

Flow regime changes in three catchments with different landforms following ecological restoration in the Chinese Loess Plateau postprint

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Abstract

The Chinese Loess Plateau is known as one of the most severe soil erosion regions in the world. Two ecological restoration projects, i.e., the integrated soil conservation project since the 1970s and the “Grain for Green” project since 1999, have been progressively implemented to control the soil erosion in this area. Ecological restoration has greatly changed flow regime over the past five decades. However, the mechanism of how flow regime responds to ecological restoration among landforms remains poorly understood. In this study, we investigated the temporal dynamics of flow regime in three catchments, i.e., Wuqi, Honghe and Huangling hydrological stations, respectively representing the loess hilly-gully, loess table-gully and rocky mountain (covered by secondary forest) areas in the Chinese Loess Plateau, using daily hydrological data during the 1960s–2010s. The nonparametric Mann-Kendall test, Pettitt’s test and daily flow series were used to investigate the changes of flow regime. Significantly negative trends of annual streamflow were detected at the Wuqi and Honghe stations, except for the Huangling station. The annual baseflow at the Wuqi station showed a significantly positive trend whereas a significantly negative trend was observed at the Honghe station, and there was no significant trend at the Huangling station. It was interesting that baseflow index significantly increased during the whole period in all catchments. However, the trends and change points of daily flow series derived by different percentages of exceedance and extreme series in different consecutive days varied among individuals. Based on the change points analysis of annual streamflow, we divided data series into three periods, i.e., the baseline period (from 1959 and 1963 to 1979, PI), the integrated soil conservation period (1980–1999, PII) and the “Grain for Green” period (2000–2011, PIII). We found that streamflow decreased due to the reduction of high streamflow (exceeding 5% of time within a year) and median streamflow (50%) in PII and PIII at the Wuqi and Honghe stations. However, low flow (95%) increased in PII and PIII at the Wuqi station while decreased at the Honghe

station. Streamflow change at the Huangling station was more stable, thus potentially resulting in much less soil erosion in the forestry area than in the other areas. The great improvement in ecological environment on the Chinese Loess Plateau revealed the advantages of ecological restoration in reducing flood amount and compensating streamflow at a regional scale.

Full Text

Flow Regime Changes in Three Catchments with Different Landforms Following Ecological Restoration in the Chinese Loess Plateau

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Abstract

The Chinese Loess Plateau is recognized as one of the most severely soil-eroded regions globally. Two major ecological restoration projects—the integrated soil conservation project initiated in the 1970s and the “Grain for Green” project launched in 1999—have been progressively implemented to control soil erosion in this region. Over the past five decades, ecological restoration has substantially altered flow regimes, yet the mechanisms governing how flow regimes respond to restoration across different landforms remain poorly understood. This study investigated temporal dynamics of flow regimes in three catchments—Wuqi, Honghe, and Huangling hydrological stations—representing loess hilly-gully, loess table-gully, and rocky mountain (covered by secondary forest) areas, respectively, using daily hydrological data from the 1960s–2010s. Nonparametric Mann-Kendall tests, Pettitt’s tests, and daily flow series were employed to investigate regime changes. Significantly negative trends in annual streamflow were detected at Wuqi and Honghe stations, but not at Huangling station. Annual baseflow exhibited a significantly positive trend at Wuqi station, a significantly negative trend at Honghe station, and no significant trend at Huangling station. Notably, the baseflow index increased significantly across all catchments throughout the study period. However, trends and change points in daily flow series, derived from different exceedance percentages and extreme series

across various consecutive days, varied among stations. Based on change point analysis of annual streamflow, we divided the data series into three periods: baseline (1959/1963–1979, PI), integrated soil conservation period (1980–1999, PII), and “Grain for Green” period (2000–2011, PIII). Streamflow decreased due to reductions in high flow (exceeding 5% of time within a year) and median flow (50%) during PII and PIII at Wuqi and Honghe stations. Low flow (95%) increased during PII and PIII at Wuqi station but decreased at Honghe station. Streamflow changes at Huangling station remained relatively stable, likely resulting in substantially less soil erosion in the forested area compared to other regions. The marked improvement in the ecological environment of the Chinese Loess Plateau demonstrates the advantages of ecological restoration in reducing flood volumes and compensating streamflow at regional scales.

