Journal homepage: http://gwse.iheg.org.cn

Evolutionary trend of water cycle in Beichuan River Basin of China under the influence of vegetation restoration

Liang Zhu[1], Jing-tao Liu[1,2*], Ming-nan Yang[1,2], Yu-xi Zhang[1,2], De-ping Wen[3]

[1] *Institute of Hydrogeology and Environmental Geology*, *Chinese Academy of Geological Sciences*, *Shijiazhuang* 050061, *China*.
[2] *Key Laboratory of Groundwater Contamination and Remediation*, *China Geological Survey* & *Hebei Province*, *Shijiazhuang* 050061, *China*.
[3] *Qinghai Provincial Flood and Drought Disaster Prevention Service Center*, *Xining* 810001, *China*.

Abstract: To understand the influence of vegetation restoration on the water cycle in semiarid areas, the effects of vegetation restoration on evolution of the key elements of water cycle were clarified by analyzing the evolutionary trend of atmospheric precipitation, ecological consumption water, and surface runoff on a river basin scale on the basis of analytical results of the changes in vegetation coverage and the long-term meteorological and hydrological monitoring data of Beichuan River Basin. The results show that the vegetation cover in the Beichuan River basin has rapidly increased in the hilly and mountainous areas since the 1980s, especially from 2000 to 2019, with the maximum and average vegetation cover rates increased by 14.98% and 52.2%, respectively. During 1956-2016, the annual precipitation in the basin remained relatively stable; the annual surface runoff slightly declined, with an average attenuation rate of 20 million m^3/10a. The main reason for the runoff decline is the increase in ecological water induced by the vegetation restoration, which has changed the spatial-temporal distribution of the water from atmospheric precipitation in the basin. Spatially, more precipitation was converted into ecological water. As a result, the remnant runoff supplied to the lower reaches reduced accordingly. Temporally, more precipitation participated in the soil water - groundwater cycle, thus prolonging the outward drainage period of the precipitation. Moreover, the large-scale vegetation restoration induced a significant decrease in the surface wind speed, evaporation from water surface and drought index. As a result, a virtuously mutual feedback relationship was formed between the vegetation and meteorological elements. Therefore, vegetation restoration is of great significance for the improvement in the water conservation capacity and semiarid climate conditions in the Beichuan River basin.

Keywords: Vegetation coverage; Water cycle in a river basin; Ecological water consumption; Water conservation

Received: 22 Apr 2021/ Accepted: 13 Jul 2021

Introduction

Significant progress has been achieved in greening of the land surface in China since the 1970s, which plays an important role in soil and water conservation, windbreaks and sand fixation (Zhao et al. 2014; Chen et al. 2019; Hu et al. 2020). However, large-scale vegetation restoration has drastically changed the pattern of the underlying surface and has made a profound impact on the water cycle conditions and hydrological processes in river basins. Especially in the areas suffering water shortage, the sustainable utilization of water has approached its limit due to the vegetation restoration in local areas, leading to new contradictions between ecology and water resources (Mark, 2019; Wu et al. 2020). The constraints of water resources on vegetation restoration have become a major concern in the process of vegetation restoration in arid and semiarid areas. Atmospheric precipitation serves as a primary water source of a terrestrial water cycle. According to material conservation, vegetation restoration will inevitably

*Corresponding author: Jing-tao Liu, *E-mail address*: liujingtao@mail.cgs.gov.cn

DOI: 10.19637/j.cnki.2305-7068.2021.03.003

Zhu L, Liu JT, Yang MN, et al. 2021. Evolutionary trend of water cycle in Beichuan River Basin of China under the influence of vegetation restoration. Journal of Groundwater Science and Engineering, 9(3): 202-211.

affect a water distribution in link of other water cycles since it consumes more water resources (Huang et al. 2011; Mattos et al. 2019; Huang et al. 2020). Owing to the effects of the large-scale returning farmland to forest and grassland on the Loess Plateau in recent decades, dry soil layers have become more common and tend to be widely distributed to the deeper portions of soil layers over the Loess Plateau (Liu et al. 2010; Wang et al. 2010; Yan et al. 2015; Zhao et al. 2019). The changes in soil moisture further affect the groundwater recharged by atmospheric precipitation. For instance, according to the observation and simulation study on an experimental scale, the annual groundwater recharge has reduced from 100 mm to 50-55 mm in the Loess Plateau in Guyuan City, Ningxia, due to the conversion of wasteland into farmland (Huang et al. 2017). Meanwhile, in the Mu Us sandy land, the groundwater recharged by atmospheric precipitation in the areas covered by vegetation, such as Salix psammophila and Caragana korshinskii, is only 10%-67% of that in bare land (Mattos et al. 2019). On a river basin scale, the surface runoff in the forested small river basins in southwestern part of Shanxi Province is attenuated by about 80% compared with the forestless small river basins in the area (Wang et al. 2014). Meanwhile, the baseflow in the Abay River basin has decreased by 4.4% as the forest area increases under the same precipitation condition (Gashaw, 2016). Vegetation restoration will change soil water, groundwater and surface runoff, which will further change the water cycle conditions in river basins and finally affect the water resource situation in the river basins (Gao et al. 2019; Tesfaldet et al. 2020). Therefore, it is greatly significant for the scientific understanding of coordinated development between vegetation ecology and water resources in arid and semiarid areas to study the evolutionary trend of the water cycle under the influence of large-scale vegetation restoration. Present studies on the effects of vegetation restoration of the water cycle in China mainly focus on observation tests and simulation studies on a point or slope scale are mostly concentrated on the Loess Plateau. However, the interactions between vegetation and the water cycle in Qinghai-Tibet Plateau considerably differ from those in the Loess Plateau due to the difference of hydrothermal conditions.

