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# Effects of Vegetation Restoration on the Hydrological Regimes of the Chinese Loess Plateau: A Comparative Analysis of Forested and Less-Forested Catchments

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**Abstract:** Large-scale vegetation restoration can significantly affect catchment hydrology. Assessing the impact of vegetation restoration on hydrological regimes is important for water resource management. We chose three less-forested catchments (LFCs, forested area <30%) undergoing major vegetation restoration, i.e., Wuqi, Zhidan, and Liujiahe, and two forested reference catchments (FCs, forested area >77%) that have had secondary forests for more than 150 years, i.e., Zhangcunyi and Huangling, of the Beiluo River basin located in the Loess Plateau (LP) to compare and analyze the stationary and variation characteristics of streamflow and its components from 1958 to 2019. Results show that the mean annual streamflows were 25.07~34.21 and 21.62~48.02 mm in the LFCs and FCs, respectively. The mean streamflow in the LFCs decreased by 50% on average from before the year 2000 to after. The decreasing trend of high flows and increasing trend of low flows is represented in the daily flow duration curves of the LFCs. The result of baseflow separation shows that the average percentages of baseflow in the streamflow were 31.89~43.36% in the LFCs and 58.23~60.14% in the FCs. The Mann–Kendall tests showed significant decreasing trends in annual streamflow (−0.27~−0.70 mm/a) and stormflow (−0.29~−0.64 mm/a) in the LFCs from 1958 to 2019, while the baseflow exhibited increasing trends except for in the Zhidan catchment. The seasonal streamflow and stormflow showed significant decreasing trends in the summer and non-flood season, while the winter and non-flood season's baseflow increased in LFCs. In FCs, however, the streamflow and its components showed only slight fluctuations over the study period in annual trends, decadal variability, and seasonal trends over the study period, suggesting that FCs have stable hydrological regimes. These results indicate that 20 years of large-scale vegetation restoration greatly influenced hydrological regimes by reducing stormflow and increasing baseflow, and played an important role in streamflow regulation. Conversely, areas with well-preserved vegetation can effectively mitigate the effects of weather and other factors on runoff with stable hydrological regimes. This study can help vegetation restoration and water resource management on the LP.

**Keywords:** streamflow regime; vegetation restoration; runoff components; Loess Plateau

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**Citation:** Yi, H.; Wang, Y.; Lou, Y.; Han, X. Effects of Vegetation Restoration on the Hydrological Regimes of the Chinese Loess Plateau: A Comparative Analysis of Forested and Less-Forested Catchments. *Forests* **2023**, *14*, 1199. https://doi.org/10.3390/f14061199

Academic Editor: Matthew Therrell

Received: 1 May 2023
Revised: 26 May 2023
Accepted: 6 June 2023
Published: 9 June 2023



## 1. Introduction

Streamflow is an important component of river systems that governs the ecosystem health, serving as a key link in the water cycle [1]. Watershed streamflow is influenced by various factors including climate, vegetation status, topography, and human activities [2–7]. In recent years, land cover changes due to human activities have greatly affected the hydrological regimes by impacting the volume of streamflow (components) [7–17], and thus changing the watershed water balances and water resource availability in the region [16,18–20]. This is especially true in the Loess Plateau in China (LP) where extensive vegetation restoration has been implemented [14,15,19–24].

The LP is one of the global hot-spots of soil erosion, with the average sediment export rates varying from 5000 to 10,000 t $km^2a^{-1}$ and sediment yield in some tributaries reaching 20,000 to 30,000 t $km^{-2}a^{-1}$ [25]. Severe soil erosion has caused a series of environmental problems, such as land degradation, soil fertility decrease, biodiversity decline, and crop yield reduction [26]. In order to control the soil erosion, many ecosystem restoration programs have been implemented in the LP since the 1950s [27–29]; in particular, the integrated soil conservation project of small watersheds was implemented in the 1970s [30] and the Grain for Green program in 1999 [29]. These projects consisted of engineering measures such as terraces and check dams, and vegetation measures such as the replanting of trees and grass [31]. These measures have made considerable impacts and have reduced sediment exported from the LP to the Yellow River by $2.24 \times 10^8$ t $year^{-1}$ in 1996, as compared to the sediment yield in 1970 [32]. The vegetation measures have increased total vegetation cover from 56% in 2000 to 76.8% in 2017 [33] and have been suggested as the main underlying surface factors affecting water and sediment changes in the LP [34]. Moreover, with the improvement in vegetation structure, the improvement in rainfall interception and soil infiltration by vegetation measures will become more and more significant [31], which will have a significant impact on the hydrological cycle of the LP area in the future.

Extensive vegetation restoration is believed to have profound impacts on hydrological regimes in terms of an improvement in the underlying surface roughness, the evapotranspiration, and the infiltration of water into soil [35,36]. On the LP, many studies have noted that runoff decreased with the implementation of vegetation restoration [7,19,20,24,37], whereas the impacts of vegetation restoration on baseflow were not consistent. For example, Liu et al. [16] found that the streamflow and surface runoff decreased, while the baseflow increased with the increases in forest cover in 13 catchments of the LP. Liu et al. [17] concluded that streamflow yield decreased with the increase in shrubs–herbs–arbor vegetation, and the baseflow coefficient increased slightly with the expansion of vegetation coverage in the Wuding River basin in the LP over nearly 50 years. Furthermore, Chao [38] found that annual streamflow and stormflow showed a significant decreasing trend and the baseflow showed a significant increasing trend or stable status with the vegetation restoration in the upper reaches of the Beiluo River from 1959 to 2011. However, Huang et al. [8] illustrated that conservation measures resulted in a significant decreasing linear trend in annual surface runoff and baseflow of the Jialuhe River catchment of the Yellow River. Dou et al. [39] also found significant downward trends in annual runoff, surface runoff, and baseflow in their study on the impact of conservation measures on streamflow responses in the Wuding River of the LP over the last 50 years. Additionally, Mu et al. [40] seemingly found no significant effect of conservation measures on baseflow in two typical loess hilly-gully watersheds of the LP over 26 years with similar physical landform characteristics. Moreover, there are some studies indicating a limited streamflow response to land cover changes, especially when the vegetation cover has reached a certain high degree. For example, Buttle et al. [41] indicated that implications of forest disturbance on streamflow from relatively large rivers in the Canadian boreal forest were limited; Zhang et al. [42] found that the effect of preventing water and soil runaway is relatively stable when the vegetation coverage is greater than 60%; Liu et al. [17] found that the river runoff after the improvement in forest and grass vegetation will eventually stabilize at a threshold value greater than the baseflow without the influence of human activities; Zhang et al. [21] concluded that a stable streamflow regime can be achieved in vegetated areas.

