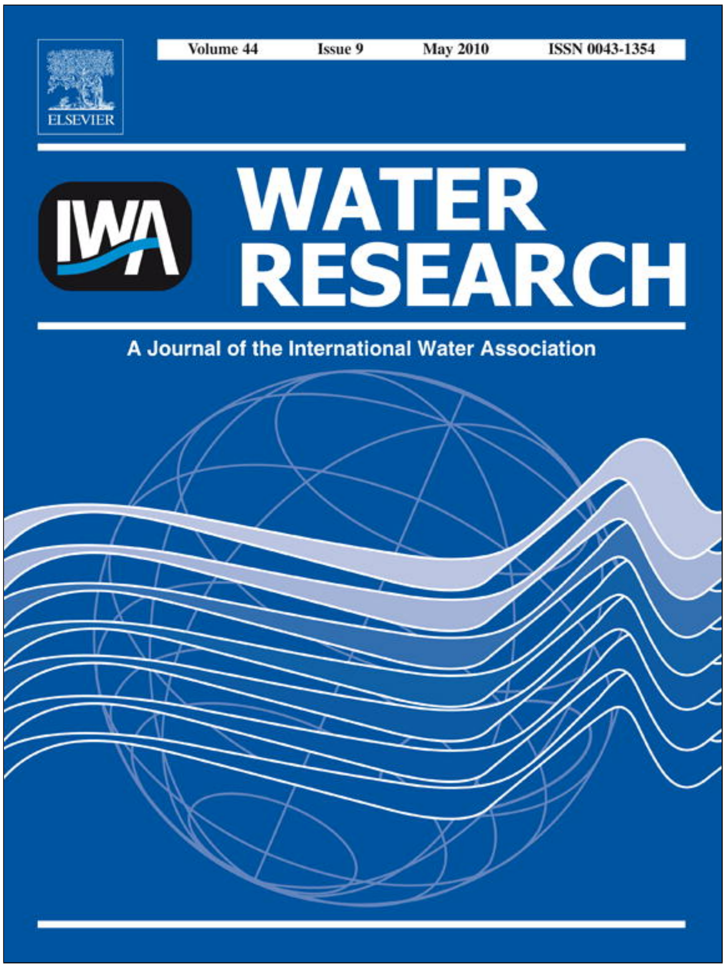
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Tree-ring hydrologic reconstructions for the Heihe River watershed, western China since AD 1430

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ABSTRACT

Based on the tree-ring-width analysis, the total precipitation from previous July to current June of the Qilian Mountains from 1634 to 2000 AD and the average runoff from previous September to current June in the middle section of the Heihe River from 1430 to 2007 have been reconstructed. This allowed detailed examination of the hydrologic history of the watershed of the Heihe River in western China. Precipitation, runoff and groundwater level were found to be significantly correlated with each other on the decadal scale. The three curves display quite synchronous trends of natural variation before AD 1940 to present before the onset of man-made disturbances. A remarkable period is AD 1925–1940 when the precipitation is low in the upper section, the runoff decreases in the middle section, and the groundwater level declines in the downstream section. After 1940, the groundwater level shows a lag effect, which may be a result of high water consumption in the middle and downstream sections. All three tree-ring based hydrologic indices commonly display the most significant periodicities around 80 (78–82), 50 (49–58) and 2 year. These cycles correspond to large-scale oscillation found in the climate system and appear mainly related to ocean-atmosphere interaction.

1. Introduction

The issue of freshwater resources in terms of quality and quantity is already a priority worldwide. In the arid inland drainage basin in western China, the hydrologic characteristics are low precipitation, high evaporation and distinct drought periods. Both climatic variation and human activities lead to extremely fragile water resources in this region where water shortage is a major environmental and social concern.

The Heihe River watershed is a very important industrial and agricultural region in western China. In the past 40 years, precipitation increased in the middle part of Qilian Mountains and resulted in increased runoff of the Heihe River (Ding et al., 2000). However, at the same time, the water consumption in the middle section was quickly increasing, leading to a sharp decrease of water flowing into the downstream section. Eco-environmental disasters, such as river-lake drying up, tree death in a wide area and frequent sandstorms have aggravated the ecological crisis in the whole Heihe River watershed. The water quality of the Heihe River is highest in the upper section and lowest in the lower sections (Zhang et al., 2006). To better understand the dynamic distribution and evolution patterns of the Heihe drainage basin, it is important to explore the relationship between the water resources and climatic

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variations on a long time scale, because it enables the recent observed changes to be viewed from a long-term perspective. Normally, this is difficult to do because meteorological and hydrologic records are very short (Gou et al., 2007).

Tree-rings have been successfully applied to reconstruct high-resolution hydrologic variables (known as dendrohydrology) such as precipitation and runoff of rivers worldwide (Chalise et al., 2003; Hardman and Reil, 1936; Hawley, 1937; Meko et al., 2001; Pederson et al., 2001; Polacek et al., 2006; Schulman, 1945; Stockton and Jacoby, 1976; Woodhouse, 2000; Woodhouse and Meko, 2002). They provide an excellent opportunity to understand the hydrologic variations in the past.

In western China, hydrologic reconstructions from tree rings have been carried out in several regions (Gou et al., 2007; Li et al., 1997; Yuan et al., 2005, 2007). However, systematical studies of hydrologic circulation in China using tree rings have not been reported. For the purposes of management and the sustainable development in the Heihe River watershed, it is very important to explore the relationship of the dynamic variations of water resources with the climatic change, which could yield quantitative information on the history, regularity, and mechanisms of hydrologic variability over multi-centennial time scales.

In this paper, we selected the Heihe River watershed as our study region and present tree-ring based precipitation, runoff, and groundwater level for the past several hundred years in the different sections of the watershed. The historical natural variability relationships between precipitation, runoff and groundwater were investigated with reference to global atmospheric circulation. Also the impacts of human activities on these relationships were explored.

2. Materials and methods

2.1. Study area

The Heihe River (Fig. 1) is the second largest inland river in China. It originates from the Qilian Mountains, flowing through Qinghai, Gansu and Inner Mongolia provinces and converges at the East and West Juyan Lakes. The main course of the Heihe River is 821 km long with a drainage area of 130 000 km^2. Annual total runoff is 24.5×10^8 m^3 . There are two main gauge stations in the Heihe River, the Yingluo Gorge and Zhengyi Gorge Hydrologic stations.

The upper section of the Heihe River, south of the Yingluo Gorge Hydrologic station, is located in the Qilian Mountains whose climate is characterized by high precipitation, low evaporation and low temperature. The streamflow of the Heihe River mainly comes from Qilian Mountains (Li et al., 2006b). The Qilian Mountains have abundant vegetation and the main tree species are Qinghai fir (*Picea crassifolia* Kom.) and Qilian juniper (*Sabina przewalskii* Kom.), where the elevation is higher than 2400 m.

