Quantitative impact of precipitation and human activity on runoff in the upper and middle Taoer River basin

Ying Sun, Xiujuan Liang, Changlai Xiao and Zhang Fang

ABSTRACT

Improved analysis and usage of water resources in the Taoer River basin requires an evaluation of the contributions of precipitation and human activities to runoff. In this study, we apply an integrated method combining the non-parametric Mann–Kendall trend test and the double-mass curve to analyze runoff data from 1961 to 2010. The major findings are as follows: (1) annual runoff showed a statistically significant decrease, while precipitation showed no significant trend; (2) an abrupt change point was identified in 1998 at four representative stations, resulting in the study period being divided into pre-change and post-change periods for subsequent analysis. The double-mass curves were approximately linear in the pre-change periods, indicating that the dominant factor was probably climate change. Annual precipitation–runoff curves showed a decreasing trend from 1998, probably because of human activity; (3) the contributions of human activity to runoff in the post-change period for the four selected stations were 58.31%, 17.81%, 37.17%, and 47.66%, and the influence of human activity increased after the abrupt change point.

Key words | change point, human activity, precipitation, quantity, runoff, trends

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INTRODUCTION

Climate and human activity are important factors influencing runoff in many parts of the world (Stewart *et al.* 2004; Hanna *et al.* 2008; Guo *et al.* 2014; Li *et al.* 2014a). Climate change affects not only the environment, but also many aspects of social and economic development (Chen *et al.* 2009), and human activity is believed to be another major cause of changes in land cover characteristics and hydrological cycles. Both factors have important implications for water resource management and the ecological and environmental protection of river basins.

Over the years, many studies (e.g. Dettinger & Cayan 1995) have focused on assessing runoff trends and the impact of human activity and climate variability on runoff. Owing to the spatial variability of these impacts, studies are typically performed on a local scale (basin or sub-basin scale) (Guo *et al.* 2014). Piao *et al.* (2007) emphasized that the temporal changes in land use related to increased atmospheric CO_2 cause a small but significant decrease in global runoff because of the responses of leaf-level processes and vegetation dynamics. Chen *et al.* (2016) investigated annual runoff and showed significant decreasing trends in the Yellow River basin, yet no significant trends were found in precipitation because most of the runoff reduction was attributed to human activity. Jiang *et al.* (2015) separated the impact of climate change and human activity on runoff variability in the Weihe River basin using the decomposition method and the sensitivity method, and their results showed that climate change not only altered the hydrological factors (precipitation, potential evaporation, etc.) but also watershed characteristics, while the impacts of human activity on runoff mainly involved changing the watershed characteristics. Li *et al.* (2014c) employed the Mann–Kendall and Pettitt tests to analyze a significant downward trend in annual runoff in the Luanhe River basin, and plotted

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double-mass curves of annual rainfall and annual runoff, estimating the comprehensive effects of land use/land cover change on annual runoff decrease. Generally, the runoff of many rivers, especially in arid and semi-arid regions, has decreased significantly (Guo *et al.* 2016), resulting in a shortage of water resources and a deterioration of the ecological environment.

The Taoer River, northeastern China, is a representative ecologically sensitive area that has experienced significant climate change and rapid social developments since 1961 (Li *et al.* 2014a). Climatic factors are regarded as direct influencing factors, of which precipitation is the most influential factor in river runoff (Loukas & Quick 1996; Liuzzo *et al.* 2010). With rapid growth in the population of the Taoer River basin over the last 50 years, the expansion of agricultural acreage, and the corresponding decline in water area, the structure of land use has changed dramatically (Liu *et al.* 2017). All these factors have influenced the natural water cycle and runoff, making the upper and middle reaches of the Taoer River an ecologically sensitive area of northeastern China (Zhang *et al.* 2017).

This study focuses on the characteristics of precipitation and runoff changes in the upper and middle reaches of the Taoer River and a quantitative analysis of precipitation and human activity. The objectives of this paper were to: (1) analyze annual precipitation and runoff trends in the upper and middle reaches of the Taoer River basin using long time-series data from 1961 to 2010; (2) detect change points in the annual runoff time series to classify undisturbed and disturbed periods; and (3) separate and quantify the contributions of precipitation and human activity to runoff variability. The results of this study will greatly assist in the decision-making and planning of water resource managers.

STUDY AREA AND DATA

Study area

The Taoer River basin (~45°6′–47°12′N, ~117°18′–124°6′E), in the transitional zone of the western slope of the Song-Nen Plain of northeastern China (Figure 1), has an area of approximately 4.3×10^4 km^2, and a river length of 563 km. As an important part of the Northeast China Plain, the basin is a major rice-production area, supporting a population of 3.6 million (Liang *et al.* 2010). Based on the topography, river channel, and vegetation characteristics, the river is divided into three parts, with the Chaersen reservoir and Taonan hydrological station representing the