Although it is widely acknowledged that vegetation (especially forest) restoration has significant effects on water yield [7,27,37,43,44], the relationship between vegetation restoration and runoff is not well understood in relatively large watersheds (≥1000 km$^2$) all over the world as well as on the LP [45,46]. In addition, most of the previous studies have focused on quantifying the impact of vegetation on total streamflow [14,44], and thus the understanding of the responses of different streamflows and their components to vegetation restoration are still not clear. Therefore, it is necessary to have a better understanding of the responses of the hydrological regime, including streamflow, stormflow, and baseflow, to the vegetation restoration at different time scales in medium to large catchments for future water resource planning and management.

In this study, two underlying surfaces (the upper and middle reaches of the Beiluo River) with contrasting vegetation conditions on the central Loess Plateau were selected to compare and assess the impact of vegetation restoration on streamflow and its components in large watersheds in the LP. The consequences of this study can provide an important reference for the future ecological management of the LP and other similar areas around the world, and contribute to the understanding of the impact of vegetation change on runoff processes.

## 2. Materials and Methods

### *2.1. Description of Study Area*

The Beiluo River basin (longitude 107°32′–110°11′ E; latitude 34°–37°19′ N) is located in the LP in China (Figure 1). The Beiluo River rises in the Dingbian country of Shaanxi Province, and flows through Wuqi, Zhidan, Huangling, Huanglong, etc., before entering the Weihe River in the Dali country. The main stream's length is 680 km with a total gauging area of 26,905 km$^2$. The annual precipitation is 514.2 mm [47], of which 70% is concentrated in the four months from June to September. The landform in the basin could be divided into the hilly-gully, rocky mountain, table-gully, and terrace-plain areas (Figure 1), accounting for 26.9%, 41.8%, 23.2%, and 8.1% of the whole basin, respectively [46,47].

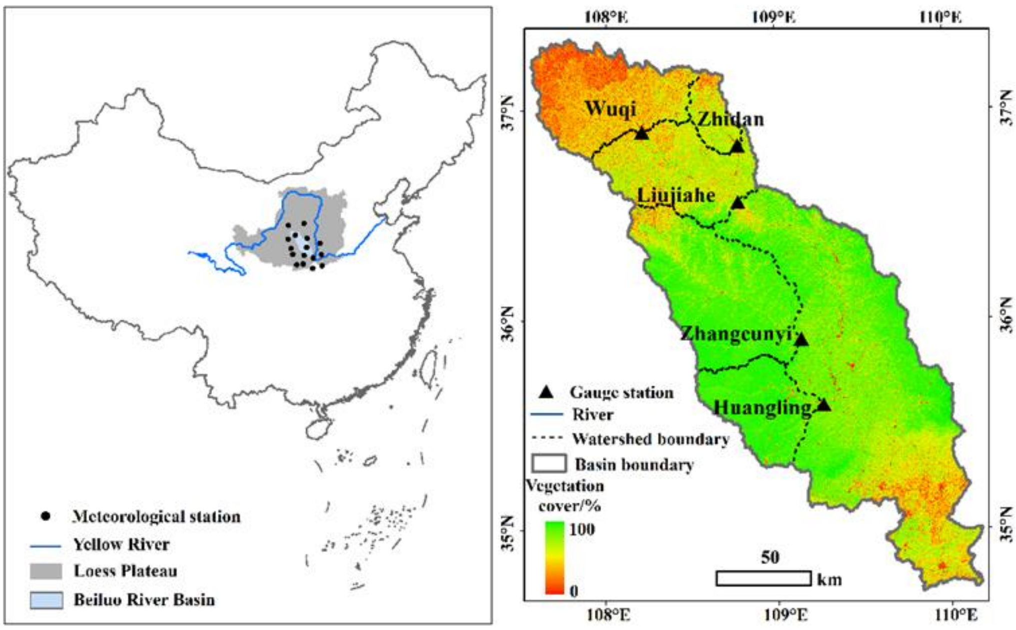


**Figure 1.** Location of the Beiluo River basin.

The Wuqi (3408 km$^2$), Zhidan (774 km$^2$), and Liujiahe (7325 km$^2$) hydrological catchments are located in the upper reaches of the Beiluo River (Figure 1) (precipitation: 425–500 mm/a; $ET_0$: 943–959 mm/a; Table 1), which was confirmed to be one of the most seriously eroded areas in the LP [25]. The forest cover of these catchments is about 40%, so we define them as less-forested catchments (LFCs). Major plantation species include

*Hippophae rhamnoides*, *Caragana korshinskii* and *C. intermedia*, *Prunus armeniaca*, *Populus simonii* and *P. hopeiensis*, *Robinia pseudoacacia*, *Pinus tabuliformis*, and *Platycladus orientalis* [48]. The upper reaches of the Beiluo River experienced mass land-use changes caused by soil conservation measures implemented in the late 1950s [28]. In particular, the Chinese government implemented the Grain for Green program in 1999, which resulted in rapid and substantial improvement in the vegetation coverage of the upper catchment since 2000 [49]. Overall NDVI for the LFCs increased from 16–23% in 1970 to 57–80% in 2019 (Table 1).

**Table 1.** Basic information for the five study watersheds.

| Gauging Station | Controlled Area ($km^2$) | Mean Annual Precipitation (mm) | Mean Annual $ET_0$ (mm) [c] | Vegetation Cover (%) [d] |
|---|---|---|---|---|
| Wuqi [A] | 3408 | 425 | 959 | 16–57 |
| Zhidan [A] | 774 | 490 | 943 | 23–80 |
| Liujiahe [A] | 7325 | 500 | 947 | 22–70 |
| Zhangcunyi [B] | 4715 | 555 | 977 | 65–88 |
| Huangling [B] | 2266 | 585 | 1061 | 68–92 |

[A] Less-forested watershed; [B] Largely forested watershed; [c] $ET_0$ indicates the FAO reference evapotranspiration according to the P–M method [49]; [d] Vegetation cover fractions based on NDVI data derived from Landsat images taken in 1970 (smaller values) and 2019 (larger values).

The Zhangcunyi (4715 $km^2$) and Huangling (2266 $km^2$) hydrological catchments are located in the middle reaches of the Beiluo River (Figure 1) (precipitation: 555–585 mm/a; $ET_0$: 977–1061 mm/a; Table 1), with a natural secondary forest area with the best preservation of vegetation, known as the Ziwuling and Huanglong Mountain forest area. The forest cover for these two catchments is over 80% and the soil erosion is slight, so we define them as forested reference catchments (FCs). The dominant vegetation cover consists of mature (>150 years), naturally regenerated forests dominated by *Quercus wutaishan* and *Pinus tabuliformis* [50].