The middle stream section is the Hexi corridor, from Yingluo Gorge to Zhengyi Gorge Hydrologic station, where precipitation is low and evaporation is high. In addition, agriculture and animal husbandry have a long history in the Hexi corridor. The region is one of the most important commodity grain bases in China. Almost all of the irrigation water in this area comes from the Heihe River, so the middle section is the area of greatest economic impact and water consumption.

The remaining areas, north of the Zhengyi Gorge Hydrologic station, is the downstream section. The Ejin Qi is located in the downstream section, in the Badain Jaran Desert. The many-year averaged annual precipitation is 37–42 mm, and the annual potential evaporation is extremely high at 3504–3755 mm (Wu et al., 2002; Su et al., 2005; Zhang et al., 2006: Hu and Song, 2007). The precipitation in the Badain Jaran Desert is less than that of Ejin Qi. Strong winds make Ejin Qi the main source of sandstorms in northern China. Even so, the second largest *Populus euphratica* forest of China is in Ejin Qi (2.6×10^8 m^2) (Wang et al., 2003), nourished by the Heihe River, which helps to form the Ejin Qi oasis. The Heihe River vanishes at the East and West Juyan Lakes.

Previous studies indicate that the shallow groundwater (about 1–5 m) in the Ejin Qi oasis is mainly recharged by the infiltration of the Heihe River, which accounts for 66.4% of the total shallow groundwater recharge. Other recharge sources are attributed to water from pores and fractures in the bedrock of the mountains located at the China-Mongolia border. Scant local precipitation at Ejin Qi is negligible to recharge of the shallow groundwater. The deep confined water (15–100 m) is mainly recharged by the lateral leakage of phreatic wateraround the Ejin Qi oasis. There is slight vertical upward exchange among the aquifers(Wu et al., 2002; Su et al., 2005; Zhang et al., 2006).

2.2. Development of the tree-ring chronologies

In the upper section, three sampling sites were selected (Fig. 1) on the south slope of Qilian Mountains to reconstruct precipitation and runoff. Trees were sampled according to the standard of the International Tree-Ring Data Bank (ITRDB).

The sampling sites are Zhamashike (100°02′E, 38°11.5′N, elevation 3300 m, designated the "QQL01" group, 43 increment cores from 21 trees), Qingyanggou (100°18′E, 38°10′N, elevation 3300 m, 62 increment cores from 31 trees) and Baiyanggou (100°16′E, 38°11′N, elevation 3300 m, 33 increment cores from 18 trees). The tree species is Qilian Juniper (*S. przewalskii* Kom.) in all sampling sites. The trees grow under poor soil conditions, and the forest stands are rather open. Because Qingyanggou and Baiyanggou are close to each other and have similar elevations, we combined the samples from these two sites together as a collection designated "QBYG". In the downstream section, the tree-ring based groundwater level reconstruction for Ejin Qi (named EJN) is from another study (Sun et al., 2006).

All samples (cores) from the upper section were dried, mounted, surfaced, and cross-dated using skeleton plot method (Stokes and Smiley, 1996). Each individual ring was thus accurately assigned a calendar year. The cross-dated tree rings were measured on a Lintab tree-ring-width measuring system within a precision of 0.001 mm. The quality control of cross-dating was carried out using COFECHA (Holmes, 1983). Cores with any ambiguities were excluded from further analyses. In the end, 41 cores from QQL01 and 91 cores from QBYG were used for the further analysis. Two cores from QQL01 and four from QBYG were rejected.

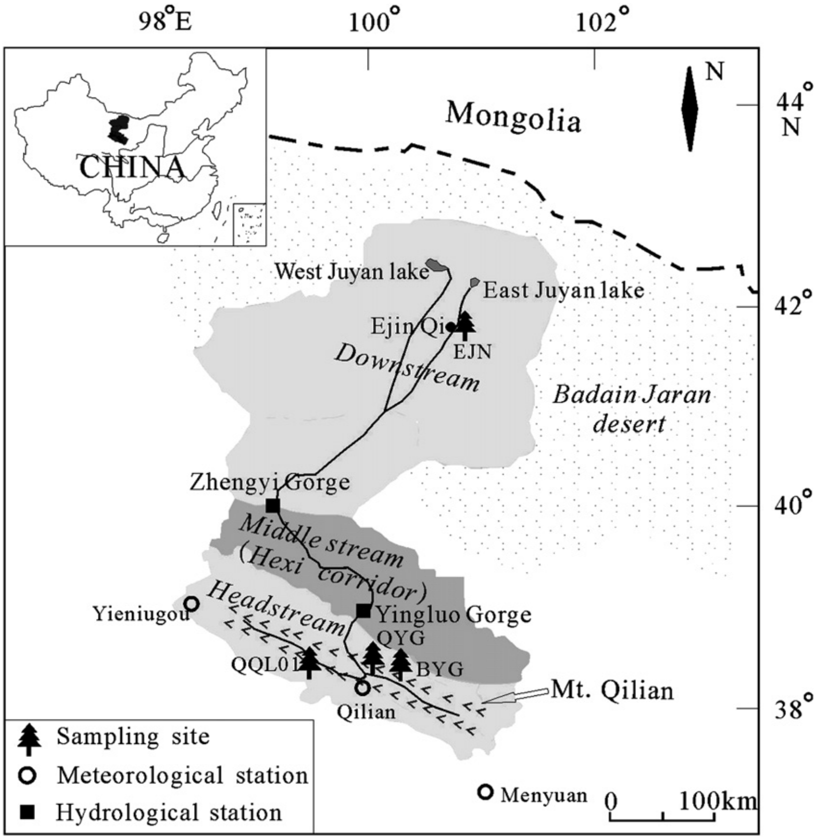

Fig. 1 – Map of the Heihe River watershed (dark gray and gray area), sampling sites (▲), meteorological stations (○) and hydrologic stations (■). Dotted area is the Badain Jaran desert.

Each individual ring-width measurement series was detrended and standardized to ring-width indices using the ARSTAN program (Cook and Kairiukstis, 1990; Dendrochronology Program Library, http://www.ltrr.arizona.edu/software.html). Undesirable growth trends related to age and stand dynamics unrelated to climatic variations were removed from each series during the detrending process. To preserve the maximum common signal at the lowest frequency possible we used a conservative method, employing negative exponential curves or straight-lines, to fit each ring-width measurement series, and then the individual index series were combined into a single chronology by computing a bi-weight robust estimate of the mean (Cook and Kairiukstis, 1990). After all these processes, we obtained three kinds of chronologies, standard chronology (STD), residual chronology (RES) and ARSTAN chronology (ARS).