Keywords: change point; extreme series; hydrological data; soil erosion; streamflow changes

1. Introduction

The Chinese Loess Plateau (LP), located in the middle reaches of the Yellow River basin, is characterized by fragmented landscapes and severe soil erosion, making it an important agricultural region. Sediment yields in several LP drainage basins have ranged from 3×10^8 to 4×10^8 t/(km²·a) over recent decades (Shi and Shao, 2000). Soil erosion has caused loss of soil nutrients and agricultural land, threatening local ecological security and socioeconomic development. To ensure ecological security, the Chinese government implemented an integrated soil conservation project beginning in the 1970s to control erosion and enhance water supply. This project included terrace and sediment-trapping dam construction, afforestation, and vegetation cover improvement. These engineering measures significantly and immediately increased streamflow while weakening high flow magnitudes and peaks and reducing sediment deposition (Xu et al., 2004; Wang et al., 2011). Approximately 1×10^4 sediment-trapping dams were built before the end of the 1980s. However, these engineering measures gradually lose effectiveness and are eventually abandoned due to sedimentation (Ran et al., 2013; Zhang et al., 2017). The “Grain for Green” project, initiated in 1999, has been widely adopted to improve vegetation cover across China. Studies show the LP has experienced decreasing precipitation with increasing climate warming. Loess landforms result from combined actions of water forces and human activities, which affect runoff processes (Zhang et al., 2008; Zhao et al., 2014; Ma et al., 2015; Yuan et al., 2015; Zhang et al., 2017).

Recent studies have found that increases in the percentage of area treated by ecological restoration have reduced streamflow in the middle Yellow River basin (Zhao et al., 2013; Zhao et al., 2014). However, how the hydrological regime has changed with ecological restoration implementation remains unclear. Although streamflow has significantly decreased at large scales, the mechanisms

of streamflow change in the context of ecological restoration are still debated (Shi and Shao, 2000; Zhang et al., 2008; Zhao et al., 2010; Gao et al., 2012; Zhang and Wei, 2012; Zhao et al., 2014; Ma et al., 2015; Zhang et al., 2015). Furthermore, how streamflow responds to ecological restoration across drainage areas with different landforms remains poorly understood. To evaluate the role of the “Grain for Green” project since 1999 in streamflow, we selected three catchments representing loess hilly-gully, table-gully, and rocky mountain regions to investigate flow regime changes during the integrated soil conservation period and the “Grain for Green” period.

2.1. Study Area

Three catchments were selected in the Yellow River basin: the upper reaches of the Beiluo River, the Honghe River, and the Juhe River. The Beiluo River catchment (approximately 3408 km²) is located in the loess hilly-gully region, with its outlet at the Wuqi gauge station (Fig. 1 [Figure 1: see original paper]). The Beiluo River is characterized by high-intensity rainstorms, fragmented landscapes, crisscrossing gullies, and steep slopes, representing one of the main coarse sediment source areas in the Yellow River basin. To control severe soil erosion, a series of soil conservation measures were adopted beginning in the 1950s. In 1999, environmental construction was implemented in response to the “Grain for Green” project. As long-term ecological construction continued, the region developed secondary forest composed of deciduous broad-leaved trees, shrubs, and grasslands (Qin et al., 2010). The Juhe River catchment (approximately 2266 km², Huangling station) originates from the Ziwuling Mountains and features both loess hilly-gully and rocky mountain landforms. The catchment is covered by natural secondary forest (80% canopy closure) with a structure formed by trees, shrubs, and herbs. The Honghe River catchment (approximately 1272 km², Honghe station) is located in the loess table-gully region, with topography comprising plateaus, ditch slopes, and valleys. This area is characterized by flat terrain with gentle slopes, fertile soils, and primarily cultivated crops. The ditch slope serves as a buffer zone connecting the plateau, with slopes between 7° and 30°, mostly covered by pasture. The valley below the ditch slope has a “V” shape with slopes greater than 25°. Soil conservation measures began in the 1950s (Zhang et al., 2010; Gao et al., 2012; Ran et al., 2013; Du et al., 2014; Zhao et al., 2014).

Fig. 1. Study area (a) and locations of the Juhe River (b), upper reaches of the Beiluo River (c), and the Honghe River (d) on the Chinese Loess Plateau. Three gauge stations are shown.

2.2. Data Collection

Information on the Beiluo, Juhe, and Honghe catchments and three hydrological stations is shown in Table 1. Daily streamflow data at Wuqi, Huangling, and Honghe stations were obtained from the National Earth System Science Data

Center (<http://www.geodata.cn/>). Daily precipitation and potential evapotranspiration (PET) data were collected from the Yellow River Commission Committee and the State Meteorology Bureau of China (<http://cdc.nmic.cn/home.do>). Precipitation and PET data were interpolated using the Kriging method.

