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Tree ring-based reconstruction of October to November runoffs in the Jiaolai River since 1826

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Abstract

The Horqin Sandy Land is a typical desertification region in China hounded by ecological and environmental problems, which continue to affect economic and social development.Hence,hydrological climate changes in this region need to be investigated. The current study reconstructed the runoff sequences in the southwest edge of the LiaoHe River into the XiaWa station of the JiaoLai River during the months of October to November from 1826 to 2005. A comprehensive timeline for the regional tree wheel width of the Horqin Sandy Land was employed. The timeline has been in use for 183 yr. For the past 180 yr, the runoff has experienced six and four consecutive Feng and dry sections, respectively. From 1982 to 2005, the runoff reached the longest section of a continuous low-flow runoff, with the mean average runoff amounting to only 63.58 % of the entire period. Runoff has 3-, 11-, 15-, 24-, and 30-yr quasi-periodic variations, consistent with changes in similar areas worldwide. The period of 1826 to 1917 presents a more gentle change. In 1956, the runoff increased, and then significantly decreased for nearly 50 yr. The drop rate is 1.7766 million m^3/10 yr, which shows a consistent downward trend with the precipitation (14.74 mm/10 yr). The overall reduction in precipitation accounts for 29.86 % of the initial value, which is far less than 75.58 % of the runoff. If the runoff and precipitation drop continue, more extensive and longer ecological and environmental problems are foreseen to occur.

1 Introduction

China is one of several countries experiencing severe desertification. The rapid progression of dry land degradation has become an important ecological and socio-economic problem (Wang et al., 2002; Wang and Zhu, 2001). The Horqin Sandy Land is located between east longitude 117°45′ to 124°06′ and north latitude 42°36′ to 45°20′ (Fig. 1). It belongs to the alluvial plain of the Liaohe River. In ancient times, the Horqin Sandy Land was a prairieland with lush vegetation and beautiful sceneries. Now, it has become a typical Chinese desertification area, one of China's four sandy lands. Related research on the environmental changes in this area has begun in the 1950s, producing some substantive results (Wang and Zhu, 2001; Dong et al., 1998; Wang et al., 2004a, 2006; Li et al., 2007; Zhao et al., 2008) on the desertification process, evolution, structure, and drive mechanism. The results suggest that climate fluctuations could directly affect to some extent the process of desertification via through the different periods of precipitation and temperature combinations (Wang et al., 2004b; Zhao et al., 2008). The desertification is mainly subjected to millennial- and centennial-scale climate fluctuations (Dong et al., 1998). Hence, a long-time-scale research on hydrological climate changes is particularly important.

Runoff and precipitation are closely related. The amount of runoff not only directly affects river ecology, but also has a profound impact on changes in river environments. Consequently, future trends in the ecological environment and past runoff variations need to be explored.

A number of studies have been conducted on runoffs in the Liaohe River. This river is located in the Horqin Sandy Land (Zhang et al., 2007; Hao et al., 2008; Yang et al., 2009; Fang et al., 2009; Jiang et al., 2009; Wang et al., 2011; Zhang and He, 2011; Gu et al., 2011), and the study period covers the years 1950s to 2008. The research involved the Liaohe River, the Liaohe tributaries, and other tributaries of the Laoha River. Zhang et al. (2007) have shown that the measured runoff in the Liaohe Laoha River has significantly decreased since 1950. Fang et al. (2009) have revealed that from the 1960s to the early 21st century, the variations in annual runoff and the annual runoff coefficient of the Laoha River were more-less-less-more-less. The decadal variation is much greater than the annual rainfall, and Wang et al. (2011) have pointed out that the measured runoff in Liaohe Tieling showed a significant reduction trend since the mid-1960s.

However, these studies are mainly based on observational data from hydrological observation stations, and the data life is generally 50 yr. These data are clearly insufficient for studying longer-time-scale changes in runoff. The hydro-climatic information revealed by tree-ring records is an effective means to address this limitation. Tree ring-based reconstructions present information that feature accurate positioning, good continuity, high resolution, and precise correlation with hydrological climate change (Fritts, 1976; Shao, 1997a; Nicoletta, 2004). Such reconstructions are applied in research on hydro-climatic events abroad, such as runoff, drought, flood, rainfall, temperature, glaciation, and volcanic activity (Stockton and Meko, 1975; Hughes et al., 1978; Cook and Jacoby, 1983; Briffa et al., 1995; Van et al., 1998; Clevel, 2000; Magda et al., 2001; Meko et al., 2001; Woodhouse, 2001; Esper et al., 2003; Law et al., 2006; Michael et al., 2006; Joseph et al., 2006; Sophie et al., 2007; Giovanna et al., 2010; Samuli et al., 2010).