Subsample signal strength (SSS) was used to assess the adequacy of replication in the early years of the chronology, which can ensure the reliability of the reconstructed climate (Wigley et al., 1984). In this paper, to utilize the maximum length of the tree-ring chronologies and ensure the reliability of the reconstructions, we restricted our analysis to the period with an SSS of at least 0.75. This threshold corresponds to a minimum sample depth of 4 trees for the QQL01 (from AD 1634) and 7 trees for QBYG (from AD 1430).

Based on the correlation analyses between ring-width indices and climatic or runoff data described below, we used the RES chronology of QQL01 to analyze the precipitation in the upper section, and the STD chronology of QBYG to study the runoff in the middle section. The statistical characteristics of residual chronology of QQL01 and standard chronology of QBYG are shown in Table 1.

2.3. *Climatic and hydrologic data*

Three meteorological stations around the sampling sites are available. They are Qilian (100°15′E, 38°11′N, elevation 2790 m, 1957–2000), Menyuan (101°37′E, 37°23′N, elevation 2851 m, 1957–2000) and Yeniugou (99°35′E, 38°25′N, elevation 3320 m, 1960–2000). Considering the proximity to the sampling sites and the length of the climate records, we decided to use the climatic data from Qilian station to identify the climate signal in the tree-ring series, and the other stations were used as references. The runoff data are from the Yingluo Gorge Hydrologic station (100°11′E, 38°48′N, elevation 1674 m, 1944–2000), which is the boundary between the upper and the middle sections (Fig. 1). The monthly mean precipitation, the monthly mean temperature of Qilian, Yeniugou and Menyuan, and monthly mean runoff of the Yingluo Gorge are shown in Fig. 2.

2.4. *Statistical methods*

Because the observation series is short, only 44 years of precipitation (1957–2000) and 56 years of runoff (1945–2000), Bootstrap (Efron, 1979; Young, 1994) and Jackknife statistical

Table 1 – Statistical characteristic of the two chronologies of QQL01 and QBYG.

Statistic	QQL01	QBYG
Master series	1533–2000	1358–2007
Mean sensitivity	0.21	0.21
Standard deviation	0.18	0.22
Mean correlation among all series	0.48	0.31
% Variatance in first principal component	50.94	34.83
Expressed population signal	0.91	0.94
First year of subsample strength>0.75 (no. of trees)	1634(4)	1430(7)

methods (Mosteller and Tukey, 1977) were applied to verify the reliability and stability of our reconstructions.

The Bootstrap, introduced by Efron was hailed as the latest important work in the field of time-series statistics (Efron, 1979; Kotz and Johnson, 1992). The original data are re-sampled many times to simulate sampling variability and to provide an approximation for the unknown population by using the Bootstrap method. An outstanding feature of the Bootstrap method is that it uses a mass of iterative calculations rather than analytic expressions, which makes the Bootstrap a flexible statistical method.

The Jackknife relies on leaving out one observation in the calibration period at a time, and then the statistic desired is computed on the remainder (Gordon, 1980).

We also use the sign test (S_1, S_2), product mean (t) and reduction of error (RE) (Fritts, 1991) to verify our precipitation and runoff reconstructions.

All statistical processes were performed by the commercial software SYSTAT 12 in this paper. To identify the relationship between the hydrologic factors and tree growth, correlation functions are used to do analyses in this paper.

3. Results

3.1. Precipitation

Correlation results show the QQL01 and QBYG tree-ring chronologies are significantly positively correlated with precipitation of previous August, September, October and current February, April, May, June at the Qilan station. After combination, higher correlation coefficients between ring-width indices and precipitation are found for the period from previous July to current June (P_{76}) during the period 1957 to 2000 at both two sites. For QQL01, the STD chronology $r = 0.61$ ($p < 0.0001$, $n = 44$), and the RES chronology $r = 0.693$ ($p < 0.0001$, $n = 44$). For QBYG, the STD chronology $r = 0.652$ ($p < 0.0001$, $n = 44$), and the RES chronology $r = 0.666$ ($p < 0.0001$, $n = 44$) (Fig. 3).

It is important to note that precipitation of P_{76} is significantly correlated with the total precipitation of prior year (previous January to December), with $r = 0.68$ ($n = 44$, $p < 0.0001$). This means that P_{76} could be representative of annual total precipitation to a large extent. We thus henceforth call P_{76} the yearly precipitation.

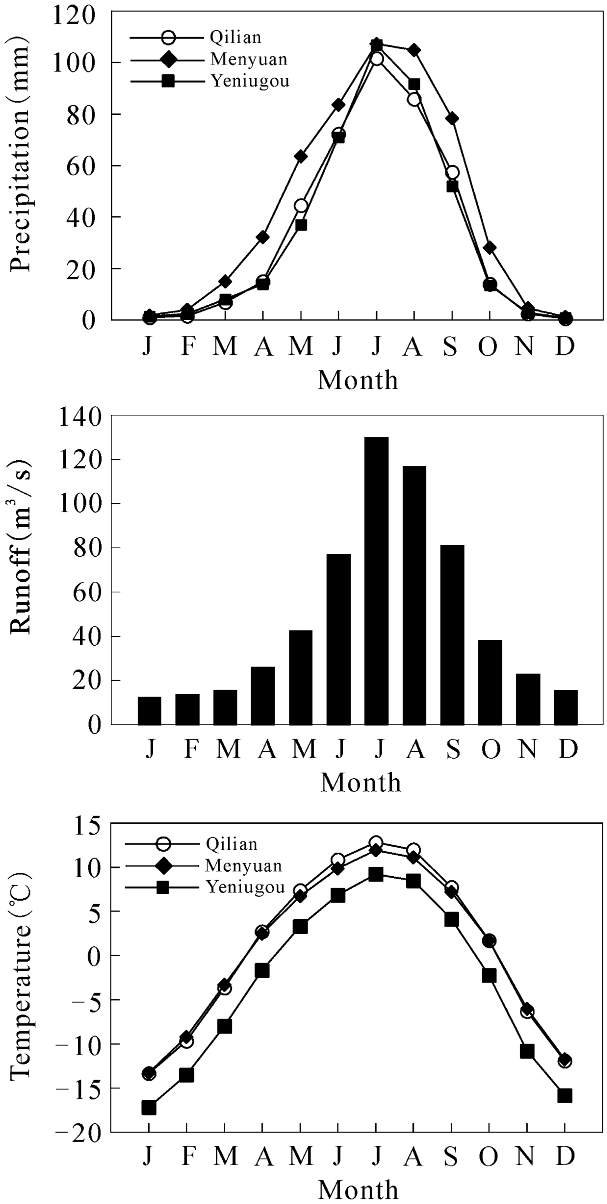

Fig. 2 – Average monthly precipitation and temperature from the three meteorological stations (Qilian: 1957–2000; Menyuan: 1957–2000; Yeniugou: 1960–2000), and the average monthly runoff of the Yingluo Gorge Hydrologic station (1944–2000).

