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Research Article

Dynamic Impacts of Climate and Land-Use Changes on Surface Runoff in the Mountainous Region of the Haihe River Basin, China

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The relative contributions of different factors to the variation in surface runoff have been broadly quantified. However, little attention has been paid to how these relative contributions have changed over time. We analyzed the changes in surface runoff during 1980–2010 in six subbasins in the mountainous region of the Haihe River Basin, one of the most serious water shortage regions in China, and identified the changes in the relative contributions of climate (precipitation and temperature) and land-use to surface runoff decrease. There was a decreasing tendency in surface runoff in all subbasins, four of which had an abrupt change point around 1998. Comparing the relative contributions before and after 1998 in the four subbasins, the average influence of climate was found to decline dramatically from 67.1% to 30.5%, while that of land-use increased from 23.9% to 69.5% mainly due to the increase of forest area. Our results revealed that the primary environmental factor responsible for runoff variations was not constant, and an alternation may accentuate the impact and stimulate an abrupt change of runoff in semiarid and semihumid mountainous regions. This will help in taking tracking measures to deal with the complex water resource challenges according to different driving factors.

1. Introduction

Water resources and the range of services they provide underpin poverty reduction, economic growth, and environmental sustainability [1]. By linking land and oceans, river runoff is an important component of the water resource used for sustainable development and human consumption, and it affects the livelihoods of billions of people [2, 3]. In many areas, the volume of river runoff has displayed a decreasing tendency due to excess exploitation by humans and climate change, and water scarcity has become a global environmental problem that hinders human safety and social development [4–7].

Many studies have identified climate change and changes in land-use (LU) to be the two main factors influencing the variation in river runoff. In a water-limited region, the influence of climate change is usually represented by various stages of the water cycle, for example, rainfall and evapotranspiration [8–10]. Empirical models, such as time-series analyses and hydrological mechanisms, have been used to study the influence of climate change on runoff variation [11–13]. The continuous increase in anthropogenic activities can be simplified and represented as LU changes, enabling the application of comprehensive models and statistical methods [14–16]. Also, the impacts of LU changes on surface runoff at different spatial and temporal scales have been studied [17–21].

In China, almost the entire country has experienced the dilemma of economic development and water shortage [22, 23], with the Haihe River Basin (HRB) being the most severely stressed region [24–26]. The HRB is located in mid-eastern China, where the climate is semiarid and semihumid, with the highest rate of water sources exploitation among all of China's river basins [27]. The long-term shortage of water resources in the HRB has triggered a series of problems, such as a decrease in surface runoff [28, 29], lake and wetland shrinking [30], groundwater overexploitation [25], aggravation of water pollution [31, 32], and the degradation of ecosystem function [33, 34].

Numerous studies have assessed the trends in river runoff, the factors that influence it, and the relative contributions of different environmental factors (e.g., [35, 36]). In the HRB, runoff has shown a significant downward trend in recent decades [28, 37, 38]. A decrease in runoff from the headstream in mountainous areas has limited the downstream surface flow in the HRB [39–41]. Previous studies have focused mainly on the entire HRB and have identified the factors that influence runoff variation [38, 42–44], but they have paid less attention to the variational relative contributions of these factors which have influence on surface runoff over time. Such studies would improve our understanding of the dynamic relationships between surface runoff and environmental factors, as well as the management of complex water resource challenges.

In this study, we used the mountainous area of the HRB as an example and analyzed the surface runoff tendencies of six subwatersheds over the period of 1980–2010 and their responses to different driving factors at different stages of the study period. The main objectives were to (i) determine the tendencies of surface runoff, climate factors, and LU from 1980 to 2010 and identify the break point of the change in surface runoff and (ii) compare the differences in the relative contribution of different environmental factors before and after the break point to provide water resource management information.