In China, to study the chronology established, the tree ring and hydrological climate relationship, as well as the reconstruction, the study objects of Sabina, spruce, pine, white stick, larch, and elm in cold and dry regions were selected. Such regions included the Qinghai-Tibet Plateau, Qaidam Basin, Xinjiang, Qilian Mountain, Changbai Mountain, Qinling, and Inner Mongolia. The research has made great progress (Wu et al., 1989; Shao et al., 1997b, c; Gou et al., 2006; Ma and Liu, 2007; Zhu et al., 2008; Eryuan et al., 2008; Liu et al., 2004, 2009a, 2010; Li et al., 2010; Ma et al., 2011). Part of the runoff is reconstructed in the Urumqi mountain basin, Black River, Tongtianhe, Huangshui, and Yellow River (Li et al., 1997; Kang et al., 2002, 2008; Qin et al., 2004; Wang et al., 2004; Liu et al., 1997b, 2007; Sun et al., 2011). The long sequence of changes in runoff characteristics are analyzed.

Regardless of short time changes in runoff characteristics and the reconstruction of a long sequence, studies on the JiaoLai River are relatively limited. In the current paper, the 183-yr Horqin sandy area elm tree ring width chronologies established by Ma et al. (2011) in a station in the JiaoLai River tributary during the months of October to November from 1826 to 2005 was used to study the runoff characteristics. The results provide some basic information on long-term changes in the Liaohe source runoff, ecological and environmental protection, as well as catchment economy progress.

2 Data used

2.1 Chronological data

The ring width chronology and reconstruction of elm in the Sandy Land were used (Ma and Liu, 2011). The ring width chronology for 1826 to 2008 (183 yr) is shown in Fig. 2 (Ma and Liu, 2011).

2.2 Hydrological and meteorological data

The precipitation data selected were in accordance with the chronology of the establishment of meteorological stations. The 1951 to 2010 monthly (year) precipitation data were obtained from the eight meteorological stations closest to the sites. These stations were the Horqin Left Back Banner, TongLiao, Kailu, Horqin Left Middle Banner, Jarud Qi, Horqin Right Middle Banner, and Horqin Left Right Banner. Data from meteorological administration-integrated materials were also obtained. The uniformity of every meteorological element indicated that precipitation data from the sites did not exhibit significant deviations as well as random changes, and that data changes were relatively homogenous and consistent. Hence, the data were considered as reliable representations of the climate conditions in the region. Data from adjacent sites were used to interpolate measurements because some of the stations had incomplete information. The average data of the eight stations were used for area face value.

According to the same basin and proximity principle, the monthly (yearly) runoff data from 1957 to 2010 of the Xiawa station in the JiaoLai River were collected. This station is located at the edge of the Horqin Sandy Land and the import point to the sand of the JiaoLai River. There is less human activity upstream, so the measured runoff data was closer to the natural values.

The ground precipitation in the Horqin Sandy Land is basically the same with the precipitation in the upstream watershed area. By combining all factors, the selected precipitation sites and hydrological stations were used in the present study.

3 Related analysis and explanation

3.1 Correlation of chronology and runoff

Tree ring climatology considers that rings formed in the year t are influenced not only by the climate at that time, but also by the climate of the previous 1 to 2 yr (Fritts, 1976). Therefore, the standard chronological sequence and standard chronological $t+1$, $t+2$, and $t+3$ sequences in relation to the runoff in low-lying stations, as well as the correlation coefficients are shown in Table 1. The standard chronology had a significant relationship with the runoff in March, April, August, September, October, and November, as well as the annual runoff. The correlation in October and November was the highest.

The results of the correlation analysis between the annual and monthly runoffs show that the runoff in July accounted for 30.19 % of the annual runoff, and had the maximum correlation coefficient of 0.814. Although the runoff in October and November were responsible for only 4.82 % and 3.63 % of the annual runoff, the annual runoff coefficient ranked only second to July; the coefficients were 0.755 and 0.699, respectively, ranking second and third. Based on the contrast curve among the annual runoff, runoff in October, runoff in November, and runoff in October to November (Fig. 3), the four curves were concluded to have basically the same trend. Therefore, using a rebuilding chronology for the October–November runoff to analyze wet and dry season changes, cycle changes, which can represent the changes in annual runoff to some degree, were constructed. The reconstruction can also be carried out in August, considering the better correlation coefficients in October–November, which has a more significant meaning in reconstruction.

