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Natural discharge changes of the Naryn River over the past 265 years and their climatic drivers

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Abstract

Originating in the Tianshan Mountains in arid Central Asia, the natural discharge change of the Naryn River is strongly affected by climate change. As the main source of water for the region, this river is crucial to both the natural environment and the socio-economic development. To extend the discharge record and better understand past and future changes in Naryn River discharge, we developed four tree-ring width chronologies and analyzed the relationship between tree growth and discharge. The resulting reconstruction dates back to 1753 and has an R^2 of 0.374 (1939–2017). Interannual discharge variations of the Naryn River indicate that 1917 was the driest year of the past 265 years, while 1956 was the wettest. The record also indicates that the majority of extreme flood years occurred in the past century; prior to about 1900 C.E., the discharge of the Naryn River was relatively stable. Since 1900 C.E., discharge volume has gradually increased, as has discharge variability. At decadal time scales, the 2010s are notable for the frequency of major floods, whereas the 1910s were the driest. Between the 1870s and the 1910s, the Naryn River experienced a period of low discharge that continued for nearly half a century. The discharge of the Naryn River over the past 265 years appears to vary over quasi-periods of 60, 21, 11, and 2-4 years, which are driven by large-scale climate systems.

Keywords Tree rings · Discharge · Tianshan Mountains · Central Asia · Naryn River · Climate change

1 Introduction

Climate change poses a serious challenge to the survival and development of humankind and is a major international policy issue today (Campbell et al. 2011; Carter et al. 2015). Global warming accelerates the water cycle (Douville et al. 2002) and the expansion of drylands (Ma 2007; Huang et al. 2016), and leads to an increasing risk of megadrought for many ecosystems (Ning et al. 2019; Zhang et al. 2019a). Characterized by an arid continental climate (Kottek et al. 2006), Central Asia covers 5×10^6 km^2 and has a population of approximately 60 million people. Ecosystem stability, agricultural production, and socioeconomic development in this region are critically dependent on its scarce water resources (Tangdamrongsub et al. 2011; Siegfried et al. 2012).

The mountain system is an important water source in arid regions (Viviroli et al. 2007; Immerzeel et al. 2010; Immerzeel and Bierkens 2012). The Tianshan Mountains are particularly key "water towers" in Central Asia because they provide water to millions of people in this

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geopolitically important region and act as an ecological barrier (Siegfried et al. 2012). Emerging from the Tianshan Mountains, the Naryn River flows into the Syr Darya, which is the longest and one of the most important rivers in Central Asia. The Central Asian republics depend on the Syr Darya for drinking water, irrigation, and hydroelectric power (Taltakov 2015). It is also one of the most important sources of water for the Aral Sea, which is the biggest lake in Central Asia. Formerly, the Aral Sea was one of the four largest lakes in the world, but it has been shrinking almost continuously since at least 1850. The shrinkage of the Aral Sea has been called "one of the planet's worst environmental disasters". If the loss of the Aral Sea is to be curtailed, it is important to understand natural versus human-induced changes in discharge. As the source of the Syr Darya, it is vital to understand long-term changes in the natural discharge of the Naryn River. A better understanding of natural discharge in the past will help researchers and water managers estimate future trends in water availability and manage this limited resource for both socioeconomic development and ecological integrity.

Instrumental records in Central Asia are typically short and discontinuous, especially for the Naryn River. It is therefore important to develop proxy records of hydrologic change. Tree rings can provide reliable records of the long-term natural variability in discharge that extend well beyond the instrumental record. Because they can be precisely dated, offer annual resolution, and are comparable with instrumental data, tree rings are considered good proxies for the study of climate and hydrological changes. They provide information over hundreds to thousands of years and have been used in many different regions of the world (e.g., Pederson et al. 2001, 2013; Davi et al. 2006, 2013; Akkemik et al. 2008; D'Arrigo et al. 2011; Margolis et al. 2011; Meko and Woodhouse 2011; Leland et al. 2013; Cook et al. 2013; Shah et al. 2013, 2014; Harley et al. 2017; Maxwell et al. 2017; Rao et al. 2018; Strange et al. 2019). Long-term information regarding changes in discharge and hydroclimate can be used in water resource planning, and can play a key role in placing present-day events and projected future conditions into a broader context than that offered by instrumental observations alone. Previous dendrochronological studies in arid Central Asia have focused mainly on reconstructing climate change, including temperature (Chen et al. 2012; Zhang et al. 2020), precipitation (Yuan et al. 2001, 2003; Solomina et al. 2012, 2016; Zhang et al. 2016a), Standardised Precipitation-Evapotranspiration Index (SPEI) (Zhang et al. 2019a), and even the mass balance of glaciers (Zhang et al. 2019b). To date, however, few discharge reconstructions have been developed for the Tianshan Mountains in China (Yuan et al. 2007; Zhang et al. 2016b, c) and Kazakhstan (Panyushkina et al. 2018).

Here, we develop four new tree-ring width chronologies for the Naryn River drainage basin in the inner Tianshan Mountains. We find the best response relationship between the tree-ring chronologies and discharge, develop a reliable 265-year natural May–August discharge reconstruction for the Naryn River, analyse the temporal variations in water discharge, and place recent discharge variations and trends into the context of the past three centuries. Finally, we compare the discharge record with global atmospheric circulation indices to identify the major climatic factors forcing river discharge.

2 Data and methods

2.1 Study areas, climate and discharge data

The Naryn River, which originates in the Tianshan Mountains of Kyrgyzstan, is one of the main tributaries of the Syr Darya River (Fig. 1). The Naryn River starts at the confluence of the Big and the Small Naryn Rivers, then flows into Ferghana Valley, where it merges with the Karadarya River to form the Syr Darya River (Hagg et al. 2013). It is 807 km long (together with Chong-Naryn River) and has an annual flow of 13.7 cubic kilometres. The basin covers 59,100 km^2. There are a number of hydroelectric power stations on the Syr Darya and its tributaries. The Toktogul hydroelectric power station, which was constructed on the Naryn River in the 1970s and expanded in the 1980s, regulates the river's flow (Taltakov 2015). The existence of reservoirs along the river's length interferes with our understanding of natural discharge variability. We therefore only use discharge data from hydrological stations upstream of the Syr Darya (i.e. along the Naryn River).

For this study, monthly discharge data were collected from the Naryn (upstream), Ust. Kekirim (midstream), and Toktogul reservoir (downstream) hydrological stations (Fig. 1). The basic information for these three stations is shown in Table 1. The discharge at the Naryn hydrologic station is most representative of the natural discharge of the Naryn River because the quantity of water flowing past this station is least affected by human influence. For example, there are fewer reservoirs and power station dams upstream of the Naryn hydrologic station, and there are few agricultural diversion and other human activities. This station also has the longest observation record and the best data preservation (Table 1). The locations and types of gauges at the hydrological stations have not changed over the study period; the discharge data are therefore expected to be homogenous. Because some discharge data are missing, we used continuous data for the period 1939–2017 for analysis.

Monthly climate data were obtained from the World Meteorological Organization (WMO; http://www.wmo.