3.2. Temperature

The relationships between the QQL01 and QBYG tree-ring chronologies and temperature are weak. The significant correlations were prior August (negative), November, and December (positive). After combination, ring-width indices were found to be significantly correlated with the mean temperature from prior September to current February with $r = 0.37$ ($p < 0.05$, $n = 44$) for the QQL01 STD chronology, and $r = 0.55$ ($p < 0.001$, $n = 44$) for the QBYG STD chronology from prior September to current March (Fig. 3). However, these correlations cannot effectively be used to do further temperature reconstructions since their explained variances are so low.

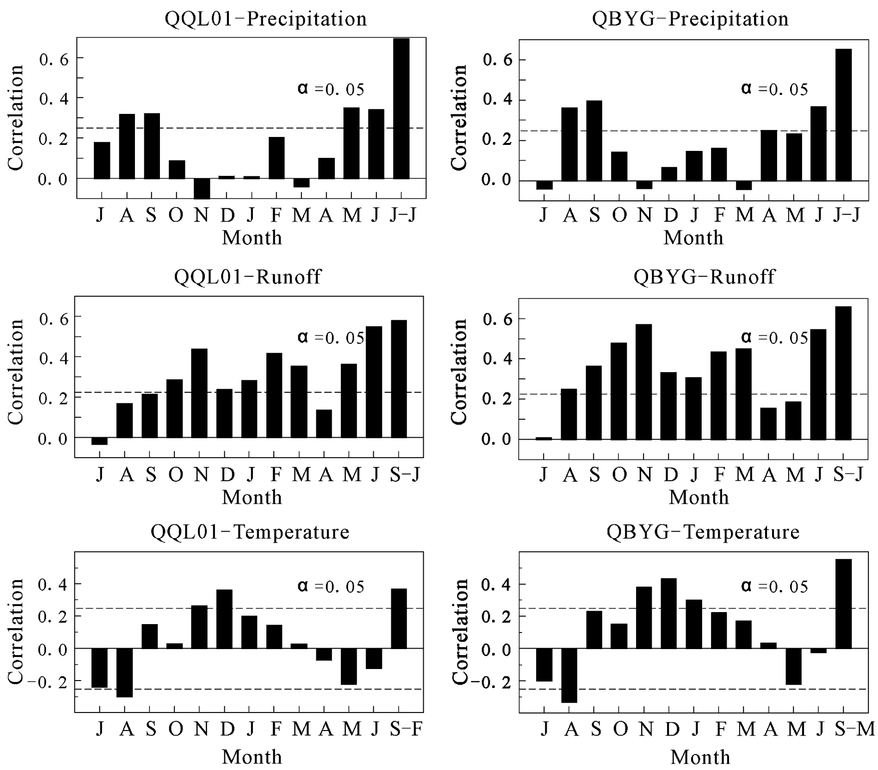

Fig. 3 – Correlation function analyses between ring-width chronology (RES chronology of QQL01, STD chronology of QBYG) and precipitation (1957–2000), temperature (1957–2000) and runoff (1944–2000) data. J–J = previous July to current June; S–J = previous September to current June; S–F = previous September to current February; S–M = previous September to current March.

3.3. *Runoff*

Tree growth can be used as a proxy of runoff (unit: m^3/s) because the same climatic factors, particularly precipitation and evapotranspiration, influence both tree growth and runoff in the same drainage basin (Meko and Graybill, 1995). Consequently, trees from a broad region surrounding a watershed can be used for reconstructions of streamflow in the watershed (Woodhouse and Meko, 2002).

Correlations were also calculated between the ring-width indices of QQL01 and QBYG and runoff data from the Yingluo Gorge Hydrologic station. The results show that ring-width indices of both sites have a strong positive correlation with runoff data (except QQL01 has a negative correlation with prior July). After the different combinations between months, we found that the highest correlation exists between ring-width indices of QBYG and runoff from prior September to current June (R_{96}) for the period 1945–2000 ($r = 0.659$, $p < 0.0001$, $n = 56$) (Fig. 3).

Consequently, the RES chronology of QQL01 was used to reconstruct the precipitation in the upper section of the Heihe River for the period AD 1634–2000, and the STD chronology of QBYG to reconstruct the runoff in the middle section of the Heihe River during the period AD 1430–2007. It should be noted that the residual chronology (RES) best captures common variability on inter-annual high-frequency signal in the precipitation reconstruction. The disadvantage is that some low-frequency signal was lost. The STD could capture the most low-frequency variation in the runoff reconstruction.

3.4. *Precipitation reconstruction from 1634 to 2000 AD for Qilian Mountains*

Because the best precipitation relationship exists between the QQL01 tree-ring index series and yearly precipitation, we designed a transfer function using simple linear regression model:

$$P_{76} = 164.24 * W_t + 236.196 \quad (1)$$

$$\left(n = 44,\ r = 0.693,\ R^2 = 0.48,\ R^2_{adj} = 0.47,\ F = 38.89,\ p < 0.0001,\ D/W = 1.57\right)$$

where P_{76} is the yearly precipitation, and W_t is the associated tree-ring index of the QQL01 chronology at the t year. During the calibration period 1957–2000, the predictor variable accounts for 47% of the variance (adjusted for loss of degrees of freedom) in the precipitation data. D/W, the Durbin–Watson statistic used to detect the presence of autocorrelation in the residuals from a regression analysis, is 1.57. It indicates no autocorrelation among our residuals (when $n = 44$, there is no autocorrelation with the D/W value 1.57–2.43) (Durbin and Watson, 1950).

Fig. 4 shows the comparison between the estimated and observed yearly precipitation in the upper section of the Heihe

River. The comparison shows that the estimated values tracked observed precipitation very well before 1985. Thereafter, the estimated values are generally lower than the observed. This probably results from the fact that tree growth at the sampling sites does not respond to precipitation beyond a certain level (Touchan et al., 1999).

For verification for the model (1), 80 iterations were used during the Bootstrap re-sampling process. The results obtained from Bootstrap and Jackknife revealed that all values of r, R^2_{adj}, standard error, F-value, p-value, t-value and Durbin–Watson statistics are close to the values found on the original data set for QQL01 samples (Table 2). The small differences between each statistic indicate that the calibration regression model (1) for the QQL01 is stable and reliable during the calibration period. The results of sign test (S_1, S_2), product mean (t) and reduction of error (RE) (Fritts, 1991) for the precipitation reconstruction in QQL01 are listed in Table 3. All statistical items are significant at the 99% level. The above verification tests indicate that precipitation reconstruction captured the low- and high-frequency variances of the recorded data well.

Consequently, the total yearly precipitation during 1634–2000 AD in the Qilian Mountains was reconstructed based on model (1) and presented in Fig. 5a, where the smooth line is 11-year moving average, and the horizontal line is the yearly mean precipitation ($M_1 = 399$ mm for AD 1634–2000) with a standard deviation $\sigma_1 = 30$ mm.

