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Separating the impacts of climate change and land surface alteration on runoff reduction in the Jing River catchment of China

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ABSTRACT

The Loess Plateau of China is subject to severe water shortages, and the runoff reduction observed in most watersheds exacerbates the problem. Quantifying the contributions of environmental changes to runoff reduction is thus very important for water resources management. Taking the Jing River catchment as the study area, the changes in runoff for the period of 1961–2010 at three gauge stations—the catchment outlet (Zhang Jia Shan, ZJS) and the two others from the upper reach (Yang Jia Ping, YJP, and Yu Luo Ping, YLP) were analyzed in this study. Using the Budyko framework, the spatiotemporal variations of the contributions of precipitation (P), potential evapotranspiration (ET_0), and land surface conditions (represented by the parameter n in the Choudhury–Yang equation) to runoff changes were evaluated. A significant downward trend in runoff was detected for the ZJS and YJP stations. The sensitivity of the runoff changes to the different environmental factors considered was different. The sensitivity coefficient was the greatest for P, intermediate for ET_0, and smallest for the land surface condition (n). However, the sensitivity coefficients are becoming greater over time. The decrease in P was the dominant factor in the runoff reduction at the three stations, but its effect was largely offset by the increase in n at YLP. The contribution of land surface alteration to runoff reduction has been increasing in recent years, which indicates that the improvement of vegetation coverage and the construction of terraces and check dams have strengthened their impacts on runoff. Therefore, careful attention should be paid to the hydrological effects of soil conservation measures on runoff.

1. Introduction

The Loess Plateau (6.4×10^5 km^2) is located in the upper and middle reaches of the Yellow River in northern China (Fig. 1). Because of the high erodibility of loessial soil and the intensive rainstorms and low vegetation coverage of the area, the Loess Plateau has become one of the most severely eroded areas in the world (Zhu et al. 1983). Several measures have been implemented since the 1950s in attempts to control soil loss in the area, including biological measures (replanting trees and improving pastures) and engineering measures (building terraces and sediment trapping dams). The effects of such soil conservation measures on water yield need to be assessed because the region is highly vulnerable to water shortages (Mu et al. 2007b).

Three methods have been developed to assess the hydrological effects of environmental changes: the paired catchments approach, hydrological modeling, and statistical methods (Li et al. 2009). The paired catchments approach is superior to modeling of small catchments in compensating for climate variability, but it is difficult to apply this approach to medium or large catchments because the natural conditions are rarely similar in large catchments (Huang et al. 2003; Mu et al. 1999). Hydrological models, including process-based models and conceptual models, are powerful tools for investigating the relationships between climate, human activities, and water resources (Jothityangkoon et al. 2001; Leavesley 1994). However, few process-based models can be directly used for this purpose because they lack a component for engineering measures (McVicar et al. 2007). Conceptual models and regression-based statistical models have thus been widely used to quantify the effects of environmental changes on runoff.

The climate elasticity method based on catchment-scale water and energy balance, such as the Budyko hypothesis (Budyko 1961; Budyko 1974), has been very popular in recent years because of its simple formulation but full representation of climate and land surface changes (Dooge et al. 1999; Sankarasubramanian et al. 2001). Using the water balance equation of $P = Q + ET + \Delta S$ (where P, Q, ET and ΔS respectively represents precipitation, runoff, actual evapotranspiration and changes in water storage) and the Budyko solution for ET, some analytical formulas have been developed to represent the impacts of