### *2.2. Data Sources*

In this paper, we collected observed daily runoff data of the five hydrological stations from the Hydrological Yearbooks (1958–2019) published by the Hydrological Bureau of the Ministry of Water Resources of the People's Republic of China (http://www.mwr.gov.cn/ (accessed on 3 August 2020)). Primary quality control was implemented to check the accuracy of the data. In order to enhance the comparison between hydrological stations, the runoff was converted into runoff depth. The annual, monthly, and seasonal values were accumulated based on daily data.

Daily meteorological variables, including precipitation, air temperature, sunshine duration, wind speed, and relative humidity at 16 meteorological stations in and around the Beiluo River region (Figure 1) for the period 1950–2018 were provided by the National Climatic Center of the China Meteorological Administration (http://cdc.nmic.cn/, (accessed on 29 January 2019)). The potential evapotranspiration data for five hydrological stations were calculated on a daily scale using the P–M method [51]. All the meteorological data were spatially averaged across the study area by the Cokriging interpolation algorithm using ArcGIS software.

Landsat images with a 30/80-m resolution covering the Beiluo River basin around 1970, 1980, 1990, 2000, 2010, and 2019 were collected from the United States Geological Survey (USGS; https://earthexplorer.usgs.gov/, (accessed on 29 December 2021)). The corresponding vegetation coverage (mixed categories) in each watershed was derived from the NDVI using the dimidiate pixel model [49].

## 2.3. Data Processing Methods

### 2.3.1. Flow Duration Curve

A flow duration curve (FDC) was applied to display the relationship between the magnitude and frequency of runoff for five catchments in the Beiluo River basin in this study.

Each value of discharge $Q$ has a corresponding exceedance probability $P$, and an FDC is simply a plot of $Q_P$, the $P$th quantile or percentile of streamflow, versus exceedance probability $P$, where $P$ is defined by the equation:

$$P = 1 - P\{Q_P \leq \mathrm{q}\} \tag{1}$$

The quantile $Q_P$ is a function of the observed runoff, and it is often termed the empirical quantile function due to its dependence on observations [52].

### 2.3.2. Basic Flow Index

The baseflow index (BFI) was first proposed by the Institute of Hydrology in 1980 [53]. The turning point test factor ($f$) and time interval ($N$) need to be determined when the BFI method is used to estimate baseflow. The procedure is performed as follows: the water year is divided into N-day increments, and the minimum flow during each N-day period is identified. If the product of a given minimum and turning point test factor is less than the adjacent minimums, then that minimum is a turning point. The process is repeated to determine all inflection points, and straight lines are drawn between turning points to define the baseflow hydrograph; the area beneath the hydrograph is an estimate of the volume of baseflow for the period [54]. In this study, the daily baseflow data of five hydrological stations were obtained by dividing daily runoff using the BFI method. In the end, the baseflow hydrograph estimated by the BFI method was stable with $f$ = 0.95 and $N$ = 5.

### 2.3.3. Mann–Kendall Trend Test

The Mann–Kendall trend test proposed and developed by Mann and Kendall [55,56] is a rank-based nonparametric method. The Mann–Kendall trend test can handle data that are missing, below the detection limits, or non-normally distributed. It has been widely used to test the significance of trends in hydrological time-series data.

In this study, the Mann–Kendall test was applied to decide the trend of the runoff component data. The Mann–Kendall trend test was performed using the R package "trend" (https://cran.r-project.org/web/packages/trend/, (accessed on 26 March 2023)) under the R environment software 3.6.3 (https://cran.r-project.org, accessed on 29 February 2020).

### 2.3.4. Anomaly and Cumulative Anomaly

The anomaly value represents the degree of deviation between a data point and the average value of the series within a certain period, including negative anomalies (data greater than the average) and positive anomalies (data less than the average). The cumulative anomaly value is obtained by adding all anomaly values in the series. From the cumulative anomaly curve, the long-term significant evolution trend, continuous change, and change point of streamflow and its components can be intuitively determined [57]. The calculation formula is as follows:

$$L_i = \sum_{i}^{N} (P_i - \overline{P}) \tag{2}$$

where $L_i$ is the accumulated anomaly value in the $i$-th year, $P_i$ is the streamflow and its component variable value in the $i$-th year, and $P$ is the multi-year average value of the streamflow and its component.

## 3. Results

### *3.1. Variation Characteristics of Daily Streamflow and Its Components in LFCs and FCs*

To examine changes in the streamflow regime of the catchments, daily flow duration curves for each decade of records were constructed as shown in Figure 2. A common feature of the FDCs of daily streamflow from LFCs is that they gradually decrease in the high flows (0 to 5th percentiles on the FDC) of the curve, while they gradually increase in the low flows (70th to 100th percentile on the FDC) at different period points, especially in the 2000s and 2010s (Figure 2a1–c1). The FDCs from FCs showed a parallel change characteristic because, when compared with the 1960s and 1970s, the low flow of the FDCs show an increase at different period points (Figure 2d1,e1). As to the Huangling catchment, there is a uniform change in all the percentile flows of FDCs at each period point (Figure 2e1).