2. Study Area

The HRB is located in north China. A total of 58.6% of its area is mountainous in the west and north, with an elevation between 65 and 3058 m (Figure 1). The HRB is a temperate continental monsoon region, with a semiarid and semihumid climate, in which 75–85% of precipitation occurs in the flood season (from June to September). The area consistently experiences sand-dust storms in spring [45]. The HRB encompasses one of the largest metropolitan regions in China, including Beijing, Tianjin, and Hebei Province, which together account for 8.1% of the population and 10.1% of the GDP, but 0.93% of the natural water resource of the whole nation [46, 47]. As the largest urbanized region and one of the major grain producing areas in northern China, long-term water shortages have led to a series of environmental issues in the HRB [25, 48]. Many water conservation projects have been adopted in the HRB, including dams, weirs, gates, and water divisions, as well as water-saving measures in farming and industry [47], and they have helped to alleviate the water crisis. Additionally, several ecological restoration and revegetation projects have been completed since the 1970s [49]. As the water-producing region of the basin, the mountainous area of the HRB was selected for study. Based on the classification of Haihe River Water Conservancy Commission, there are six subwatersheds in the mountainous area of the HRB, that is, Luan River Basin (LRB), Chaobai River Basin (CRB), Yongding River Basin (YRB), Daqing River (DRB), Ziya River Basin (ZRB), and Zhang River Basin (ZRB) (Figure 1).

3. Materials and Methodology

3.1. Surface Runoff and Environmental Factor Trend Analysis. A trend analysis was used to determine the change in the direction of runoff. The Mann-Kendall method was applied for the trend analysis:

$$
\begin{gathered}
S=\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\operatorname{sgn}\left(X_j-X_k\right) \\
\operatorname{sgn}\left(X_j-X_k\right)=\begin{cases}1 & X_j-X_k>0\\ 0 & X_j-X_k=0\\ -1 & X_j-X_k<0\end{cases} \\
\operatorname{var}(S)=\frac{n(n-1)(2n+5)}{18} \\
Z=\begin{cases}\dfrac{S+1}{\sqrt{\operatorname{var}(S)}} & S>0\\ 0 & S=0\\ \dfrac{S-1}{\sqrt{\operatorname{var}(S)}} & S<0,\end{cases}
\end{gathered}
\tag{1}
$$

where X_j and X_k are the sequential data values of the time series in years j and k; and n is the length of the time series. Positive values of Z indicate increasing trends, while negative values indicate decreasing trends in the time series. When $|Z| > Z_{1-\alpha/2}$, the null hypothesis is rejected and a significant trend exists in the time series. $Z_{1-\alpha/2}$ is the critical value of Z from the standard normal table, and, for the 1%, 5%, and 10% levels of significance, the value of $Z_{1-\alpha/2}$ is 2.58, 1.96, and 1.65, respectively.

3.2. Environmental Factors. Based on the previous studies of the HRB, climate and LU have been identified as the primary factors responsible for the decrease in runoff [37, 38, 42, 43]. Considering the in situ conditions of the mountainous region of the HRB, which is less disturbed by human activities than elsewhere in the basin, the following environmental factors were selected as the influencing factors: precipitation, air temperature, proportion of forest, farmland, and grass, and the leaf area index (LAI) (Table 1).

3.3. Trend Analysis and Calculation of the Contribution of Each Factor. An abrupt change analysis was used to identify the break point. In this study, the Pettitt test ((2) to (6)) and