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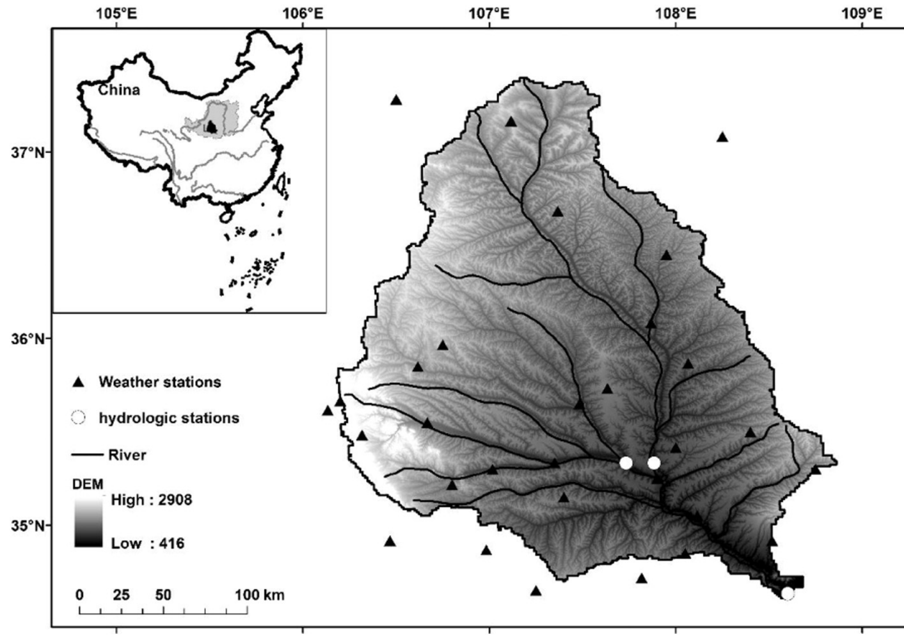

Fig. 1. Location of the Jing River catchment and the hydrologic and weather stations.

environmental factors on runoff or actual evapotranspiration. Roderick and Farquhar (2011) derived the relationship of the elasticity of runoff to three parameters, i.e., precipitation, potential evapotranspiration, and land surface conditions. Yang and Yang (2011) related the elasticity of runoff to precipitation, net radiation, air temperature, wind speed, and relative humidity and then separated the contributions of different climatic variables. Assuming ΔS as zero for long-term water balance, the elasticity method is effective to describe the sensitivity of runoff to environment factors. However, the analytical formulas have been rarely used for analysis of inter-annual variations in the elasticity coefficients though it might provide important information for water resources management.

Spatiotemporal variations exist in the hydrological effects of both human activities and climate variability on the Loess Plateau. In general, human activities account for >50% of the changes in runoff in most catchments (Zhang et al., 2008a; Zhao et al. 2014), while climate variability plays a more important role in some catchments (Hu et al. 2007; Li et al. 2009). Decade-scale variations in hydrological effects have also been observed (Mu et al. 2007a). Opinions differ on the extent of the total runoff change that has occurred in the Loess Plateau, as well as to the extent to which each factor has influenced that change. Therefore, assessing the changes and their causes at the catchment scale is important because it can provide important information for use in environmental protection and water resource management.

The objectives of this study were to (i) analyze the spatiotemporal changes in runoff in a sample catchment for the period of 1961–2010, (ii) assess the inter-annual variability of the elasticity coefficients of runoff to climatic factors and land surface conditions, and (iii) further quantify the contributions of various factors to runoff changes. A method was developed to analyze the inter-annual variability of the elasticity coefficient and the spatiotemporal variability of the runoff as well as its attribution was analyzed in detail to obtain information for use in water resource management.

2. Materials and Methods

2.1. Study area

The Jing River is a second-order tributary of the Yellow River, and its catchment is located in the south of the Loess Plateau (Fig. 1). The catchment covers an area of 45,421 km^2. The average annual precipitation is 542.5 mm, 50–60% of which falls between June and September in heavy storms. The average annual temperature for the period of 1961–2010 is 9.6 °C. The southern part of the catchment is warmer and wetter than the northern part. Farmlands and grasslands cover 88% of the whole catchment (Li et al., 2013a). The soil is predominantly silt loam, with a silt content >50%. The elevation varies from 416 to 2908 m, and the northwestern portion of the catchment is higher than the southeastern portion. The catchment is composed of five types of landform. The two main types (hilly–gully terrain and tableland–gully terrain) cover 81.2% of the catchment. These are the most eroded regions of the catchment.

Since the 1950s, a series of soil conservation practices has been implemented in the catchment. These measures have included both biological measures, such as planting of trees and improvement of pastures, and engineering measures, such as construction of terraces and sediment-trapping dams. The controlled area has increased, and accelerated after 1970s. The total controlled area reached 7562 km^2 by 1996, accounting for 23% of the water-eroded area (Ran et al. 2006).