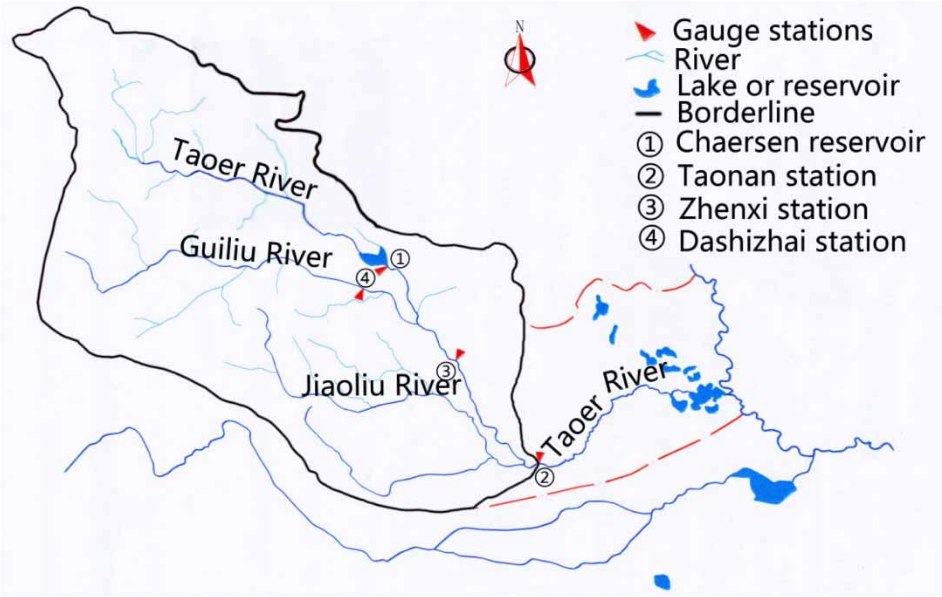

Figure 1 | Sketch map of the study area.

boundaries. From west to east, the basin changes from the upper to lower reaches, with topography changing from mountains to hills to plains, and the climate from semi-humid to semi-arid (Zhang *et al.* 2017).

The upper and middle reaches were selected as the study area, which covers 27,633 km^2. The elevation ranges from 150 to 1,709 m. It has a cold temperate continental monsoon climate, with mean annual temperatures ranging from -2 to 5 °C, mean annual evaporation ranging from 1,836 to 1,960 mm, and annual precipitation ranging from 350 to 400 mm. Precipitation in the rainy season (June to September) accounts for 84%–89% of the annual total.

Study data

Considering multiple factors, four stations were selected: the gauging stations at Chaersen reservoir and Taonan hydrological station were selected as they are located at the outlet of the upper and middle reaches, respectively, and Dashizhai hydrological station was selected to consider the infusion of the tributary. In addition, Zhenxi hydrological station was selected to improve the accuracy of the results (Figure 1). The data set was chosen to cover the longest period of simultaneous runoff and precipitation records and to provide good spatial distribution within the study area (Moraes *et al.* 1998); therefore, annual precipitation and runoff data were collected from 1961 to 2010, provided by Songliao Water Resources Committee.

The annual runoff and precipitation trends were estimated using the non-parametric Mann–Kendall trend test (the MK test), and the abrupt change points within the series were determined using the double-mass curve. Finally, statistical analysis was used to calculate the impact of precipitation and human activity on the upper and middle reaches of the Taoer River basin.

METHODS

In this study, a series of methods combining the non-parametric Mann–Kendall test (the MK test), the double-mass curve, and statistical analysis were used to investigate changes in precipitation and runoff in the upper and middle reaches of the Taoer River.

Non-parametric Mann–Kendall test

The non-parametric MK test (Mann 1945; Kendall 1975) detects significant characteristics and trends in annual precipitation and runoff. For the series $X = \{x_1, x_2, \ldots, x_n\}$, in which $n > 10$, the standard normal test statistic Z is estimated as follows:

$$Z = \begin{cases} (S-1)/\sqrt{\operatorname{var}(S)}, & S > 0 \\ 0, & S = 0 \\ (S+1)/\sqrt{\operatorname{var}(S)}, & S < 0 \end{cases} \tag{1}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{2}$$

$$\operatorname{sgn}(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{3}$$

$$\operatorname{var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] / 18 \tag{4}$$

where $1 \le t \le n$.

The statistical Z test follows the standard normal distribution. A positive Z indicates an increasing trend and a negative Z indicates a decreasing trend. The critical value $Z_{\alpha/2}$ at the $\alpha = 5\%$ significance level of the trend test equals ±1.96 (Guo *et al.* 2014).

The sum S_k consists of the number r_i, related to the term x_n:

$$S_k = \sum_{i=1}^{k} r_i, \quad r_i = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \le x_j \end{cases}, \ (j = 1, 2, \ldots, i;\ k = 1, 2, \ldots, n) \tag{5}$$

For large n, under the null hypothesis H_0 of no change, S_k is normally distributed around the mean and the variance is given by:

$$E[S_k] = k(k-1)/4;\ \operatorname{var}(S_k) = k(k-1)(2k+5)/72 \tag{6}$$

In testing the statistical significance of S_k for this null hypothesis, the two-tailed significance test is used, the null hypothesis being rejected for a large value of the statistics UF_k given by:

$$UF_k = (S_k - E[S_k])/\sqrt{\mathrm{var}(S_k)} \tag{7}$$

Being the normalized variable, which is the forward sequence, the backward sequence UB_k is calculated using the same equation but with a reversed series of data.