The Beichuan River basin is a major water conservation area in the upper reaches of the Yellow River and a key area of ecological environment construction in China. Since the 1980s, large-scale artificial afforestation has led to a rapid increase in vegetation cover. As a result, the ecological environment and water conservation capacity in the river basin have been significantly improved. However, it has also caused some problems such as the reduction of runoff coefficient and the variations in the water cycle. Based on long-series meteorological and hydrological data and remote sensing data, the effects of vegetation restoration on the evolution of key water cycle elements were clarified by analyzing the evolutionary trend of water cycle elements on a river basin scale. It will be greatly significant for the scientific understanding of coordinated development between ecological construction and water resources in the upper reaches of the Yellow River.

1 Study area

The Beichuan River basin is located in the eastern part of Qinghai Province. The Beichuan River is a primary tributary of the Huangshui River and a secondary tributary of the Yellow River, with a total length of 149 km and the river basin covering a total area of 3 371 km^2 (2 774 km^2 above Qiaotou hydrological station). The river basin, extending in a C-shape from northwest to southeast, lies in the border area of the Qinghai-Tibet Plateau and the Loess Plateau and mainly consists of mountains, longitudinal valleys and small basins. The area falls within a continental semiarid climate with typical vertical zones, characterized by a progressive decrease in temperature and evaporation and an increase in precipitation from the bottom to the top of the valley. Specifically, the average annual atmospheric temperature and average annual evaporation reduce from 6.2°C to –6°C and from over 1 000 mm to about 800 mm, respectively; the average annual precipitation increases from about 350 mm to over 600 mm as the elevation increases.

The Quaternary alluvial-diluvial strata in most tributary valley areas of the Beichuan River are thin and low in water bearing capacity. However, the Quaternary deposits become much thicker in the valley of the main stream below the confluence of the Heilin and Baoku Rivers. As a result, a large amount of the river water begins to recharge the groundwater of the downstream aquifers. In Qiaotou area, almost all the phreatic water along the river valley discharges back into the river due to a notable uplift of the basement. Therefore, the Beichuan River above the Qiaotou area can be considered as a closed river basin (Fig. 1).

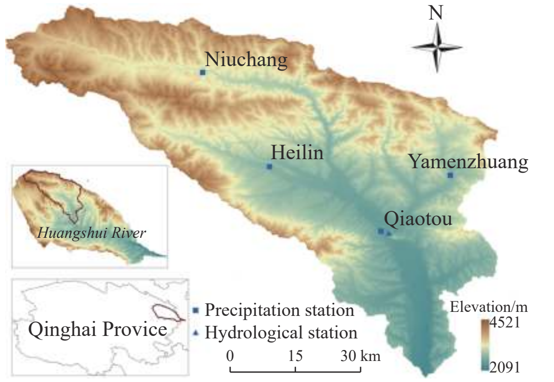

Fig. 1 Geographical location and elevation of the study area

According to monthly data of precipitation and runoff over the years in the river basin, the most precipitation occurs in four consecutive months from June to September, accounting for 70.8% of the total annual precipitation. Meanwhile, the most runoff occurs in four consecutive months from July to October, accounting for 71.4% of the total annual runoff (a month lagging behind the maximum precipitation in the four consecutive months). Therefore, the Beichuan River is a typical river recharged by precipitation and groundwater (Fig. 2).

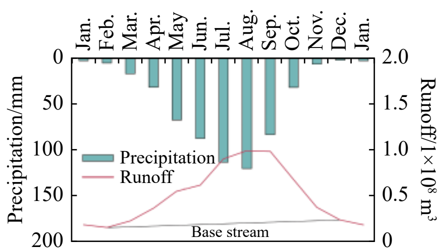

Fig. 2 Average monthly precipitation data and the amount of runoff over the years

2 Data and methods

2.1 Data of vegetation cover

The data of vegetation cover were sourced from the imagery Landsat-5 TM, Landsat 8 OLI, and the MODIS ET product MOD16A2. Among them, the Landsat data were obtained from the official website of the US Geological Survey (USGS), with a spatial resolution of 30 m and a revisit period of 16 days. In this paper, eight images of vegetation cover from June to September in 2000 and 2019 were selected. They were preprocessed to obtain the Normalized Difference Vegetation Index (NDVI) values of each month. Then the maximum NDVI value of each month was synthesized using the Cell Statistics tool of ArcGIS 10.1. Afterward, the monthly NDVI values of the surface were integrated, based on the reflectance data of the red visible and near-infrared channels of Landsat to obtain the yearly NDVI values. Finally, the fractional vegetation cover was further calculated by using the pixel dichotomy model, with the equation as follow:

$$f_{veg} = (\mathrm{NDVI} - \mathrm{NDVI}_{soil}) / (\mathrm{NDVI}_{veg} - \mathrm{NDVI}_{soil}) \quad (1)$$

Where: f_{veg} is the fractional vegetation cover, *NDVI* is the vegetation index of mixed pixels, $NDVI_{veg}$ is the vegetation index of pure vegetation pixels, and $NDVI_{soil}$ is the vegetation index of pure soil pixels. The NDVI value corresponding to the frequency of 0.5% on the cumulative frequency distribution table of NDVI was taken as $NDVI_{soil}$, and the NDVI value corresponding to the frequency of 99.5% was taken as $NDVI_{veg}$.