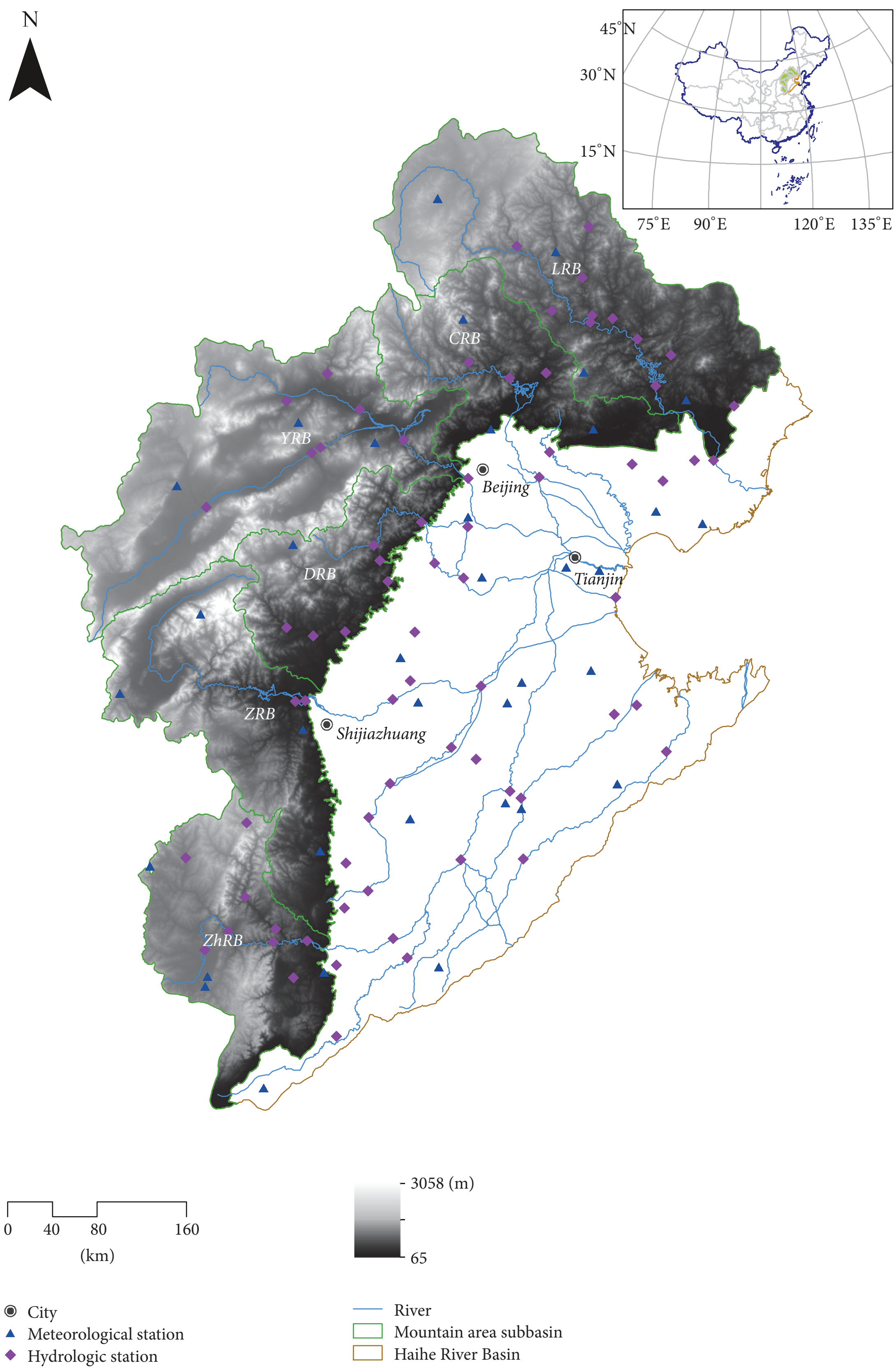

FIGURE 1: Haihe River Basin (HRB) and the subbasins in the mountainous region of the basin. Luan River Basin (LRB) and Chaobai River Basin (CRB) are located in the north; Yongding River Basin (YRB) and Daqing River Basin (DRB) are located in the center; Ziya River Basin (ZRB) and Zhang River Basin (ZhRB) are located in the south.

Table 1: Environmental factors used to analyze the decrease in runoff.

Category	Factor	Description and unit of measure
Meteorology	Precipitation	Annual precipitation, mm
	Air temperature	Annual air temperature, °C
Land-use	Proportion of forest	Forest area/total area
	Proportion of grassland	Grassland area/total area
	Proportion of farmland	Farmland area/total area
	Leaf area index (LAI)	Calculated by the temporal spatial filter method [50]

the moving T Test (see (7)) were both applied for an abrupt change analysis, enabling a cross validation to be performed.

$$U_{t,n} = U_{t-1,n} + \sum_{i=1}^{N} \operatorname{sgn}(X_t - X_i) \quad 1 \le t \le N \quad (2)$$

$$\operatorname{sgn}(X_t - X_i) = \begin{cases} 1 & X_t - X_i > 0 \\ 0 & X_t - X_i = 0 \\ -1 & X_t - X_i < 0 \end{cases} \quad (3)$$

$$U_{1,n} = \sum_{i=1}^{N} \operatorname{sgn}(X_1 - X_i) \quad 2 \le t \le N. \quad (4)$$

The most probable change point t was found where its value satisfied the following:

$$K_t = \max_{1 \le t \le N} |U_{t,n}| \quad (5)$$

and the significance probability associated with the value K_t was approximately evaluated as

$$p = 2 \exp\left\{-\frac{6k_t^2}{(n^3 + n^2)}\right\}, \quad (6)$$

where $U_{t,n}$ is the statistical index.

$$t = \frac{\overline{x}_1 - \overline{x}_2}{s \cdot \sqrt{1/n_1 + 1/n_2}},$$
$$s = \sqrt{\frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2}},$$
$$s_1 = \sqrt{\frac{\sum_{t=1}^{n_1} x_t - \overline{x}_1}{n_1 - 1}},$$
$$s_2 = \sqrt{\frac{\sum_{t=1}^{n_2} x_t - \overline{x}_2}{n_2 - 1}}, \quad (7)$$

where t is the statistical value; x_i is the subdataset; n_i is the length of the subdataset; $\overline{x}_i$ is the average of the subdataset; and s_i is the standard deviation.