We define a dry year as $M_1 - 1\sigma_1$, and a wet year as $M_1 + 1\sigma_1$, respectively. Within the reconstructed 367-year series, 48 years are categorized as “dry year” (accounting for 13.1% of the whole series), and 49 years as “wet year” (accounting for 13.3%), while the rest 270 years as “normal year” (accounting for 73.6 %).

After applying an 11-year moving average, the reconstructed precipitation series displays some dry/wet intervals. For this smoothed series, yearly mean precipitation M_1 is 399 mm, with a standard deviation $\sigma_2 = 8.6$ mm. We define a dry interval as the $M_1 - 0.5\sigma_2$ and wet as $M_1 + 0.5\sigma_2$, respectively (dry, <395 mm; normal, 396–402 mm; wet, >403 mm). For the last 357 years, the driest period was from AD 1918 to 1942 (25 years), largely coinciding with a spring-summer drought in Helan Mountain (Liu et al., 2005). The wettest period was from AD 1887 to 1909 (23 years) (Table 4). Liu et al. (2006) and Treydte et al. (2006) pointed out that precipitation in northern Tibet, China and northern Pakistan had increased since 1970s. The same situation occurred in the Qilian Mountain range (the wet interval 1978–1995).

The reconstruction was tested for periodicities in the power spectrum analysis. The results show remarkable 6.02, 5.95 and 2.30 year cycles at 99% confidence level for the past 367 years.

It should be noted that only the high-frequency signals have been retained, and most of the low-frequency signals have been removed in the residual chronology (RES). However, the standard chronology is also significantly correlated with yearly precipitation, with $r = 0.61$. Just because its explained variance is lower than that of RES, we finally chose RES for precipitation reconstruction. To study the natural variation of precipitation, the low-frequency signals retained in the standard chronology must be taken into consideration from long-term perspective. We therefore tested the standard chronology for periodicities. The results show that the major cycles concentrate on 123, 98.4, 82, 54.67, 49.2 and 2.3 year at 99% confidence level.

This precipitation reconstruction can be compared with a Qinghai fir (*P. crassifolia*) tree-ring-width-based precipitation reconstruction (total precipitation of previous July to current June) for the last 250 years at Babao, about 40 km east of the QQL01 site (Fig. 5b, Yang et al., 2005). The two series show synchronous variation of trends although they are from different tree species. It also demonstrates that the precipitation in this paper is reliable.

3.5. *Runoff reconstruction from 1430 to 2007 AD for the middle section of the Heihe River*

Because there is a best correlation between QBYG standard chronology and the runoff data (from previous September to current June), the transfer function for runoff reconstruction was designed as follows:

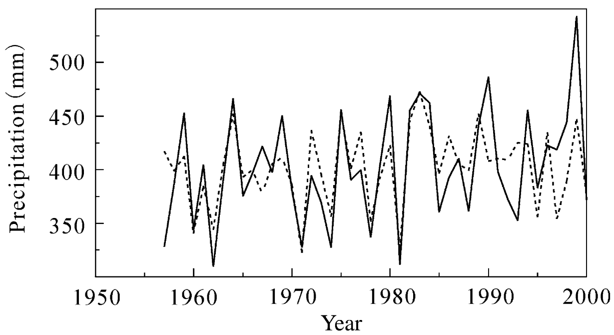

Fig. 4 – Comparison of the estimated (dashed line) and observed (solid line) total precipitation from previous July to current June in the upper section of the Heihe River during 1957–2000.

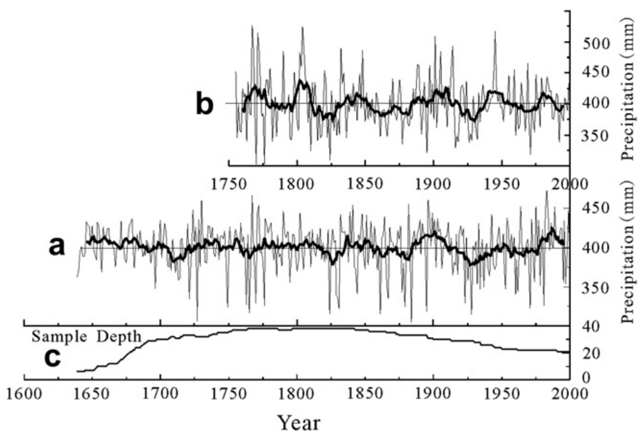

Fig. 5 – Comparison of reconstructed total precipitation of previous July to current June between QQL01 (a) and Babao (b) (Yang et al., 2005) sites. Smoothed lines are 11-year moving average. (c) Sample depth of the Qilian Mountain precipitation reconstruction.

Table 2 – Verification results of Bootstrap and Jackknife methods for QQL01 and QBYG regressions.

Statistical items	Calibration period	Verification period	
		Bootstrap (80 iterations)	Jacknife
		Mean (range)	
QQL01 (Precipitation, 1957–2000 AD)			
r	0.693	0.68 (0.44–0.85)	0.693 (0.66–0.73)
R^2	0.48	0.47 (0.19–0.73)	0.48 (0.44–0.53)
R^2adj	0.47	0.45 (0.17–0.72)	0.47 (0.43–0.52)
SE	37.53	36.69 (27.56–43.36)	37.52 (34.67–37.98)
F	38.89	39.87 (9.86–110.72)	38.05 (32.40–45.97)
p	0.0001	0.00004 (0.0001–0.003)	0.0001
D/W	1.57	1.55 (1.41–1.73)	1.57 (1.40–1.74)
QBYG (Runoff, 1945–2000 AD)			
r	0.659	0.66 (0.49–0.77)	0.659 (0.63–0.71)
R^2	0.43	0.43 (0.24–0.59)	0.43 (0.40–0.50)
R^2adj	0.42	0.42 (0.22–0.59)	0.42 (0.39–0.49)
SE	4.39	4.27 (3.31–5.33)	4.39 (4.15–4.43)
F	41.42	44.18 (16.83–79.74)	40.72 (34.99–53.11)
p	0.0001	0.0001	0.0001
D/W	2.36	2.30 (2.12–2.36)	2.36 (2.00–2.46)

$$R_{96} = 18.505 * W'_t + 16.718 \quad (2)$$

$$\left(n = 56,\ r = 0.659,\ R^2 = 0.43,\ R^2_{adj} = 0.42,\ F = 41.42,\ p < 0.0001,\ D/W = 2.36\right)$$

where R_{96} is the averaged runoff from previous September to current June, and W'_t is the associated QBYG standard chronology at t year. For the calibrated period 1945–2000, the predictor variable accounts for 42% of the variance in the runoff data after adjusted the loss of degrees of freedom. D/W value (= 2.36) indicates no autocorrelation among residuals (when $n = 56$, there is no autocorrelation with the D/W value 1.62–2.39). Fig. 6 shows the comparison of the estimated and the observed average runoff in the middle section of the Heihe River during the calibrated period from 1945 to 2000.