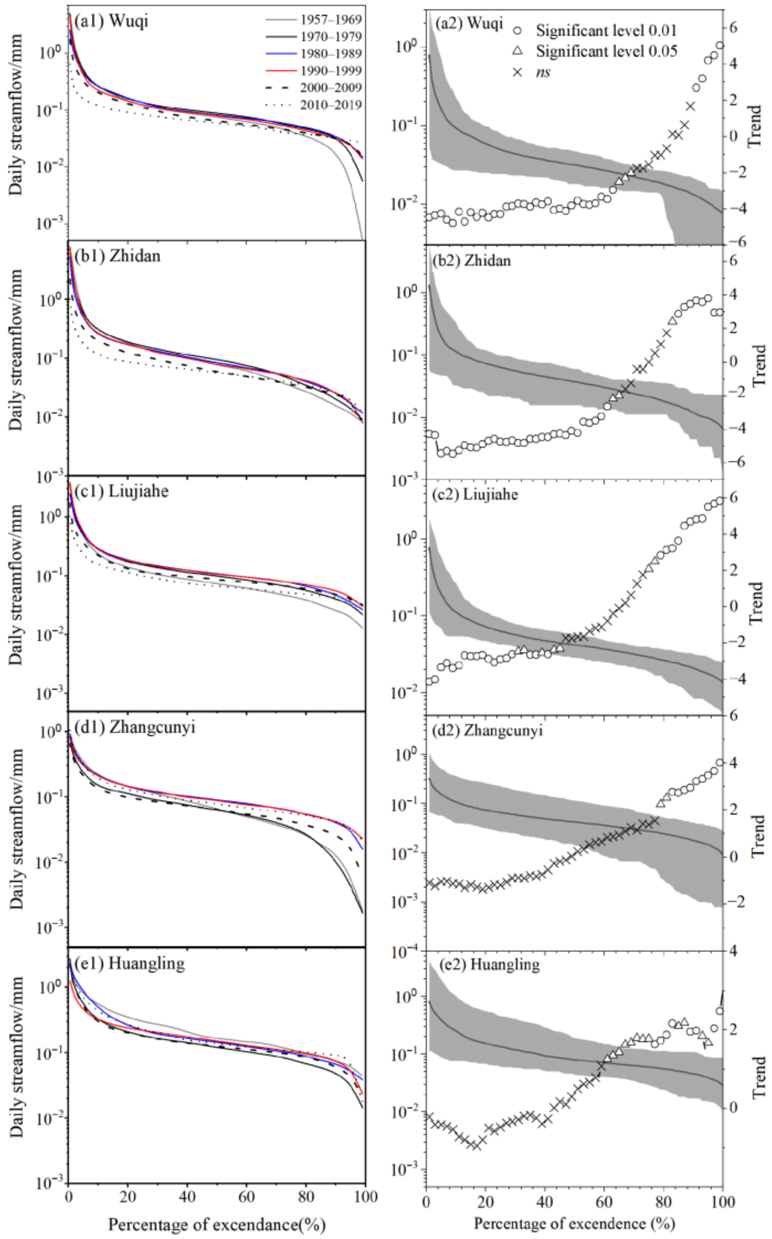


**Figure 2.** The flow duration curve and its trends, statistically significant levels, and ranges of daily streamflow series at the (**a**) Wuqi, (**b**) Zhidan, (**c**) Liujiahe, (**d**) Zhangcunyi, and (**e**) Huangling catchments. The solid line represents the means of all daily streamflow series, the upper and lower boundary of the gray strip represents the maximum and minimum of all daily series.

The long-term trends in each percentile's flows of FDC were analyzed using the Mann–Kendall trend test to identify trends of runoff components in the LFCs and FCs. Compared with the other catchments, little relative variability in daily streamflow occurred in FCs, indicated with gentle slopes in the FDCs (Figure 2d2,e2). Moreover, the dynamic daily streamflow range in LFCs is larger than that in FCs (Figure 2a2–c2), indicating that the flows had high variability. The FDCs of daily streamflow from LFCs have a significant negative trend in high flows and positive trend in low flows, but FCs have a significant positive trend in low flows, implying that a much more stable daily streamflow can be achieved in highly vegetated areas. In addition, the FDCs of daily baseflow also indicated that there has been a significant positive trend in low flows in all catchments, except for the Zhidan catchment.

### *3.2. Trends of Annual, Seasonal, and Monthly Streamflow and Their Components in LFCs and FCs*

To further understand the variation in hydrological regimes, the BFI method was used to split the total streamflow into stormflow and baseflow, and the trend and variation in annual, seasonal, and monthly streamflow and their components were analyzed based on the Mann–Kendall trend test and the cumulative anomaly method.

As shown in Figure 3a,d,g, the annual streamflow in the LFCs of the Beiluo River basin showed a decreasing trend at a rate of 0.27–0.70 mm/a, and, simultaneously, the baseflow showed a slight increasing trend except in the Zhidan catchment (with a decreasing trend at a rate of 0.03 mm/a). Conversely, the annual streamflow and baseflow in FCs of Beiluo River basin exhibited a slight increasing trend (Figure 3j,m).

The anomaly and cumulative anomaly revealed that the total streamflow in the LFCs has a change point around 2000, and the anomaly is mainly negative after 2000, while the baseflow is relatively stable during the 60-year overall study period (Figure 3b,c,e,f,h,i). Conversely, the anomaly and cumulative anomaly for total streamflow and baseflow for the FCs were very different from those observed for the LFCs: the positive and negative anomalies of total streamflow and baseflow alternate during the study period. For example, the total streamflow and baseflow in the Zhangcunyi catchment were mainly negative anomalies in 1958–1975, positive anomalies in 1976–1994, but negative anomalies in 1995–2019 (Figure 3k,l), while in the Huangling catchment they were mainly negative anomalies in 1967–1980, positive anomalies in 1980–2000, but negative anomalies in 2000–2019 (Figure 3n,o). That indicates that the wet years and dry years of total streamflow and baseflow in FCs are obvious.