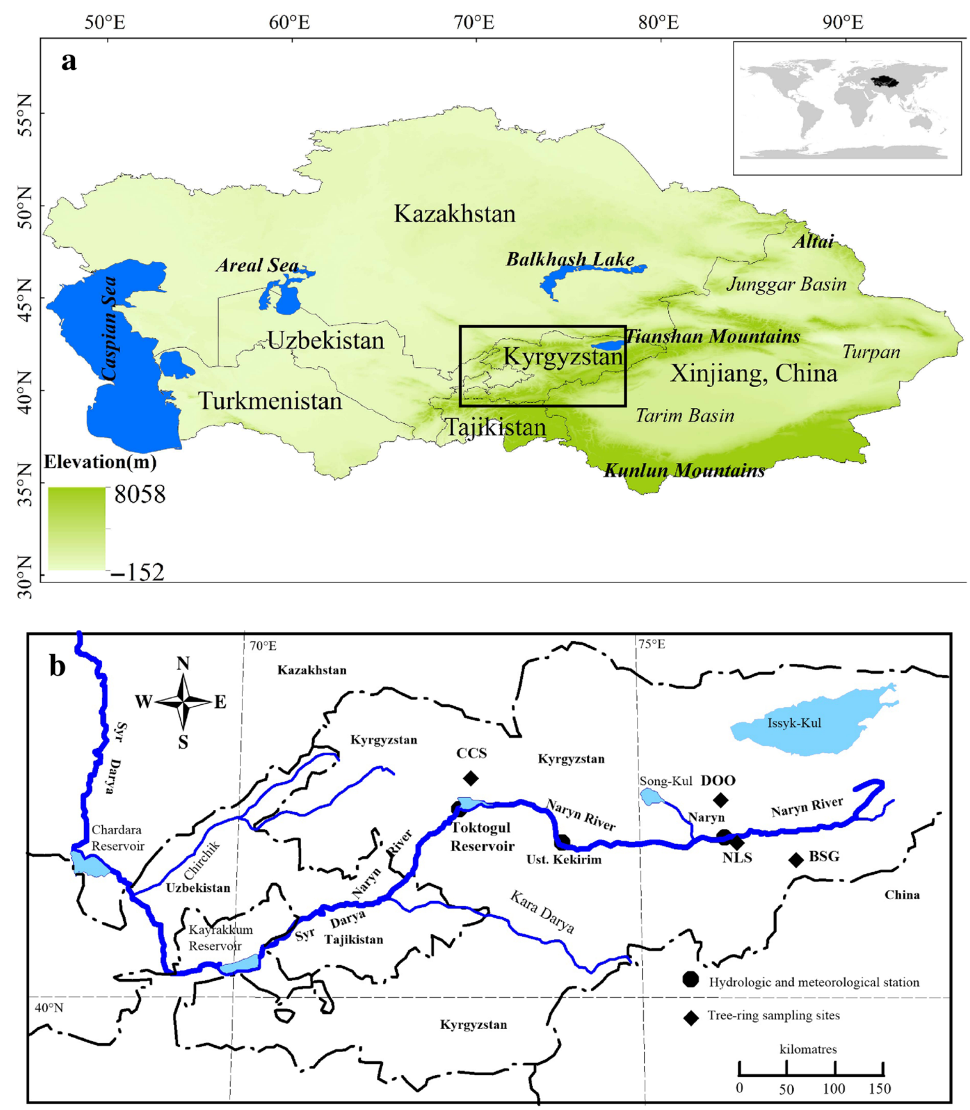


Fig. 1 Schematic diagram of the study area and sampling sites. **a** Location of study area; **b** distribution of tree-ring sampling sites, meteorological and hydrological stations in the Naryn River Basin

Table 1 Information about the hydrological stations along the Naryn River

Station	Code	Latitude	Longitude	Elevation	Start	End	Years
Naryn	NRY	41.43°N	76.02°E	2039 m	1933	2017	85
Ust. Kekirim	UKE	41.42°N	73.98°E	1260 m	1934	1980	47
Toktogul reservoir	TOK	41.66°N	72.64°E	1015 m	1951	1995	45

int/pages/index_en.html). We collected mean temperature (1886–2017) and precipitation (1891–2004) data for the Naryn meteorological station (41.43° N, 76.00° E, 2041.0 m) because it is the station nearest the sampling site, with a straight-line distance of only 10 km. Water vapor flux data were derived from the data-sets of the NCEP/NCAR Reanalysis Project (Ning et al. 2017) and were integrated from the ground up to 300 hPa. The vapour pressure data come from the high resolution global monthly grid data-set of the Climate Research Unit (CRU TS 4.03) at the University of East Anglia, UK. The resolution of the data-set is $0.5° \times 0.5°$, covering 9 terrestrial variables of global land. The sea surface temperature (SST) data are derived from the monthly version of the Hadley Centre Sea Ice and Sea Surface Temperature data-set (https://www.metoffice.gov.uk/hadobs/hadisst/).

2.2 Development of the tree-ring chronologies

Tree-ring samples were collected in 2013, 2016, and 2018 from the Naryn River Basin in the inner Tianshan Mountains (Fig. 1, Table 2). Information about the sampling sites is

Table 2 Basic information about the tree ring samples

Site	Code	Latitude	Longitude	Elevation	Tree/Core	Reliable period SSS > 0.85
Doolon	DOO	41.81°N	75.76°E	2800–2850 m	24/48	1790–2013
Bosogo	BSG	41.23°N	76.45°E	2700–2850 m	29/57	1707–2017
Chychkan	CCS	72.87°N	42.13°E	2363–2400 m	21/42	1811–2017
Naryn	NLS	76.08°N	41.33°E	2800–2820 m	27/54	1753–2017

shown in Table 2. The nearest sampling site (NLS) is located 10 km SE of the city of Naryn, close to the Naryn meteorological and hydrologic stations. All sampling sites are characterized by forests of pure Schrenk spruce (*P. schrenkiana Fisch.* et Mey.), which are shallow rooted, shade-loving trees that are widely distributed throughout the Tianshan Mountains. Trees were sampled using standard dendroclimatological techniques (Stokes and Smiley 1968). Location information and basic chronology statistics are provided in Fig. 1 and Table 2. We only sampled trees with no visible signs of injury or disease in order to minimize the influence of non-climatic factors on tree growth. In general, two cores were taken from each Schrenk spruce tree using 10-mm diameter increment borers (Haglof, Sweden). In total, we sampled 201 cores from 101 trees (Table 2).

All tree-ring samples were air dried, glued onto slotted mounting boards, and sanded to a high polish in preparation for ring-width measurement according to standard dendrochronological procedures (Stokes and Smiley 1968). Cores were first visually cross-dated with reference to prominent pointer or marker years. After a rigorous visual cross-dating of the tree-ring cores, ring widths were measured to an accuracy of 0.001 mm with the Lintab 6 measuring instrument and TSAP-Win program (Frank Rinntech, Heidelberg, Germany). The quality control of cross-dating was carried out using COFECHA (Holmes 1983). Cores with any ambiguities were excluded from further analyses.

We established the tree-ring width chronologies using the ARSTAN program (Cook 1985; Cook and Krusic 2011). The ARSTAN standardization process removes non-climatic variability in each tree-ring series and averages the detrended ring-widths of all series from a site to reduce the noise caused by individual trees (Fritts 1976). We then used the spline function method to detrend the growth tendency of the trees, using a step length that was 2/3 of the common interval (the window length of the spline function is 80–120 years). Following this method, we obtained three types of chronologies: standard (STD), residual (RES), and ARSTAN (ARS). To retain the low-frequency variability within the tree-ring data, we used standard chronologies for all analyses. Chronology variance was stabilised with the r-bar weighted method and the expressed population signal (EPS) was used to determine a common period for the individual chronologies in the program ARSTAN (Cook and Krusic 2011). We also used subsample signal strength (SSS) to assess the adequacy of replication in the early years of the chronology, and thus, the reliability of the reconstructed environmental signals (Wigley et al. 1984). To use the maximum length of the tree-ring chronologies and to ensure the reliability of the reconstructions, we restricted our analysis to the period with an SSS of at least 0.85.

2.3 Methods

To reconstruct discharge and validate the reconstruction, we followed standard dendrochronology procedures (Fritts 1976). The relationship between discharge and tree-ring width was analyzed using Pearson correlation analysis and the Statistical Product and Service Solutions (SPSS) program. All statistical procedures were evaluated at $p < 0.05$ or $p < 0.01$ levels of significance. Annual discharge modeling was conducted using the transfer function approach (Fritts 1976; Cook and Kairiukstis 1990). We used linear regression to estimate the dependent discharge variable from a set of potential tree-ring predictors (Fritts 1976). Once the regression model was fully evaluated, the model was applied to the full period of tree-ring data to generate the reconstruction. The calibration model was evaluated based on the variance in the instrumental record explained by the model after adjusting for the loss of degrees of freedom (R^2 cal). The leave-one-out cross-validation method (Michaelsen 1987) was used to verify the reliability and stability of the discharge reconstruction. The testing statistics used including the reduction of error (RE), the sign test and Pearson's correlation coefficient (Cook and Kairiukstis 1990). The multi-taper method (MTM) of spectral analysis (Mann and Lees 1996) and the Morlet wavelet were used to investigate the periodicity of the discharge reconstruction (Torrence and Compo 1998).