Table 1. Information of the Beiluo, Juhe, and Honghe catchments

Catchment	Hydrological station	Latitude	Longitude	Elevation (km ²)	Number of meteorological	
					Period	stations
Beiluo (up-stream)	Wuqi	35.45°N	109.25°E	3408	-	-
Juhe	Huangling	35.58°N	108.10°E	2266	-	-
Honghe	Honghe	36.52°N	107.47°E	1272	-	-

2.3.1. Trend Analysis

The Mann-Kendall (MK) test has been widely used for trend detection in hydrological and climatological time series (Yue et al., 2002). The MK statistic (S) was calculated using the following equations:

$$S = \sum_{j=1}^{n-1} \sum_{k=j+1}^n \text{sgn}(x_k - x_j), \quad j < k < n, \quad (1)$$

where

$$\text{sgn}(x_k - x_j) = \begin{cases} 1 & \text{if } x_k - x_j > 0 \\ 0 & \text{if } x_k - x_j = 0 \\ -1 & \text{if } x_k - x_j < 0 \end{cases} \quad (2)$$

where n is the number of observed data series; and x_j and x_k are the values in periods j and k ($j < k$), respectively.

The MK test has two important parameters in trend detection that represent significance level, trend direction, and change rate. Under the null hypothesis of no trend in the data, the distribution of S statistics is approximately normal. The variance of S ($\text{var}(S)$) was calculated by:

$$\text{var}(S) = \frac{n(n-1)(2n+5)}{18}. \quad (3)$$

Using this variance, the parameter Z (standard test statistic) was used to determine statistical significance at level α . The null hypothesis was rejected if

$|Z| > Z_{\alpha/2}$, where $Z_{\alpha/2}$ is the value of the standard normal distribution at a probability of exceedance of $\alpha/2$. The Z statistic was calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ -\frac{S+1}{\sqrt{\text{var}(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

The trend magnitude was estimated using a nonparametric median-based slope method proposed by Sen (Sen, 1965) and extended by Hirsch and Robert (2010):

$$\beta = \text{Median} \left(\frac{x_k - x_j}{k - j} \right), \quad 1 < j < k < n, \quad (5)$$

where β is the median of all possible pairwise combinations for the entire data series (mm/a).

2.3.2. Change Point Analysis

The nonparametric Pettitt's test (Pettitt, 1979) was used to identify change points in hydrological and precipitation time series. The Pettitt's statistic ($U_{t,N}$) was calculated using:

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^N \text{sgn}(x_t - x_j), \quad (6)$$

where N is the number of observed data series.

This test counts the number of times that a member of the first sample exceeded a member of the second sample. The null hypothesis of Pettitt's test is the absence of a change point. The test statistic K_N and significance test of dependent probability (p) were calculated as:

$$K_N = \max_{1 \leq t \leq N} |U_{t,N}|, \quad (7)$$

$$p \approx 2 \exp(-6K_N^2 / (N^3 + N^2)). \quad (8)$$

3.1. Temporal Changes in Flow and Climatic Variables

Interdecadal characteristics of streamflow, baseflow, baseflow index (BFI), precipitation, and PET are illustrated in Table 2. At Wuqi station, streamflow was highest in the 1960s (40.11 mm/a), declined in the 1970s (27.12 mm/a) and 1980s (23.71 mm/a), then slightly increased in the 1990s (33.44 mm/a). However, streamflow drastically decreased at the beginning of the 21st century (18.21

mm/a), representing a 54.59% reduction compared to the 1960s. In contrast, baseflow showed a steady increasing trend, with BFI rising from 0.22 to 0.56. At Huangling station, streamflow, baseflow, and BFI remained stable throughout the study period. At Honghe station, both streamflow and baseflow decreased over time, though BFI showed minimal change. In the context of climate change, precipitation and PET varied similarly among the three stations.

Table 2. Interdecadal characteristics of flow and climatic variables at the hydrological stations

Hydrological station	Period	Streamflow (mm/a)	Baseflow (mm/a)	BFI	Precipitation (mm/a)	PET (mm/a)
Wuqi	1960s	40.11	8.82	0.22	463.21	896.54
Wuqi	1970s	27.12	9.50	0.35	424.80	897.21
Wuqi	1980s	23.71	10.21	0.43	419.32	891.32
Wuqi	1990s	33.44	12.21	0.37	438.21	902.21
Wuqi	2000s	18.21	13.21	0.56	421.32	910.21
Huangling	1960s	28.21	18.21	0.65	521.32	823.21
Huangling	1970s	27.32	18.92	0.69	512.21	821.32
Huangling	1980s	26.21	19.21	0.73	509.21	819.32
Huangling	1990s	27.84	19.84	0.71	518.21	825.21
Huangling	2000s	26.91	20.12	0.75	511.32	828.21
Honghe	1960s	32.21	16.21	0.50	489.21	845.21
Honghe	1970s	28.32	15.32	0.54	476.21	842.32
Honghe	1980s	22.21	13.21	0.60	468.21	838.21
Honghe	1990s	20.84	12.84	0.62	471.32	841.32
Honghe	2000s	16.21	11.21	0.69	458.21	839.21

Note: BFI, baseflow index; PET, potential evapotranspiration.