2.2 Meteorological and hydrological data

The precipitation and runoff data of Qiaotou, Heilin, Yamenzhuang, and Niuchang meteorological stations as well as Qiaotou hydrological station during 1956-2016 were derived from the "Dataset of the Third Assessment of Water Resources in Qinghai Province". Among them, the runoff data are natural runoff restored month by month according to the development and utilization of water resources in the basin. The wind speed data during 1961-2016 were sourced from China Meteorological Data Service Center (http://data.cma.cn/). The data on the annual evaporation from water surface of Qiaotou Meteorological Station during 1970-2016 were collected from the Datong Bureau of Meteorology, Qinghai Province. They are the evaporation values of an E_{601}-type evaporation pan (diameter: 60 cm) converted from the evaporation data monitored by the E_{20} pan (diameter: 20 cm). The drought index was calculated, based on the ratio of evaporation from water surface to precipitation. It was used to reflect the drought degree in the river basin. The higher the drought index, the drier the climate is.

2.3 Research method

The water cycle elements of a closed river basin generally include atmospheric precipitation, ecological consumption water and runoff. Among them, the runoff is composed of baseflow and surface runoff. Based on the water cycle model of a river basin, this paper analyzes the relationship among atmospheric precipitation, ecological water, surface runoff and baseflow in a closed basin, which can be expressed as follows:

$$Q = R + S + U_g \quad (2)$$

$$R = P + G \quad (3)$$

Where: Q is the precipitation, R is the natural runoff restored; S is the ecological consumption water which mainly includes the evapotranspiration and the water held by soil and vegetation in the basin, U_g is the underflow with 0 in a closed river basin; P and G are surface runoff and underground baseflow, respectively, of which the G can be calculated by baseflow separation.

Among them, the changes in ratios of S to R and P to G can be used to reflect the changes in the temporal-spatial distribution of water resources in the river basin. Therefore, two indices were defined as follows, namely the precipitation distribution coefficient (K_Q) and runoff distribution coefficient (K_R):

$$K_Q = S/R \quad (4)$$

$$K_R = G/P \quad (5)$$

Where: K_Q denotes the relationship between the volume of ecological water consumption within the river basin and the runoff discharged outward the river basin, thus reflecting the changes in the spatial distribution of water resources in the river basin; K_R represents the relationship between the baseflow and surface runoff, which reflects the changes in the temporal distribution of water resources in the river basin (i.e. the change in the period of atmospheric precipitation discharging outwards).

Given that the thick vadose zones distribute in most areas of the river basin and that the groundwater cannot be effectively recharged by rainfall in most cases. The baseflow was separated from the monthly runoff hydrograph by using straight line method. According to the hydrograph, the stream flows in the period from February to December were taken for the baseflow separation (Fig. 2), because in the months from December to the next February the runoff greatly reduced in the frozen winter time. In fact, the runoff rapidly decreased in October, while the freezing period started in November and the surface was almost frozen in December, resulting in no additional water available for feeding the river and groundwater. Only from March, the melt of ice, snow and frozen soil layers could provide enough sources to rechargethe river and accordingly increased its runoff.

3 Results and discussion

3.1 Evolution relationship between vegetation coverage and water cycle elements

Large-scale vegetation restoration in the Beichuan River basin commenced in the 1980s. Especially in recent decades, the vegetation coverage in the river basin has greatly been increased. For instance, it has increased from 7.2% to over 75% in the hilly and mountainous areas on both sides of Datong County, Xining City of Qinghai Province (Chen et al. 2001). However, since no remote sensing data is available for establishing the vegetation coverage before the implementation of large-scale vegetation restoration, its vegetation cover cannot directly be compared with recent ones. As such the spatial distribution and variation of the vegetation cover in the Beichuan River basin are analyzed on the basis of the changes in the vegetation cover data derived from the year 2000 and 2019. Affected by the intensive returning farmland to forest and grassland since the late 1980s, the river basin has generally boasted good vegetation cover conditions especially after the year of 2000, with a rate of vegetation cover of over 80% in most areas (Table 1). The areas with a high vegetation cover rate are mainly located in the middle-low mountainous areas with an elevation of 2 600-3 500 m, which are nearly undisturbed by human activities and have favorable natural conditions for vegetation growth. The areas with a vegetation cover rate of less than 50% are mainly located in the main stream valley and the high mountain areas with an elevation of greater than 4 000 m. In the valley areas, the surface cover has been greatly changed by urban development and industrial activities. In the high mountain areas, most bedrocks have been heavily weathered and subjected to the freez-thawing erosion during the long snow and ice cover period, forming a typical alpine stony desertification landscape.