2.2. Data collection

Three hydrologic stations, i.e., Yang Jia Ping (YJP), Yu Luo Ping (YLP), and Zhang Jia Shan (ZJS), were selected in this study because they are the most important outlets of two sub-watersheds and the whole watershed, respectively (Fig. 1). The ZJS station is the outlet of the Jing River before it feeds into the Wei River. The control areas of the YJP, YLP, and ZJS stations are 14,124 km^2, 19,019 km^2 and 43,216 km^2, respectively, which correspond to 31%, 42%, and 95%, respectively, of the total area of the Jing River catchment. The amounts of runoff of YJP and YLP and the lower reaches from the two stations to ZJS account for 54%, 32%, and 14%, respectively, of the total runoff of the catchment. Monthly runoff data for the three catchments for the period of 1961–2010 were collected from the Yellow River Conservancy Commission (YRCC). Daily meteorological data for 26 stations for the period of 1961–2010 were collected from the China Meteorological Administration. The meteorological data consisted of precipitation, daily maximum and minimum temperatures at a height of 2 m, atmospheric pressure, wind speed at a height of 10 m, mean relative humidity and sunshine duration data.

2.3. Attribution analysis of runoff variation

The elasticity method, based on the Budyko hypothesis, was used to analyze the contributions of climate change and land surface alteration to runoff variation. The sensitivity of runoff to environmental factors was analyzed based on the water balance equation, and the contributions of environmental changes to runoff variations were then quantified. The methods are described in detail as follows.

2.3.1. Water balance equation

The water balance for a catchment can be described by the following equation:

$$Q = P - ET - \Delta S \tag{1}$$

where P, ET, Q, and ΔS represent the precipitation, actual evapotranspiration, runoff, and change in water storage, respectively. The values of Q and P can be observed directly, but the values of ET and ΔS cannot be observed directly on the catchment scale and must be estimated indirectly.

The Budyko framework is a powerful method for ET estimation by various empirical formulas, such as the Fu equation (Fu 1981; Zhang et al. 2004), the Zhang equation (Zhang et al. 2001), the Choudhury–Yang equation (Choudhury 1999; Yang et al. 2008) and the Wang–Tang equation (Wang and Tang 2014). These equations were all developed based on the relationships between P, ET_0, and the controlling parameters (the land surface conditions), and they yield similar performance in terms of ET estimation. The Choudhury–Yang equation was selected for use with the following equation, in which ET_0 is estimated by the Priestley and Taylor method (Priestley and Taylor, 1972):

$$ET = \frac{P \times ET_0}{\left(P^n + ET_0^n\right)^{1/n}} \tag{2}$$

where n is the controlling parameter that determine the shape of the Budyko curve, which primarily represents the integrated effects of the catchment landscape characteristics on the water balance (Xu et al. 2014; Yang et al. 2014a).

The value of ΔS is usually assumed to be zero for the purposes of long-term analysis. In this study, elasticity coefficients were calculated for both annual scale and long-term periods based on the assumption of invariant water storage. The reliability of this hypothesis for annual scale analysis will be examined in the discussion section.

The water balance equation can therefore be expressed in the following form:

$$Q = P - \frac{P \times ET_0}{\left(P^n + ET_0^n\right)^{1/n}} \tag{3}$$

According to Eq. (3), the annual value of n can be estimated using the annual data for Q, P, and ET_0.