3 Results

3.1 Climatic and hydrological changes in the Naryn River Basin from observational data

The Naryn River Basin is characterized by a continental climate with hot summers and cold winters. The mean annual temperature is 3.15 °C, with an average maximum of 17.36 °C in July and an average minimum of − 16 °C in January (Fig. 2a). Annual total precipitation is 284 mm at the Naryn meteorological station, and ranges between 280 mm and 450 mm throughout the basin depending on elevation (Kriegel et al. 2013). The majority of precipitation falls in spring and early summer (May–July) (Fig. 2a). Mean temperature and precipitation have slowly increased since the beginning of the observational record (0.1 °C/10a and 4.6 mm/a, respectively), exhibiting a weak warming-wetting trend (Fig. 2b).

This warming-wetting trend is similar to those observed in other regions of the Tianshan Mountains and arid Central Asia. Chen et al. (2011), for example, showed that annual precipitation in Central Asia has increased significantly over the past 80 years. The climate in Xinjiang, located to the east of the study area, has changed from a warm-dry regime to a warm-wet one since the middle 1980s. The average annual precipitation from 1987 to 2000 was 22% higher than that of the previous 15 years, increasing by 36 mm in northern Xinjiang (Shi et al. 2007).

The average annual discharge (1933–2017) at the Naryn hydrologic station is 93.3 m^3/s. In the summer, discharge can reach 219.8 m^3/s, whereas it averages a mere 26.9 m^3/s in winter. Maximum discharge occurs in July (243.1 m^3/s) when the snow in the mountains melts and contributes to river flow (Fig. 2c). Snow melt contributes a remarkable portion of discharge. Glacier melt also contributes to discharge in the summer (Kriegel et al. 2013). As a result of the warming and wetting process, the discharge of the Naryn River has increased significantly (Fig. 2d).

3.2 Relationship between discharge and tree-ring width

We compared the discharge data for the upper (Naryn, NRY), middle (Ust. Kekirim, UKE), and lower (Toktogul reservoir, TOK) reaches of the Naryn River with all of the tree-ring chronologies. Correlation and response analysis revealed significant positive correlations between the tree-ring chronologies and discharge variability in May, June, July, and August at a 95% confidence level (Table 3). The correlation coefficient between the NLS chronology and the Naryn hydrologic station discharge exceeded the 99% significance level in May, June, July, and August, respectively. Further analysis showed a correlation of 0.612 between the NLS chronology and May–August discharge ($p < 0.0001$, $n = 79$; Fig. 3). In addition, the discharge changes recorded at the three hydrological stations are consistent with one another. The correlation coefficients of the annual discharge between the Naryn hydrological station and two lower stations (Ust. Kekirim and Toktogul reservoir) exceed 0.7. Therefore, the discharge data of the Naryn hydrological station can be used to represent discharge changes across the Naryn River Basin.

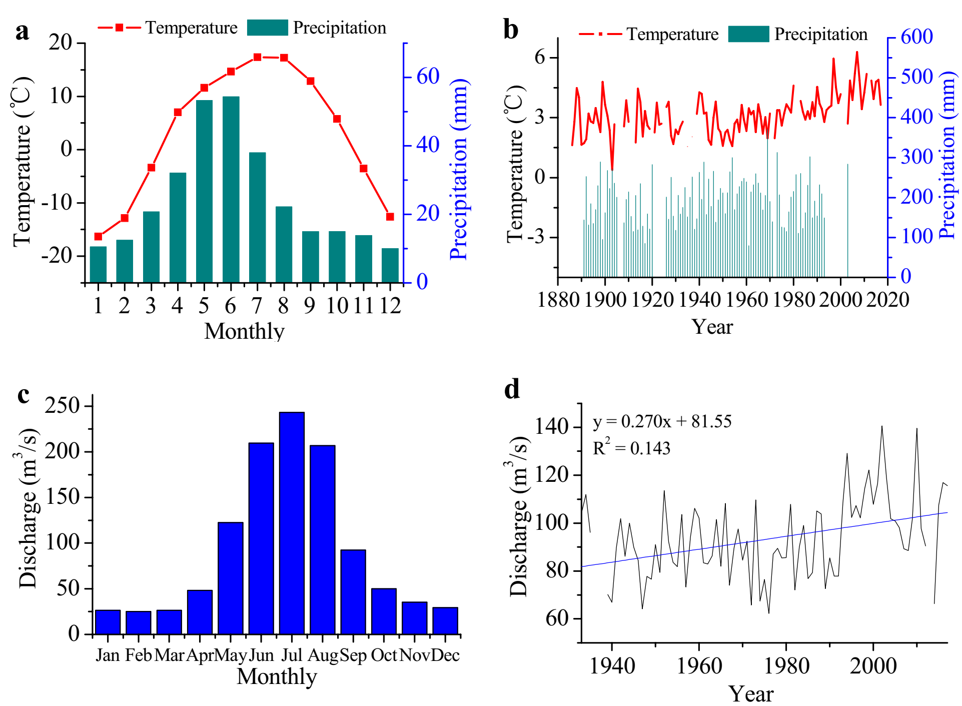


Fig. 2 Observed climatic and hydrological changes in the Naryn River Basin. **a** Monthly variation of mean temperature and precipitation; **b** annual variation of mean temperature and precipitation; **c** monthly variation of discharge; **d** annual variation of discharge

Table 3 The correlation analysis between the tree-ring chronologies and discharge at the three hydrologic stations

	NLS	BSG	DOO	CCS
NRYp10	●	○	●	
NRYp11	●	○		
NRYp12	●			
NRYc1				
NRYc2	○			
NRYc3	○	○		
NRYc4				
NRYc5	●	●		○
NRYc6	●	●	●	
NRYc7	●	●		
NRYc8	●	○		
NRYc9	●	○		
NRYp10c9	●	●	●	
NRYc6c8	●	●	●	
NRYc5c8	●	●	●	
TOKp10	●	●	●	●
TOKp11	●	●	●	●
TOKp12	○	●	○	●
TOKc1	●	●	○	●
TOKc2	●	●		●
TOKc3	○	●	●	●
TOKc4		●	●	○
TOKc5	○	●		●
TOKc6	●	●	●	●
TOKc7	●	●	○	○
TOKc8	○	●	○	●
TOKc9	○	●	○	●
TOKp10c9	●	●	●	●
TOKc6c8	●	●	●	●
TOKc5c8	●	●	●	●
UKEp10	●	●	●	●
UKEp11	●	●	●	●
UKEp12	●	●	○	
UKEc1	●	○		
UKEc2	●	●	○	
UKEc3	○	●	●	
UKEc4		●	●	
UKEc5	●	●	○	●
UKEc6	●	●	●	○
UKEc7	●	●		●
UKEc8	○	○		●
UKEc9				
UKEp10c9	●	●	●	●
UKEc6c8	●	●	●	●
UKEc5c8	●	●	●	●

NRY, TOK and UKE represent the discharge at the Naryn, Toktogul reservoir, and Ust. Kekirim hydrological stations, respectively. p10–p12 represents October-December of the previous year, c1–c9 represents January- September of the current year, p10c9 represents previous October–current September, c6c8 and c5c8 represent June–August and May–August of the current year, respectively

A black dot indicates significance at 99%; a white dot indicates significance at 95%

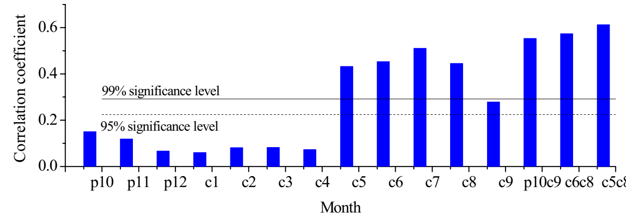


Fig. 3 Correlation coefficient between the observed discharge and the NLS tree-ring chronology. p10–p12 represents October–December of the previous year, c1–c9 represents January -September of the current year, p10c9 represents previous October–current September, and c6c8 and c5c8 represent June–August and May–August of the current year, respectively

3.3 Discharge reconstruction and validation

Based on the strong correlation between the tree-ring chronologies and the observed May–August discharge, the discharge from May to August was reconstructed for the last two centuries. A transfer function was developed:

$$Q_{5-8} = 44.5 + 151.9 \times NLS\,(R^2 = 0.374,\ n = 79,\ p < 0.0001, F_{1,77} = 46.1,\ DW = 1.327) \quad (1)$$

where Q_{5-8} is the mean discharge from May to August, NLS is the standardized width chronology of the NLS sampling site. DW represents the Durbin-Watson value (Durbin and Watson 1951). During the calibration period (1939–2017), the reconstruction tracks the instrumental record very well, with an explained variance of 37.4% (36.6% after adjusting for the loss of degrees of freedom; Fig. 4a). The reconstructed series reveals the discharge variability of the Naryn River over the past 265 years (Fig. 4c).