3.2 Physiological mechanism explanation on the relationship between trees and runoff

The main supply source of runoff formation is precipitation. In different seasons and at different times, the groundwater comes from direct precipitation or snowmelt, and then supplies the runoff. According to the correlation between the precipitation sequence in the Horqin Sand Land and the runoff series in the XiaWa station (Table 2), the precipitation in July, August, and September, as well as the annual precipitation significantly correlated with the March to April, July to November, and annual runoffs. Among them, the precipitation in July had a significant correlation with the March to April, July to November, and annual runoffs, respectively. The runoff in July accounted for 30.19 % of the annual runoff, whereas precipitation in July was 32.18 % of the total annual precipitation, which was the largest contribution to the runoff. Rainfall in August was significantly related to the August to October runoff, and the August runoff accounted for 24 % of the annual runoff. On the other hand, the precipitation in August accounted for 21.46 % of the annual precipitation, and ranks second in terms of runoff contribution. The precipitation in September had a significant correlation with the September to November runoff, and the runoff in September was 7.51 % of the annual runoff. In contrast, precipitation in September accounted for 8.84 % in the total annual precipitation. Annual precipitation was significantly related to the March to April, July to November, and annual runoffs. When precipitation transforms, some of it directly forms surface runoff, and some permeates the ground to supply surface runoff in the underground runoff form. Based on a combination of the above relationship, the formation of precipitation runoff can be concluded to have some lag. Therefore, the precipitation in July, August, as well as September, was greater, and accounted for a significant proportion in the annual precipitation. The precipitation not only plays an important role in the formation of monthly surface runoff, but also affects the runoff information in October to November to some degree.

Precipitation also plays an important role in the growth of trees, especially the precipitation in July, August, and Sep, which were significantly correlated with the chronology (Ma et al., 2011). Summer was the peak of elm growth. At that time, elm growth depended most on water. Good water conditions during this period effectively and rapidly promoted elm growth. This phenomenon was the same in September

Considering the comprehensive situations in Tables 1 and 2, Fig. 4 shows that precipitation played a major role in runoff formation and tree growth. In July, August, and September, the precipitation not only played an important role on tree growth, but also on runoff formation. Changes in the runoff also represented changes in precipitation. Considering the lag effect, the precipitation in July, August, and September had a significant impact on the runoff in October to November This phenomenon explained the good relationship between the chronology and the August to November runoff. The good relationship among the chronology sequences in years $t+1$, $t+2$, and $t+3$ with the runoff also fully illustrated the delayed runoff response.

4 Reconstruction runoff

From the above response relationship, the standard sequence and standard chronology in years $t+1$, $t+2$, and $t+3$ were used to reconstruct runoff in the XiaWa station of the JiaoLai River from October to November since 1826 to 2005. The following equation was adopted:

$$R_t = -800.79 + 438.43 \times I_t + 98.01 \times I_{t+1} + 231.54 \times I_{t+2} + 818.15 \times I_{t+3}$$
$$\left(N = 49, r = 0.74, R^2 = 0.54, R^2_{\text{adj}} = 0.51, F(4,44) = 13.05, P < 0.001\right) \quad (1)$$

where R_t is the runoff from October to November in year t, I_t denotes the index of standard tree ring chronology in year t (dimensionless), I_{t+1} is the index of standard tree ring chronology in year $t+1$ (dimensionless), I_{t+2} is the index of standard tree ring chronology in year $t+2$ (dimensionless), and I_{t+3} is the index of standard tree ring chronology in year $t+3$ (dimensionless).

Compared with the reconstructed sequence exhibiting the same trend as the corresponding sequence of the measured value (shown in Fig. 5), some extreme values cannot be completely consistent with the reconstructed values. In other words, part of the tree ring reconstruction results underestimates extreme hydrology and climate events (Fritts, 1976). However, the reconstruction equation yielded good results for the reconstruction of the average minimum winter temperature. The reconstructed and measured values demonstrated good synchronization.