For the calculation of the relative contributions of different environmental factors, a multiple linear regression model was used to identify the main influencing factors, and the variance was used to quantify the relative contribution of each factor [51, 52]. The multiple linear regression analyses were conducted using SPSS software (Version 21) [53], while the analysis of the relative contributions was performed using the R statistical analysis software (Version 0.98) [54].

3.4. Data Collection. The study used hydrology, climate, land-use (area of forest, farmland, and grassland), and LAI data from 1980 to 2010. The observed annual runoff, precipitation, and air temperature were collected from 36 hydrologic stations, which were obtained from the "Hydrological almanac of Haihe River Basin" and 72 meteorological stations, using information downloaded from the China Meteorological Data Service Center (http://data.cma.cn/). The spline interpolation method was used to calculate and estimate the mean meteorological data based on the ArcMap 10.1 platform. Thematic mapper (TM) images were obtained from an online source (US Geological Survey) [55] and were used to extract land-use information and the normalized difference vegetation index (NDVI) was used to calculate the LAI by the temporal spatial filter method.

4. Results

4.1. The Changing Trend of Environmental Factors and Runoff. During the period of 1980–2010, the trend analysis indicated a declining trend in all subbasins. The Mann-Kendall method identified significantly decreasing tendencies ($|Z| > 1.96$, $p < 0.05$) in all subbasins except the ZRB. Air temperature displayed a significant upward trend in all subbasins ($|Z| > 2.58$, $p < 0.01$), but there was no significant trend for precipitation (Figure 2).

From the LU changes, farmland area displayed a declining trend in all subbasins ($|Z| > 1.65$, $p < 0.1$), except the ZhRB. The forest and grassland areas displayed an upward and downward tendency ($|Z| > 1.65$, $p < 0.1$), respectively, but this was not significant in both the YRB and ZRB. In all subbasins, LAI displayed a significant increasing trend ($|Z| > 2.58$, $p < 0.01$) due to the large increase of forest cover, while the trend slowed down after 1989 (Figure 3).

4.2. Identification of the Abrupt Change Point of Runoff and Environmental Factors. A Pettitt test and moving t-test were applied to identify the abrupt change point of runoff. The results showed that an abrupt change point of runoff existed in the north (LRB and CRB) and central (DRB and YRB) regions around 1998 (from 1997 to 1999, Figure 4), while no change point was detected in the south (ZRB and ZRB).