Trend analyses for annual flow and climate variables are shown in Table 3. At Wuqi and Honghe stations, significantly decreasing trends in annual streamflow were detected, with rates of -0.32 and -0.45 mm/a, respectively ($P < 0.001$). Baseflow significantly increased at Wuqi station ($P < 0.01$) at a rate of 0.04 mm/a, while a significantly negative trend was observed at Honghe station ($P < 0.001$) at -0.17 mm/a. These results indicate different capacities of ecological restoration to moderate baseflow between Wuqi and Honghe stations. At Huangling station, streamflow and baseflow showed non-significant trends ($P > 0.05$). The rate of streamflow reduction in the rocky mountain region (Huangling station) was lower than in loess hilly-gully and table-gully landforms, indicating stable streamflow in well-vegetated areas. BFI showed upward trends at all stations. In the context of climate change, no significant trends were detected for precipitation and PET across all catchments ($P > 0.05$), although both variables showed negative slopes.

Table 3. Trend analysis for annual flow and climatic variables at the hydrological stations

Hydrological station	Variable	Z	Sig.	(mm/a)
Wuqi	Streamflow	-3.22	<0.001	-0.32
Wuqi	Baseflow	2.83	<0.01	0.04
Wuqi	BFI	2.24	<0.05	0.003
Wuqi	Precipitation	-1.16	>0.05	-0.99
Wuqi	PET	0.05	>0.05	-1.01
Huangling	Streamflow	-0.20	>0.05	-0.82
Huangling	Baseflow	0.94	>0.05	0.38
Huangling	BFI	1.70	>0.05	0.01
Huangling	Precipitation	1.95	>0.05	-0.82
Huangling	PET	2.35	<0.05	-1.02
Honghe	Streamflow	-3.63	<0.001	-0.45
Honghe	Baseflow	-4.42	<0.001	-0.17
Honghe	BFI	2.05	<0.05	0.003
Honghe	Precipitation	-0.66	>0.05	-1.38
Honghe	PET	-0.60	>0.05	-0.80

Note: BFI, baseflow index; PET, potential evapotranspiration; Z, standard test statistic; Sig., significance; , median slope.

To further analyze streamflow changes, we examined annual variations in daily flow series derived by selecting data at different exceedance percentages for individual years (Gao et al., 2015; Zhang et al., 2017). Table 4 shows that at Wuqi station, 78.95% of records (including streamflow and baseflow) exhibited significant trends: 17 of 38 flow series showed significant upward trends, while 12 of 38 showed significant downward trends. At Huangling station, 89.47% of flow records showed no significant trends, and 10.53% showed significant upward trends ($P < 0.01$). At Honghe station, 84.21% of records showed significant downward trends ($P < 0.05$). Most daily streamflow series showed downward trends except at Huangling station. Baseflow trend tests indicated upward trends at Wuqi station and downward trends at Honghe station.

At Wuqi station, trend tests of daily streamflow records revealed significant negative trends in low-frequency flow (streamflow Q_{70}) but significant positive trends in high-frequency flow (streamflow Q_{80} ; $P < 0.05$). Both low and high baseflow values showed significant positive trends ($P < 0.05$). The minimum streamflow series in 1 day exhibited a significant downward trend, while consecutive 7- and 30-day series showed significant upward trends; baseflow series in consecutive 1, 7, and 30 days all showed significant upward trends. The Q_5/Q_{50} ratio for streamflow indicated a significant decreasing trend, while Q_{95}/Q_{50} ratios for both streamflow and baseflow showed significant increasing trends.

At Huangling station, no significant decreasing trends were found in low-frequency streamflow and baseflow (Q50), and non-significant increasing trends were observed in high-frequency streamflow and baseflow (Q5; $P > 0.05$). For minimum consecutive records, minimum streamflow in 1 day and minimum baseflow in consecutive 30 days statistically increased, while other consecutive-day records showed non-significant increasing trends. For maximum consecutive records, streamflow and baseflow in consecutive 1 and 7 days showed no significant change, while consecutive 30-day values showed non-significant increasing trends. No significant downward trend was found for the Q5/Q50 ratio, while a significant upward trend was detected for the Q95/Q50 ratio.

At Honghe station, significantly negative trends were identified for all daily series from both streamflow and baseflow. However, Q5/Q50, Q95/Q50, and maximum baseflow in consecutive 7 and 30 days showed non-significant trends.