Most areas in the river basin have experienced an increase in vegetation coverage of the year 2000 and 2019. Among them, the areas with a vegetation cover rate of over 80% are the most prominent in terms of areal size change (Table 1). The software ArcGIS was employed to calculate the difference of vegetation cover rate of the year 2019 and 2000, which resulted in the generation of vegetation cover variation map (Fig. 3). The result shows that the areas with vegetation restoration (variation >0) and degradation (variation <0)

Table 1 Statistics of changes in the vegetation cover in the Beichuan River basin according to the data of 2000 and 2019

Range of vegetation coverage (%)	2000		2019	
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)
<50	51.49	1.53	75.93	2.25
50-60	126.23	3.74	120.88	3.59
60-70	279.86	8.30	222.50	6.60
70-80	991.26	29.41	659.51	19.56
80-100	1 922.15	57.02	2 292.60	68.01
Average	75.32		80.33	

account for 88% and 12% of the total river basin area, respectively. The vegetation degradation mainly occurs in the main stream valley area and some tributary valley areas where they have been heavily affected by the development activities of mankind. Especially after the year of 2000, the valley areas have been intensively developed with the rapid economic development of Qinghai Province. As a result, the vegetation covers in the areas have demoted, with the maximum and average vegetation cover rates decreased by 64.7% and 11.56%, respectively. In contrast, the vegetation cover in the vast middle-high mountainous and hilly areas on both sides of the river valley has mainly shown an increasing trend, with the maximum and average vegetation cover rates increased by 52.2% and 14.98%, respectively. It is noted that the areas with the highest vegetation restoration intensity are mainly distributed in the low mountainous and hilly areas on both sides of the river valley to the south of Datong County; they fall in the study area of the "Greening Project of Southern and Northern Mountains in Xining City" and boast the most notable vegetation restoration.

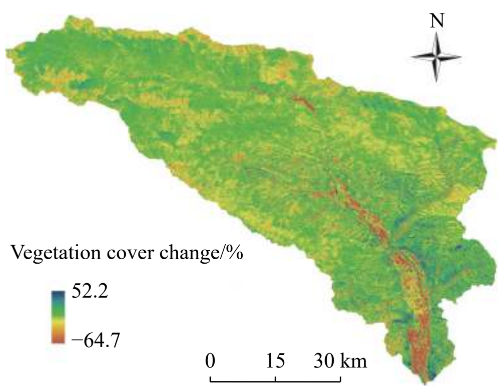

Fig. 3 Variation of vegetation cover rate between 2019 and 2000 in the Beichuan River basin

In the years of 1956-2016, the average annual precipitation over the years above Qiaotou hydrological station in the Beichuan River basin was 568.5 mm. The maximum and minimum precipitations in this period were 769.9 mm in 1961 and 413.1 mm in 1991, respectively, with the extreme ratio of 1.86. Meanwhile, the precipitation stably fluctuated in this period. The average annual runoff and average annual runoff coefficient over the years of 1956-2016 were 626 million m^3 and 0.39, respectively. The maximum and minimum runoffs in this period were 1.078 billion m^3 in 1989 and 363 million m^3 in 1991, respectively, with the extreme ratio of 2.97. Meanwhile, the annual runoff showed a general descending trend during 1956-2016, decreased by 20 million m^3/10a on average (Fig. 4). According to the cumulative departure curves of precipitation and runoff in 1956-2016, the precipitation and runoff in the Beichuan River basin fluctuated in a "wet-dry-wet-dry-wet" trend, of which the three peaks occurred in the early 1960s, the late 1980s, and around 2015. The two valleys occurred in the early 1980s and around 2000 (Fig. 5).

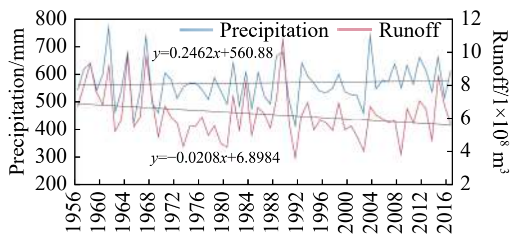

Fig. 4 Variations of precipitation and runoff in the Beichuan River basin during 1956-2016

According to the baseflow separation results of the Beichuan River basin during 1956-2016, the average baseflow and average baseflow coefficient over the years above Qiaotou hydrological station in the basin were 215 million m^3 and 0.14, respectively. As shown in Fig. 6, the baseflow has a smaller fluctuation range than the surface runoff and their variation coefficients are 0.20 and 0.33, respectively. In such a long period from the year of 1956, both the surface runoff and the baseflow

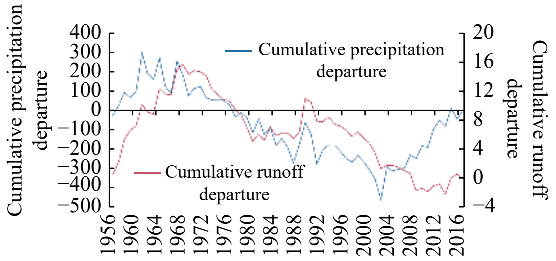

Fig. 5 Cumulative departure curves of precipitation and natural runoff in the Beichuan River basin during 1956-2016