2.3.2. Sensitivity analysis

Because the water balance equation can be rewritten as $Q = f(P, ET_0, n)$, the elasticity of runoff to a particular independent variable x can be calculated as follows (McCuen 1974):

$$\varepsilon_{x_i} = \frac{\partial Q}{\partial x_i} \times \frac{x_i}{Q} \tag{4}$$

where ε_{x_i} is the elasticity coefficient and x_i represents P, ET_0, or n. Assuming that $\varnothing = \frac{ET_0}{P}$, the elasticity coefficients of Eq. (4) are as follows (Xu et al. 2014; Yang et al. 2015):

$$\varepsilon_P = \frac{\left(1+\varnothing^n\right)^{1/n+1} - \varnothing^{n+1}}{\left(1+\varnothing^n\right)\left[\left(1+\varnothing^n\right)^{1/n} - \varnothing\right]} \tag{5a}$$

$$\varepsilon_{ET_0} = \frac{1}{\left(1+\varnothing^n\right)\left[1-\left(1+\varnothing^{-n}\right)^{1/n}\right]} \tag{5b}$$

$$\varepsilon_n = \frac{\ln\left(1+\varnothing^n\right) + \varnothing^n \ln\left(1+\varnothing^{-n}\right)}{n\left[\left(1+\varnothing^n\right) - \left(1+\varnothing^n\right)^{1/n+1}\right]} \tag{5c}$$

A positive/negative elasticity coefficient of a certain variable indicates that Q will increase/decrease with an increase/decrease of the variable. Using the above equations, the annual or periodic elasticity coefficients of runoff with respect to P, ET_0, and n can be obtained for different hydrological stations, and the temporal evolution of the elasticity coefficients can be determined.

2.3.3. Quantification of contribution

The runoff change induced by a certain factor can be estimated by the product of the factor change and its partial derivative. Thus, the contribution of each factor to changes in runoff can be calculated using the following differentiating equation:

$$dQ = \frac{\partial Q}{\partial P} dP + \frac{\partial Q}{\partial ET_0} dET_0 + \frac{\partial Q}{\partial n} dn \tag{6}$$

or more briefly:

$$\mathrm{L\_}(Q) = \mathrm{C\_}(P) + \mathrm{C\_}(ET_0) + \mathrm{C\_}(n) \tag{7}$$

where $\mathrm{L\_}(Q)$ is the actual linear trend of Q and $\mathrm{C\_}(P)$, $\mathrm{C\_}(ET_0)$, and $\mathrm{C\_}(n)$ are the contributions of changes in climate (P, ET_0) and land surface (n), respectively, to the variation in Q. The sum of $\mathrm{C\_}(P)$, $\mathrm{C\_}(ET_0)$, and $\mathrm{C\_}(n)$ is simplified as $\mathrm{C\_}(Q)$.

The relative contributions of each factor to the runoff change can be calculated as:

$$\mathrm{RC\_}(x_i) = \frac{C\_(x_i)}{L\_(Q)} \times 100\% \tag{8}$$

where x_i represents each of the above three variables.

The non-parametric Mann–Kendall test was used to detect the change point of the annual runoff series. This test has the advantages of robustness for data with a non-normal distribution along with a power nearly as great as its parametric competitors (Liang et al. 2010). Details of the theory and calculation steps have been described by Modarres and Sarhadi (2009).

After the study period was divided into two sub-periods before and after abrupt changes occurred, the contributions of the different variables considered to runoff changes were quantified for the two periods. The variations in the contribution of each variable to runoff change could then be detected and used to provide information for use in water resource management.

3. Results

3.1. Changes in runoff and environmental factors

The annual runoff had a downward trend for all the three gauge stations (Table 1). However, the downward trends were only significant for the whole catchment (ZJS) and one of the two sub-watersheds of the upper reach (YJP). The annual runoff for ZJS and YJP decreased by 0.65 and 1.14 mm yr^{-1}, which accounted for 1.7% and 2.4%, respectively, of the corresponding annual runoff. The change in precipitation exhibited a trend similar to that of runoff, decreasing in ZJS and YJP by 1.94 and 2.01 mm yr^{-1}, whereas the decrease in YLP was insignificant. However, ET_0 exhibited an insignificant upward trend for all stations. The increase in n was significant in YJP but insignificant in ZJS and

Table 1
Averages and changes of runoff and environmental factors in the Jing River during 1961–2010.