When the null hypothesis is rejected (i.e., if any of the points in the forward sequence are outside the confidence interval), detection of an increasing ($UF_k > 0$) or a decreasing ($UB_k < 0$) trend is indicated. The sequential version of the test used here enables detection of the approximate time of occurrence of the trend by locating the intersection of the forward and backward curves of the test. If the intersection occurs within the confidence interval, then it indicates a change point (Moraes *et al.* 1998; Li *et al.* 2007).

The double-mass curve

The theory of the double-mass curve (Searcy & Hardison 1960) is based on the fact that a graph of the sum of one quantity against the sum of another quantity during the same period will plot as a straight line, so long as the data are proportional; therefore, the slope of the line will represent the constant of proportionality between the quantities. A break in the slope of the double-mass curve means that a change in the constant of proportionality between the two variables has occurred, or that the proportionality will be constant for all rates of the quantity. If the possibility of a variable ratio between the two quantities can be ignored, a break in the slope indicates the time at which a change occurs in the relationship between the two quantities.

Quantitative analysis

Although the effects of precipitation and human activity on runoff can be complex, the statistical relationship between runoff and influencing factors can still be established, and has been performed by many other studies (Lee & Chung 2007; Xu *et al.* 2008; Hastenrath 2013; Jiang *et al.* 2015). For the purpose of comparison with previous research, this study examined the effect of precipitation and human activity on runoff for the period from 1961 to 2010. An *abrupt year* means that in the trend analysis, the series of data (precipitation, runoff, and so on) have a significant change in the trend starting from a certain year, so that the tendencies before and after are not continuous any more. Based on observed runoff (OR) and precipitation data before the abrupt year, linear regressions (for which reliabilities were verified with the *F*-test) of runoff and precipitation were established, and every time-period's theoretical value (TR) of runoff after the abrupt year was calculated. Taking the multi-year mean runoff before the abrupt year as the reference value, the difference (C_P) between the theoretical value and the reference value is the effect of precipitation on runoff, and the ratio of the difference and the variation of the observed runoff is the contribution of precipitation to runoff (CR_P); the difference (C_H) between the theoretical value and the observed value is the impact of human activity on the change in runoff, and the ratio of the difference and the variation of the observed runoff is the contribution of human activity to runoff (CR_H).

RESULTS AND DISCUSSION

Trends in precipitation and runoff

The rank-based MK test was chosen to analyze precipitation and runoff trends because hydrological variables might not be normally distributed. The null hypothesis of no trend is rejected if the test results differ significantly from zero; this includes linear and non-liner a trends. The precipitation and runoff time series (from the beginning of 1961 to the end of 2010) of the selected stations were collected and the statistical results from the MK test are shown in Table 1.

As indicated in Table 1, annual precipitation at Chaersen reservoir and Taonan station show decreasing trends, which occur at the Zhenxi and Dashizhai stations; however, the trends for all selected stations are insignificant because the absolute MK *Z* values are less than 1.96 ($Z_{0.05} = 1.96$). Moreover, annual runoff in the study area shows a decreasing trend at all stations, but only those of Chaersen reservoir

Table 1 | Mann–Kendall (MK) test for trend analysis of annual precipitation and runoff

	Precipitation		**Runoff**	
Station name	***Z***	**Significant (%)**	***Z***	**Significant (%)**
Chaersen	−0.39	N	−2.01	95
Taonan	−1.09	N	−1.12	N
Zhenxi	0.49	N	−0.97	N
Dashizhai	0.76	N	−2.03	95

N indicates confidence level under 90%.

and Dashizhai station are significant at a confidence level of 95%. To further analyze runoff changes in the study area, the MK sequential trend test with a forward UF_k and backward UB_k was applied.

Figure 2 indicates similar runoff changes for the four representative stations. Before the mid-1980s, trends in annual runoff were highly variable, but basically showed a downward trend. During the mid-1980s to the early 20th century, the trends in annual runoff showed an increase, but were not significant, except for the trend at Taonan station, which was significant at confidence levels of 95% between 1992 and 2000. After 2000, annual runoff trends decreased. The above analysis not only indicates spatial differences in runoff trends in the study area, but also temporal differences. The turning point in runoff trend occurred around 2000, and changed an upward trend to a downward trend. This downward trend was significant year by year, which may be because runoff is not only related to precipitation, but also to human activity. In recent years, with the rapid development of irrigation districts in the study area, the demand for water has been constantly increasing.

Abrupt change points in runoff

The results of the MK test for abrupt change points are also shown in Figure 2, and indicate that abrupt changes occurred around 2000. However, the presence of multiple intersections makes it difficult to locate the exact beginning of the change points. To better locate the change points, the double-mass curve method was applied. Figure 3 shows the

