow year as having streamflow less than the

Table 4 Calibration and verification statistics for the streamflow reconstruction of the Kuqa river

Calibration	Verification	R_1	R_1^2	R_2	R_2^2	RE	CE	ST
1958–1981	1982–2006	0.783	0.613	0.738	0.544	0.705	0.461	16+/9−
1982–2006	1958–1981	0.738	0.544	0.783	0.613	0.774	0.452	18+/6−
1958–2006		0.800	0.639					

R_1: correlation coefficient for the calibration period; R_1^2 explained variance in the regression model for the calibration period; R_2: correlation coefficient for the verification period; R_2^2: explained variance of the regression model for the verification period; RE: reduction in the calculated error statistic for the verification period; CE: coefficient of efficiency for the verification period. ST: sign test.

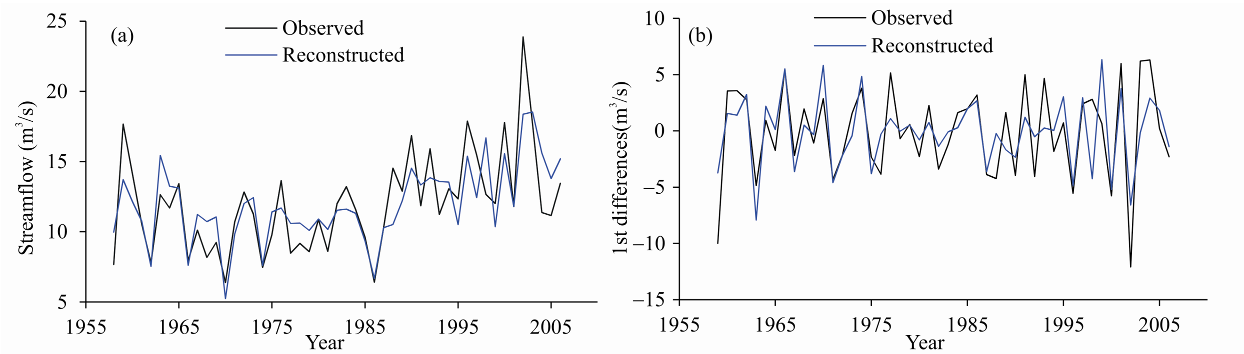

Fig. 5. (a) Comparison between the observed and reconstructed streamflow data; (b) comparison between the first-order differences of the observed and reconstructed streamflow data for the common period.

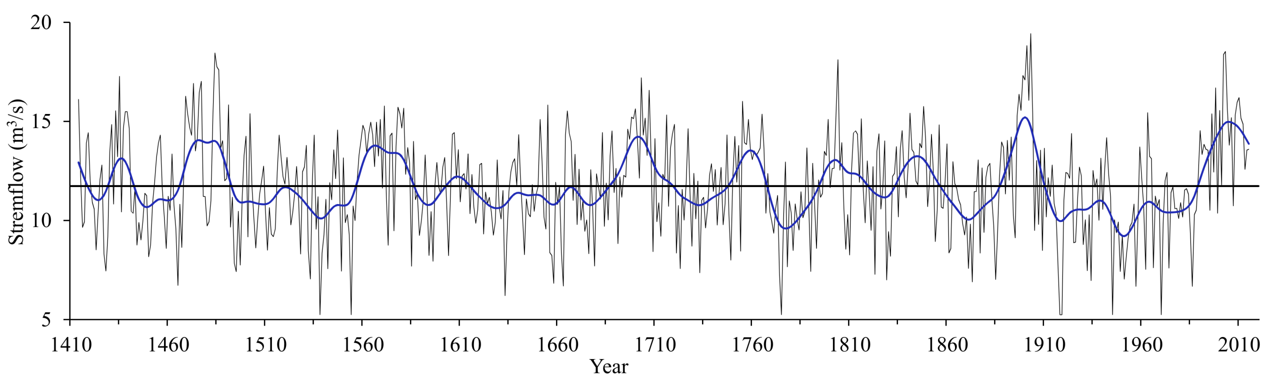

Fig. 6. Streamflow reconstruction from July in last year to current June (thin line) for the Kuqa river. The thick line is the 25-year low-pass filtered streamflow reconstruction; solid horizontal line is the long-term mean of the streamflow reconstruction.

mean −2σ (6.7 m^3/s). Of the 602 years of reconstruction, 12 years were categorized as extremely low streamflow years and 14 years were extremely high streamflow years. The years 1911 to 1988 CE comprised the most significant and critical low streamflow period; six of the 12 extremely low streamflow years occurred during this period.