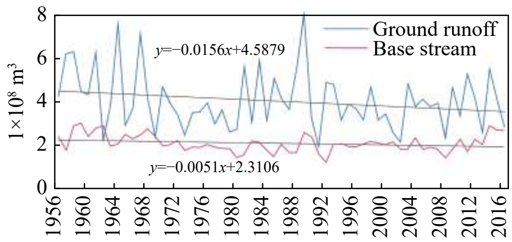

Fig. 6 Variations of baseflow and surface runoff in the Beichuan River basin during 1956-2016

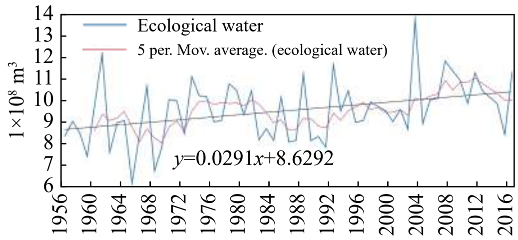

Fig. 7 Variations of ecological water consumption in the Beichuan River basin

have shown a descending trend, with an average descending rate of 16 million m^3/10a and 4 million m^3/10a, respectively.

As regards to ecological water consumption in the Beichuan River basin during 1956-2016, this part of water was calculated using Equation (2) based on the water balance model of a closed river basin. The calculation result (Fig. 7) shows that the ecological water increases, while it also fluctuates on a yearly basis, with an average increase of 29 million m^3/10a. The average annual ecological water is 950 million m^3, accounting for 60.3% of the average annual precipitation over the years. The maximum and minimum ecological water consumptions during 1956-2016 were 1.378 billion m^3 in 2003 and 780 million m^3 in 1991, respectively. Overall, the ecological water was the largest portion of water used across the river basin during 1956-2016.

3.2 Influence of vegetation restoration on water cycle change

3.2.1 Influence of vegetation recovery on ecological water and runoff

To investigate the effect of vegetation restoration on the changes in the water cycle in the Beichuan River basin, the periods of 1956-1970 and 2000-2016 before and after the vegetation restoration were respectively selected to conduct a comparative analysis.

The trend curve of ecological water during 1956-1970 below that of 2000-2016 on the scatter diagram (Fig. 8A) indicates that the average ecological water consumed in 2000-2016 is higher than that during 1956-1970 under the same precipitation condition. In other words, the ecological water notably increases due to the increase of the vegetation coverage in the river basin. As calculated according to the relationship between the precipitation and ecological water of the two periods, the average annual ecological water in the river basin during 2000-2016 increased by 111 million m^3 (39.93 mm), comparing with that during 1956-1970 under the condition of average annual precipitation over the years (568.5 mm), with an increasing rate of 12.4%.

The trend curves of surface runoff (Fig. 8B) and baseflow (Fig. 8C) during 1956-1970 are both above those of 2000-2016 on the scatter diagrams indi-

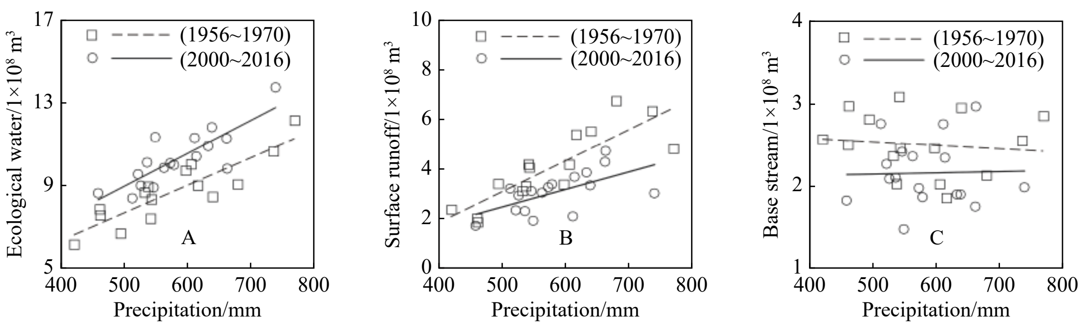

Fig. 8 Changes in ecological consumption water, surface runoff, and baseflow before and after the vegetation restoration

cate that the surface runoff and baseflow notably decrease along with the restoration of vegetation in the basin under the same precipitation condition. As calculated according to the functional relations of the precipitation with the surface runoff and baseflow in the two periods, the surface runoff and baseflow during 2000-2016 decreased by 82 million m^3 (29.50 mm) and 29 million m^3 (10.43 mm), respectively, with a decreasing rate of 18.6% and 11.9%, compared with those in the years of 1956-1970. Table 2 shows the statistics of the changes in the major water cycle elements before and after vegetation restoration under the average annual precipitation condition over the years.

As shown by the relationships of the precipitation versus ecological consumption water and precipitation versus surface runoff for the years of 1956-1970 and 2000-2016, the resulting curves of the two periods tend to interact in the wet years but increasingly depart in the dry years. This suggests that the effects of vegetation restoration on ecological water consumption and surface runoff are slightly obvious in dry years but remarkable during the wet years. The influence of vegetation restoration on the water cycle in the river basin is not uniform but increased with an increase in atmospheric precipitation.