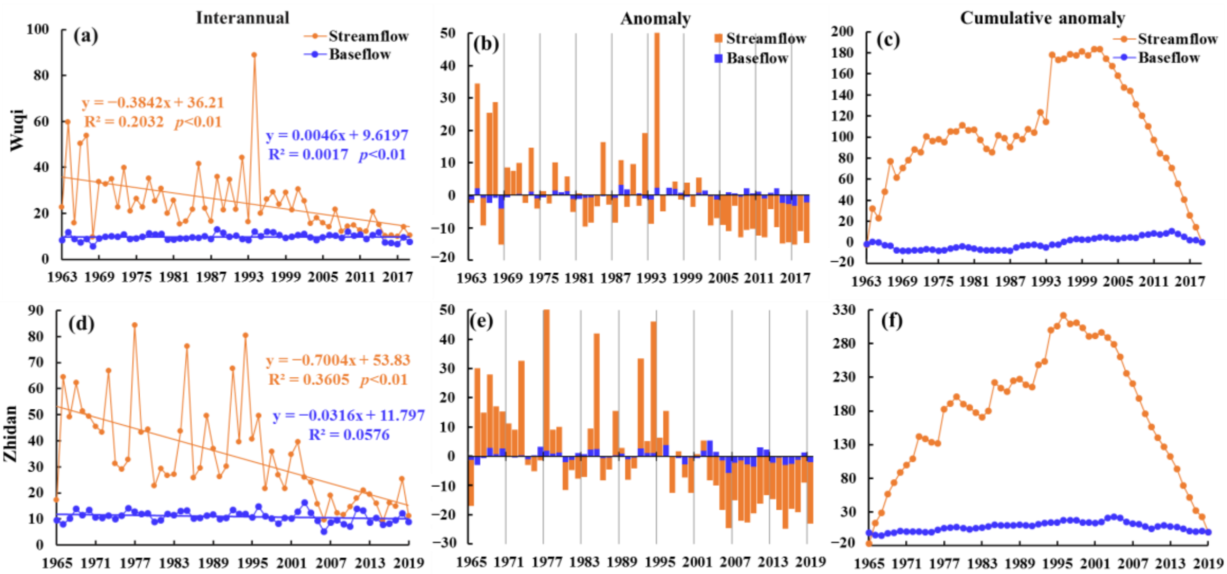


**Figure 3.** *Cont.*

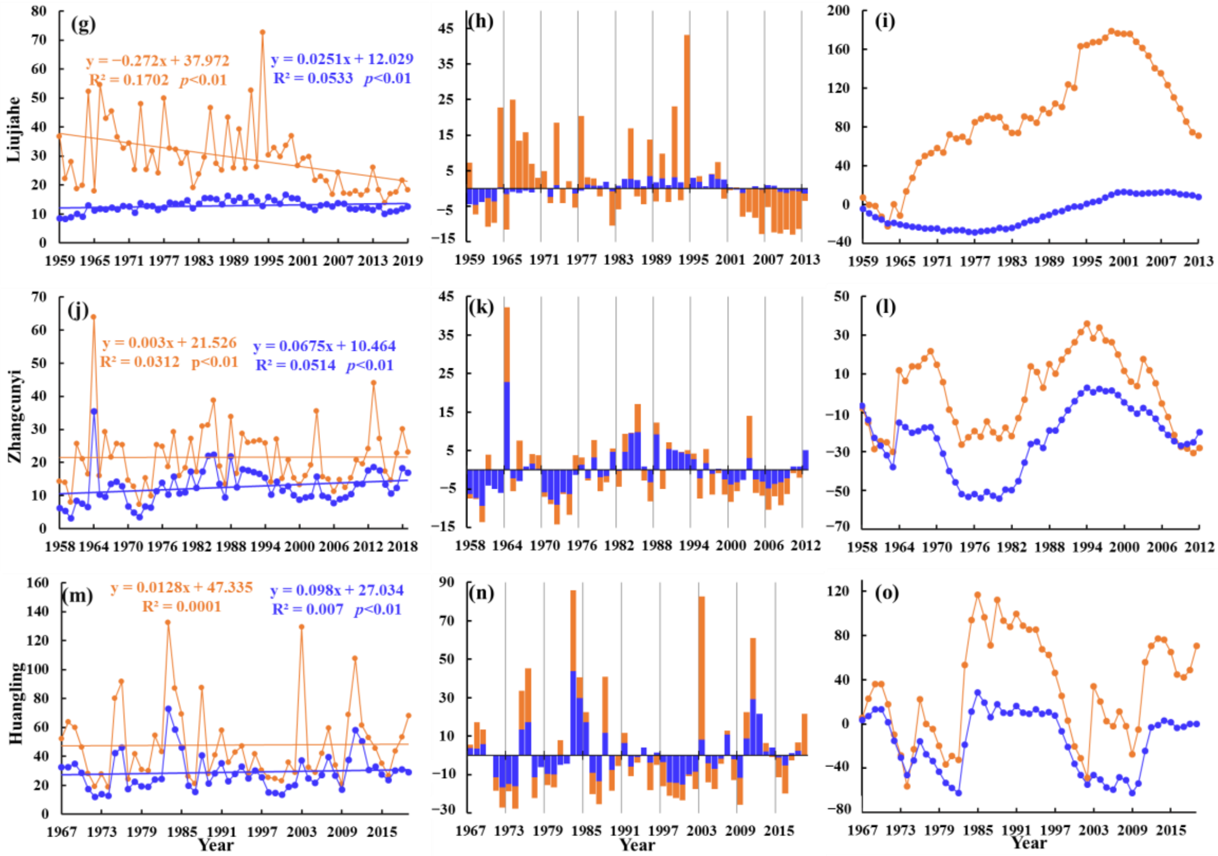


**Figure 3.** Interannual anomaly and cumulative anomaly of streamflow and its components in the Beiluo River basin.

Table 2 shows that the precipitation in all five watersheds showed a non-significant decreasing trend with time, while $ET_0$ in four out of the five watersheds also exhibited a decreasing trend (Table 2). However, the mean annual streamflow was 25.07~34.21 mm in the LFCs and 21.62~48.02 mm in the FCs during 1958–2019. The average proportion of baseflow in streamflow was approximately 31.89~43.36% in the LFCs and 58.23~60.14% in the FCs during the study period (Table 2). The annual streamflow for LFCs exhibited a significant decrease at a rate of −0.27~−0.70 mm/a at $p < 0.001$ but exhibited insignificant changes in FCs during 1958–2019. The trends of annual stormflow exhibited a significant decrease in all five catchments. The annual stormflow for LFCs showed a significant decrease at a rate of −0.29~−0.64 mm/a ($p < 0.001$), while the FCs showed the weakest trend of −0.05~−0.11 mm/a. For the baseflow, the Zhidan catchment showed significant decreasing trends, and the Zhangcunyi catchment showed statistically significant increasing trends ($p < 0.05$), while other catchments showed no significant increasing trends over the period of record.

To investigate the variation characteristics of streamflow and its components on the monthly scales, the monthly streamflow and baseflow for each decade of records were constructed as shown in Figure 4. Changes in the LFCs and FCs of the streamflow and its components showed different patterns during the study period. In the LFCs (Figure 4a–c), we observed the streamflow had two peaks: a first one in spring (March) and a second in summer (July to August). Mean monthly baseflow was highest in two months: March and October. The peaks of the streamflow in LFCs decrease during the entire study period, except for in the 1990s, while baseflow presents little change in mean values between each period (Figure 4c). Similar to LFCs, we also observed that the streamflow and baseflow had two peaks: in spring (March and April) and late summer (August) or autumn (September and October) in FCs. However, the peaks for streamflow and baseflow in FCs are gentler than those in LFCs (Figure 4a–e).

**Table 2.** Trend tests of annual precipitation, reference evapotranspiration $ET_0$, total streamflow, stormflow, and baseflow for five watersheds in the Beiluo River basin from 1958 to 2019 (mm/a).

| Station | Precipitation | $ET_0$ | Streamflow | Stormflow | Baseflow |
|---|---|---|---|---|---|
| | Z/p/β | Z/p/β | M/Z/p/β [1] | M/Z/p/β | M/Z/p/β |
| Wuqi | −0.33/ns/−0.47 | 0.28/ns/0.10 | 25.07/−5.38/***/−0.38 | 15.32/−5.44/***/−0.36 | 9.75/0.42/ns/0.01 |
| Zhidan | −0.31/ns/−0.17 | 0.17/ns/0.06 | 34.21/−5.58/***/−0.70 | 23.30/−5.59/***/−0.64 | 10.91/−1.79/*/−0.03 |
| Liujiahe | −0.76/ns/−0.80 | 0.20/ns/0.02 | 29.54/−4.05/***/−0.27 | 16.73/−4.94/***/−0.29 | 12.81/1.20/ns/0.03 |
| Zhangcunyi | −1.18/ns/−1.17 | 0.50/ns/0.13 | 21.62/0.46/ns/0.01 | 9.03/−1.81/*/−0.05 | 12.59/1.79/*/0.07 |
| Huangling | −0.75/ns/−0.42 | −0.84/ns/−0.45 | 48.02/0.24/ns/0.01 | 18.66/−1.51/ns/−0.11 | 29.36/1.25/ns/0.10 |

[1] M/Z/p/β indicate the mean value, statistical trend test assessment value, and significance level and average slope change, respectively; the symbols '*, ***, ns' indicate the significance level of 0.05, 0.001, and not significant, respectively.