Station	Q, mm yr^{-1}		P, mm yr^{-1}		ET_0, mm yr^{-1}		n	
	Average	Slope	Average	Slope	Average	Slope	Average	Slope
Whole period								
ZJS	37.2	−0.65**	542.5	−1.94*	936.5	0.41	2.783	0.004
YJP	46.8	−1.14**	537.7	−2.01*	921.3	0.42	2.518	0.013*
YLP	22.4	−0.15	530.2	−1.75	938.2	0.60	3.293	−0.017
Period I (1961–1995 for ZJS; 1961–1984 for YJP)								
ZJS	42.5	−0.58	552.2	−3.32	930.3	−0.21	2.714	−0.01
YJP	62.3	−1.57	567.3	−3.25	915.7	−0.01	2.383	0.005
Period II (1996–2010 for ZJS; 1985–2010 for YJP)								
ZJS	25.0	−0.54	520.1	0.15	951.0	−1.50	3.028	0.027
YJP	32.5	−0.54	510.4	0.40	926.4	0.73	2.728	0.021

The unit of Q, P and ET_0 is mm; the slope unit of them is mm/yr. *$p < 0.05$; **$p < 0.01$.

YLP. According to the Budyko framework, an increase in n will increase ET_0 and further decrease runoff.

The annual runoff in YLP did not occur abrupt change; however, that in YJP and ZJS respectively changed abruptly in 1985 and 1996 ($p < 0.05$). Therefore, the whole study period of 1961–2010 can be divided into two sub-periods to compare the values of environmental factors and further qualitatively attribute the changes in runoff. Take ZJS as an example, although runoff decreased in both two sub-periods, precipitation and parameter n decreased in the first sub-period while increased in the second sub-period. In general, upward trend in precipitation should increase runoff while that in parameter n should decrease runoff. However, the combined effect caused a downward trend in runoff, which implies that the changes in land surface might have greater impacts on runoff than those in precipitation.

3.2. Elasticity of runoff to environmental factors

The elasticity coefficients of runoff with respect to the potential evapotranspiration, precipitation, and land surface are presented in Table 2 for the whole catchment and the sub-watersheds and for the whole study period and the sub-periods. Overall, runoff was negatively correlated with ET_0 and n but positively correlated with P. The absolute values of the three elasticity coefficients were the largest for P, intermediate for ET_0, and the smallest for n. The elasticity coefficients ranged from −1.96 to −3.00 for ET_0, from 2.96 to 4.00 for P, and from −1.88 to −2.69 for n. These ranges suggest that a 1% increase in ET_0, P, or n would result in a 1.96–3.00% decrease, 2.96–4.00% increase, or 1.88–2.69% decrease in runoff. However, spatiotemporal variations existed in the elasticity coefficients. Spatially, the variation in the elasticity coefficients was the largest for YLP, intermediate for the whole catchment ZJS, and the smallest for YJP. The coefficients were greater in the second sub-period than in the first sub-period.

To further assess the temporal evolution of the impacts of climate change and land surface change on runoff, the annual elasticity coefficients for the period of 1961–2010 for the three stations were determined and are presented in Fig. 2. The absolute values of ε_{ET_0} and ε_P increased in YJP and ZJS but decreased in YLP, which suggests that Q became more sensitive to climate change in YJP and ZJS but less sensitive in YLP. The absolute values of ε_n all increased significantly for the three hydrological stations, which suggests that Q became more sensitive to variation in the land surface conditions.

Table 2
Elasticity coefficients of runoff to climate variables and catchment land surface condition changes.

	ε_{ET_0}	ε_P	ε_n
Whole period			
ZJS	−2.44	3.44	−2.30
YJP	−2.15	3.15	−2.11
YLP	−3.00	4.00	−2.69
Period I (1961–1995 for ZJS; 1961–1984 for YJP)			
ZJS	−2.34	3.34	−2.18
YJP	−1.96	2.96	−1.88
Period II (1996–2010 for ZJS; 1985–2010 for YJP)			
ZJS	−2.74	3.74	−2.63
YJP	−2.42	3.42	−2.41

3.3. Attribution of temporal changes in runoff

The changes in runoff due to climate change (ET_0 and P) and land surface alteration (n) were estimated using Eqs. (6)-(8), and the results are shown in Table 3. The calculated changes in Q (C_(Q)) were very similar to the observed Q trend (L_(Q)), which suggests that the method used was effective in assessing the contributions of the relevant environment factors to the runoff variation. For the period of 1961–2010, climate change and land surface alteration both decreased runoff in ZJS and YJP, and changes in P made the greatest contributions to the runoff changes (76% and 86% for ZJS and YJP, respectively). However, climate change decreased runoff while land surface alteration increased runoff in YLP, and the contribution of the former change was greater than that of the latter change. The spatial variations in the land surface were possibly the dominant cause of the different change trends in runoff.