The model passed all calibrations. The cross-validation test yielded a positive RE (0.345), which indicates the predictive skill of the regression model. The statistically significant sign test (51 +, 28 −, p < 0. 05) and correlation (r = 0.588, p < 0.0001), and the first difference sign test (56 +, 22 −, p < 0.01) and correlation (r = 0.672, p < 0.0001) between the recorded data and the leave-one-out-derived estimates, respectively, also indicate the validity of the reconstruction. In addition, the first-order differential shows a high correlation (r = 0.689, p < 0.0001, n = 78, Pearson) between the reconstructed and observed time series (Fig. 4b). The reliability of the reconstruction is further validated by the consistency of high-frequency change in the reconstructed and observed time series.

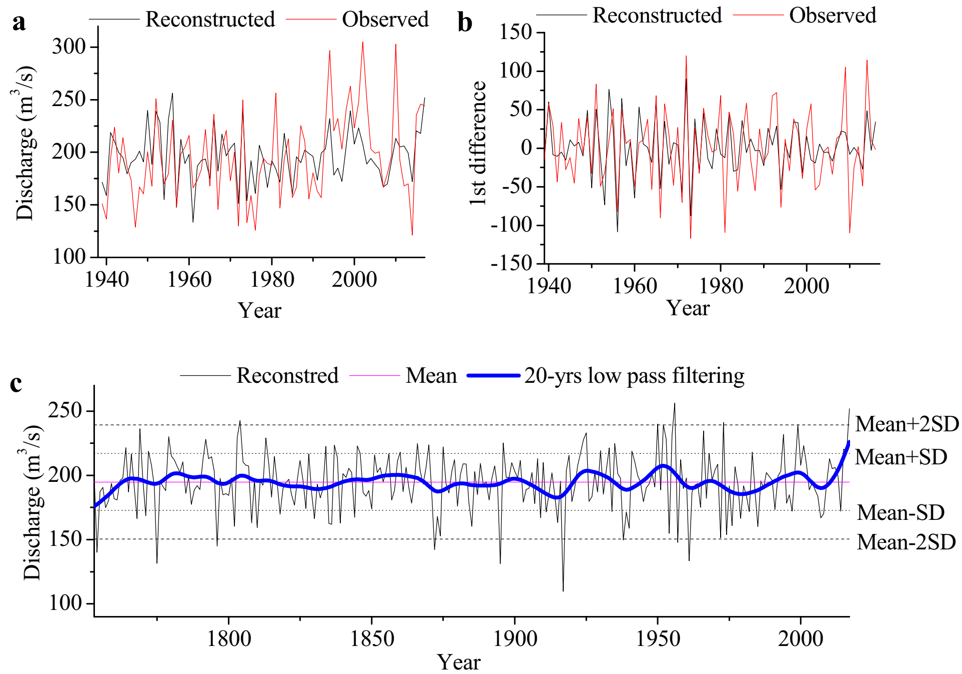


Fig. 4 A 265-year discharge reconstruction for the Naryn River. **a** Comparison of the reconstructed May–August discharge (gray line) and the observed discharge from the Naryn hydrologic station (red line) for the common period 1939–2017. **b** Comparison of the first differences (year-to-year changes) of the reconstructed and the observed discharge (red line). **c** The reconstructed May–August discharge for the Naryn River (gray, 1753–2017) and the 20-year running mean of the reconstructed discharge (blue)

Table 4 Ranking of the extreme drought and flood years over the past 265 years

Rank	Extreme drought		Extreme floods	
	Year	Discharge (m^3/s)	Year	Discharge (m^3/s)
1	1917	109.7	1956	256.2
2	1895	131.2	2017	252.0
3	1775	131.5	1804	242.7
4	1961	133.5	1973	241.3
5	1754	140.2	1950	240.0
6	1872	142.2	1999	239.4
7	1796	145.0	1952	239.2
8	1957	147.8	1769	236.2
9	1938	149.6	1966	234.7
10	1972	151.6	1925	233.0

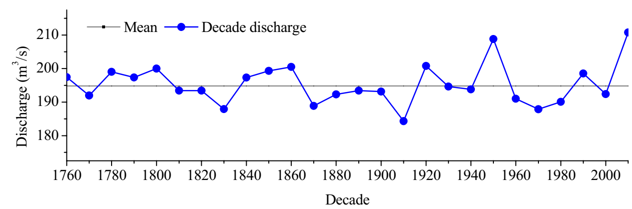


Fig. 5 The interdecadal variation of the Naryn River discharge reconstruction over the past 265 years

3.4 Long-term discharge changes of the Naryn River

Interannual variations indicate that 1917 was the driest of the past 265 years, whereas 1956 was the wettest. Discharge was relatively stable during the 1800s, but both discharge volume and variability of the Naryn River have increased over the last century. Most of the extreme flood years have occurred since 1900 C.E. (Table 4). However, 1917 was a year of extreme drought that has been widely observed in tree-ring reconstructions (Yuan et al. 2001, 2003; Zhang et al. 2016d, 2019c) and is observed in this study as well for other rivers in the Tianshan Mountains (Yuan et al. 2007; Zhang et al. 2016b, c). Many historical documents confirm that 1917 was a particularly dry year throughout the Tianshan Mountains (Shi et al. 2007). As is the case for other rivers in the Tianshan Mountains, the discharge of the Naryn River has increased rapidly over the past half century (Fig. 2d). This is likely related to the current warming and wetting process, which leads to increased glacial melt (Kriegel et al. 2013). The combined increase in precipitation and glacial melt has led to the increased discharge of the Naryn River.

At decadal time scales, the 2010s are notable because significant flooding occurred during this period, whereas the 1910s were one of the driest decades. From the 1870s to the 1910s, the Naryn River experienced a period of low water that continued for nearly half a century. The other two periods of continuous low water are the 1960–1980s and the 1810–1830s. The periods of continuous flooding are the 1780–1800s and the 1840–1860s (Fig. 5). We compared long-term changes in discharge between the Naryn and other rivers in the Tianshan Mountains, namely Manasi

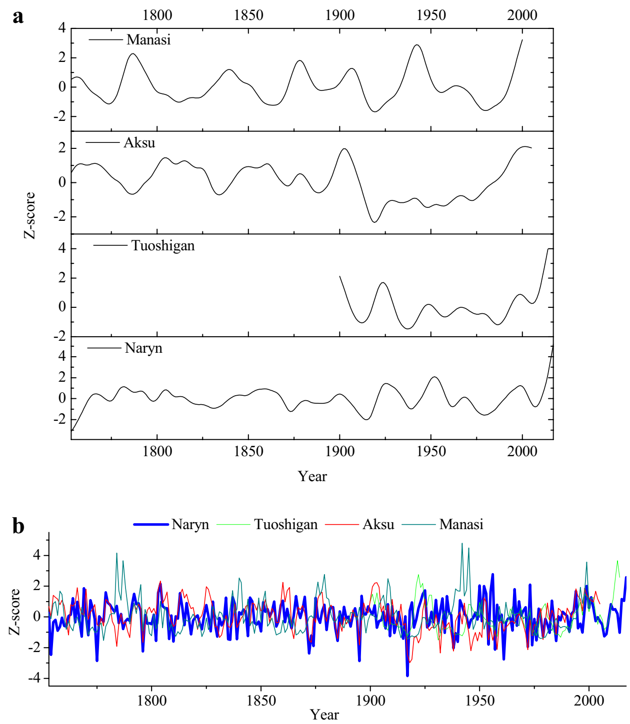


Fig. 6 A comparison of the Naryn River discharge reconstruction with that of the Tuoshigan River (Zhang et al. 2016a), the Aksu River (Zhang et al. 2016c) and the Manasi River (Yuan et al. 2007) in the Tianshan Mountains. **a** Comparison of the four 20-years low-pass filtering of reconstructions; **b** comparison of the four reconstructions

River (Yuan et al. 2007), Aksu River (Zhang et al. 2016c), and Tuoshigan River (Zhang et al. 2016a). The results show that the discharge changes of the Naryn River are consistent with those of other rivers, regardless of long-term changes in frequency (Fig. 6). This consistency confirms the reliability of the reconstruction.