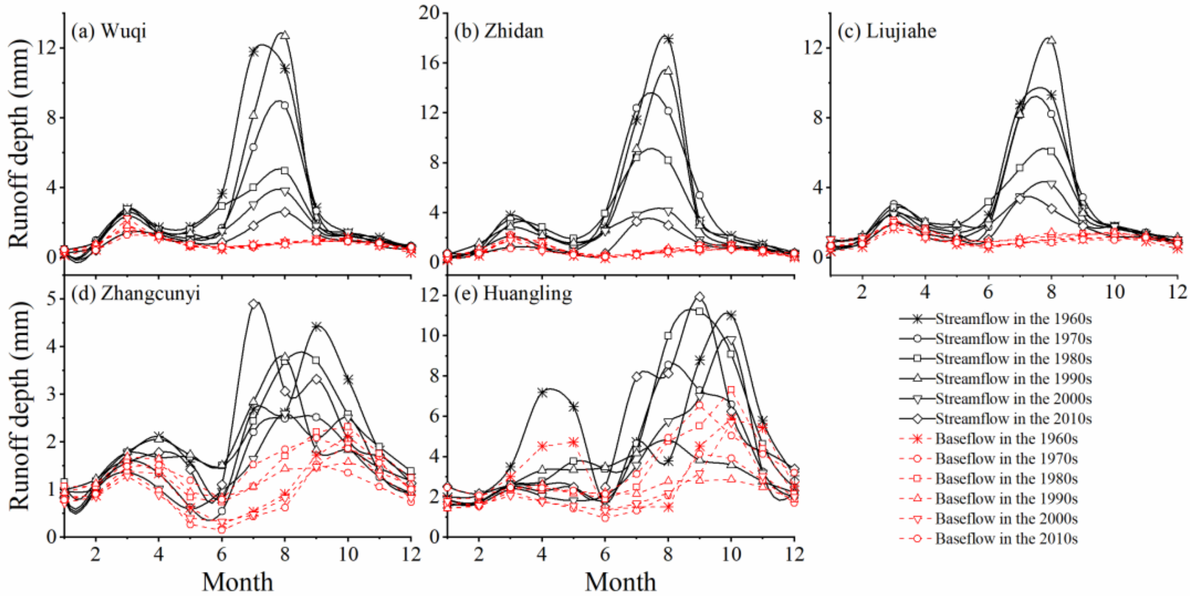


**Figure 4.** Comparison of annual distribution hydrographs of streamflow and its components in LFCs (**a**–**c**) and FCs (**d**,**e**) in the Beiluo River basin.

To further investigate their variability, the trends of seasonal streamflow, stormflow, and baseflow from five catchments were analyzed (Table 3). The streamflow for all three LFCs significantly decreased ($p < 0.05$) in spring, summer, autumn, flood season, and non-flood season, whereas in FCs they showed only slight decreases ($p > 0.05$). The stormflow changes for all three LFCs exhibited significant negative trends on seasonal time scales ($p < 0.001$), whereas the changes for the FCs were significantly negative trends only in spring, winter, and non-flood season ($p < 0.001$). The baseflow changes for LFCs exhibited positive trends in winter, with the increase being significant for the Zhidan and Liujiahe catchments ($p < 0.001$), whereas the changes for FCs were significantly positive trends in summer (Table 3).

**Table 3.** Summary of Mann–Kendall trend analyses for streamflow, stormflow, and baseflow from LFCs and FCs in the Beiluo River basin (mm/a).

| Catchment | Components | Spring | Summer | Autumn | Winter | Flood Season | Non-Flood Season |
|---|---|---|---|---|---|---|---|
| Wuqi | Streamflow | −0.046 *** | −0.274 *** | −0.036 ** | −0.006 | −0.251 *** | −0.106 *** |
| | Stormflow | −0.038 *** | −0.276 *** | −0.030 *** | −0.009 *** | −0.243 *** | −0.085 *** |
| | Baseflow | −0.002 | 0.003 | −0.007 | 0.003 | −0.002 | 0.004 |

**Table 3.** *Cont.*

| Catchment | Components | Spring | Summer | Autumn | Winter | Flood Season | Non-Flood Season |
|---|---|---|---|---|---|---|---|
| Zhidan | Streamflow | −0.118 *** | −0.423 *** | −0.083 *** | 0.002 | −0.441 *** | −0.210 *** |
| | Stormflow | −0.058 *** | −0.411 *** | −0.060 *** | −0.015 *** | −0.430 *** | −0.162 *** |
| | Baseflow | −0.035 *** | 0.001 | −0.014* | 0.017 *** | −0.007 | −0.021 |
| Liujiahe | Streamflow | −0.034 * | −0.226 *** | −0.032 ** | 0.016 *** | −0.222 *** | −0.058 ** |
| | Stormflow | −0.028 *** | −0.219 *** | −0.026 *** | −0.009 *** | −0.217 *** | −0.061 *** |
| | Baseflow | −0.003 | 0.003 | −0.002 | 0.024 *** | −0.001 | 0.026 * |
| Zhangcunyi | Streamflow | 0.002 | 0.029 | 0.003 | −0.004 | 0.014 | 0.009 |
| | Stormflow | −0.018 *** | −0.004 | −0.016 * | −0.005 *** | −0.012 | −0.032 *** |
| | Baseflow | 0.019 | 0.033 ** | 0.026 | 0.001 | 0.03 | 0.035 |
| Huangling | Streamflow | −0.022 | 0.013 | −0.007 | 0.03 | 0.015 | 0.064 |
| | Stormflow | −0.028 *** | −0.048 | −0.023 | −0.011 *** | −0.036 | −0.061 *** |
| | Baseflow | −0.001 | 0.061 * | 0.019 | 0.043 | 0.049 | 0.106 |

The symbols '*, **, ***' indicate the significance level of 0.05, 0.01, and 0.001, respectively. Spring: March to May; Summer: June to August; Autumn: September to November; Winter: December to the following February; Flood season: July to September; Non-flood season: October to the following June.

### 3.3. Stationary of Streamflow and Its Component in LFCs and FCs of Beiluo River Basin

We tested differences in the mean values between different periods for LFCs and FCs by using ANOVA (analysis of variance). Significant differences were found in the decadal mean values of streamflow and stormflow in the LFCs before and after 2000, which is consistent with Figure 3. The mean decreased by an average of 50% after 2000, compared to that before 2000 (Figure 5a,b). Compared to the streamflow in the LFCs, there were no significant differences in mean values between different periods observed for the streamflow for either of the Zhangcunyi or Huangling catchment, as evidenced by *p*-values greater than 0.05 (Figure 5a). In addition, there were no significant differences in mean values between each period observed for the stormflow and baseflow for the Huangling catchment (Figure 5b,c). This indicates that the FCs with a history of 150 years and mature and stable vegetation structures have stable hydrological regimes. These changes again illustrated the variability and stability in these catchments.