The main factors controlling the changes in runoff varied for the different sub-periods. The runoff reduction in ZJS and YJP for Period I (the sub-period before abrupt change, 1961–1995 for ZJS and 1961–1984 for YJP) was controlled by changes in precipitation (the contributions of which were 157% and 84%, respectively). However, land surface alteration became the dominant factor in ZJS and YJP for Period II (the period after abrupt change, 1996–2010 for ZJS and 1985–2010 for YJP). The temporal variations in the dominant factors controlling runoff suggest that land surface alteration due to soil conservation measures became more pronounced.

4. Discussion

To assess the temporal variations in the sensitivity of runoff to climate and land surface, the annual elasticity coefficients of Q with respect to ET_0, P, and n were estimated by neglecting ΔS. Neglecting ΔS is reasonable for long-term analysis (Koster and Suarez 1999; Potter and Zhang 2009; Yang et al. 2007), but whether or not it is reasonable

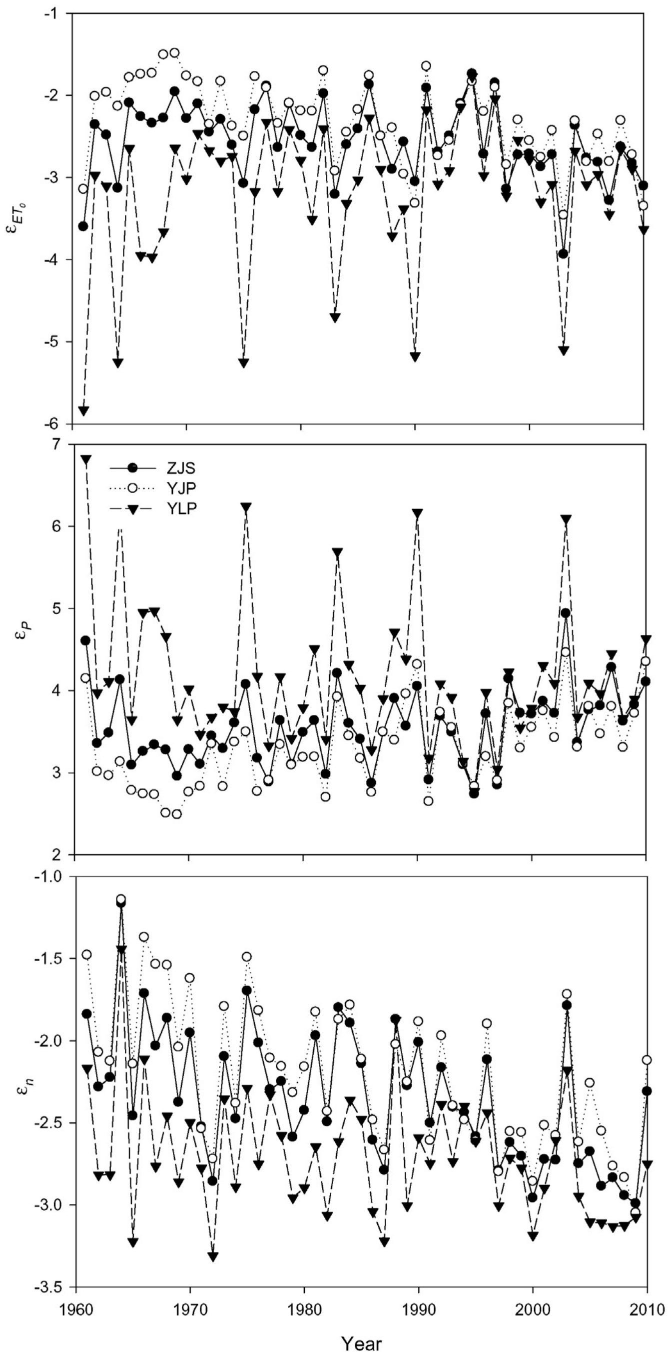

Fig. 2. Inter-annual changes in elasticity coefficients for (a) potential evapotranspiration ε_{ET_0}, (b) precipitation ε_P, and land surface condition ε_n.