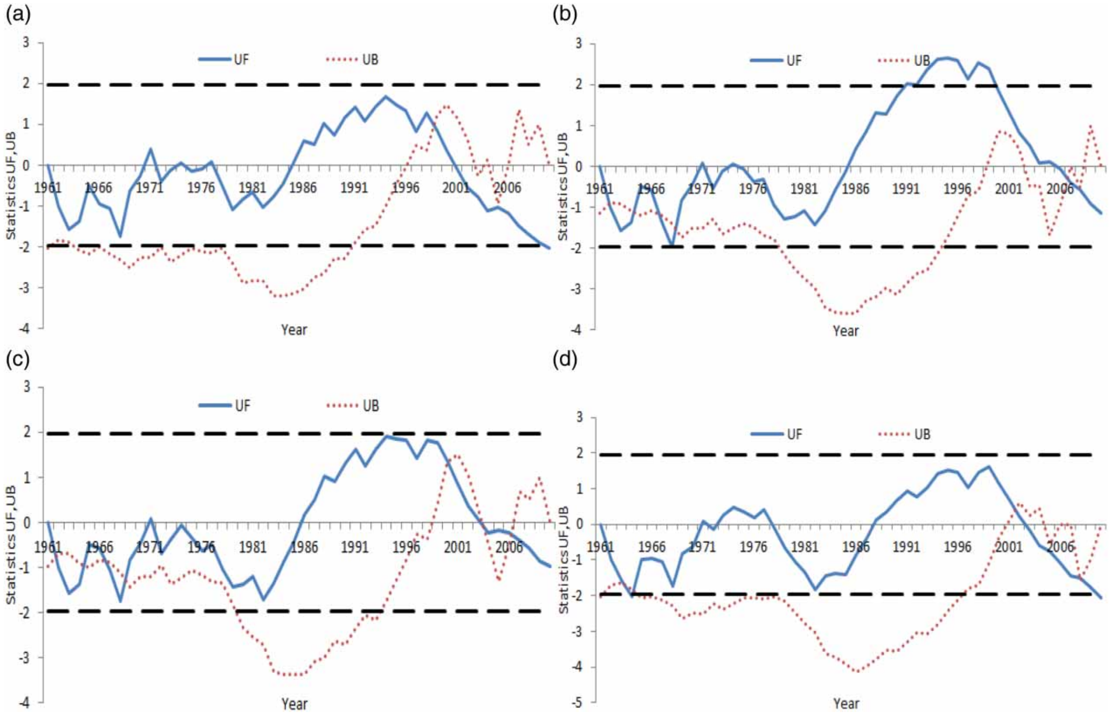

Figure 2 | Mann–Kendall sequential trend test of annual runoff with forward (UF_k) and backward (UB_k) for (a) Chaersen reservoir, (b) Taonan station, (c) Zhenxi station, and (d) Dashizhai station.

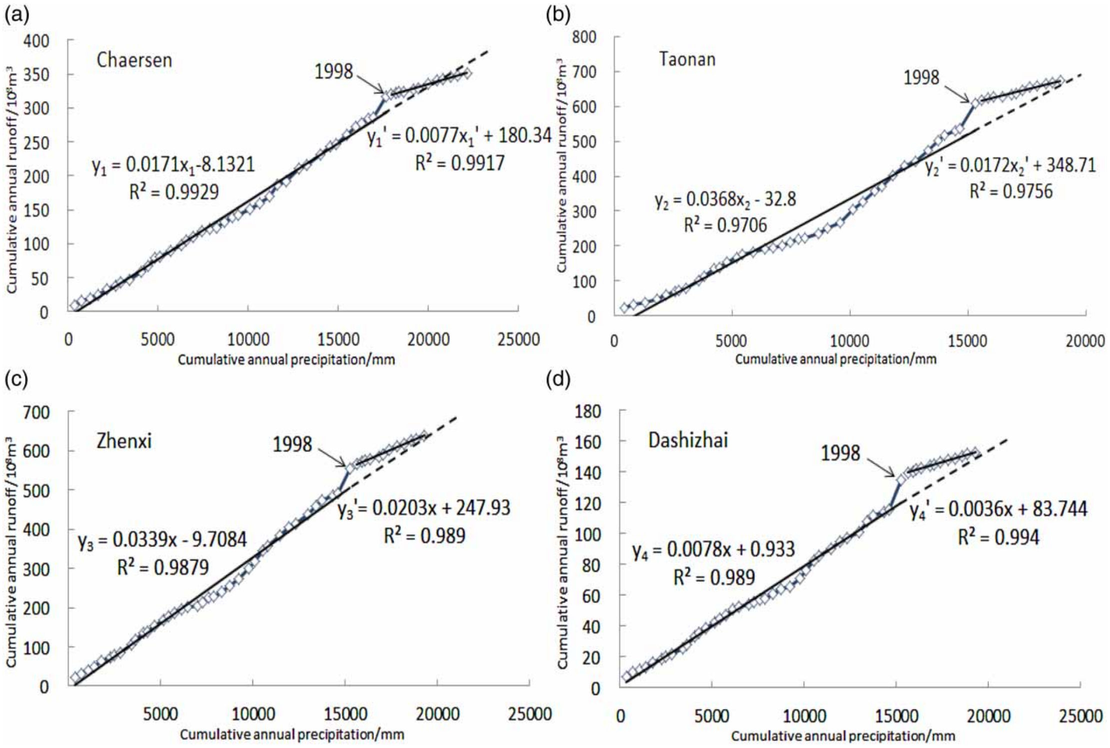

Figure 3 | Double-mass curves for annual precipitation and runoff for (a) Chaersen reservoir, (b) Taonan station, (c) Zhenxi station, and (d) Dashizhai station.

cumulative annual precipitation and annual runoff of selected stations.