3.2.2 Influence of vegetation restoration on evapotranspiration

Climate change is an important driving factor in the change of water cycle, especially in the alpine regions, where the temperature-induced cryosphere melting exerts a considerable influence on the water cycle. Relevant data show that the mean annual temperature has increased in Beichuan River basin since the 1970s. However, the Beichuan River basin is located on the eastern margin of the Qinghai-Tibet Plateau, where there is no modern glacial activity and only a small area of seasonal frozen soils distributed in the high mountains. Therefore, the influence of the temperature induced cryosphere melting on the water cycle can be ignored in the basin.

As a key factor in the water cycle, evapotranspiration is mainly composed of vegetation transpiration and soil water and surface water evaporations. It changes in nearly the same trend as the atmospheric temperature when other factors are not considered. However, the evapotranspiration capacity reflected by evaporation from water surface (E_{601} evaporation pan) decreased with an increase in atmospheric temperature in the Beichuan River basin (Fig. 9A), indicating that the atmospheric temperature is not the decisive factor affecting the evapotranspiration change in the basin. In essence, the evapotranspiration change in the basin is the comprehensive result of terrain and meteorological factors such as the properties of the underlying surface, elevation, surface albedo, and aerodynamic impedance.

As an important part of evapotranspiration, the vegetation transpiration roughly increases by

Table 2 Statistics of changes in water cycle elements before and after vegetation restoration under the condition of average annual precipitation over the years

	Ecological consumption water (100 million m^3)	Surface runoff (100 million m^3)	Baseflow (100 million m^3)
1956-1970	8.92	4.40	2.43
2000-2016	10.03	3.58	2.14
Difference (100 million m^3)	1.11	−0.82	−0.29
Change rate (%)	12.4	−18.6	−11.9

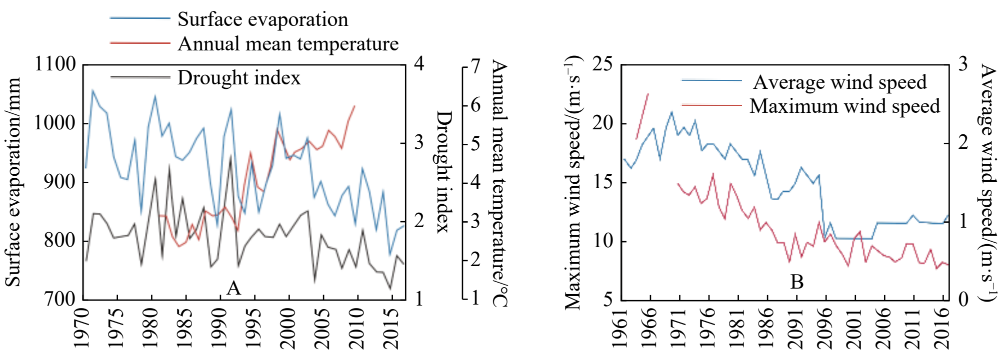

Fig. 9 Variations of drought index (A) and surface wind speed (B) in the Beichuan River basin

vegetation cover rate. However, large-scale vegetation restoration can practically increase air humidity, reduce air mobility, change a local microclimate, and then further change the vegetation transpiration intensity per unit area (Mcnaughton et al. 1983). The drought index in the Beichuan River basin decreased while fluctuating during 1970-2016 (Fig. 9A), especially after the 1980s. It reduced by 22.5% over the past ten years (1.48) compared with that in the 1970s and 1980s (1.91), and the climate gradually transformed from a semi-arid and semi-humid climate to a humid and semi-humid climate in the localized climate zone. Although this climate transformation may be primarily controlled by the climate change in the Qinghai-Tibet Plateau region, the influence of large-scale vegetation restoration on it cannot be ignored.

Wind speed serves as an important factor affecting the evaporation on water surface. Both the maximum and average wind speeds decreased in the period of 1961-2016 (Fig. 9B), especially before 2000. Relevant researches have shown that surface cover can significantly weaken the near-surface wind speed (Li et al. 2002; Xu et al. 2003). Therefore, the decrease in near-surface wind speed induced by vegetation restoration may be one of the factors that reduce the potential evapotranspiration capacity of the Beichuan River basin. Meanwhile, the sunlight shading and wind blocking caused by large-scale vegetation can largely reduce the evaporation from the forest soils. As indicated by the monitoring and research results of the upper reaches of the adjacent Heihe River in the Qilian Mountains, the soil water evaporation in a Picea crassifolia forest was only 45.5% outside the forest (Zhou et al. 2018). In addition to the transpiration changes induced by vegetation growth, it is necessary to fully take the changes in soil water evaporation caused by vegetation cover in the research into account of the influence of vegetation restoration on evapotranspiration. The vegetation restoration reduces the evaporation of surface soil water in the Beichuan River basin to a certain extent, which may be an important factor that causes the evapotranspiration capacity of the river basin to decrease.