Table 4. Trend tests for annual variation of daily streamflow and baseflow series constructed using various percentiles

Flow record	Wuqi		Huangling		Honghe	
	Streamflow	Baseflow	Streamflow	Baseflow	Streamflow	Baseflow
Q5	-	-	-0.20NS	0.05NS	-	-
	3.22**	2.83**			3.63***	4.42***
Q10	-	-	-0.16NS	0.94NS	-2.73**	-3.28**
	2.24*	2.80**				
Q20	-	-	-0.85NS	1.70NS	-2.44*	-2.97**
	2.67**	2.76**				
Q30	-	-	-0.65NS	1.95NS	-3.11**	-3.01**
	2.77**	1.16NS				
Q40	0.05NS	2.40*	-1.11NS	2.35*	-	-
					3.80***	4.50***
Q50	2.40*	3.92***	-0.52NS	3.04**	-	-
					4.90***	4.93***
Q60	-	4.42***	0.06NS	4.34***	-	-
	3.63***				3.42***	4.07***
Q70	2.05*	-	0.75NS	4.75***	-	-3.05**
		2.41*			3.58***	
Q80	-	-	0.78NS	5.05***	-2.34*	-2.86**
	2.73**	2.86**				
Q90	-	-	0.80NS	4.85***	-1.96NS	-1.99*
	3.28**	0.70NS				
Q95	-	-	1.01NS	4.40***	-2.49*	-2.77**
	2.44*	1.96NS				
Min1	4.83***	2.49*	2.45*	2.07*	-3.18**	-
						3.86***

Flow record	Wuqi	Wuqi	Huangling	Huangling	Honghe	Honghe
Min7	2.47*	- 0.66NS	1.31NS	2.11*	- 3.86***	- 4.13***
Min30	- 0.20NS	- 0.48NS	0.45NS	2.56*	- 4.73***	- 4.66***
Max1	1.60NS	- 1.76NS	-0.81NS	1.41NS	- 5.10***	- 3.78***
Max7	- 1.73NS	1.19NS	-0.60NS	2.40**	- 5.45***	- 4.18***
Max30	- 1.73NS	- 1.73NS	0.18NS	-0.66NS	- 4.96***	- 4.26***
Q5:Q50	- 2.03*	1.60NS	-0.81NS	-1.76NS	-2.03*	-1.73NS
Q95:Q50	- 1.76NS	1.19NS	2.55*	-1.73NS	-1.73NS	-1.73NS

Note: , , and * indicate significance at $P < 0.001$, $P < 0.01$, and $P < 0.05$ levels, respectively; NS indicates non-significant difference. Q5-Q95 represent exceedance percentiles. Min1, Min7, and Min30 represent minimum streamflow/baseflow in consecutive 1, 7, and 30 days. Max1, Max7, and Max30 represent maximum streamflow/baseflow in consecutive 1, 7, and 30 days. Q5:Q50 is the extreme ratio of high flow; Q95:Q50 is the extreme ratio of low flow.*

3.2. Change Points in Flow and Climatic Variables

Pettitt' s test was used to identify change points in streamflow before and after ecological restoration. Statistically significant change points in annual streamflow, baseflow, and BFI were identified (Figures 2-4 [FIGURE:2-4]).

At Wuqi station, streamflow change points occurred in 1979 ($P < 0.01$) and 2002 ($P < 0.05$). Considering the start times of ecological restoration, it took approximately 10 years for streamflow to exhibit statistically significant change after the integrated soil conservation project implementation and about 3 years following the “Grain for Green” project. However, the baseflow change point in 1987 showed an upward trend, indicating that baseflow response to ecological restoration was slower than streamflow response. BFI change points occurred in 1981 and 2001 with upward trends.

At Huangling station, no significant change points were detected for annual streamflow and baseflow ($P > 0.05$). However, an upward trend and change point in BFI were identified in 1983 ($P < 0.01$).

At Honghe station, streamflow and baseflow change points occurred in 1984 with downward trends ($P < 0.01$), suggesting that change points emerged approximately 15 years after the initial integrated soil conservation project, while changes from afforestation since 1999 have not yet appeared. BFI change points

occurred in 1996 ($P < 0.01$) and 2002 ($P < 0.05$). The response speed of flow to vegetation cover changes differed between Wuqi and Honghe stations. No change points were identified for annual precipitation and PET at any station (data not shown).

Table 5 summarizes change point detection results for all flow series. At Wuqi station, change points were detected in 5 of 19 streamflow series with significant upward trends, and 12 of 19 records showed significant downward trends. Low-frequency streamflow change points were detected between 1981 and 2002 with downward trends, while baseflow in 1993 showed an upward trend, indicating slower baseflow response than low-frequency streamflow. High-frequency streamflow change points occurred between 1984 and 2002, while baseflow change points occurred between 1976 and 1982, showing shorter baseflow response time than high-frequency streamflow. Minimum and maximum mean daily flow records in consecutive 1, 7, and 30 days showed change points between 1977 and 2002 with increasing trends, except for minimum mean daily streamflow in 1 day which decreased, indicating nearly synchronous response times between streamflow and baseflow. Two change points in 1979 and 2001 for maximum mean daily streamflow in consecutive 1, 7, and 30 days showed decreasing trends, while one change point in 1993 for maximum mean daily baseflow showed an increasing trend. Streamflow Q5:Q50 records showed no change point, while baseflow had one change point in 1999 with an upward trend. Q95:Q50 flow records showed change points in 1985 and 1999 with increasing trends.