4 Discussions

4.1 The response of tree growth to climate/streamflow variation

The relationships between climate/streamflow and tree-ring index revealed that moisture condition was the dominating factor affecting the radial growth of trees. The tree-ring widths were more closely related to the streamflow variation than to the precipitation (Fig. 4). This result may be because the streamflow is the product of combined action by precipitation, temperature and evaporation, which is the influencing factor for tree-ring growth. There is an obvious gradient effect for precipitation on the southern slope of the Tianshan Mountains. The mean annual precipitation in the plain area (Kuqa meteorological station) is only 70.9 mm, though it reaches 250–350 mm and even 450 mm in the maximum precipitation zone of the Kuqa River basin (Sabit et al., 2003). Hence, the source water of the Kuqa River is the precipitation in the mountain area. The trees on the southern slope of the Tianshan Mountains are distributed mainly at elevations of 2200–2800 m, which is also an abundant precipitation zone. The Kuqa meteorological station is located in the plain area, with less precipitation, strong locality and a high coefficient of variance. The consistency of precipitation in the plain area and mountain area is low; thus, relatively low correlations were found between precipitation and tree growth and the radial growth of trees. As mentioned above, the dry periods were well estimated, and the years with higher streamflow were underestimated by the model. In the high streamflow period, moisture is sufficient for tree growth and is not the limiting factor for tree-ring growth. In addition, the high annual streamflow may result from several heavy rainstorms in the mountain area, which form the peak of streamflow but do not contribute linearly to tree growth. The weak point for its incapacity for streamflow peak is also mentioned by Fritts (1976).

4.2 Applications for headwaters and small-tributary reconstructions

The streamflow reconstruction for the Kuqa River compares well with the Tizinafu River's streamflow reconstruction in the Kunlun Mountains (Shang et al., 2018). Correlation coefficient between this study and Shang et al. (2018), computed over the common period of 1665–2013, is 0.425 and increases to 0.685 after 25-year smoothing. The low and high streamflow periods in both streamflow reconstructions agree with each other on different time scales, reflecting large-scale streamflow signals for the Tarim Basin (Fig. 7). The Kuqa and Tizinafu Rivers are both located in high-altitude mountainous areas near the Tarim Basin and are influenced by mid-latitude westerlies (Huang et al., 2015). The synchronous variations in the streamflow reconstruction of the small tributaries in these two areas indicated that they were both affected by the variations in the mid-latitude westerlies in the Tarim Basin. Based on the reconstruction results of these two rivers, the runoff declined by 10% during the period 1911–1988. In the 20th century, continuous low streamflows and intensified human activities, such as increased irrigation, resulted in serious water shortages in the downstream area.

The extremely drought years in this study coincided with famous extreme drought events, such as those in 1917 and 1945 (Li et al. 2010; Chen et al., 2013). It also indicated the spatial consistency of extreme drought events. After 1987, the streamflow showed a rapid upward trend, which may have been linked with Central Asian warming and humidification (Shi et al., 2007; Chen et al., 2011; Chen et al., 2015). Simultaneous changes in climate and hydrology since the late twentieth century suggested that regional climatic changes may be responsible for the change in the hydrologic regime of the Tarim Basin.

The analyses showed here further indicate that tree rings can be applied to reconstruct headwaters and small-tributary streamflows with significant skill, and the resulting streamflow series can extend for hundreds of years. In turn, such streamflow reconstructions provide a