In the water cycle model expressed in Equation (2), the ecological consumption water S is used in two forms. One is the land evapotranspiration, in which water enters the atmosphere; the other is the water retention by soil and vegetation, from which water is stored in the basin. As analyzed above, the ecological water has increased but the evapotranspiration capacity reflected by the evaporation from water surface (E_{601} evaporation pan) decreased in the Beichuan River basin after the large-scale vegetation restoration. This means that an increase in the water conservation capacity in soil and vegetation has been working well in the basin (Eagleson, 1978; Chen et al. 2007). The ecological water in the Beichuan River basin has not been consumed by evapotranspiration, but a considerable part of it has been stored in the basin by soil and vegetation water retentions. This fully reflects the water conservation value of the vegetation restoration in the upper reaches of the Yellow River.

3.2.3 Influence of vegetation restoration on time and space changes in water resources

In addition to the changes in each individual water cycle element, the influence of vegetation restoration on the water cycle is also reflected by the temporal-spatial changes of water resources and climate changes in the river basin. The K_Q and K_R of the river basin for the years 1956-2016 were calculated using Equations (4) and (5), respectively. The K_Q results show that the average annual K_Q during 2000-2016 is 1.5 times than that during 1956-1970 under the same precipitation condition (Fig. 10A). This suggests that the runoff yield condition has changed after the vegetation restoration in the way that more precipitation has been converted to ecological water while less converted to the runoff flowing towards the lower reaches.

According to the comparison of K_R between 1956-1970 and 2000-2016, the K_R decreases with the increase in the atmospheric precipitation, which is consistent with the runoff yield pattern of most river basins. However, the K_R during 2000-2016 was slightly higher than that during 1956-1970 under the same precipitation condition (Fig. 10B). This indicates that the ratios of baseflow and surface runoff to the natural runoff increase and decrease, respectively, after the vegetation restoration; this trend is increasingly notable with the increase in atmospheric precipitation. In short, the K_R has slightly changed after the vegetation restoration. Furthermore, the precipitation is a much more sensitive factor that controls the change of runoff in the basin, while the vegetation restoration only exerts a weak effect on the change in runoff distribution.

4 Conclusions

The Beichuan River basin has experienced large-scale vegetation restoration since the 1980s. During 2000-2019, the average vegetation cover rate increased by 5.01%; and the vegetation restoration at the highest level during this period occurred

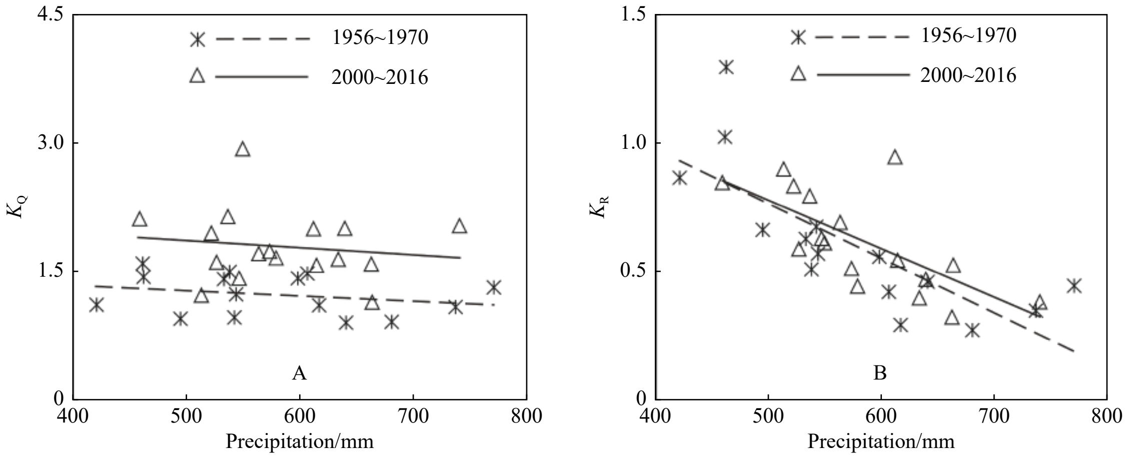

Fig. 10 Changes of precipitation distribution coefficient (A) and runoff distribution coefficient (B) before and after vegetation restoration

in the vast hilly and middle-high mountainous areas on both sides of the mainstream valley, where the maximum and average vegetation cover rates increased by 52.2% and 14.98%, respectively. As the large-scale vegetation restoration has changed the properties of the underlying surfaces, it also changed the water cycle conditions in the river basin.

(1) According to the variations of precipitation, runoff, and ecological water over the years, the water cycle conditions in the river basin changed due to the effects of large-scale vegetation restoration under the relatively stable precipitation condition. This is reflected by the increase in ecological water and the attenuation of surface runoff.

(2) Vegetation restoration has affected the spatial-temporal distribution of atmospheric precipitation inside and outside the river basin. Spatially, more atmospheric precipitation was converted to ecological consumption water after the vegetation restoration. As a result, the water supplied to the lower reaches as runoff reduced to a certain extent. Temporally, the ratio of baseflow to the natural runoff increased, which prolonged the outward discharge period of the atmospheric precipitation. In other words, more atmospheric precipitation in the river basin participated in the cycle of atmospheric precipitation-soil water-groundwater in the long period, and more water resources migrated from linear water systems to planar terrestrial ones.

(3) There is a virtuously mutual feedback between the vegetation restoration and localized climate change in the river basin. After the large-scale vegetation restoration, the surface wind speed, evaporation from water surface, drought index and soil water evaporation have significantly decreased, which eventually caused the decrease in the evapotranspiration capacity and the increase in the water retained by the soil. The changes of these elements play a significant role in improving water conservation capacity and the semiarid climate condition in the river basin.