Additional tests on the stability and reliability of the reconstruction equation are necessary to ensure the credibility of the reconstruction value when a value generated beyond the calibration period is used. According to common international practice, the reduction error RE, S_1 (sign test), S_2 (first difference symbols for the test), and t (average test value for the product) were calculated. An RE of 0.54, which was obviously greater than 0.3, was obtained. When RE is higher than 0.3, the reconstruction value is considered credible (Li et al., 2000). The values of the sign test results and first-difference symbols for the test results were 33/49 and 31/48, respectively. These were significant at the 0.05 level, indicating that the reconstructed and measured value sequences were in good agreement with the changes in high-low frequencies. The average test value for the product was 2.91, which was significant at the 0.01 level, indicating a significant difference between the identical and opposing serial number sequences. All parameters indicated that the reconstruction equation was stable and reliable. The reconstruction results for the runoff derived from this equation were also credible.

Consequently, the runoff series for the XiaWa Station of the JiaoLai River in October to November from 1826 to 2006 was rebuilt according to the reconstruction equation. The reconstruction sequence is shown in Fig. 5.

5 Characteristics of runoff

5.1 Changes in wet and dry seasons

According to the reconstructed runoff series, the average runoff in the XiaWa station of the JiaoLai River in October to November from 1826 to 2006 was 9.7238 million m^3, with the maximum being 18.5171 million m^3 (occurred in the year 1829). The minimum was 2.8576 million m^3 (occurred in the year 2005). The extreme value was 6.48, which illustrated that the runoff in the JiaoLai River had greater amplitudes between years.

Reconstructing the sequence in mean runoff changes can reflect wet and dry season changes between years. The mean changes are shown in Table 3. These data showed the wet periods were more obvious in the 1820s, 1850s, 1900s, and 1950s during the era of scale changes, whereas dry periods were remarkable in the 1880s, 1910s, and 1970s–2000s.

For further quantitative analysis of the reconstructed sequences in wet and dry season changes, the coefficient ratio K_p, which is the ratio of the runoff to the mean runoff for many years, was calculated. The following definitions were made for different K_p values: more than 1.16, special wet years; between 1.06 and 1.16, partial wet years; between 0.95 and 1.06, flat water years; between 0.84 and 0.95, partial dry years; and less than 0.84, special dry years. The reconstruction sequence is shown in Fig. 6. This sequence indicated that the years of reconstructed sequences in special wet, partial wet, flat water, partial dry, and special dry years were 40, 23, 40, 30, and 47, accounting for 22.22 %, 12.78 %, 22.22 %, 16.67 %, and 26.11 % of the total number of years. The proportions of special wet, flat water, and special dry years were large, with the largest being that of special dry years. This result revealed that the runoff in the JiaoLai River had a negative contribution to the reconstruction period.

According to the principle of at least 5 continuous years, special and partial wet years were combined with wet years, whereas special and partial dry years were combined with dry years. The results are shown in Fig. 6. The consecutive wet years in the reconstruction sequences were 1826 to 1834, 1856 to 1861, 1872 to 1877, 1897 to

1905, 1938 to 1943, and 1946 to 1960. The durations ranged from 6 to 15 yr, and the total was 51 yr. Of these 51 yr, 24 occurred in the 19th century, and the remaining 27 occurred in the 20th century (mainly in the 1960s). The longest wet period occurred from 1946 to 1960, a total of 15 yr, with the mean annual runoff at 12.9962 million m^3, which was 1.33 times the average runoff for the entire reconstruction period. There were four periods of continuous dry years, namely, 1835 to 1840, 1880 to 1885, 1912 to 1922, and 1982 to 2005. The durations ranged from 6 to 24 yr, and the total was 47 yr. Of these 47 yr, only 12 occurred in the 19th century, and the remaining 30 occurred in the 20th century (mainly in the 1980s to the late 20th century). The five years in the early 21st century were continuous dry years (from 1982 to 2005). The continued dry time reached 24 yr, and the mean annual runoff was 6.1823 million m^3, which was only 63.58 % of the average runoff for the entire reconstruction period. The continuous dry periods occurred not only in the 1980s, but also from the early 1960s to 2005. The overall runoff trend was decreasing. During the 1950s to 2000s, the runoff decreased from 14.1031 million m^3 to 3.4435 million m^3, with drop rate of 1.7766 million m^3/10 yr. The runoff significantly declined, which fully illustrated that the runoff in the JiaoLai River had been gradually decreasing for nearly 50 yr, thereby forming the longest continuous dry season during the reconstruction period.