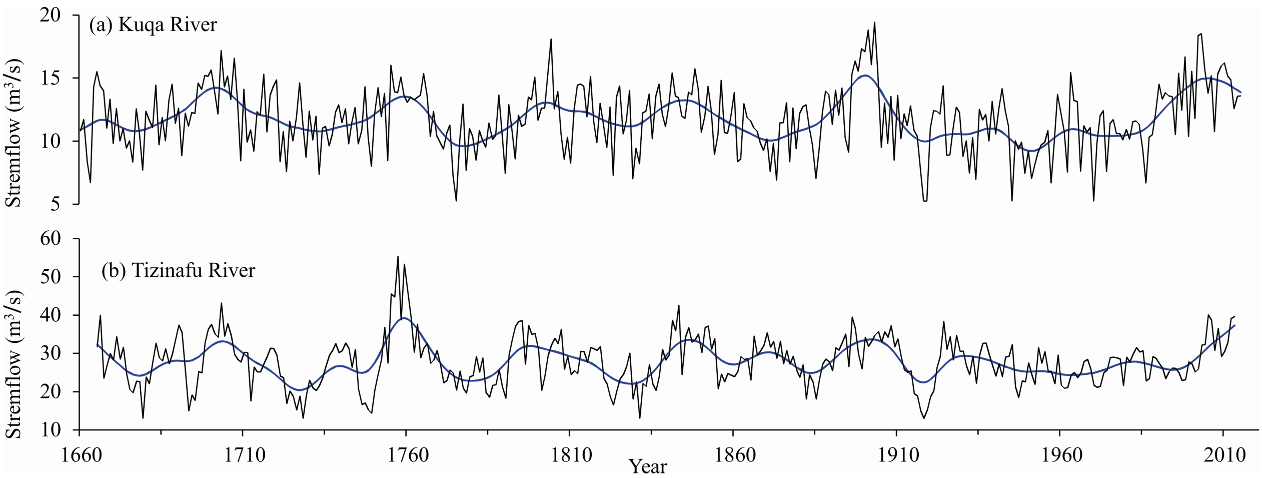

Fig. 7. Comparison between the streamflow reconstructions for Kuqa River (a)and Tizinafu River (b)(Shang et al. 2018).

unique means for understanding instrumental streamflow in a longer-term and more historical record-rich context (Fritts, 1976). In the case of the Kuqa reconstruction, we see that apparent extreme drought events and upward trends in recent records have appeared frequently in the past, and instrumental streamflow covered only a small range of the potential hydrological variation in this river basin. Moreover, the two streamflow reconstructions show novel scenarios for runs of low or high streamflow years, rapid switching between low or high streamflow periods, and annual variation that are well outside the scopes of the instrumental streamflow data. Such dendrohydrological reconstructions can be used to better evaluate the potential for severe sustained low streamflow (Meko and Woodhouse, 2011; Cook et al., 2013; Liu et al., 2015, 2017; Woodhouse and Pederson, 2018) and test the water supply capacity of rivers to meet future demand (Margolis et al., 2011; Yang et al., 2012).

Some studies address how tree-ring-based evaluations of past streamflow can be viewed in a probabilistic framework (Margolis et al., 2011; Meko and Woodhouse, 2011). These methods reveal great promise for promoting the application of streamflow reconstructions to aid sustainable development and indicate the uncertainty inherent in streamflow reconstruction. Probabilistic analyses may be especially relevant in the instrumental streamflow of headwaters and small tributaries if short calibration periods or other factors introduce uncertainties into the resulting streamflow reconstructions. Dendrohydrological reconstructions provide insights into the range of natural streamflow variation that are grounded in well-established physical relationships between streamflow and tree rings. In addition, streamflow reconstructions provide past hydrological knowledge that can be used to examine longer-term variation and trends that may not be well shown in simulated hydrological data or shorter instrumental records.

5 Conclusions

A regional tree-ring chronology spanning 1414–2015 was developed from the Kuqa River basin, Xinjiang, China. Using dendrohydrological techniques, further regional hydrological reconstruction can be developed for this basin. The results of streamflow reconstruction of the Kuqa River indicated regional streamflow changes during 1414–2015. As shown in our research, regional streamflow variations showed an upward trend and became more persistent since the late twentieth century, and a clear low streamflow period has occurred since 1911.

Admittedly, our study is based on tree-ring cores from only four sites of the Kuqa River and covers a small tributary basin. Thus, it is of critical importance to further construct large-scale streamflow reconstructions over the Tarim Basin. These streamflow reconstructions will enable us to better comprehend problems such as the recent hydrological trend towards wetter conditions in Central Asia, the climate forces responsible for the instrumental streamflow variation and the plan for future water resource allocation.

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