Acknowledgements

This study was supported by "Hydrological geological survey in the Huangshui River basin" (No. DD20190331D). Professor Kang Weidong of Northwestern University provided valuable opinions on the writing ideas, and Fei Xie provided help in remote sensing data processing.

References

Chen C, Park T, Wang XH, et al. 2019. China and India lead in greening of the world through land-use management. Nature Sustainability, 2(2): 122-129.

Chen GC, Zhou LH, Peng M, et al. 2001. Remote sensing interpretation and its characteristics of the forest and shrub vegetation in Huang Shui area, Qinghai Province. Acta Botanica BorealiOccidentalia Sinic, 21(4): 719-726.

Chen LD, Huang ZL, Gong J, et al. 2007. The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China. Catena, 70(2): 200-208.

Eagleson PS. 1978. Climate, Soil, and Vegetation 1. Introduction to Water Balance Dynamics. Water Resources Research, 14(5): 705-712.

Gao YX, Liu JC, Feng X, et al. 2019. Experimental study on unsaturated soil water diffusivity in different soils in Hebei Piedmont Plain. Journal of Groundwater Science and Engineering, 7(2): 165-172.

Gashaw G. 2016. Evaluating the effect of climate change and land use/cover change on catchment hydrology of Gumara watershed, Upper Blue Nile basin, Ethiopia. Open Water Journal, 3(1): 1-14.

Hu CH, Zang XM, Zhao Y. 2020. Cause analysis of the centennial trend and recent fluctuation of the Yellow River sediment load. Advances in Water Science, 31(5): 725-733.

Huang TM, Pang ZH. 2011. Estimating groundwater recharge following land-use change using chloride mass balance of soil profiles: A case study at Guyuan and Xifeng in the Loess Plateau of China. Hydrogeology Journal, 19(1): 177-186.

Huang TM, Pang ZH, Liu JL, et al. 2017. Groundwater recharge in an arid grassland as indicated by soil chloride profile and multiple tracers. Hydrological Processes, 31(5): 1047-1057.

Huang TM, Pang ZH, Yang S, et al. 2020. Impact of afforestation on atmospheric recharge to groundwater in a semiarid area. Journal of Geophysical Research: Atmospheres, 125(9): 1-19.

Li SG, Harazono Y, Zhao HL, et al. 2002. Micrometeorological changes following establishment of artificially established artemisia vegetation on desertified sandy land in the Horqin sandy land, China and their implication on regional environmental change. Journal of Arid Environments, 52(1): 101-119.

Liu WZ, Zhang XC, Dang TH, et al. 2010. Soil water dynamics and deep soil recharge in a record wet year in the southern Loess Plateau of China. Agricultural Water Management, 97(8): 1133-1138.

Mark Z. 2019. China's tree-planting drive could falter in a warming world. Nature, 573(7775): 474-475.

Mattos TS, Oliveira PTSD, Lucas MC, et al. 2019. Groundwater recharge decrease replacing pasture by eucalyptus plantation. Water, 11(6): 1213-1226.

Mcnaughton KG, Jarvis PG. 1983. Predicting effects of vegetation changes on transpiration and evaporation. Additional Woody Crop Plants, 7(2): 1-47.

Tesfaldet YT, Puttiwongrak A, Arpornthip T. 2020. Spatial and temporal variation of groundwater recharge in shallow aquifer in the Thepkasattri of Phuket, Thailand. Journal of Groundwater Science and Engineering, 8(1): 10-19.

Wang XY, Bi HX;Gao LB, et al. 2014. Discrimination of factors influencing the runoffs of different spatial scales on loess region in Western Shanxi. Journal of Northwest A & F University(Natural Science Edition), 42(1): 159-166.

Wang YQ, Shao MA, Shao HB, et al. 2010. A preliminary investigation of the dynamic characteristics of dried soil layers on the Loess Plateau of China. Journal of Hydrology, 381(1-2): 9-17.

Wu AM, Hao AB, Guo HP, et al. 2020. Main progress and prospect for China's hydrogeological survey. Journal of Groundwater Science and Engineering, 8(3): 195-209.

Xu XK, Lin ZH, Xue F, et al. 2003. Correlation analysis between meteorological factors and the ratio of vegetation cove. Acta Ecologica Sinica, 23(2): 221-230.

Yan WM, Deng L, Zhong YQW, et al. 2015. The characters of dry soil layer on the loess plateau in China and their influencing factors. PLoS One, 10(8): 1-14.

Zhao CL, Jia XX, Gongadze K, et al. 2019. Permanent dry soil layer a critical control on soil desiccation on China's Loess Plateau. Scientific Reports, 9(1): 3296.

Zhao XN, Zhang BQ, Wu PT. 2014. Changes in key driving forces of soil erosion in the Middle Yellow River Basin: vegetation and climate. Natural Hazards, 70(1): 957-968.

Zhou S, Yu BF, Zhang Y, et al. 2018. Water use efficiency and evapotranspiration partitioning for three typical ecosystems in the Heihe River Basin, northwestern China. Agricultural and Forest Meteorology, 253-254, 261-273.