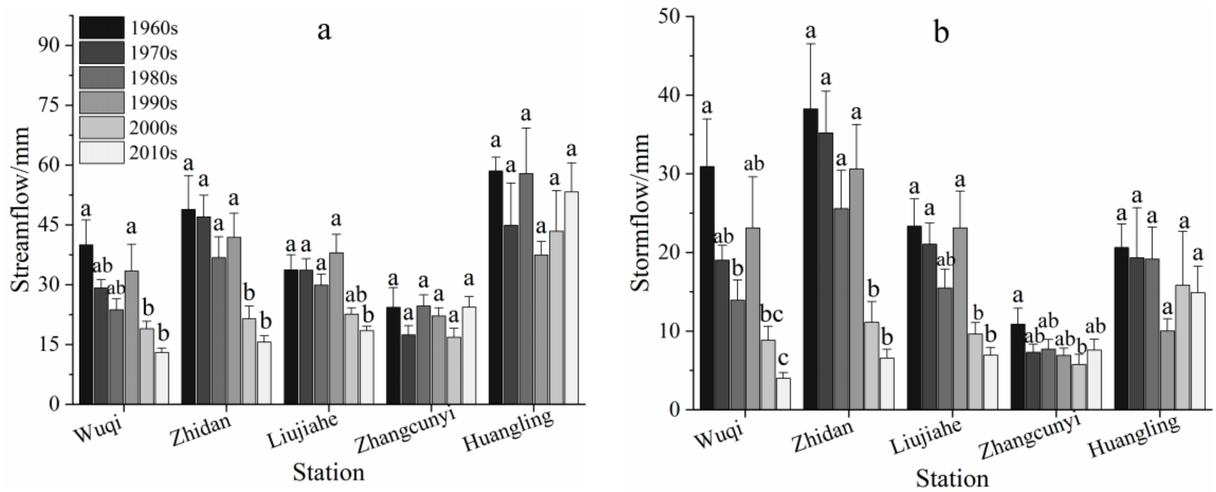


**Figure 5.** *Cont.*

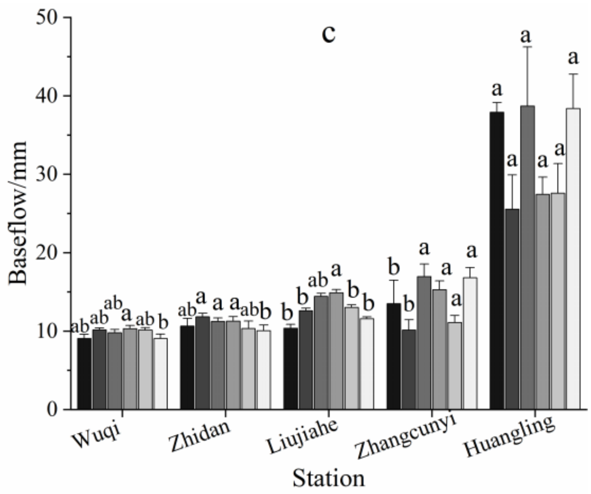


**Figure 5.** The analysis of variance for the streamflow, stormflow, and baseflow of LFCs and FCs in each decade year (the values are means ± standard error).

## 4. Discussion

### *4.1. Impact of Vegetation Restoration on Hydrological Regimes in LFCs*

Annual precipitation and annual PET in the LFCs and FCs showed no significant trends [50] (Table 2), and thus suggested that streamflow and its component changes can be attributed mainly to the vegetation restoration, which is the most important human activity in the LP in recent decades [58]. Therefore, it is important to have a better understanding of how vegetation restoration affects hydrological regimes for future water security and water resources management of the LP.

Our results showed that the annual streamflow in LFCs showed relatively uniform reductions, except for in the 1990s, whereas the streamflow increased slightly in FCs (see Figure 3). The stormflow showed more drastic reductions, and baseflow exhibited an increase (expect for in the Zhidan catchment) in all five catchments (Table 2). There are several reasons for this.

Firstly, the engineering measures such as dams and terraces were the main measures to prevent soil and water erosion during the 1960s to 1980s, while vegetation measures, though having also been applied, had a limited effect on runoff due to the low survival rate of vegetation [59]. The dams affect streamflow by storing water within reservoirs for irrigation purposes [60]. Meanwhile, the gentle slope of terraces enhances precipitation infiltration and reduces stormflow, and the blocked stormflow will be converted into baseflow outflow as Zhang et al. [61] and Li et al. [62] suggested. Thus, engineering measures dominantly contributed to the changes in total streamflow and its components before the 1990s.

In addition, the unusual streamflow of LFCs in the 1990s (see Figures 3 and 4) may be caused by extreme precipitation. For instance, the 100-year precipitation event was observed in Wuqi and Zhidan on 30 August 1994, when the six-hour-long precipitation reached 251 mm [63].

Since the 1980s, the engineering measures have gradually been filling up and losing their function [31,64], thereby having relatively less impact on runoff reduction after the 1990s. Conversely, vegetation measures have gradually taken the place of engineering measures and become the dominant factor in the change in streamflow and its components after 2000. In particular, the Grain for Green project has achieved initial success and the total vegetation cover in these LFCs has increased from 23% in 1970 to 80% by 2019 [65]. With the increase in vegetation cover, more precipitation is intercepted by the vegetation canopy, and the intercepted water will quickly return to the atmosphere through evaporation [15]. At the same time, vegetation transpiration also consumes substantial precipitation, resulting in the reduction in effective precipitation for runoff production. In addition, the water permeability and water storage performance of litter cover, forest roots, and soil layers are conducive to the infiltration of precipitation into the soil, which can transform the precipitation in the rainy season into soil water [66,67]. The soil water can be partially converted into baseflow through cracks and other ways, which might be the main reason for baseflow increases since 2000. As for the unusual case at the Zhidan catchment, where decreases in baseflow were detected (see Table 2), the exploitation of groundwater may be the reason [68].