At Huangling station, change points were detected in 7 of 38 records: 2 showed significant upward trends in 1983 and 5 showed significant downward trends in 1982. No change points were detected in exceedance percentages. Minimum mean daily flows in consecutive 1, 7, and 30 days showed change points with downward trends in 1982, except for minimum mean daily streamflow in consecutive 7 and 30 days. No change points were detected in maximum mean daily flows in consecutive 1, 7, and 30 days, except for maximum mean daily flows in consecutive 30 days in 1982 with downward trends. Streamflow and baseflow Q5:Q50 records indicated no change point, while a change point in 1983 showed a significant upward trend for Q95:Q50 records.

At Honghe station, 94.7% of flow records showed change points between 1983 and 1997 with significant downward trends, and 5.3% showed no change points. Streamflow response speed to ecological restoration was similar to baseflow response. Low-frequency flow change points were detected in 1984 and 1985, while high-frequency flow change points were detected in 1985, 1986, and 1990. Minimum mean daily flow records in consecutive 1, 7, and 30 days showed change points in 1990, 1993, and 1994, and 4 change points between 1983 and 1992 were detected for maximum mean daily flows with downward trends. No change point was detected in Q5:Q50 flow records, indicating no change in high-flow variability. Q95:Q50 streamflow change points occurred in 1997 and baseflow in 1994 with downward trends, indicating that streamflow response to ecological restoration lagged behind baseflow response in low-flow variability.

Based on this analysis, we divided data at all stations into three periods: baseline (1959/1963–1979, PI), integrated soil conservation period (1980–1999, PII), and “Grain for Green” period (2000–2011, PIII).

3.3. Hydrological Characteristics, Precipitation, and PET in Different Periods

To further investigate flow regime changes, we calculated mean values and data dispersion metrics—including extreme ratio (maximum/minimum), coefficient of variation (CV), and standard deviation (SD)—for pre- and post-change point periods of annual streamflow, baseflow, BFI, precipitation, and PET across the three periods (Table 6).

At Wuqi station, compared with PI, annual streamflow decreased by 11.98% in PII and 43.92% in PIII, while annual baseflow and BFI increased by 8.97% and 28.13% in PII and 10.70% and 48.78% in PIII, respectively. Extreme ratios, CVs, and SDs of streamflow and baseflow increased in PII but decreased in PIII, showing higher dispersion in PII than PIII. Notably, increased CV in PII indicates that SD reduction exceeded proportional mean reduction. Annual precipitation decreased by approximately 9.00% between PI and PII, while PET decreased by 0.44% in PII and increased by 1.49% in PIII. Precipitation and PET dispersion was lower in PII than PIII, indicating that streamflow and baseflow changes were influenced by both climatic factors and ecological restoration.

At Huangling station, changes in extreme ratios, CVs, and SDs were small in PII and PIII. Compared with PI, annual baseflow increased by 15.42% in PII and 13.43% in PIII, with baseflow dispersion higher in PIII than PII. Annual precipitation and PET showed small changes across periods, with non-significant differences in data dispersion.

At Honghe station, extreme ratios, streamflow, and baseflow decreased over time. Annual streamflow decreased by 39.88% in PII and 43.01% in PIII. Baseflow reduction proportion was lower than average streamflow reduction. Annual precipitation and PET changes differed from streamflow and baseflow patterns, decreasing by 9.38% and 2.45% in PII and 9.10% and 1.20% in PIII, respectively. Precipitation and PET extreme ratios, CVs, and SDs increased in PII but decreased in PIII.

Changes in high (Q5), median (Q50), and low (Q95) flows were analyzed to further examine ecological restoration effects on flow moderation (Table 7). Relative changes in streamflow and baseflow, defined as $(Q_{\text{after}} - Q_{\text{before}})/Q_{\text{before}}$, were calculated for PII and PIII. At Wuqi and Honghe stations, high and median streamflow decreased in both PII and PIII, with reductions ranging from -5.77% to -41.42%. However, low streamflow relative changes significantly increased at Wuqi station but decreased at Honghe station. High, median, and low baseflow relative changes increased by 12.84%, 12.92%, and 171.00% in PII and by 28.40%, 2.87%, and 237.78% in PIII at Wuqi station, but decreased at Honghe station. Larger relative flow changes

were observed in PIII at Wuqi station. At Huangling station, low and median streamflow and baseflow changed slightly, but high streamflow and baseflow increased by 55.17% and 114.19% in PII and by 36.21% and 81.08% in PIII, respectively.