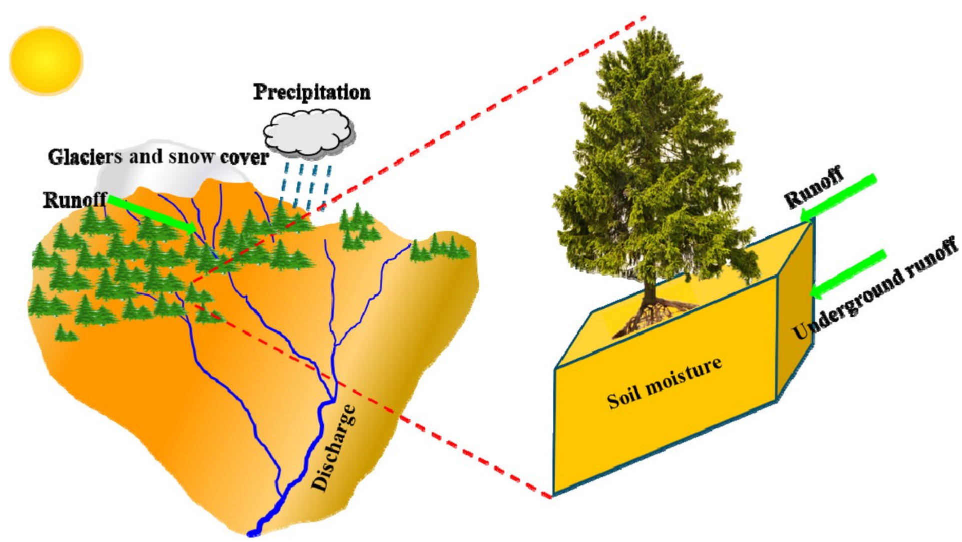
4 Discussion

4.1 Relationship between discharge, radial growth, and climate

The Tianshan Mountains are considered to be the "water tower" of Central Asia, providing water to millions of people. These mountains are mainly affected by the westerlies, which collide with the northern slopes of the mountains and produce the rain and snowfall on which the region depends. As shown in Fig. 7, the more precipitation in spring directly leads to the increase of Naryn river discharge. Meanwhile, the rise in temperature effectively replenishes the river discharge. The increase in discharge is driven by melting snow and ice in the upper reaches of the Naryn River, as well as by the increase in precipitation from May to August (Fig. 2a). Climate change is therefore a decisive factor in the changes in May–August discharge (Fig. 7). Meanwhile, Schrenk spruce experiences the most radial growth from May to August, and is the more sensitive to climate change during this period. Zhang et al. (2016d) analyzed intra-annual radial growth using data from continuously monitored dendrometers in the Tianshan Mountains and found that the critical growing season for Schrenk spruce is from late May to late July, and that the rapid growth stage is from mid-June to early July.

The total annual and May to August precipitation of the study area is only 284 mm and 189 mm, respectively. This minor amount of precipitation is not enough for the normal growth of Schrenk spruce, which likes a humid environment. The mean annual temperature is 3.15 °C and the mean temperature in May–August is 15.21 °C. The elevation of the Naryn meteorological station is 2039 m a.s.l., and the elevation of the NLS sampling site is as high as 2800 m a.s.l.

Fig. 7 The relationship between tree growth, climate, and discharge in the Naryn River Basin



An increase in temperature facilitates rapid cell division and enlargement, leading to the formation of a wide annual ring. Walter (1997) suggested that the optimum temperature range for the net photosynthesis of evergreen coniferous trees is between 10 and 25 °C. Using the dry adiabatic lapse rate, we estimate the mean temperature at the sampling site in May–August to be about 10.26 °C, which is at the low end of the range. The continuous warming and wetting that has been observed since the 1980s is therefore conducive to the formation of early wood. In contrast, low temperatures or less precipitation in May–August will slow cell division or even result in stagnation. Many previous studies have shown that spring drought has a notable impact on the radial growth of Schrenk spruce. Hence, both discharge and tree growth is controlled by climate (temperature and precipitation) and therefore share an indirect but robust relationship (Fig. 8). Thus, tree rings can be used to reconstruct a reliable discharge record for Naryn River.

4.2 Possible climate drivers of discharge changes

Further correlation analysis shows that there is a significant positive correlation ($r = 0.409$, $p < 0.01$, $n = 54$) between May and August discharge at the Naryn hydrologic station and precipitation at the Naryn meteorological station. This indicates that precipitation plays an important role in discharge changes. In order to understand possible climatic drivers of discharge change, we analyzed the water vapor flux from May to August across mid-latitude Eurasia, and compared the correlation between change in discharge and large-scale water vapor pressure, and sea surface temperatures (HadISST1). Our results indicate that the water vapor of the Naryn River Basin originates mainly from the Atlantic Ocean and is transmitted by westerly circulation (Fig. 9a). Changes in the discharge of the Naryn River are significantly related to the water vapor pressure across a wide swath of Central Asia and Northwest China (Fig. 9b). Meanwhile, the discharge has a significant positive correlation with North Atlantic SSTs (Fig. 9c). Guan et al. (2019) suggest that the water vapor in Central Asia is derived from the Atlantic Ocean in summer.

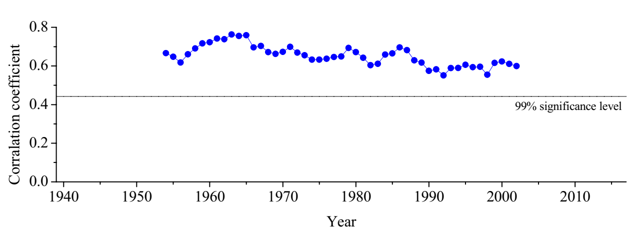


Fig. 8 21-year sliding correlation between tree-ring width and discharge

A study by Aizen et al. (1997) showed that the main factor determining changes in river discharge is the type of precipitation (liquid or solid). The Tianshan Mountains cast a significant rain shadow; as a result, the region to the west of the mountains is largely dependent on moisture carried by the westerlies. A later study by Aizen et al. (2001) shows that annual and seasonal precipitation at the mid-latitudes of Asia can be linked to major components of mid-latitude atmospheric circulation. Burt and Howden (2013) found that the hydroclimatology of rainfall and river flow in upland areas is closely coupled with the strength of atmospheric circulation. Stronger westerly winds could lead to abundant precipitation in the Tianshan Mountains and hence to an increase in the discharge of the Naryn River. This suggests that atmospheric circulation might indirectly influence the discharge of the Naryn River on both short- and long-term scales by affecting precipitation.

Naryn River is an inland river, and its main water sources are glacial meltwater and precipitation in the high mountains. As a result, the impact of climate change on discharge is particularly strong. Changes in discharge are directly linked to changes in air temperature and precipitation. Upward trends in both precipitation and temperature accelerate the melting of snow/ice and are the direct cause of the clear and rapid increase in discharge observed in the 1980s (Fig. 2b). We suggest that the recent and rapid increase in the discharge of the Naryn River is the result of both global warming and changes in mid-latitude atmospheric circulation.