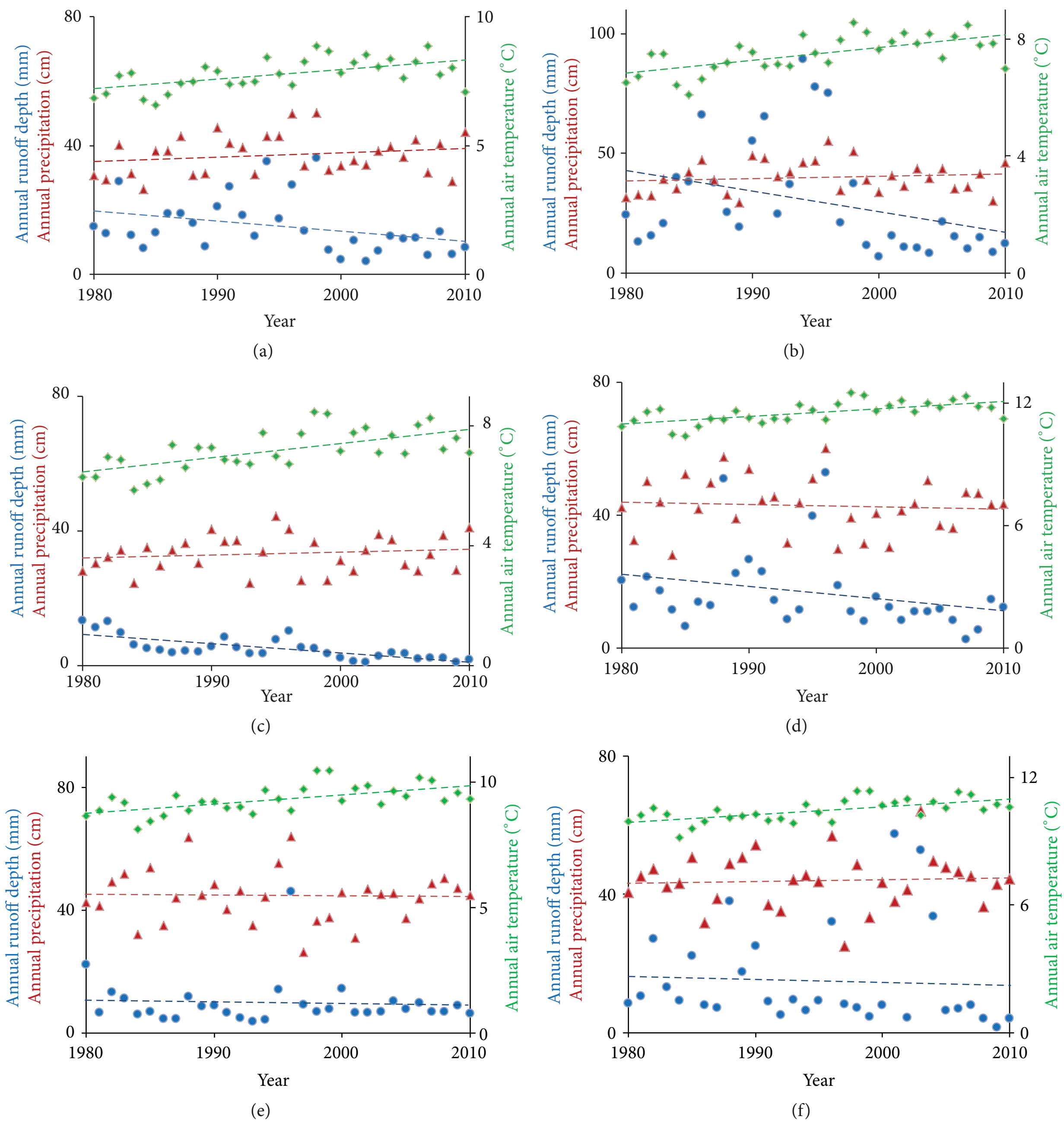

FIGURE 2: Tendency of annual runoff depth (blue circle), precipitation (red triangle), and air temperature (green diamond). The dashed lines represent the linear fitted trend from 1980 to 2010. (a) is Luan River Basin (LRB), (b) is Chaobai River Basin (CRB), (c) is Yongding River Basin (YRB), (d) is Daqing River Basin (DRB), (e) is Ziya River Basin (ZRB), and (f) is Zhang River Basin (ZhRB).

An abrupt change point was also identified for the other environmental factors that displayed significant trends. The change point of air temperature was in 1993 for LRB, CRB, and DRB and in 1996 for YRB, ZRB, and ZhRB. The area of forest, farmland, and grassland had a change point around 1994–1998, while the change point for LAI was detected at 1988-1989.

4.3. The Contribution of Different Environmental Factors to the Variation in Runoff. Figure 5 shows the relative contributions of different environmental factors to the variation in runoff in the subbasins from 1980 to 2010. Other than in YRB, the effect of climate was most significant, with an overall contribution of 54–92%, which gradually increased from north to south. The influence of precipitation was stronger than air temperature. In YRB, LU was the principal factor influencing changes in runoff, followed by climate. The reasons for this discrepancy may be due to this subbasin having the largest area of farmland (more than 40% during the study period) of the six subbasins studied.

Table 2: Correlation coefficients for the relationship between runoff and environmental factors form 1980 to 2010.

	LRB	CRB	YRB	DRB	ZRB	ZhRB
Meteorology						
Precipitation	0.53^{**}	0.56^{**}	—	—	0.45^{*}	0.51^{**}
Air temperature	-0.38^{*}	—	-0.68^{**}	-0.46^{**}	—	-0.38^{*}
Land-use						
Farmland	0.56^{**}	0.49^{**}	0.81^{**}	—	—	—
Forest	-0.52^{**}	-0.49^{**}	—	-0.41^{*}	—	—
Grassland	0.55^{**}	0.51^{**}	-0.55^{**}	0.38^{*}	—	—
LAI	—	—	—	—	—	—

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{-}$the value was not statistically significant. LRB: Luan River Basin; CRB: Chaobai River Basin; YRB: Yongding River Basin; DRB: Daqing River Basin; ZRB: Ziya River Basin; ZhRB: Zhang River Basin.