for short-term (e.g., annual-scale) analysis should be investigated. According to observations by GRACE (the Gravity Recovery and Climate Experiment), ΔS in the Yellow River basin during the period of 2003–2008 was approximate 7 mm yr^{-1} (Zhao et al. 2011; Zhong et al. 2009). Assuming ΔS to be 7 mm yr^{-1} for the Jinghe River catchment (ZJS), the annual *ET* would be overestimated by 7 mm yr^{-1}, according to the water balance equation $P - Q = ET + \Delta S$, which would account for 1.4% of the mean annual *ET*. In addition, the parameter *n* would be overestimated by 8.7% for given values of ET_0 and *P*. Accordingly, the elasticity coefficients of *Q* with respect to ET_0, *P*, and *n* would be overestimated by 10.4%, 7.7%, and 7.2%, respectively. The above relative errors in the annual elasticity coefficients were <10% for the most part. Therefore, the annual elasticity coefficients determined by neglecting ΔS should be suitable for use assessing the inter-annual trend in the sensitivity of *Q* with respect to ET_0, *P*, and *n*.

The controlling parameter in the Budyko equations (*n* in this study) is related to soil properties (Milly 1994; Potter et al. 2005; Zhang et al., 2008b), topography (Yang et al. 2007; Yang et al. 2014a; Yokoo et al. 2008) and vegetation (Donohue et al. 2007; Donohue et al. 2010; Li et al., 2013b; Yang et al. 2009; Zhang et al. 2001). For short periods, during which soil properties and topography remain almost constant, the vegetation coverage is thus considered to the major factor influencing the controlling parameter *n* (Xu et al. 2014). Previous study in this area found that the land surface condition has been greatly altered by the improvement of vegetation coverage, especially from the increase of forest and grasslands (Wang et al. 2015). In this study, annual normalized-difference vegetation index (NDVI) values were thus extracted to calculate the vegetation coverage (*M*), according to the procedure described by Yang et al. (2009). The relationships between *n* and *M* for the Jing River catchment exhibited similar inter-annual variations for the period of 1981–2010, and their upward trends after the abrupt changes in runoff were both significant (Fig. 3a). These results suggest that vegetation changes had positive impacts on the value of *n* and thus that runoff decreased with the increase of *n* (Table 2 and Fig. 3).

However, *n* was not significantly correlated with *M* for the whole period or for the sub-period when vegetation increased substantially (Fig. 3b), as was also reported by Yang et al. (2014a) for China as a whole. This implies that *n* might represent the combined effects of some other factors. In addition to vegetation changes, the land surface and topography have been greatly altered by numerous engineering measures, such as construction of terraces and check dams. For example, the terraced area increased from 22.69 to 2356.28 km^2 during the period of 1956–1996 and has increased at an even faster rate since then (Ran et al. 2006). According to the relationships between annual runoff and index of dryness under different land use developed in a subwatershed of this study, the conversion of slope farmland to terrace can lead to enormous runoff decline (Zhang et al. 2015). The weak correlation between *n* and *M* might therefore be partially due to land surface changes resulting from engineering measures.

The relationships between *M* and *n* were further analyzed for those points that deviated considerably from the trend line shown in Fig. 3b. These points were found to correspond to either large or small annual precipitation amounts, which suggests that climate seasonality has an important influence on the catchment water balance. Similar observations have been reported in some other studies. For example, rainfall and potential evaporation seasonality, storm depth, the frequency of daily rainfall events, and differences in the timing of precipitation and potential evapotranspiration could also influence the annual *ET* ratio or the inter-annual variability of *ET* (Li 2014; Potter et al. 2005; Shao et al. 2012; Yokoo et al. 2008). Although the effects of the above factors with respect to the parameter *n* cannot be quantified, the land surface alteration, due to both vegetation improvement and engineering construction, might have the greatest impact on the catchment water balance because the contributions of *n* to runoff reduction increases with increasing vegetation improvement and engineering construction. Therefore, more attention should be paid to the implementation of soil conservation measures, since the development of this area depends on its water resources.