A Morlet wavelet analysis shows that the changes in the discharge of the Naryn River over the past 265 years may occur over quasi-periods of 60 years, 21 years, and 11 years (Fig. 10). The multi-taper method (Thomson, 1982) also suggests quasi-periods of 21 and 11 years. At the same time, the discharge of the Naryn River appears to fluctuate over short-term quasi-periods of 2–4 years (Fig. 10). Previous dendrohydrological studies of rivers in the Tianshan Mountains have exhibited quasi-periods of 2–4 years and 11 years (Liu et al. 2010; Gou et al. 2010; Yuan et al. 2007; Zhang et al. 2016b, c). The quasi-period of 2–4 years suggests that changes in the discharge of the Naryn River may be related to westerly circulation. Huang et al. (2013) suggested that the 2–4-year period is linked to variations in the westerly circulation in the mid-troposphere. Other studies have found that the 2–4-year period is characteristic of climate change in Central Asia. Because the Naryn River exhibits this quasi-period, it is likely that its discharge is affected by large-scale climate systems. The quasi-periods of 20 years and 11 years are consistent with sunspot activity (Rind 2002), indicating that discharge changes are also related to solar activity.

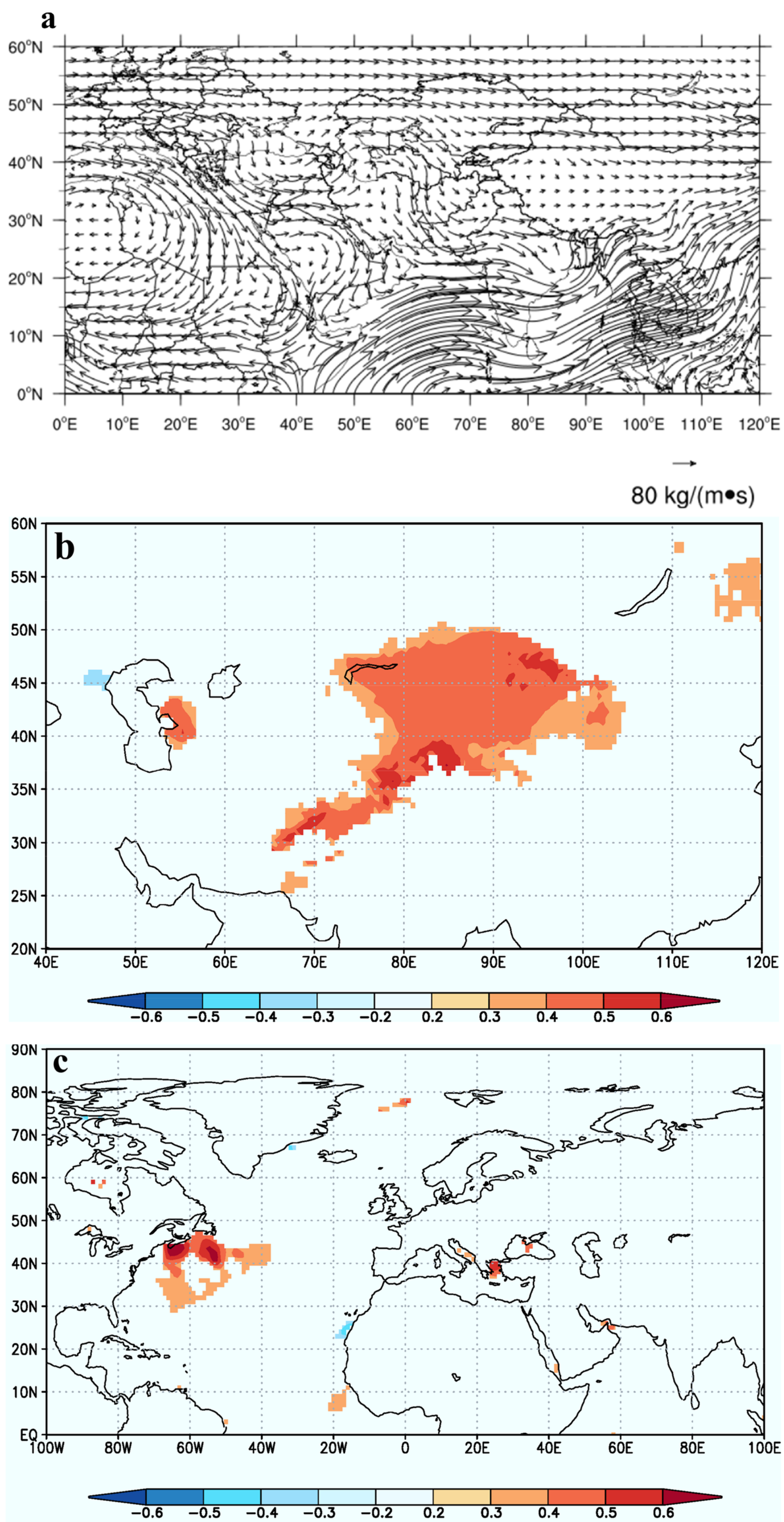


Fig. 9 **a** Water vapor flux from May to August during the period 1981–2010. **b** Spatial correlation between the discharge reconstruction for the Naryn River and the May–August vapor pressure (1981–2010). **c** Spatial correlation between the discharge reconstruction and HadISST1 (1981–2010)

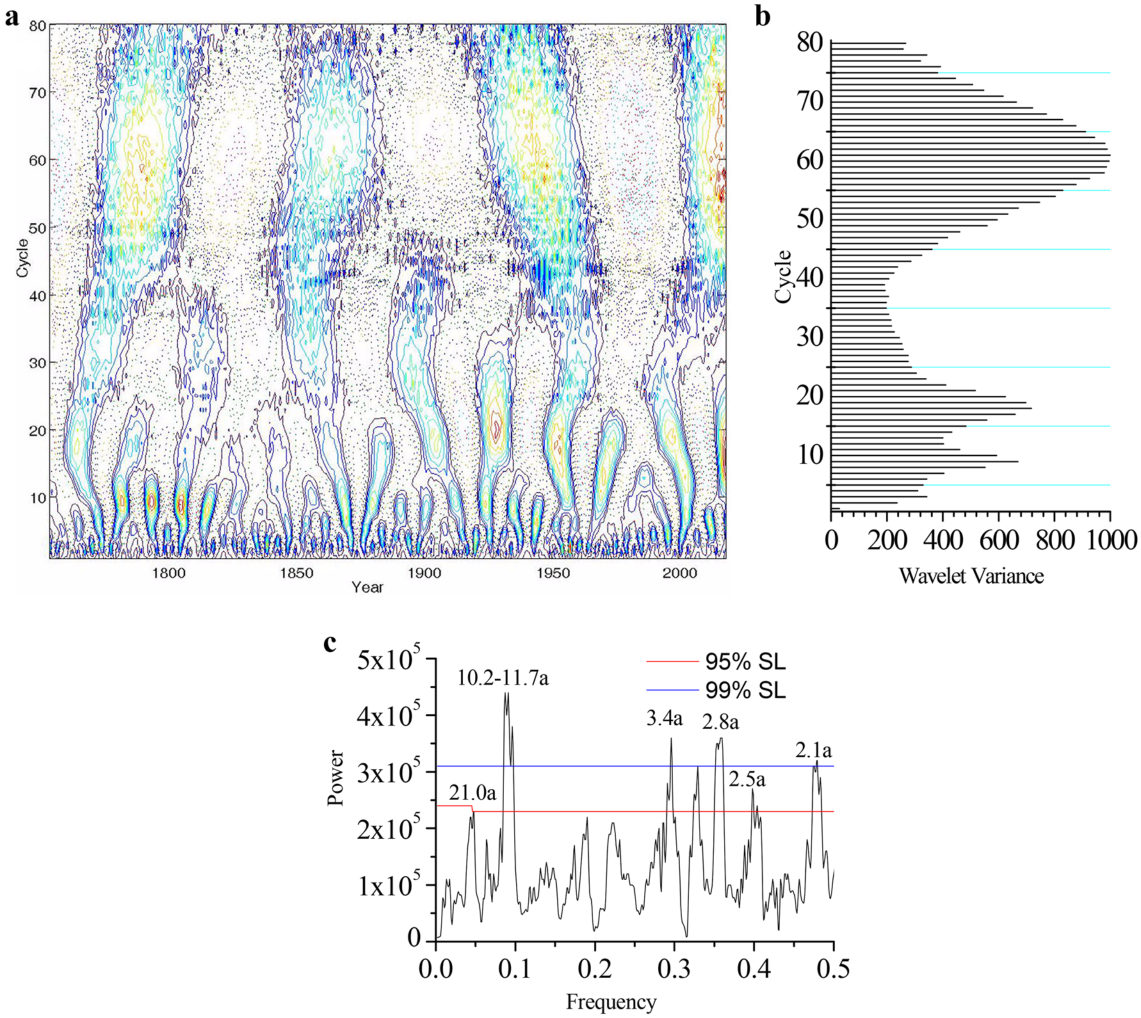


Fig. 10 Cycle analysis for the reconstructed May–August discharge (1753–2017 C.E.). **a** Morlet wavelet analysis; **b** the variance of the Morlet wavelet analysis. **c** The Multi-Taper Power spectra. 99% SL and 95% SL represent significance levels at 99% and 95%, respectively

5 Conclusions

Our understanding of the full range of natural discharge variability, including how modern flow compares to that of the past, is poorly understood for the Aral Sea basin (include Syr Darya) because the instrumental record is quite short. To help address this limitation, we used tree-rings and hydrological data from an undammed section of the Naryn River to develop a hydrological series that extends back to 1753 (265 years).