Bootstrap and Jackknife tests indicate that all values of r, R^2_{adj}, standard error, F-value, p-value, t-value and Durbin–Watson statistics are close to the values found on the total data set for QBYG samples (Table 2). Other Statistical characteristics, such as the sign test (S_1, S_2), product mean (t) and reduction of error (RE) all demonstrate that the model (2) is stable and reliable during the calibration period (Table 3).

In terms of model (2), the average runoff from previous September to current June for the middle section of the Heihe River was reconstructed from 1430 to 2007 AD (Fig. 7a). The 578-year mean (M_2) is 35 m^3/s, and a standard deviation $\sigma_3 = 3.9$ m^3/s.

This 578-year runoff reconstruction displays many high/low flow fluctuations. A low flow year is defined as $M_2 - 1\sigma_3$ and high as $M_2 + 1\sigma_3$, respectively. Thus, for the whole series, 89 years are categorized as "low flow year" (accounting for 15.4% of the whole series), and 88 years as "high flow year" (accounting for 15.2%), while the rest 401 years as "normal year" (accounting for 69.4%). Annually, some extreme low flow years could be identified by the historical documents (Yuan, 1994) recording as drought disasters, such as, 1505 (24.3 m^3/s, the unit is the same in the following.), 1730 (22.1), 1763 (25.2), 1776 (27.5), 1827 (27.8), 1927 (31.2), 1928 (22.9), 1932 (24.9), 1934 (25.7); while some high flow years as flooding, such as, 1780 (38.9), 1804 (37.3), 1805 (37.4), 1806 (38.2), 1889 (37.3), 1905 (41.2), 1914 (39.1).

Many high/low flow intervals emerge in the entire reconstructed runoff series after calculating an 11-year moving average. The mean of smoothed series is $M_3 = 35$ m^3/s, and a standard deviation $\sigma_4 = 2.3$ m^3/s. A low flow interval is defined as $M_3 - 0.5\sigma_4$ and high as $M_3 + 0.5\sigma_4$, respectively (low flow, $<$33.85 m^3/s; normal, 33.86–36.14 m^3/s; high flow, $>$ 36.15 m^3/s). It is easily noticed that there were two intervals with lower flow, 1926–1975 (50 years, 31.97 m^3/s) and 1592–1654 (63 years, 33.09 m^3/s) (Table 5).

Table 3 – Statistical characteristics of verification of QQL01 and QBYG reconstructions.

	S_1	S_2	t	RE	n
QQL01 (precipitation)	34 (29,31)	31 (29,31)	4.07	0.48	44
QBYG (runoff)	35 (36,38)	41 (36,39)	3.91	0.43	56

Table 4 – Dry and wet intervals based on the 11-year moving average for the QQL01 region yearly precipitation during AD 1639–1995. The average is 399 mm, and 1σ = 8.6 mm (dry, $<$395 mm; normal, 396–402 mm; wet, $>$403 mm).

Rank	Dry period			Wet period		
	Period	Year	Mean (mm)	Period	Year	Mean (mm)
1	1918–1942	25	387	1978–1995	18	412
2	1874–1884	11	390	1887–1909	23	412
3	1819–1834	16	390	1673–1683	11	409
4	1861–1866	6	391	1645–1667	23	408
5	1639–1642	4	392	1849–1853	5	407
6	1956–1976	21	394	1733–1743	11	407

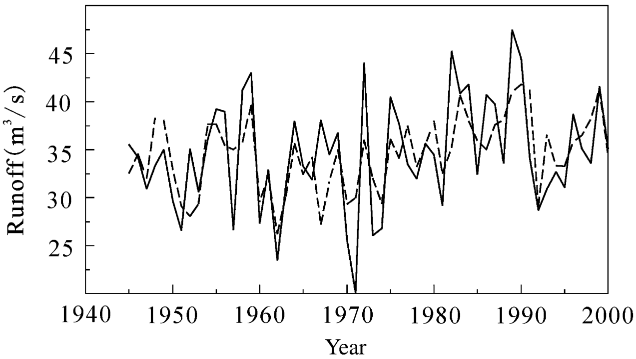

Fig. 6 – Comparison between estimated (dashed line) and observed (solid line) average runoff from previous September to current June in the middle section of the Heihe River during the calibrated period AD 1945–2000.

This runoff reconstruction could be roughly compared with streamflow series of the Yellow River for the last 593 years (Fig. 7b; Gou et al., 2007), especially when two curves are smoothed by an 11-year moving average. Two curves show very similar variation trends after 1900. Runoff in two rivers actually increased over much of the twentieth century. They are significantly correlated on annual scale with $r = 0.3$ ($p < 0.0001$, 1430–2000), and after 1900, $r = 0.34$ ($p < 0.0001$, 1900–2001).

The power spectrum analysis shows that the major periodicities of runoff reconstruction concentrate on 77.78, 70, 58.33, 53.85 and 2.78 years at 99% confidence level for record of the past 578 years.

3.6. Groundwater level data

In the downstream section, we used the existing annual groundwater level reconstruction data from Sun et al. (2006). Because the authors did not do periodicity analysis in their paper, we have analyzed it. As calculated, the power spectrum analysis shows that the major periodicities of groundwater level are 77, 70, 51.33 and 2.20 years at 95% confidence level over the past 232 years.

3.7. Relationship between precipitation, runoff and groundwater level

We tested the relationship between yearly precipitation, seasonal runoff and groundwater level. During the observation period, the precipitation in the upper stream is highly correlated with runoff of the middle stream section with $r = 0.73$ ($n = 44$, 1957–2000, $p < 0.001$), but it has no significant relationship between runoff and groundwater level because the records of the groundwater level is too short, only 10 years. For the entire reconstructions, annual precipitation is significantly correlated with runoff ($r = 0.62$, $n = 367$, $p < 0.0001$).

However, on decadal scale, all series are significantly correlated after smoothing by an 11-year moving average (Table 6). They display quite synchronous natural variation trends in the period before AD 1940 when there were no man-made disturbances (Fig. 8). Obviously, the groundwater level has lower consistency with the precipitation and runoff after AD 1940, which may be the consequence of the increased water consumption in middle and downstream sections since that time.