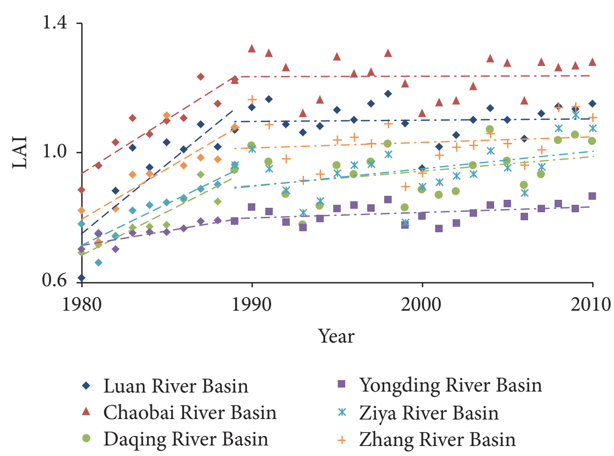

Figure 3: Changes in the annual leaf area index (LAI) in the six subbasins. The figure shows the results of a linear fitting to the LAI values before (the dashed line) and after (the dash dotted line) 1989.

Figure 6 shows the relative contributions before and after 1998 in the subbasins. The results show a similar pattern to that of the overall contributions from 1980 to 2010, with climate being the most significant contributor in LRB, CRB, and DRB, while LU was dominant in YRB before 1998. After the change point, the contribution of climate decreased dramatically, and, accordingly, the proportional contribution of LU increased markedly.

5. Discussion

5.1. The Correlation between Runoff and Environmental Factors. A correlation analysis was also conducted, with the results listed in Table 2. There was a positive correlation between runoff and both precipitation and the area of farmland and a negative correlation with both air temperature and the area of forest, which was in accordance with previous studies [28, 56, 57]. However, grassland is also in the potent function of water conservation [58], but it had a positive relationship with runoff in LRB, CRB, and DRB, also. The reason for this was attributed to the large decline in the area of grassland (decreased by 50%), which weakened the water retention capacity. From the subbasin perspective, the variation in runoff in the southern subbasins (ZRB and ZhRB) was only related to climate factors, and in all six subbasins there was no correlation with the LAI.

Considering the relative contributions from 1980 to 2010, the LAI had the least impact (had an influence in YRB with a contribution of 17.52%, only), with the correlation analysis indicating it has no relationship with the variation in runoff. Unlike the other subbasins, LU change was the dominant factor in YRB (farmland was the uppermost contributor). This was reflected by the large correlation coefficient between farmland and runoff (0.81, $p < 0.01$). Climate factors accounted for more than 80% of the overall variation in runoff in the southern subbasins, which was much higher than in the other subbasins, while other factors had no relationship with runoff in ZRB and ZhRB.

5.2. The Driving Forces of the Abrupt Change Point of Runoff and the Differences in the Contribution of the Environmental Factors to the Variation in Runoff. According to our analysis, climate and LU were the major factors responsible for the decline in runoff in the mountainous region of the HRB, and the driving force of changes in these parameters also needs to be investigated. Based on previous studies, global warming is likely to be the primary factor responsible for the rise in air temperature. During 1981–1985 and 1993–1998, long-lasting and high-intensity El Niño/La Nina events occurred alternately and had a large impact on the climate of north China [59], including a rise in air temperature. During the period investigated by this study there was also a substantial increase in the area of forest and a decline in the area of farmland and grassland due to ecological restoration projects. The Three-North Shelter Forest Program (scheduled from the late 1970s to 2050) and the Beijing-Tianjin Sand Source Control Project (scheduled from the early 2000s to 2022) [49] cover most of the northern and central part of the mountainous region of the HRB, where an abrupt change point of runoff was identified. The variation of the LAI increased dramatically until around 1989 due to afforestation and then tended to be stable or slowly increase with a value fluctuating around 0.8–1.4. After more than 10 years of afforestation, the LAI was limited by the variety of land-use and trees in the HRB, and the observed tendency of the LAI was in accordance with Liu et al. [60].