Table 6. Changes in hydrological characteristics, precipitation, BFI, and PET across periods

Index	Hydrological station	PI	PII	PIII	Change (%)
Streamflow	Wuqi	32.21	28.35	18.21	-11.98 (PII), -43.92 (PIII)
(mm/a)					
Streamflow	Huangling	27.32	26.84	26.91	-1.76 (PII), -1.50 (PIII)
(mm/a)					
Streamflow	Honghe	28.32	17.04	16.21	-39.88 (PII), -43.01 (PIII)
(mm/a)					
Baseflow	Wuqi	10.21	11.12	11.31	+8.97 (PII), +10.70 (PIII)
(mm/a)					
Baseflow	Huangling	18.92	21.84	21.46	+15.42 (PII), +13.43 (PIII)
(mm/a)					
Baseflow	Honghe	15.32	12.84	11.21	-16.19 (PII), -26.83 (PIII)
(mm/a)					
BFI	Wuqi	0.32	0.39	0.62	+28.13 (PII), +48.78 (PIII)
BFI	Huangling	0.69	0.81	0.80	+17.39 (PII), +15.94 (PIII)
BFI	Honghe	0.54	0.75	0.69	+38.89 (PII), +27.78 (PIII)
Precipitation	Wuqi	468.21	426.84	421.32	-8.84 (PII), -10.01 (PIII)
(mm/a)					
Precipitation	Huangling	521.32	511.84	511.32	-1.82 (PII), -1.92 (PIII)
(mm/a)					
Precipitation	Honghe	489.21	443.32	444.21	-9.38 (PII), -9.10 (PIII)
(mm/a)					
PET	Wuqi	891.32	887.32	904.21	-0.44 (PII), +1.49 (PIII)
(mm/a)					
PET	Huangling	823.21	821.32	828.21	-0.23 (PII), +0.61 (PIII)
(mm/a)					
PET	Honghe	845.21	824.54	835.21	-2.45 (PII), -1.20 (PIII)
(mm/a)					

Note: PI, baseline period (1959/1963–1979); PII, integrated soil conservation period (1980–1999); PIII, “Grain for Green” period (2000–2011); max/min ratio, maximum/minimum ratio; CV, coefficient of variation; SD, standard deviation.

Table 7. Relative changes in high (Q5), median (Q50), and low flow (Q95) in PII and PIII

Hydrological station	Flow type	Q5 (%)	Q50 (%)	Q95 (%)
Wuqi	Streamflow	-18.21	-15.32	+45.21
Wuqi	Baseflow	+12.84	+12.92	+171.00
Huangling	Streamflow	+55.17	+2.34	+1.21
Huangling	Baseflow	+114.19	+8.45	+3.21
Honghe	Streamflow	-41.42	-32.18	-28.45
Honghe	Baseflow	-28.32	-25.43	-22.18

Note: PII, integrated soil conservation period (1980–1999); PIII, “Grain for Green” period (2000–2011).

4.1. Responses of Streamflow and Baseflow to Ecological Restoration

An identified change point implies transformation of flow regime from one state to another. Notably, flow regime responses to ecological restoration differed between Wuqi (loess hilly-gully region) and Honghe (loess table-gully region) stations. Baseflow response time to ecological restoration was longer than streamflow response at Wuqi station. The change point in streamflow and baseflow caused by ecological restoration since 1999 may not have yet appeared at Honghe station. Scott and Smith (1997) reported that catchment response time depends on the extent of vegetation change, tree growth rate, restoration area, mean annual precipitation, soil permeability, and other characteristics. Increased infiltration from ecological restoration can recharge groundwater systems, resulting in shorter response times. Vegetation effects on flow reduction become efficient only when accumulated vegetation coverage exceeds a critical threshold of approximately 20.00% (Cai, 2001). Artificial vegetation (afforestation and pasture) area percentage was 4.75% in 1979 but increased to 23.20% in 2002 in the Wuqi catchment, while it only increased from 5.22% in 1984 to 12.83% in 1999 in the Honghe catchment. This explains the difference in response times between the two stations.

Furthermore, flow reduction varies when the percentage of revegetated area is less than 20.00%. For instance, numerous sediment-trapping dams, with area percentages much less than 20.00%, caused streamflow decreases exceeding 30.00% in some Yellow River areas (Xu et al., 2004; Wang et al., 2011; Moghadam et al., 2015). More than 1×10^4 sediment-trapping dams and reservoirs were built in the 1970s in the Chinese Loess Plateau. Our results show that streamflow and baseflow responses to ecological restoration differed across landforms, likely due to gradual changes from cumulative soil and water conservation measures. As conservation area increased, flow regime characteristics changed. Small-scale implementation of soil and water conservation in PII had weaker effects on streamflow and baseflow moderation than in PIII. With rapidly increasing restoration area, significant flow regime changes occurred in the 1990s and early 21st century. Although change points also occurred in the 1980s,

streamflow and baseflow were further regulated in PIII (Table 7). Ecological restoration reduced surface runoff generation while increasing infiltration and water recharge, thereby increasing baseflow (Zhang et al., 2008; Nie et al., 2011; Nian et al., 2014; Moghadam et al., 2015; Yuan et al., 2015; Zhang et al., 2017).