4. Discussion

Physiologically, correlations between tree growth, precipitation and temperature could be explained as follows: the precipitation from August to October in the previous year is the critical factor for moisture storage for the next year's growth. In May and June, the pre-summer-monsoon season with low rainfall causes dry soil, affecting tree growth and accelerating evapotranspiration as

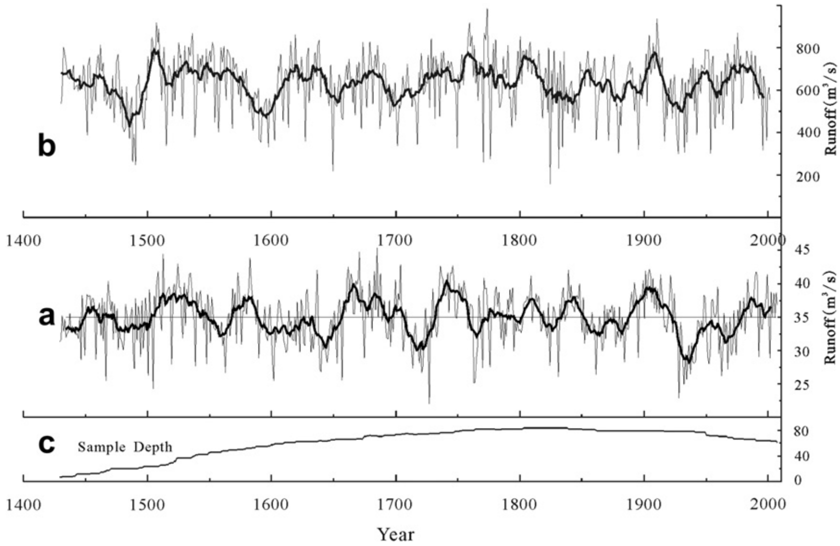

Fig. 7 – Comparison between reconstructed runoff of the Heihe River and Yellow River. (a) 578-year reconstruction of average runoff from prior September to current June based on Qilian Juniper (*Sabina przewalskii* Kom., this paper). The mean runoff is 35 m^3/s for years AD 1430–2007. (b) 593-year reconstructed steam flow of Yellow River (Gou et al., 2007). Two curves are smoothed by an 11-year moving average. (c) Sample depth of the Heihe River runoff reconstruction.

Table 5 – High and low flow periods based on the 11-year moving average for the Heihe River during AD 1435–2002. The average is 35 m^3/s, and $1\sigma = 2.3$ m^3/s (low flow, <33.85 m^3/s; normal, 33.86–36.14 m^3/s; high flow, $>$ 36.15 m^3/s).

Rank	Dry period			Wet period		
	Period	Year	Mean (m^3/s)	Period	Year	Mean (m^3/s)
1	1709–1730	22	31.64	1733–1758	26	38.38
2	1926–1975	50	31.97	1891–1919	29	37.81
3	1761–1768	8	32.76	1659–1690	32	37.79
4	1556–1565	10	32.83	1508–1540	33	37.63
5	1855–1867	13	32.87	1836–1848	13	37.22
6	1879–1884	6	33.08	1804–1814	11	37.08
7	1592–1654	63	33.09	1570–1587	18	37.01
8	1435–1447	13	33.26	1982–1995	14	36.98
9	1476–1497	22	33.36			

temperature rises, which leads to plant water deficiency. Thus, tree growth is positively related to May and June precipitation and negatively with temperature. The correlations between tree growth and climatic factors have reasonable physiological implications, which have been revealed by the previous studies for western China (Zhang et al., 2003; Shao et al., 2005; Liu et al., 2006, 2007; Gou et al., 2007).

The severe drought in the late 1920s was captured by the precipitation, runoff (1925–1935) and groundwater level (1925–1940) reconstructions. This event was found in many previous tree-ring based studies in whole northern China and even in Korea and Mongolia (Gou et al., 2007; Li and Zhang, 1992; Xu, 1997; Liu and Ma, 1999; Liang et al., 2003; Liu et al., 2003, 2005, 2007, 2009a,b). It reveals that the East Asian Summer monsoon circulation was very weak with extremely low precipitation over an exceptionally large region in the East Asia during that time period.

Generally, precipitation, runoff and groundwater commonly show an increasing trend after 1930s (Fig. 8). A similar trend is indicated in the upper section of Yellow River (Gou et al., 2007), Tienshan, western China (Li et al., 2006a), Mongolia (Pederson et al., 2001), and northern Pakistan (Treydte et al., 2006). Since 1980, the precipitation series shows a significantly decreasing trend. This is probably because the western China regional response to the global warming in the late twentieth century. The recent ecological and environmental deteriorations in western China, such as vegetation retrogression and degrading grasslands must therefore be taken into account as well. However, this decrease is still in the range of earlier precipitation fluctuations reconstructed for the past several centuries.

Ninety-one percent of the total water resources in the Heihe River watershed was influenced by the precipitation in the recharge region (headstream), while only 9% of that by temperature (Zhang et al., 2004). The headstream in the Qilian Mountains is the pace-setter during the temporal-spatial dynamic variations of the water resource in the Heihe River watershed. Fig. 9 displays a conceptual picture of the hydrographic circulations in the Heihe watershed. In the study region, the atmospheric circulation affects the precipitation, the precipitation affects the runoff and the runoff from the middle section affects the groundwater level in the Ejin Qi oasis (Li et al., 2006b). Previous studies indicated that groundwater is mainly recharged by Heihe River in the winter-half year (Sun et al., 2006; Wang and Cheng, 1998; Zhang et al., 2006). High runoff leads to shallow groundwater table in the Ejin Qi, and *vice versa* (Hu and Song, 2007).

These relationships can be clearly observed in our three tree-ring based hydrologic reconstructions, particularly by the good correspondence between precipitation and runoff, in the natural variations before 1940 (Fig. 8). When precipitation increases in the upper section, the runoff is high in the middle section, and the groundwater level is shallow in the downstream section, and *vice versa*. Even the precipitation in the upper section has a good relationship with the groundwater level in the downstream ($r = 0.51$). However, human activities with high impacts, such as some dams and reservoirs built for agricultural irrigation, disrupt the good relationships between the precipitation, runoff and groundwater to a large extent after 1940s. As it recorded, there were 2 reservoirs in 1940s, and 95 in 1985 (Wang and Cheng, 1998). Consequently, a mass of water has been kept in the middle section. Dams and reservoirs were primarily built during the periods 1954–1963 and 1968–1978. During these two intervals, precipitation and runoff were at their peaks, but groundwater was at a minimum (Fig. 8).

Table 6 – Correlations between the precipitation, runoff, and groundwater level reconstructions in the Heihe River watershed.