Instrumental observations in Central Asia are insufficient for understanding long-term climate and hydrological changes. With their annual resolution and sensitivity to climate, tree rings are reliable proxies that can be used to extend the instrumental record. The tree ring reconstruction provides a valuable source of information about discharge changes in Naryn River, and confirms that discharge patterns in recent decades are unusual compared to the longer-term record.

The results of this study provide better understanding of the relationship between climate, glaciers, discharge, and ecological changes in the arid regions of Central Asia. Furthermore, this study provides qualitative information about the long-term hydrologic variability of the region that should be useful to water managers, stakeholders, and decisionmakers.

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Compliance with ethical standards

Conflict of interest All authors declare that there are no conflicts of interest.

References

Aizen VB, Aizen EM, Melack JM, Dozier J (1997) Climatic and Hydrologic change in the Tien Shan, Central Asia. J Clim 10:1393–1404

Aizen EM, Aizen VB, Melack JM, Nakamura T, Ohta T (2001) Precipitation and atmospheric circulation patterns at mid-latitudes of Asia. Int J Climatol 21(5):535–556

Akkemik U, D'Arrigo R, Cherubini P, Kose N, Jacoby GC (2008) Tree-ring reconstructions of precipitation and discharge for northwestern Turkey. Int J Climatol 28:173–183

Burt TP, Howden NJK (2013) North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. Water Resour Res 49:3504–3515. https://doi.org/10.1002/wrcr.20297

Campbell JL, Driscoll CT, Pourmokhtarian A, Hayhoe K (2011) Discharge responses to past and projected future changes in climate at the Hubbard Brook Experimental Forest, New Hampshire, United States. Water Resour Res 47:W02514. https://doi.org/10.1029/2010WR009438

Carter JG, Gavan G, Connelly A, Guy S, Handley J, Kazmierczak A (2015) Climate change and the city: building capacity for urban adaptation. Prog Plan 95:1–66

Chen F, Huang W, Jin L, Chen J, Wang J (2011) Spatiotemporal precipitation variations in the arid Central Asia in the context of global warming. Sci China Earth Sci 54:1812–1821

Chen F, Yuan Y, Wei W, Wang L, Yu S, Zhang R, Fan Z, Shang H, Zhang T, Li Y (2012) Tree ring density-based summer temperature reconstruction for Zajsan Lake area, East Kazakhstan[J]. Int J Climatol 32:1089–1097

Cook ER (1985) A time-series analysis approach to tree-ring standardization. Dissertation, The University of Arizona Press, Tucson, AZ

Cook ER, Kairiukstis LA (1990) Methods of dendrochronology: applications in the environmental sciences. Kluwer Academic Publishers, Boston

Cook ER, Krusic PJ (2011) Software. Tree Ring Laboratory of Lamont-Doherty Earth Observatory: New York, NY. http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software. Accessed 10 July 2011

Cook ER, Palmer JG, Ahmed M, Woodhouse CA, Fenwick P, Zafar MU, Wahab M, Khan N (2013) Five centuries of Upper Indus River flow from tree rings. J Hydrol 486:365–375

D'Arrigo R, Abram N, Ummenhofer C, Palmer J, Mudelsee M (2011) Reconstructed streamflow for Citarum River, Java, Indonesia: linkages to tropical climate dynamics. Clim Dyn 36:451–462

Davi NK, Jacoby GC, Curtis AE, Baatarbileg N (2006) Extension of drought records for central Asia using tree rings: West-Central Mongolia. J Clim 19:288–299

Davi NK, Pederson N, Leland C, Baatarbileg N, Suran B, Jacoby GC (2013) Is eastern Mongolia drying? A long-term perspective of a multidecadal trend. Water Resour Res 49:151–158

Douville H, Chauvin F, Planton S, Royer JF, Salas-Mélia D, Tyteca S (2002) Sensitivity of the hydrological cycle in increasing amounts of greenhouse gases and aerosols. Clim Dyn 20(1):45–68

Durbin J, Watson GS (1951) Testing for serial correlation in least squares regression. Biometrika 38:159–178

Fritts HC (1976) Tree rings and climate. Academic Press, London

Gou X, Deng Y, Chen F, Yang M, Fang K, Gao L, Yang T, Zhang F (2010) Tree ring based streamflow reconstruction for the Upper Yellow River over the past 1234 years. Chin Sci Bull 55:4179–4186

Guan X, Yang L, Zhang Y, Li J (2019) Spatial distribution, temporal variation, and transport characteristics of atmospheric water vapor over Central Asia and the arid region of China. Glob Planet Change 172:159–178

Hagg W, Mayer C, Lambrecht A, Kriegel D, Azizov E (2013) Glacier changes in the Big Naryn basin, Central Tian Shan. Glob Planet Change 110:40–50

Harley GL, Maxwell JT, Larson E, Grissino-Mayer HD, Henderson J, Huffman J (2017) Suwannee River flow variability 1550-2005 CE reconstructed from a multispecies tree-ring network. J Hydrol 544:438–451

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull 43:69–78

Huang W, Chen F, Feng S, Chen J, Zhang X (2013) Interannual precipitation variations in the mid-latitude Asia and their association with large-scale atmospheric circulation. Chin Sci Bull 58:3962–3968

Huang J, Yu H, Guan X, Wang G, Guo R (2016) Accelerated dryland expansion under climate change. Nat Clim Change 6:166–171. https://doi.org/10.1038/nclimate2837

Immerzeel WW, van Beek LPH, Bierkens MFP (2010) Climate change will affect the Asian Water Towers. Science 328:1382–1385

Immerzeel WW, Bierkens MFP (2012) Asia's water balance. Nat Geosci 5(12):841–842

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130

Kriegel D, Mayer C, Hagg W, Vorogushyn S, Duethmann D, Gafurov A, Farinotti D (2013) Changes in glacierisation, climate and runoff in the second half of the 20th century in the Naryn basin, Central Asia. Glob Planet Change 110:51–61

Leland C, Pederson N, Hessl A, Nessl B, Davi N, D'Arrigo R, Jacoby G (2013) A hydroclimatic regionalization of central Mongolia as inferred from tree rings. Dendrochronologia 31:205–215

Liu Y, Sun J, Song H, Cai Q, Bao G, Li X (2010) Tree-ring hydrologic reconstructions for the Heihe River watershed, western China since 1430 AD. Water Res 44:2781–2792

Ma Z (2007) The interdecadal dry/wet trend and shift of North China and their relationship to the Pacific Decadal Oscillation (PDO). Chin Sci Bull 52(15):2130–2139

Mann ME, Lees JM (1996) Robust estimation of background noise and signal detection in climatic time series. Clim Change 33(3):409–445

Margolis EQ, Meko DM, Touchan R (2011) A tree-ring reconstruction of streamflow in the Santa Fe River, New Mexico. J Hydrol 397:118–127

Maxwell RS, Harley GL, Maxwell JT, Rayback SA, Pederson N, Cook ER, Barclay DJ, Li W, Rayburn JA (2017) An interbasin comparison of tree–ring reconstructed streamflow in the eastern United States. Hydrol Process 31(13):2381–2394