5.2 Periodic changes

An analysis of the runoff reconstruction with the power spectrum revealed that the runoff reconstruction sequence had 3-, 11-, 15-, 24-, and 30-yr quasi-periodic variations under the 0.05 significance level. This result had basically the same cycle as the precipitation changes in the Horqin Sandy Land. This similarity signified that precipitation played an important role in the runoff formation.

5.3 Variation trends

The runoff sequence was reconstructed for a 10-yr moving average, as shown in Fig. 7. As can be seen from the trend line, the runoff change was gentler from 1826 to 1917 (92 yr) in the JiaoLai River during the 180 yr. Subsequently, the runoff increased in 1956, and then for nearly 50 yr, significant decreased. This finding was consistent with the aforementioned wet and dry seasonal changes.

6 Discussion and conclusion

The present study used a comprehensive timeline for the regional tree wheel width of the Horqin Sandy Land to reconstruct the runoff sequences in the XiaWa station of the JiaoLai River during the months of October to November from 1826 to 2005. The reconstructed sequence exhibited the same trend as the corresponding sequence of the measured value. The calculated results of various tests showed that the reconstruction result was stable and reliable.

There were greater amplitudes in runoffs in the JiaoLai River between years. The reconstruction sequence had six continuous wet period years, a total of 51 yr, including 27 yr that occurred in the early 20th century to the early 1960s. The multi-year average runoff in the wet period from 1946 to 1960 was 1.33 times the entire reconstruction period mean annual runoff. The runoff also went through four continuous dry periods, a total of 47 yr, which had 30 yr occurring in the 1980s to the late 20th century. The multi-year average runoff from 1982 to 2005 was only 63.58 % of the entire reconstruction period. Overall, the runoff gradually decreased for nearly 50 yr, from the early 1960s to the present, and the drop rate in runoff was 1.7766 million years m^3/10 yr. This result indicated that the runoff significantly decreased, and the total reduction was 75.58 %of the initial value.

Runoff in the JiaoLai River had 3-, 11-, 15-, 24-, and 30-yr quasi-periodic variations. Among them, the 11-yr variation had the same cycle with solar activity. The 24- and

30-yr cycles were also consistent with the precipitation cycle. This result fully explained that the runoff change in the JiaoLai River followed certain rules, with varying degrees of change similar with other areas around the globe.

Overall, during the nearly 180 yr in the JiaoLai River, the change in runoff was gentler from 1917 to 1826. Then, in 1956, the runoff gradually decreased. In nearly 50 yr, the runoff had a significant decreasing trend. A comparison with the ten year sliding curve of precipitation in the Horqin Sandy measured in July to November (Fig. 7) revealed that the precipitation decreased for nearly 50 yr, i.e. from 296.10 mm to 207.67 mm in the 1950s to 2000s, with the decreased rate of 14.74 mm/10 yr. The overall decrease accounted for 29.86 % of the initial value, which is a significant amount. In contrast, the proportional decrease in precipitation accounted for the initial value being much smaller than the proportion of runoff reduction, accounting for about half. In other words, a slight decrease in precipitation may lead to a significant reduction in runoff. Zhang et al. (2007) have drawn relatively similar conclusion. They propose that in the past 50 yr, the relationship between runoff and precipitation had an overall downward trend. The results of the present study provide further references on runoff changes in the Liaohe River, as well as possible strategies for ecological environmental protection and catchment economy progress.

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Table 1. Correlation coefficient of standard chronology and runoff.

	Runoff in March	Runoff in April	Runoff in August	Runoff in September	Runoff in October	Runoff in November	Annual Runoff
Standard chronology	0.365**	0.296*	0.455**		0.512**	0.549**	0.281*
Standard chronology in year $t+1$	0.384**	0.491**	0.298*		0.483**	0.545**	0.277*
Standard chronology in year $t+2$	0.301*	0.374**	0.449**		0.520**	0.584**	0.454**
Standard chronology in year $t+3$	0.444**	0.558**	0.386**	0.368**	0.566**	0.626**	0.455**

Note: ** is 99 % confidence level, * is 95 % confidence level.

Table 2. Correlation coefficients of runoff and precipitation.