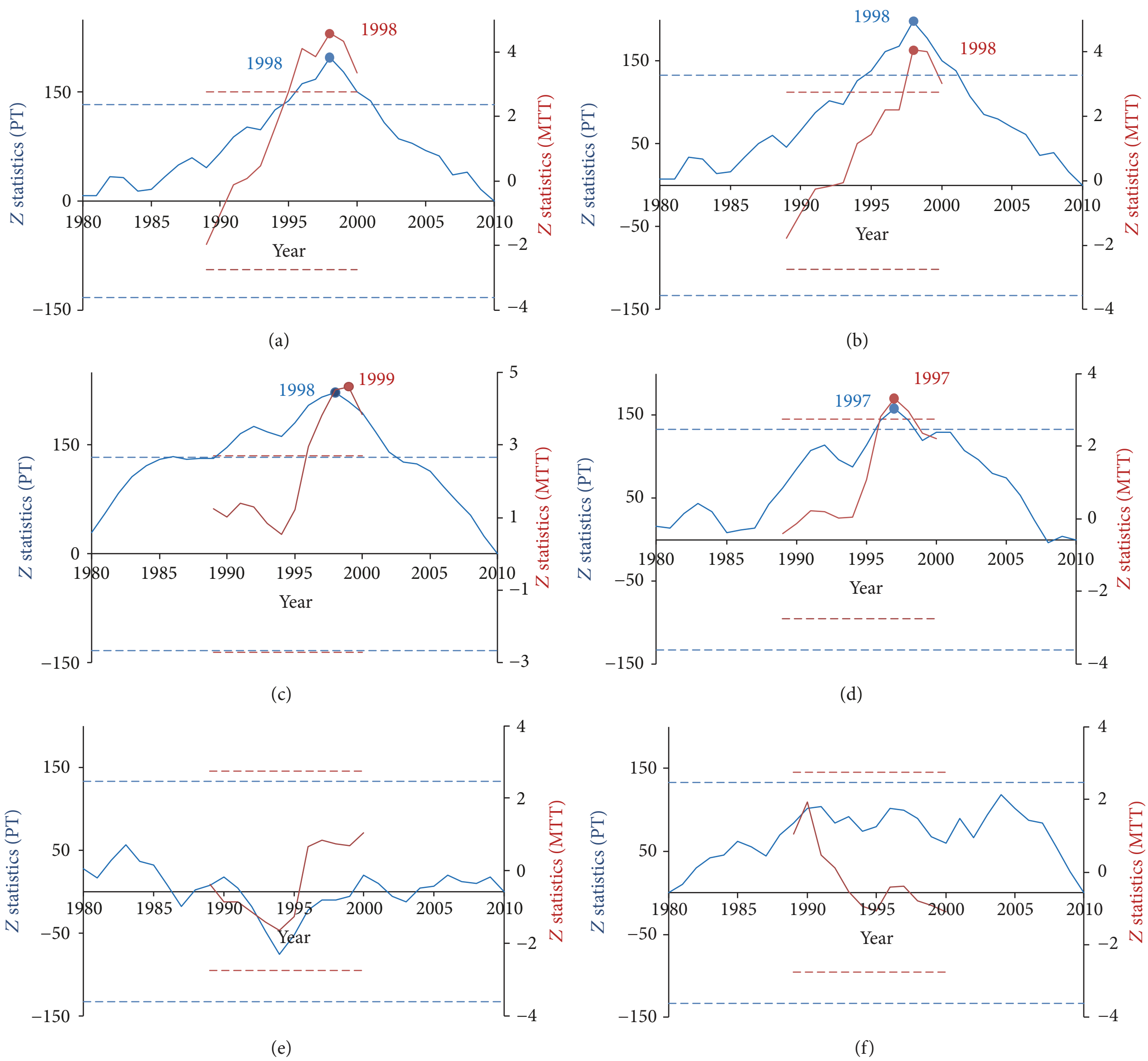

FIGURE 4: The identification of the abrupt change point of runoff in the six mountainous subbasins. The blue and red dots represent the abrupt change point of runoff obtained by a Pettitt test (PT) and moving t-test (MTT), respectively. The blue and red lines represent the statistical values obtained by the method of PT and MTT, respectively. The dashed lines represent a significance level of 0.01. (a) is Luan River Basin (LRB), (b) is Chaobai River Basin (CRB), (c) is Yongding River Basin (YRB), (d) is Daqing River Basin (DRB), (e) is Ziya River Basin (ZRB), and (f) is Zhang River Basin (ZhRB).