4.2. Integrated Influence of Landform and Vegetation Cover on Flow Regime

Given no significant trends in precipitation and PET, annual streamflow showed decreasing trends while annual BFI showed increasing trends at Wuqi and Honghe stations. However, trends in annual baseflow, daily flow at different exceedance percentages, and extreme series across consecutive days differed between the two catchments. Streamflow change rates mainly depend on human activity intensity, including the percentage of area treated by soil and water conservation measures and functional promotion of vegetation communities (Wang et al., 2013; Zhao et al., 2014; Zhang et al., 2017). Landform type also influences streamflow regime, as topography, unsaturated zone, and aquifer medium affect rainfall infiltration and water recharge. As shown in Table 2, BFI in the loess table-gully region was larger than in the loess hilly-gully region before 1969. Compared with the deep gully-dominated landform in the loess hilly-gully region, the flat loess table facilitates rainfall infiltration and thus supports higher baseflow over long periods.

Additionally, this study provides evidence that landform differences, beyond ecological restoration, create different flow response scenarios. Specifically, cumulative treated area and vegetation cover accounted for 36.4% and 34.2% of total area at Wuqi station, and 38.5% and 42.4% at Honghe station, respectively (Xu, 1998; Shi et al., 2002; Zhang et al., 2010). Surface coverage changes reduced precipitation conversion to streamflow and increased soil water storage, altering hydrological processes (Zhang et al., 2018). Ecological restoration effectively regulated daily streamflow, increased dry-season streamflow, and raised baseflow at various frequencies at Wuqi station, though this effect has not yet occurred at Honghe station. This may be because water recharge from increased infiltration requires many years due to thick soil layers (50–200 m thickness; Wang et al., 2013). It may also result from differences in restoration composition. Wuqi station is located in the forest-steppe ecotone, a typical steppe zone where natural vegetation restoration mainly constitutes shrub grassland besides reforestation from cultivated land. Honghe station is located in the forest zone where reforestation is the main restoration approach. Generally, increased forest cover promotes the hydrological cycle, with less streamflow and greater evaporation in forest catchments than in grassland catchments (Gao et al., 2012; Zhang and Wei, 2012; Wang et al., 2013; Wan et al., 2014; Zhang et al., 2017). Consequently, high-frequency streamflow and baseflow increased at Wuqi station but decreased at Honghe station. Therefore, ecological restoration and landform comprehensively altered flow regimes in PIII. Due to expanded scale and increased heterogeneity, further qualitative judgment and quantitative

analysis at regional scales are needed.

Comparing intra-annual variations between daily streamflow and baseflow, we found that flow regime at Huangling station (natural secondary forest) is more stable, with soil erosion at the Juhe River below soil-loss tolerance. Thus, natural secondary forest with reasonable community functional composition can maintain a more stable hydrological system, providing an ecological and hydrological theoretical basis for catchment management in the Chinese Loess Plateau. A rainstorm on August 30–31, 1994, at Wuqi and Huangling stations produced approximately 82 mm daily precipitation, generating 41 mm streamflow at Wuqi station but only 0.07 mm at Huangling station (Qin et al., 2010). This phenomenon supports our assumption and indicates that natural forest (or reforestation after vegetation succession) can effectively regulate peak streamflow and recharge baseflow. Therefore, future ecological restoration projects should more precisely moderate streamflow, such as by incorporating ecological functional diversity.

5. Conclusions

This study investigated flow regime responses to ecological restoration in three catchments representing loess hilly-gully, loess table-gully, and rocky mountain regions. Significantly negative trends in annual streamflow were detected at Wuqi and Honghe stations but not at Huangling station. Annual baseflow showed a significantly positive trend at Wuqi station and a significantly negative trend at Honghe station. Statistically significant change points in streamflow and baseflow were identified at all stations. Ecological restoration altered flow regimes, enabling division of data into three periods: baseline (1959/1963–1979, PI), integrated soil conservation (1980–1999, PII), and “Grain for Green” (2000–2011, PIII).

High and median streamflow decreased in PII and PIII at Wuqi and Honghe stations. However, low streamflow increased at Wuqi station but decreased at Honghe station during PII and PIII. These findings indicate that ecological restoration can moderate flow by reducing high flows and increasing low flows through water recharge, but this moderation effect depends on the scientific and technical aspects of restoration measure combinations. In other words, human activities determine streamflow change direction in catchments with different landforms.

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