	Runoff in March	Runoff in April	Runoff in July	Runoff in August	Runoff in September	Runoff in October	Runoff in November	Annual Runoff
Precipitation in July	0.395**	0.293*	0.469**	0.288*	0.398**	0.366**	0.445**	0.519**
Precipitation in August				0.572**	0.414**	0.329*		0.283*
Precipitation in September					0.574**	0.291*	0.285*	
Annual Precipitation	0.276*	0.316*	0.443**	0.359**	0.417**	0.415**	0.430**	0.381**

Note: ** is 99 % confidence level, * is 95 % confidence level.

Table 3. Mean runoff changes in the reconstruction sequence.

Times	Mean runoff ($\times 10\,000\,m^3$)	Times	Mean runoff ($\times 10\,000\,m^3$)
1820s	1415.61	1920s	911.33
1830s	1017.40	1930s	1019.15
1840s	975.48	1940s	1119.74
1850s	1225.76	1950s	1410.31
1860s	961.44	1960s	972.87
1870s	1088.97	1970s	887.31
1880s	719.28	1980s	824.57
1890s	971.15	1990s	635.25
1900s	1127.83	2000s	344.35
1910s	862.07		

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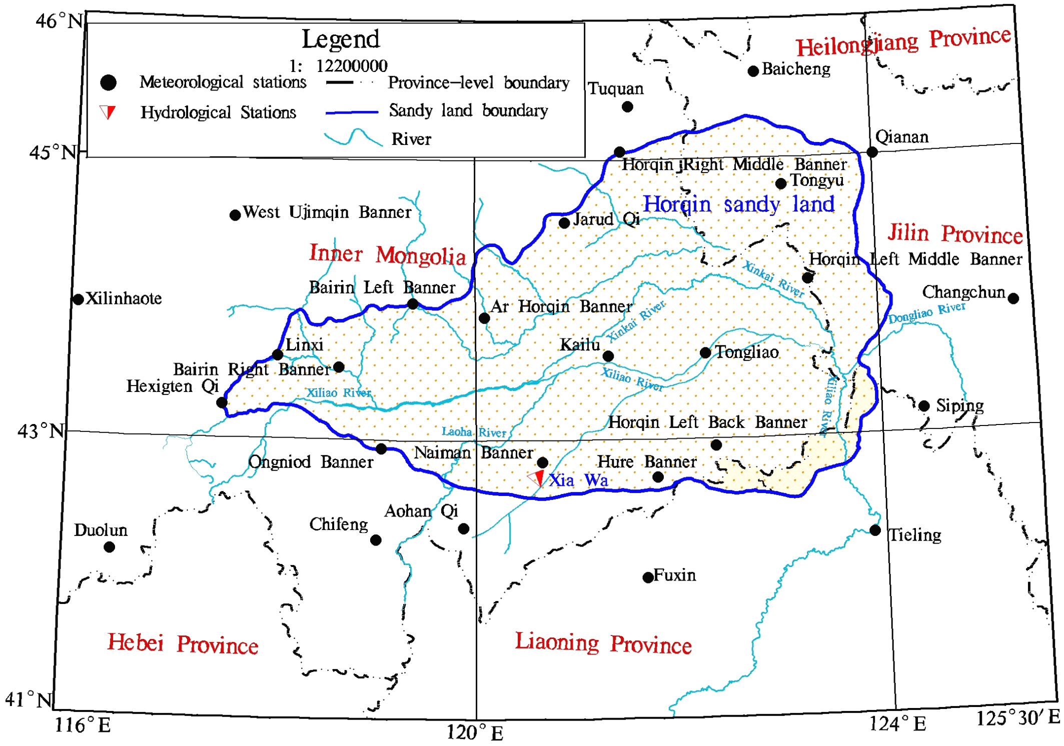

Fig. 1. Location of the Horqin Sandy Land: meteorological station and runoff stand distribution.