Generally, the double-mass curve is expected to be a straight line when runoff is not significantly affected by human activity (Wang *et al.* 2013). In this study, the relationship between cumulative annual precipitation and cumulative annual runoff can be approximately expressed by two linear regressions representing two stages based on the year of the abrupt change point (1998) and the slope change of the cumulative quantity for each station. Therefore, the study period (1961 to 2010) can be divided into two sub-stages according to the change points: the pre-change periods and the post-change periods. The distributions of cumulative points on the annual precipitation–runoff curves show no significant change at the selected stations because the curves are approximately linear during the pre-change periods. However, abrupt change points, higher than the regression lines, appear at 1998, and reflect a large flood. After 1998, the double cumulative curves of annual precipitation–runoff for the four stations begin to decrease.

The factors affecting runoff change include natural and human factors. Natural factors include the underlying surface, which remains relatively unchanged over a given period of time, and climatic conditions. Precipitation is the main climatic factor influencing runoff formation, and changes in precipitation directly affect the amount of runoff. Human activities include industrial, agricultural, and domestic water use, water conservation and water conservation projects, land use changes, etc. (Li *et al.* 2014b). However, there was no significant change in land use in the study area from 1961 to 1997, and the effect of human activities on surface runoff is mainly reflected in the increasing water demand for surface water in irrigation areas after 1998.

Using land use change as a reference and obtaining land use data from 1970 to 2010, remote sensing images were interpreted using the ArcGIS 10.0 software platform, which were interpreted in 5-year intervals. However, the double accumulative curves of precipitation and runoff before 1998 had small fluctuations, with large fluctuations during 1978 to 1987 (Figure 3). Therefore, the remote sensing images of the study area from 1975 to 1990 were

Table 2 | Results of land use by interpreting remote sensing images

Year	River (km^2)	Paddy field (km^2)	Forest (km^2)	Dry field (km^2)	Grassland (km^2)	Habitation (km^2)	Bare land (km^2)
1970	1,999.44	3,907.14	7,086.93	7,956.28	5,289.34	1,934.54	937.00
1975	1,919.73	3,932.91	6,965.05	7,944.74	5,380.95	1,997.93	969.38
1976	1,935.79	3,852.77	7,018.98	8,009.32	5,299.80	1,989.87	1,004.05
1978	1,975.07	4,013.34	7,043.39	7,881.15	5,330.37	1,917.55	950.02
1980	2,062.66	4,082.14	7,022.95	7,782.64	5,238.66	1,958.86	962.92
1982	1,975.07	4,115.34	7,043.39	7,778.84	5,330.37	1,917.55	950.02
1984	1,975.07	3,973.34	7,043.39	7,721.15	5,330.37	1,917.55	950.02
1985	1,021.21	3,987.97	5,669.32	6,591.62	6,692.69	3,656.59	1,291.44
1986	1,119.59	3,773.43	5,626.85	6,544.87	6,707.17	3,630.31	1,508.65
1988	1,254.97	3,308.29	5,862.33	7,819.91	6,465.11	3,264.40	1,135.88
1990	992.61	3,225.81	6,170.16	7,837.66	6,606.00	3,040.50	1,038.09
1995	1,198.40	3,694.79	5,869.72	6,700.86	6,746.13	3,517.28	1,183.75
2000	1,009.77	4,295.77	6,181.83	6,692.35	6,735.54	2,956.06	1,039.31
2005	1,220.83	4,358.11	6,037.83	6,437.09	6,556.69	3,221.01	1,079.33
2010	1,100.20	4,467.65	6,115.33	6,491.91	6,716.75	3,154.63	863.72

analyzed in 2-year intervals. The land-use-type area data in each year in the study area were obtained (Table 2). Taonan hydrological station is located at the outlet of the middle reaches of the basin, and the double-mass curves for precipitation and runoff for Taonan station showed the largest fluctuation range; therefore, the runoff data with the same series length as Taonan station were used to establish dynamic curves of five land use types (paddy field, forest, dry field, grassland, and bare land) and runoff over time (Figure 4).

According to the data in Table 2 and the dynamic curves in Figure 4, the results in Figure 3 can be interpreted from a land use perspective. The areas of paddy field and dry field changed markedly, whereas the variation ranges of forested land, grassland, and bare land were small. From 1985 to 1995, the area of dry field increased and the area of paddy field decreased with an increase in runoff. After 1998, runoff showed a decreasing trend, and the paddy field area showed a concurrent and substantial increasing trend, whereas the dry land area showed a decreasing trend. The