	Total data set	Before 1939
Observation data		
Precipitation *vs* Runoff	0.73 ($p < 0.0001$, 1957–2000)	
Precipitation *vs* Groundwater	–	
Runoff *vs* Groundwater	–	
Reconstructed data		
Precipitation *vs* Runoff	0.62 ($p < 0.0001$, 1634–2000)	0.62 ($p < 0.0001$, 1634–1939)
Precipitation *vs* Groundwater	−0.00 (1801–2000)	0.03 (1801–1939)
Runoff *vs* Groundwater	0.02 (1801–2002)	0.09 (180–1939)
Reconstructed data (11-year moving average)		
Precipitation *vs* Runoff	0.67 ($p < 0.0001$, 1639–1995)	0.64 ($p < 0.0001$, 1639–1934)
Precipitation *vs* Groundwater	0.36 ($p < 0.0001$, 1806–1995)	0.51 ($p < 0.0001$, 1806–1934)
Runoff *vs* Groundwater	0.25 ($p < 0.0001$, 1806–1997)	0.26 ($p < 0.002$, 1806–1934)

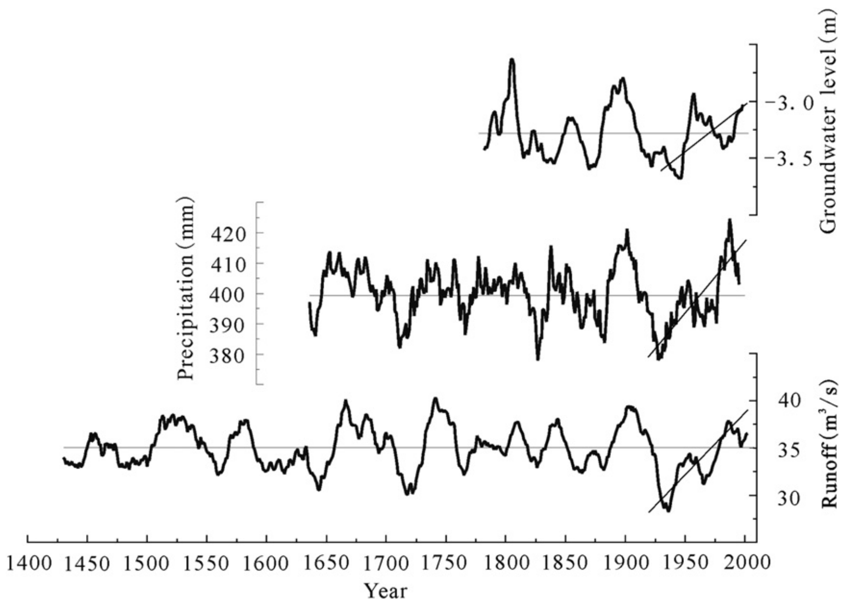

Fig. 8 – Comparison of the reconstructed precipitation, runoff (this paper), and groundwater level (Sun et al., 2006) in the watershed of the Heihe River. All curves are smoothed by an 11-year moving average. The oblique lines are increasing trends.

The runoff data from the Zhengyi Gorge Hydrologic station, which is located at the boundary between the middle and downstream sections, reduced from 11.9×10^8 cubic meters (m^3) in the 1950s to 9.42×10^8 m^3 in 1980s, and further to 6.91×10^8 m^3 in the 1990s because of water consumption increase in the middle section. However, at the same time, both observation data (Wang and Cheng, 1998) and the reconstruction in this paper show that runoff in the upper section continuously increased in the past 50 years. Since 1980s, the output of water from the middle section to downstream has increased because of the governmental management, and the groundwater table increased (Wang and Cheng, 1998), just as shown in our results.

Finally, the major periodicities reveal that three tree-ring based hydrologic indices have good relationships since they all commonly display the most significant cycles around 80–(78–82), 50–(49–58) and 2-years.

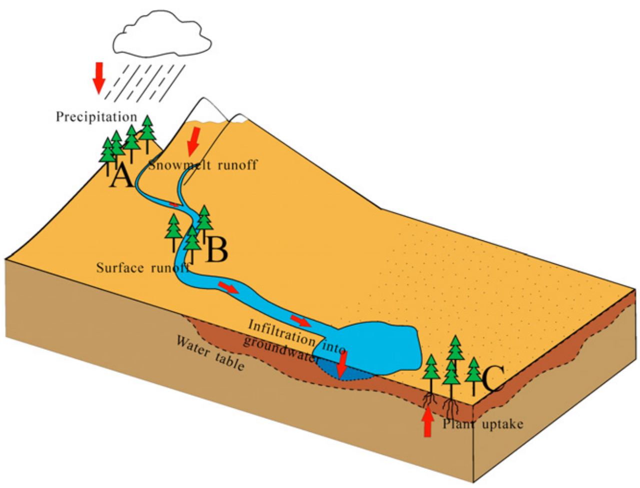

Fig. 9 – Diagram of the simple relationship among precipitation (A), runoff (B), and groundwater level (C) in the Heihe River watershed.

Previous studies have indicated that a 70–80-year cycle in the Hetao region (Qian and Lin, 2009), about 500 km east of the Heihe River watershed, corresponds to the oscillation in the global climate system of around a 60–80-year cycle that is interpreted as an internal oscillation in the atmosphere-ocean system (Qian and Lin, 2009; Schlesinger and Ramankutty, 1994). A 50-year cycle was observed in the upper Yellow River basin (Gou et al., 2007), and it is considered characteristic of drought-flood regimes in China (Lin et al., 1996). It could be related to an oscillation in the climate system of a 40–50-year cycle that has been considered to relate to the irregular oscillations of the thermohaline circulation in the North Atlantic (Qian and Lin, 2009; Greatbatch and Zhang, 1995). Furthermore, the 2-year cycle is quite similar to the quasi-biennial oscillation (QBO). The effects of the QBO exist on a large-scale, and it may indicate sea-land coupling (Qian et al., 1998). These cycles correspond to large-scale oscillation found in the climate system, and mainly relate to atmosphere-ocean interaction (Qian and Lin, 2009).

5. Conclusions

In this paper, we have presented tree-ring reconstructions of yearly precipitation, runoff, and groundwater level in the past several hundred years in different sections of the Heihe River watershed in western China.

For the whole Heihe River watershed, we found that the precipitation, runoff and groundwater level are significantly correlated with each other on a decadal time scale. They display the quite synchronous natural trends without any man-made disturbance before AD 1940. A remarkable period is 1925–1940, when the precipitation is low in the upper section, the runoff decreases in the middle section, and the groundwater level declines in the downstream section. After 1940, the groundwater level shows a lag effect, which may be resulted from the human impacts, such as increased water consumption in middle and downstream sections. The three tree-ring based hydrologic reconstructions (yearly precipitation, runoff, and groundwater level) commonly display the most significant cycles around 80–(78–82), 50–(49–58) and 2-years. These phenomena mean that hydrologic circulations in the Heihe River watershed could be mainly related to a large-scale atmosphere-ocean interaction. East Asian Summer monsoon-related precipitation is the main factor for the hydrologic circulation in the Heihe River watershed. The hydrologic reconstructions in this paper could provide valuable new information on the natural hydrologic variability for water supply and natural resources managers.

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