### *4.2. Differences between LFCs and FCs in the Stationery and Variation Characterization of Runoff Component*

LFCs and FCs had completely different hydrological regimes. Although the annual distribution of streamflow and baseflow commonly had double peaks for FCs and LFCs, the peaks of baseflow and streamflow in FCs are inconsistent with respect to the occurrence time. This is consistent with the findings of Huang et al. [69] and Xie et al. [70]. The river runoff is low in spring, and the runoff and snow melt have a strong replenishment effect on groundwater, which increases the baseflow and forms the first peak of baseflow [38]. The short-duration rainstorm and the vigorous growing of vegetation in summer would result in a larger amount of transpiration and evaporation. In addition, the thick soil layer and small cracks in the Loess area may cause a certain delay in the replenishment of the baseflow by precipitation in the flood season, which usually takes at least 51–73 days [71]. According to this time calculation, the precipitation intercepted and infiltrated by the forest in the flood season just supplies the dry season runoff from October to December, resulting in a delay in the peak of baseflow relative to the peak of streamflow (see Figure 4).

Moreover, the LFCs had a higher peak runoff than the FCs (see Figure 4), which may be due to the difference in interception and infiltration capacity between them. The Beiluo River basin is prone to short-duration heavy rain during the flood season. Runoff would likely occur when the precipitation intensity exceeds the infiltration rate as well as the water storage capacity of soil. FCs have a litter layer and a thick humus layer, which lead to much higher penetration rates of the root-soil layer than that in LFCs [72] and make FCs have stronger regulation and storage capacities than the LFCs, which could delay the flood fronts and reduce the runoff rates. In addition, the soil layer of the vadose zone in FCs is looser than that in LFCs, and precipitation easily penetrates into the soil, which promotes the transformation of stormflow into soil water and baseflow. In the dry season, river runoff is mainly supplied by water stored in the basin. The implicit moisture in forest soil can increase the low flow in the basin and keep the river runoff uniform and stable. Conversely, the low infiltration rate and water storage capacity of LFC soils result in precipitation not infiltrating and replenishing baseflow, but flowing into the catchment and channel as stormflow, leading to a rapid increase in peak flow in a short period of time.

Although the total streamflow increased non-significantly for the two FCs with similar vegetation cover during the study period (Table 2), the total streamflow of these two FCs differed significantly, with the total streamflow in the Huangling catchment being more than twice as high as that in the Zhangcunyi catchment (Table 2). There are several reasons for this. On the one hand, this could be attributed to the intense human activities such as diversion of water from rivers for irrigation in the catchment [32]. For example, the Fuzhang canal built in 1956 consumed 70% of the streamflow of the Zhangcunyi catchment [73], which greatly affects the stability of hydrological regimes of this catchment. On the other hand, the water-bearing rock group in the Huangling catchment is buried shallowly and mainly consists of mudstone and argillaceous siltstone. When these rocks encounter water, they easily deform and block water from flowing through fractures, forming an impermeable layer, which promotes lateral groundwater movement instead of very deep percolation [71].

Although the streamflow and its components of LFCs are relatively unstable compared with FCs, we found that the high-flow section of FDCs of streamflow decreases in LFCs, while the low-flow section increases with increasing vegetation coverage over the studied decades (see Figure 2), implying that the vegetation restoration can effectively regulate the hydrological regimes of LFCs. At the same time, we also note that the increase in vegetation in LFCs has resulted in a 58% reduction in runoff. Since the average annual precipitation in the LFCs is between 425 and 500 mm, its climatic conditions may not be suitable for large-scale afforestation in the future, as also confirmed in other studies [74,75]. Although revegetation attempts on the climatically unsuitable areas initially led to active growth due to the exploitation of antecedent water stored in the soil matrix [76,77], this active growth usually precludes recharging of the soil stores and leads to the formation of dry soil layers [78]. At the same time, large-scale afforestation on the Loess Plateau has led to runoff reduction, threatening water security in local and downstream areas [75]. In order to achieve sustainable forest vegetation restoration, it is necessary to implement the ecological construction principle of "soil and water determine vegetation" [75].

### 4.3. Uncertainties of Results

Baseflow is the main recharge source of river runoff, and it is important to use a stable and reliable baseflow segmentation method to analyze the time-series variation in baseflow characteristics for water resources planning and ecological protection. Although the baseflow segmentation by the BFI method is relatively reliable [79,80], the baseflow formation process is affected by many factors such as climate, soil, and geology, and the baseflow results cannot be verified by accurate monitoring data, which leads to some uncertainty in the baseflow segmentation results and thus brings uncertainty to the analytical results of the paper.

In addition, runoff may be influenced by humans taking water from the river for irrigation, which may make runoff observations low and introduce errors into the analysis results. It is also noted that streamflow measurements during winter were different from those in other months in that, since 1996, streamflow in winter has been measured on a number of fixed dates, notably on the 10th and 20th of the month from January to March and in November, and on the 5th, 15th, and 25th of the month in December. Flows during the rest of the time were deduced by interpolation between days with measured flows. This will also have some potential effect on the results.

## 5. Conclusions

Three LFCs and two FCs on the LP were selected to investigate the vegetation restoration impacts on the hydrological regimes from 1958 to 2019 using the FDC, BFI, and M–K trend test methods.

The three LFCs had significantly negative trends in annual streamflow and stormflow with average rates of $-0.27\sim-0.70$ mm/a and $-0.29\sim-0.64$ mm/a, respectively, and significant differences were found in the decadal mean values of streamflow and stormflow in the LFCs before and after 2000, which are mainly due to vegetation restoration. In addition to high flow decreases, the low flows continuously increased in LFCs, and the total and surface runoff in summer and the flood season have a significant decreasing trend, which indicated that the high flow that occurred during rainstorms decreased with vegetation restoration.

Conversely, the streamflow and its components in the FCs showed only slight fluctuations over the study period in annual trends, decadal variability, and seasonal trends over the study period, indicating that a stable streamflow regime can be achieved in areas with well-preserved vegetation.

These results suggest that vegetation restoration has played a good role in runoff regulation. Vegetation restoration has decreased total streamflow by reducing stormflow generation, and ultimately affects hydrological regimes of the restoration area. Moreover, a stable streamflow regime can be achieved in areas with high vegetation covers. Nevertheless, we need to be alert about the water security problems caused by the reduction in runoff due to vegetation restoration. These results are expected to be useful for future vegetation restoration and water resource management on the LP.

**Author Contributions:** Conceptualization, H.Y. and Y.W.; methodology, H.Y.; software, H.Y.; validation, H.Y., Y.L., and X.H.; formal analysis, H.Y.; investigation, H.Y. and Y.W.; resources, H.Y.; data curation, H.Y. and Y.W.; writing—original draft preparation, H.Y.; writing—review and editing, H.Y., Y.L., and X.H.; visualization, H.Y.; supervision, X.H.; project administration, X.H.; funding acquisition, X.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the China Postdoctoral Science Foundation (grant no. 2022M720157).

**Acknowledgments:** The authors would like to thank Xiaoping Zhang and Zhuo Chen for guidance and help on topic selection, data processing, and manuscript writing for this manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

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