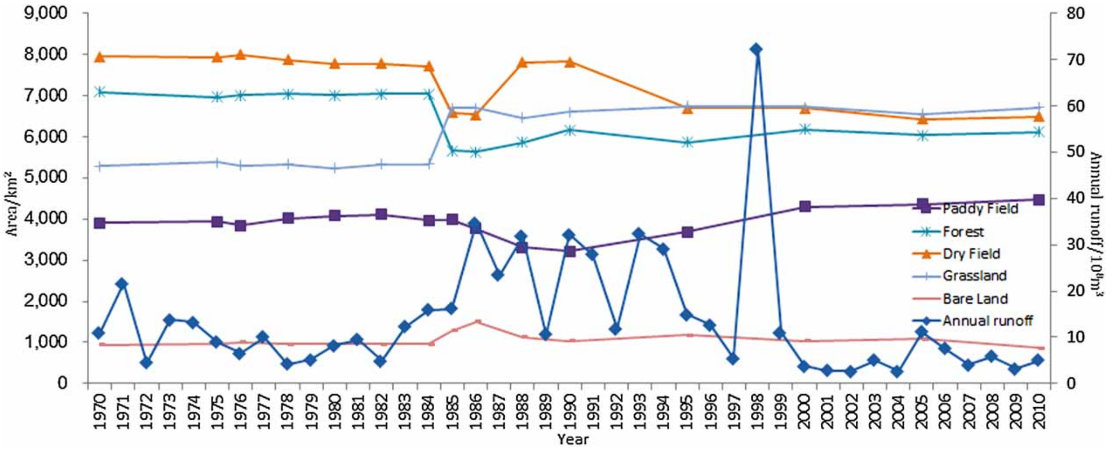

Figure 4 | Dynamic curves of the area of each land use type and runoff over time.

relationships between the areas of paddy field and dry field and runoff were similar; as the area of paddy field increased and the area of dry field decreased, runoff decreased. In contrast, as the area of paddy field decreased and the area of dry field increased, runoff increased. Before 1998, the areas of paddy field and dry field in the study area remained relatively stable, and the ranges of change were not significant. Although there were small-scale changes from paddy field to dry field or dry field to paddy field (especially during 1978–1987), this did not affect the variation trend in precipitation and runoff and the correlation between the cumulative annual precipitation and runoff. After 1998, with the development of irrigated areas and the construction of water conservation facilities, human water demands increased steadily. Hence, the reduction in runoff during the 1998 to 2010 period may be due to human activity. Figure 3 indicates an increasing influence of such activities in recent years.

Effects of precipitation and human activities on runoff

In order to separate and quantify the respective impacts of precipitation and human activity on runoff, we calculated the time series of precipitation and runoff. The study period was divided into two periods based on the abrupt change point. Under natural conditions, precipitation and runoff were correlated positively, because of the significant linear relationship before 1998, which was observed in the double cumulative curves of annual precipitation runoff. This indicated that the changes in runoff and precipitation during this period were synchronous, and that runoff was not unduly disturbed by human activity.

Using the empirical formula method of the hydrological method, the linear regression equations of precipitation and runoff before the abrupt years in the upper and middle reaches were established, and the results of the *F*-test are presented in Table 3.

From Table 3, the correlation coefficient of the regression in Equation (4) is 0.38, indicative of a low correlation between precipitation and runoff. However, the correlation coefficients of the other three equations show that they are significantly correlated, and the results of the *F*-test of the four regression equations are all significant at $\alpha = 0.05$, indicating that the four groups of regression equations are all significant. Thus, all four regression equations can be used to predict and evaluate the effect of precipitation on runoff.

Table 3 | Results of the linear regression and *F*-tests

Station	Linear regression equation	Correlation coefficient	*F*	Significant *F*
Chaersen	(1) $R_1 = 0.0212P_1 - 1.9501$	0.64	24.49	0.000019
Taonan	(2) $R_2 = 0.0472P_2 - 4.2276$	0.55	15.55	0.000370
Zhenxi	(3) $R_3 = 0.0390P_3 - 2.0952$	0.65	26.05	0.000012
Dashizhai	(4) $R_4 = 0.0053P_4 + 1.0550$	0.38	5.96	0.019833

Notes: R_i is the annual runoff (10^8 m^3); P_i is the annual precipitation (mm); $i = 1, 2, 3, 4$.

According to the linear regression equations, the theoretical values of the annual runoff after the abrupt year, which were equivalent to runoff formed by natural precipitation, can be calculated. Using the observed runoff before the abrupt change as the background value, the theoretical runoff was calculated for different periods.

However, the period from 1998 to 2000 was analyzed separately because the Taoer River basin experienced an extraordinary flood in 1998, which would have masked the impact of human activity. The results are shown in Table 4.

The pre-change period (1961–1997) was classified as the basic period, during which human activity was weak and runoff was influenced mainly by climatic factors. However, it was difficult to distinguish the dominant factor from 1998 to 2000 owing to the extraordinary flood in the Taoer River basin. In the subsequent period (2001–2010), runoff was influenced by both precipitation and human activity. After the abrupt change point (1998), precipitation and human activity contributed 41.69% and 58.31%, respectively, to reductions in runoff in the upper reaches according to data from Chaersen reservoir. The data from Zhenxi station, Dashizhai station, and Taonan station, in the middle reaches, show contributions from precipitation of 62.83%, 52.34%, and 82.19%, respectively. Meanwhile, the contributions from human activity were 37.17%, 47.66%, and 17.81%, respectively.