5.3. The Differences in the Contribution of the Environmental Factors before and after the Change Point of Surface Runoff. Comparing their proportional contributions before and after the abrupt change point of surface runoff, the proportion accounted for by climate declined by more than 50% (Figure 6), and LU became the dominant factor. This change could be ascribed to the variation in both climate and LU. In terms of the overall tendency, the factors that had a positive relationship with runoff (farmland, grassland, and precipitation) displayed a significant downward trend or no significant increase, while the factors that had a negative relationship with runoff (air temperature and forest) displayed a dramatic upward trend. Therefore, the continual decline of runoff was caused by the combined contribution of various environmental factors. When considering the different stages of the study period, the increase in the temperature trend after 1998 was weaker than before 1998, and the precipitation trend was upward after 1998. The LU factors continued to display significant trends in all stages of the period studied. It could be inferred that the extensive proportional contribution of LU after 1998 has had an extensive impact on the decline in runoff.

In the northern and central subbasins, the abrupt change point of climate was several years earlier than those of

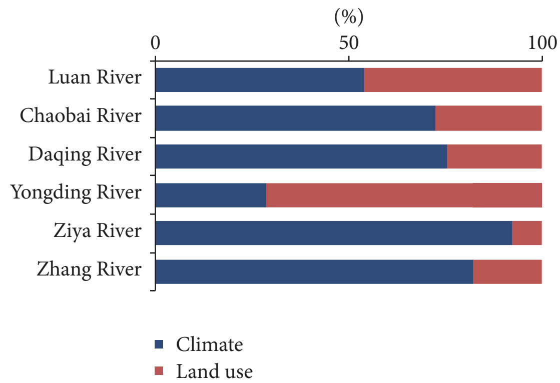

FIGURE 5: The contribution of climate and land-use changes to the variation in runoff in the six subbasins in the period of 1980–2010. The statistical significance was <0.01 in Luan River Basin (LRB), Chaobai River Basin (CRB), Yongding River Basin (YRB), and Daqing River Basin (DRB); while it was <0.1 in Ziya River Basin (ZRB) and Zhang River Basin (ZhRB).

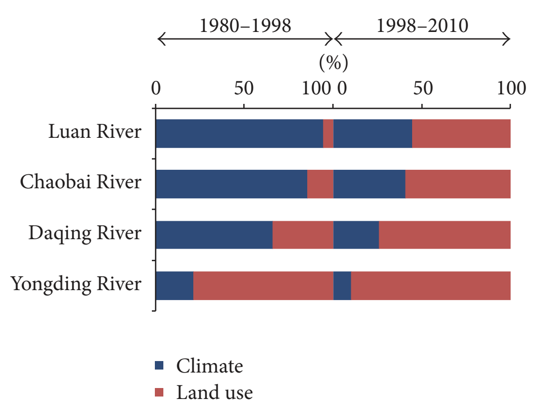

FIGURE 6: The contributions of climate and land-use changes to the variation in runoff in subbasins before and after the runoff change point (1998). The blue bar represents the contribution of climatic factors on the decrease in runoff, and the red bar represents the contribution of land-use factors. The statistical significance was <0.1.

runoff and LU. However, there was no correlation in the lag between annual runoff and either precipitation or air temperature. Therefore, the abrupt change of runoff may have been triggered by LU changes in the mountainous region of the HRB, despite the combination of accumulated climate effects.

6. Conclusion

This study investigated the trends in runoff, climate, and LU in six subbasins in the mountainous region of the HRB for the period of 1980–2010. During this period, surface runoff decreased significantly in all subbasins, except ZRB. Air temperature increased significantly, while there was no significant trend in precipitation. In terms of LU, the area of forest and LAI had a significant upward trend, while the area of farmland and grassland displayed the opposite trend.

Abrupt change points were detected for runoff, air temperature, and LU factors. The change point of surface runoff was around 1998. Apart from the LAI, the change points of the other environmental factors were relatively concentrated in the period of 1993–1999, with climatic factors having a change point several years earlier than LU factors. Multiple linear regressions of the data produced good fits for the period of 1980–2010, and for the periods before and after the abrupt change point of runoff, which indicated that climate and LU were the two main factors leading to variations in surface runoff.

Climate was the most important factor over the entire time sequence, and particularly before the abrupt change point of runoff, but sharply decreases after that. Both climate and LU factors continued to be responsible for the decrease in runoff after 1998, but the impacts of LU were remarkable and may be the critical factor stimulating the changes in runoff. The study revealed that the primary environmental factor responsible for variations in runoff was not constant, and an alternation between different factors may accentuate the impact and stimulate an abrupt change of runoff in semiarid and semihumid mountainous regions. Our results emphasize the need for the long-term monitoring of the dynamic changes of factors driving the variation in surface runoff. This will help in taking tracking measures to deal with the complex water resource challenges through focusing on the dynamic changes of the key factors driving surface runoff variation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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