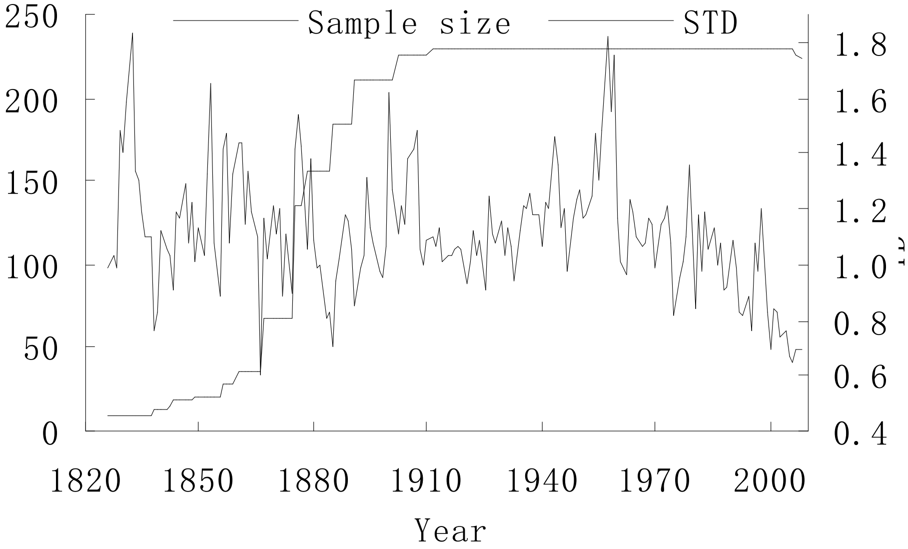

Fig. 2. Regional elm STD chronologies and sample size.

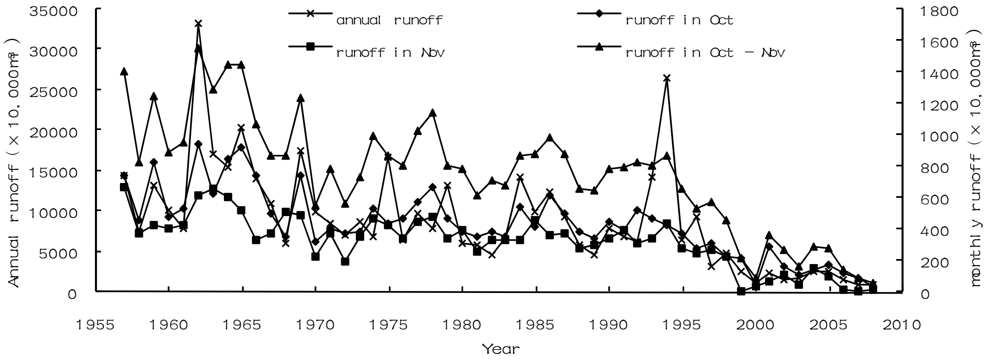

Fig. 3. Contrast curve among the annual runoff, runoff in October, runoff in November, as well as the added runoffs of October and November.

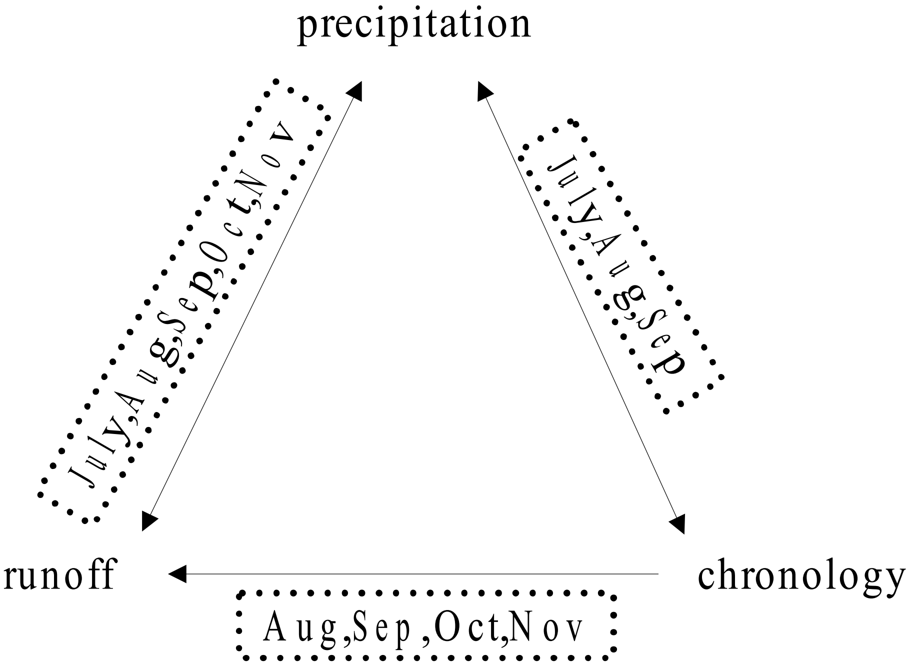

Fig. 4. Correlation of precipitation, runoff, and chronology.