After 2000, the influence of human activities on the study area increased, and the influence of precipitation

Table 4 | Influence of precipitation and human activity on runoff decline in the upper and middle reaches of the Taoer River basin

				VO		**C_P**		**C_H**	
Station	**Data period**	**OR (10^8 m^3)**	**TR (10^8 m^3)**	**Variation (10^8 m^3)**	**Ratio (%)**	**Variation (10^8 m^3)**	**CR_P (%)**	**Variation (10^8 m^3)**	**CR_H (%)**
Chaersen	1961–1997	7.74	7.74	–	–	–	–	–	–
	1998–2000	11.70	6.86	3.96	51.15	−0.88	−22.14	4.84	122.14
	2001–2005	2.92	5.79	−4.82	−62.28	−1.95	40.46	−2.87	59.54
	2006–2010	2.98	7.22	−4.76	−61.47	−0.53	11.07	−4.23	88.93
	1998–2010	4.97	6.59	−2.77	−35.79	−1.16	41.69	−1.62	58.31
Taonan	1961–1997	14.47	14.47	–	–	–	–	–	–
	1998–2000	29.07	14.46	14.60	100.86	−0.01	−0.10	14.61	100.10
	2001–2005	4.87	9.76	−9.60	−66.36	−4.71	49.07	−4.89	50.93
	2006–2010	5.16	10.85	−9.31	−64.32	−3.63	38.95	−5.68	61.05
	1998–2010	10.57	11.26	−3.91	−26.99	−3.21	82.19	−0.70	17.81
Zhenxi	1961–1997	13.29	13.29	–	–	–	–	–	–
	1998–2000	26.78	14.85	13.49	101.50	1.56	11.55	11.93	88.45
	2001–2005	5.87	9.57	−7.42	−55.85	−3.72	50.13	−3.70	49.87
	2006–2010	7.27	12.72	−6.02	−45.29	−0.57	9.54	−5.45	90.46
	1998–2010	11.24	12.00	−2.06	−15.48	−1.29	62.83	−0.76	37.17
Dashizhai	1961–1997	3.13	3.13	–	–	–	–	–	–
	1998–2000	8.24	3.36	5.11	163.12	0.23	4.43	4.88	95.57
	2001–2005	1.16	2.64	−1.97	−62.87	−0.49	24.96	−1.48	75.04
	2006–2010	1.23	3.07	−1.90	−60.59	−0.06	3.36	−1.83	96.64
	1998–2010	2.82	2.97	−0.31	−9.84	−0.16	52.34	−0.15	47.66

Notes: OR is the annual mean value of the observed runoff data (10^8 m^3); TR is the annual mean value of the theoretical runoff data (10^8 m^3); VO is the variation of the observed runoff; C_P is the contribution of precipitation to runoff; C_H is the contribution of human activity to runoff; CR_P is the contribution rate of precipitation to runoff (%); CR_H is the contribution rate of human activity to runoff (%).

decreased, more so in the upper reaches than the middle reaches. These results are consistent with the double-mass curve analysis and the analysis of land use discussed above. As the main source of water for the irrigation district, Chaersen reservoir runoff was mainly affected by human activity; a result of large irrigation areas and continually increasing water demands since 2000. Human activity had a minimal influence on runoff at Taonan station, probably owing to the presence of sink flows such as the Jiaoliu River and Guiliu River in the middle reaches, which can weaken the influence of human activity on runoff.

CONCLUSIONS

The MK test and double-mass curve were used to examine long-term trends in precipitation and runoff; runoff data for the Taoer River basin from 1961 to 2010 was divided into two stages based on a runoff change point. Statistical analysis was used to quantify the contribution of precipitation and human activity to runoff in the upper and middle reaches of the river basin. The main conclusions of this study are as follows:

(1) There is no clear precipitation trend because absolute MK Z values are all less than 1.96. Runoff shows a significant decreasing trend after approximately the year 2000.
(2) From 1961 to 2010, the pattern of runoff in the research area changed, resulting in the study period being divided into two stages. Before 1998, the double-mass curves were approximately linear, indicating that precipitation was the main factor influencing runoff. However, an abrupt change point at 1998 occurred because of a large flood, after which runoff began to decrease as water demands for irrigation gradually increased.
(3) Human activity was the main factor that affected runoff in the study area after the year of the abrupt change point, showing mean contributions to the post-change runoff period of 58.31%, 37.17%, 47.66%, and 17.81%, for all four hydrological stations. Furthermore, the

impact of human activity showed a significant increasing trend in the upper and middle reaches of the Taoer River basin. Moreover, our analysis indicated that the influence of human activity was largest on the runoff at Chaersen reservoir, which is the main source of water for the irrigation district.

With the rapid development of industry and agriculture and increased water demand for human consumption, water shortages and imbalanced supply and demand remain, and seriously threaten water security and sustainable development of the study area. This study not only contributes to understanding the characteristics of water resources' change in the area, but also recommends that watershed management plans include the development of water resources in order to promote the coordination of local ecological protection and economic development.

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REFERENCES

Chen, Y. N., Xu, C. C., Hao, X. M., Li, W. H., Chen, Y. P., Zhu, C. G. & Ye, Z. X. 2009 Fifty-year climate change and its effect on annual runoff in the Tarim River Basin, China. *Quaternary International* **208** (1–2), 53–61.

Chen, Y. Z., Guan, Y. Q., Shao, G. W. & Zhang, D. R. 2016 Investigating trends in streamflow and precipitation in Huangfuchuan Basin with wavelet analysis and the Mann-Kendall test. *Water* **8** (3), 77.