Meko DM, Woodhouse CA (2011) Application of streamflow reconstruction to water resources management. In: Hughes MK, Swetnam TW, Diaz HF (eds) Dendroclimatology, progress and prospects, developments in paleoenvironmental research, vol 11. Springer, Dordrecht, pp 231–261

Michaelsen J (1987) Cross-validation in statistical climate forecast models. J Clim Appl Meteorol 26:1589–1600

Ning L, Liu J, Sun W (2017) Influences of volcano eruptions on Asian Summer Monsoon over the last 110 years. Sci Rep UK 7:42626. https://doi.org/10.1038/srep42626

Ning L, Liu J, Wang B, Chen K, Yan M, Jin C, Wang Q (2019) Variability and mechanisms of megadroughts over eastern China during the last millennium: a model study. Atmosphere 10:7

Panyushkina IP, Meko DM, Macklin MG, Toonen WHJ, Mukhamadiev NS, Konovalov VG, Ashikbaev NZ, Sagitov AO (2018) Runoff variations in Lake Balkhash Basin, Central Asia, 1779–2015, inferred from tree rings. Clim Dyn. https://doi.org/10.1007/s00382-018-4072-z
Pederson N, Jacoby GC, D'Arrigo RD, Cook ER, Buckley BM, Dugarjav C, Mijiddorj R (2001) Hydrometeorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. J Clim 14:872–881
Pederson N, Leland C, Baatarbileg N, Hessl AE, Bell AR, Martin-Benito D, Saladyga T, Suran B, Brown PM, Davi NK (2013) Three centuries of shifting hydroclimatic regimes across the Mongolian Breadbasket. Agric For Meteorol 178–179:10–20
Rao MP, Cook ER, Cook BI, Palmer JG, Uriarte M, Devineni N, Lall U, D'Arrigo RD, Woodhouse CA, Ahmed M, Zafar MU (2018) Six centuries of Upper Indus Basin streamflow variability and its climatic drivers. Water Resour Res 54(8):5687–5701
Rind D (2002) The sun's role in climate variations. Science 296:673–677
Shah SK, Bhattacharyya A, Shekhar M (2013) Reconstructing discharge of Beasriver basin, Kullu valley, western Himalaya based on tree-ring data. Quatern Int 286:138–147
Shah SK, Bhattacharyya A, Chaudhary V (2014) Streamflow reconstruction of Eastern Himalaya River, Lachen 'Chhu', North Sikkim, based on tree-ring data of Larix griffithiana from Zemu Glacier basin. Dendrochronologia 32:97–106
Shi Y, Shen Y, Kang E, Li D, Ding Y, Zhang G, Hu R (2007) Recent and future climate change in northwest China. Clim Change 80:379–393
Siegfried T, Bernauer T, Guiennet R, Sellars S, Robertson AW, Mankin J, Bauer-Gottwein P, Yakovlev A (2012) Will climate change exacerbate water stress in Central Asia? Clim Change 112:881–899. https://doi.org/10.1007/s10584-011-0253-z
Solomina ON, Dolgova EA, Maximova OE (2012) Tree-ring based hydrometeorological reconstructions in Crimea, Caucasus and Tien-Shan. Nestor-History, Moscow-Sankt-Petersburg, p 232 **(In Russian, with extended English summary)**
Solomina ON, Bradley RS, Jomelli V, Geirsdottir A, Kaufman DS, Koch J, Mckay NP, Masiokas M, Miller G, Nesje A, Nicolussi K, Owen LA, Putnam AE, Wanner H, Wiles G, Yang B (2016) Glacier fluctuations during the past 2000 years. Quatern Sci Rev 149:61–90
Stokes MA, Smiley TL (1968) An introduction to tree-ring dating. University of Chicago, Chicago
Strange BM, Maxwell JT, Robeson SM, Harley GL, Therrell MD, Ficklin DL (2019) Comparing three approaches to reconstructing streamflow using tree rings in the Wabash River basin in the Midwestern, US. J Hydrol 573:829–840
Taltakov I (2015) The Syr Darya River—new ecological disaster in central Asia. Acta Sci Polonorum Form Circum 14(4):135–140
Tangdamrongsub N, Hwang C, Kao Y (2011) Water storage loss in central and south Asia from GRACE satellite gravity: correlations with climate data. Nat Hazards 59:749–769. https://doi.org/10.1007/s11069-011-9793-9
Thomson DJ (1982) Spectrum estimation and harmonic analysis. Proc IEEE 70:1055–1096
Torrence C, Compo GP (1998) A practical guide to wavelet analysis. Bull Am Meteorol Soc 79:61–78
Viviroli D, Dürr H, Messerli B, Meybeck M, Weingartner R (2007) Mountains of the world, water towers for humanity: typology, mapping, and global significance. Water Resour Res 43(7):W07447
Walter (1997) Physiological Plant Ecology. Springer, Berlin
Wigley TML, Briffa KR, Jones PD (1984) On the average value of correlated time series, with application in dendroclimatology and hydrometeorology. J Appl Meteorol Clim 23:201–213
Yuan Y, Li J, Zhang J (2001) 348 year precipitation reconstruction from tree-rings for the North Slope of the middle Tien Shan Mountains. Acta Meteorol Sin 15:95–104
Yuan Y, Jin L, Shao X, He Q, Li Z, Li J (2003) Variations of the spring precipitation day numbers reconstructed from tree rings in the Urumqi River drainage, Tien Shan Mts. over the last 370 years. Chinese Sci Bull 48:1507–1510
Yuan Y, Shao X, Wei W, Yu S, Gong Y, Trouet V (2007) The potential to reconstruct Manasi River streamflow in the northern Tien Shan Mountains (NW China). Tree-ring Res 63:81–93
Zhang R, Qin L, Yuan Y, Gou X, Zou C, Yang Q, Shang H, Fan Z (2016a) Radial growth response of *Populus xjrtyschensis* to environmental factors and a century-long reconstruction of summer streamflow for the Tuoshigan River, northwestern China. Ecol Indic 71:191–197
Zhang R, Yuan Y, Gou X, He Q, Shang H, Zhang T, Chen F, Ermenbaev B, Yu S, Qin L, Fan Z (2016b) Tree-ring-based moisture variability in western Tianshan Mountains since A.D. 1882 and its possible driving mechanism. Agric For Meteorol 218–219:267–276
Zhang R, Yuan Y, Gou X, Yang Q, Wei W, Yu S, Zhang T, Shang H, Chen F, Fan Z, Qin L (2016c) Streamflow variability for the Aksu River on the southern slopes of the Tian Shan inferred from tree ring records. Quatern Res 85(3):371–379
Zhang R, Yuan Y, Gou X, Zhang T, Zou C, Ji C, Fan Z, Qin L, Shang H, Li X (2016d) Intra-annual radial growth of Schrenk spruce (*Picea schrenkiana* Fisch. et Mey) and its response to climate on the northern slopes of the Tianshan Mountains. Dendrochronologia 40:36–42
Zhang R, Ermenbaev B, Zhang T, Ali M, Qin L, Satylkanov R (2019a) The Radial growth of Schrenk Spruce (*Picea schrenkiana* Fisch. et Mey.) records the hydroclimatic changes in the Chu River Basin over the Past 175 Years. Forests 10:223
Zhang R, Wei W, Shang H, Yu S, Gou X, Qin L, Bolatov K, Mambetov BT (2019b) A tree ring-based record of annual mass balance changes for the TS. Tuyuksuyskiy Glacier and its linkages to climate change in the Tianshan Mountains. Quatern Sci Rev 205:10–21
Zhang X, Li M, Ma Z, Yang Q, Lv M, Clark R (2019c) Assessment of an evapotranspiration deficit drought index in relation to impacts on ecosystems. Adv Atmos Sci 36(11):1273–1287
Zhang R, Qin L, Shang H, Yu S, Gou X, Mambetov BT, Bolatov K, Zheng W, Ainur U, Bolatova A (2020) Climatic change in southern Kazakhstan since 1850 C.E. inferred from tree rings. Int J Biometeorol 64(5):841–851. https://doi.org/10.1007/s00484-020-01873-5