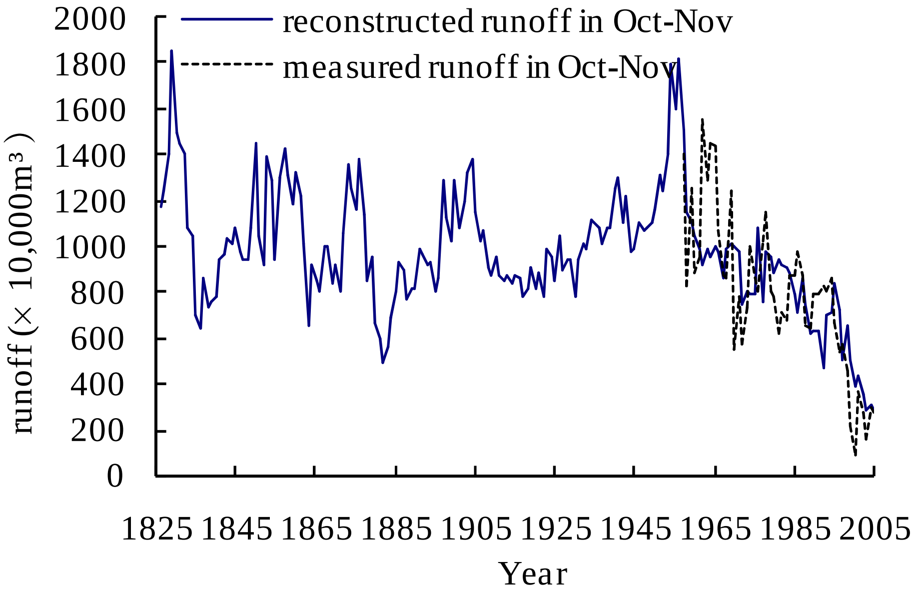

Fig. 5. Contrast curve of the runoff in measured and reconstructed values in October and November.

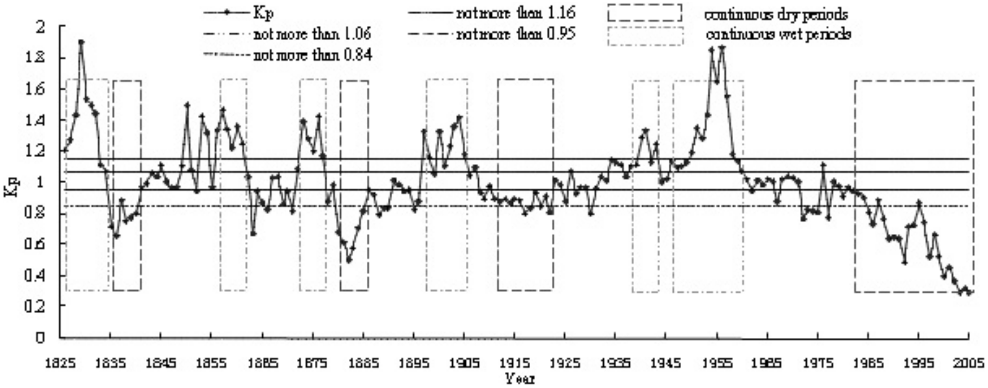

Fig. 6. Changes in the runoff reconstruction sequence K_p as well as the distribution in continuous wet and dry season times.

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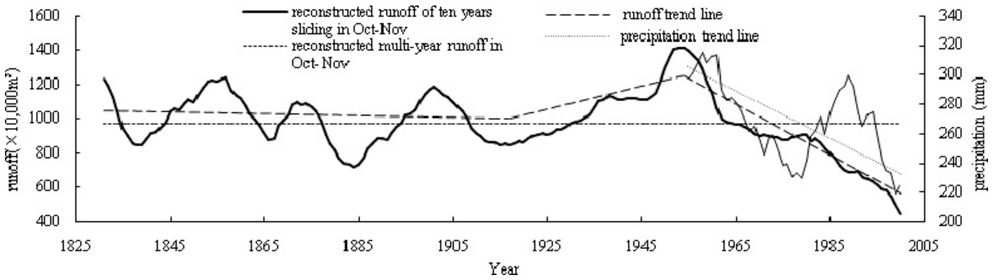

Fig. 7. Sliding changes and trends in the runoff reconstruction sequence and the measured precipitation for ten years.

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