Dettinger, M. D. & Cayan, D. R. 1995 Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *Journal of Climate* **8** (3), 606–623.

Guo, Y., Li, Z. J., Amo-Boateng, M., Deng, P. & Huang, P. N. 2014 Quantitative assessment of the impact of climate variability and human activities on runoff changes for the upper reaches of Weihe River. *Stochastic Environmental Research and Risk Assessment* **28** (2), 333–346.

Guo, Q. L., Yang, Y. S. & Xiong, X. Z. 2016 Using hydrologic simulation to identify contributions of climate change and human activity to runoff changes in the Kuye river basin, China. *Environmental Earth Sciences* **75** (5), 417.

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S. & Griffiths, M. 2008 Increased runoff from melt from the Greenland ice sheet: a response to global warming. *Journal of Climate* **21** (2), 331–341.

Hastenrath, S. 2013 Diagnostics and prediction of anomalous river discharge in northern South America. *Journal of Climate* **3** (3), 1080–1096.

Jiang, C., Xiong, L. H., Wang, D. B., Liu, P., Guo, S. L. & Xu, C. Y. 2015 Separating the impacts of climate change and human activities on runoff using the Budyko-type equations with time-varying parameters. *Journal of Hydrology* **522**, 326–338.

Kendall, M. G. 1975 *Rank Correlation Measures*. Charles Griffin, London, UK.

Lee, K. S. & Chung, E. S. 2007 Hydrological effects of climate change, groundwater withdrawal, and land use in a small Korean watershed. *Hydrological Processes* **21** (22), 3046–3056.

Li, L. J., Zhang, L., Wang, H., Wang, J., Yang, J. W., Jiang, D. J., Li, J. Y. & Qin, D. Y. 2007 Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. *Hydrological Processes* **21** (25), 3485–3491.

Li, B., Su, H. B., Chen, F., Li, H. B., Zhang, R. H., Tian, J., Chen, S. H., Yang, Y. M. & Rong, Y. 2014a Separation of the impact of climate change and human activity on streamflow in the upper and middle reaches of the Taoer River, northeastern China. *Theoretical and Applied Climatology* **118** (1–2), 271–283.

Li, E. H., Mu, X. M. & Zhao, G. J. 2014b Temporal changes in annual runoff and influential factors in the upper and middle reaches of Yellow River from 1919–2010. *Advances in Water Science* **25** (2), 155–163.

Li, J. Z., Tan, S. M., Chen, F. L. & Feng, P. 2014c Quantitatively analyze the impact of land use/land cover change on annual runoff decrease. *Natural Hazards* **74** (2), 1191–1207.

Liang, L. Q., Li, L. J. & Liu, Q. 2010 Spatial distribution of reference evapotranspiration considering topography in the Taoer river basin of Northeast China. *Hydrology Research* **41** (5), 424–437.

Liu, J. W., Zhang, C., Kou, L. M. & Zhou, Q. 2017 Effects of climate and land-use changes on water resources in the Taoer River. *Advances in Meteorology* **2017**, 1031854.

Liuzzo, L., Noto, L. V., Vivoni, E. R. & Loggia, G. L. 2010 Basin-scale water resources assessment in Oklahoma under synthetic climate change scenarios using a fully distributed hydrologic model. *Journal of Hydrologic Engineering* **15** (2), 107–122.

Loukas, A. & Quick, M. C. 1996 Effect of climate change on hydrologic regime of two climatically different watersheds. *Journal of Hydrologic Engineering* **1** (2), 77–87.

Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica* **13** (3), 245–259.

Moraes, J. M., Pellegrino, G. Q., Ballester, M. V., Martinelli, L. A., Victoria, R. L. & Krusche, A. V. 1998 Trends in hydrological parameters of a southern Brazilian watershed and its relation to human induced changes. *Water Resources Management* **12** (4), 295–311.

Piao, S. L., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D. & Zaehle, S. 2007 Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. *Proceedings of the National Academy of Sciences of the United States of America* **104** (39), 15242–15247.

Searcy, J. K. & Hardison, C. H. 1960 *Double-Mass Curves*. Geological Survey Water-Supply Paper 1541-B, US Government Printing Office, Washington, DC, USA.

Stewart, I. T., Cayan, D. R. & Dettinger, M. D. 2004 Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. *Climatic Change* **62** (1–3), 217–232.

Wang, Y., Ding, Y. J., Ye, B. S., Liu, F. J., Wang, J. & Wang, J. 2013 Contributions of climate and human activities to changes in runoff of the Yellow and Yangtze rivers from 1950 to 2008. *Science China: Earth Sciences* **56** (8), 1398–1412.

Xu, J. H., Chen, Y. N., Ji, M. H. & Lu, F. 2008 Climate change and its effects on runoff of Kaidu River, Xinjiang, China: a multiple time-scale analysis. *Chinese Geographical Science* **18** (4), 331–339.

Zhang, K., Li, L. J., Bai, P., Li, J. Y. & Liu, Y. M. 2017 Influence of climate variability and human activities on stream flow variation in the past 50 years in Taoer River, Northeast China. *Journal of Geographical Sciences* **27** (4), 481–496.

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