Another possible source of error is the Taylor series expansion of the Budyko equations. A first-order Taylor expansion has been used in many studies; however, the induced errors can increase with decreasing P and increasing ET_0 and *n* (Yang et al. 2014b). The errors between the estimated and observed changes in runoff (ε in Table 3) are very small for most of regions and periods, except for YJP. The runoff trends for YJP were overestimated for the two sub-periods by 32% and 19%, which may be because of the larger changes that occurred in *P*, ET_0, and *n* (Yang et al. 2014b).

Table 3
Contributions of three factors to the changes in runoff.

	C_(ET_0), mm	C_(P), mm	C_(n), mm	RC_(ET_0), %	RC_(P), %	RC_(n), %	C_(Q), mm yr^{-1}	L_(Q), mm yr^{-1}	δ, mm yr^{-1}
Whole period									
ZJS	−0.04	−0.47	−0.11	6	76	18	−0.62	−0.65	0.03
YJP	−0.05	−0.61	−0.05	7	86	7	−0.71	−1.04	0.33
YLP	−0.04	−0.25	0.18	37	227	−164	−0.11	−0.15	0.04
Period I (1961–1995 for ZJS; 1961–1984 for YJP)									
ZJS	0.02	−0.8	0.27	−4	157	−53	−0.51	−0.58	0.07
YJP	0.002	−1.07	−0.2	0	84	16	−1.27	−1.57	0.30
Period II (1996–2010 for ZJS; 1985–2010 for YJP)									
ZJS	0.04	0.03	−0.54	−9	−6	115	−0.47	−0.54	0.07
YJP	−0.06	0.09	−0.53	12	−18	106	−0.50	−0.54	0.04

RC_(ET_0), RC_(P) and RC_(n) represent the relative contribution of ET_0, P and n to the change in Q, respectively, which were calculated by Eq. (8).
δ is the error between L_(Q) (the observed change trend of Q) and the sum of the contributions of each factor to the change in runoff C_(Q).

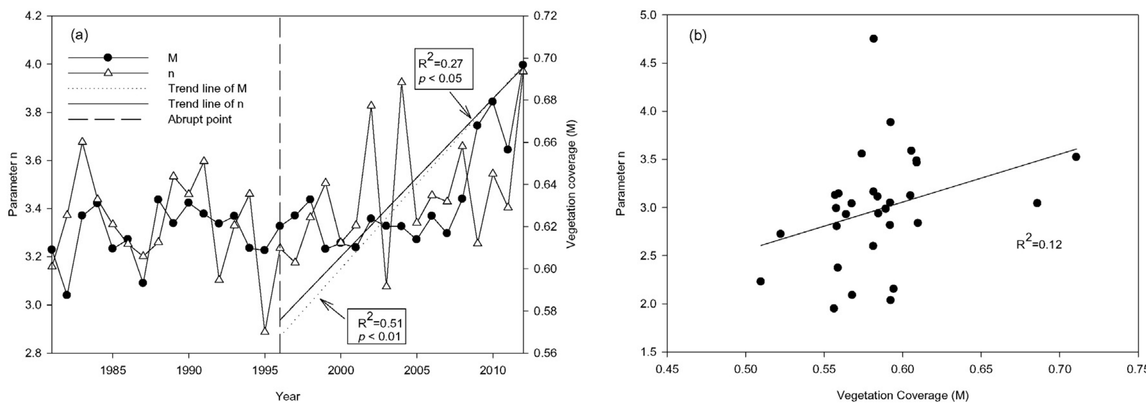

Fig. 3. Relationships between parameter n and vegetation coverage for ZJS station from 1981 to 2010.

5. Conclusions

Climate changes and human activities have led to great changes in the hydrological cycle of the Loess Plateau, and quantifying their separate contributions to runoff changes can provide useful information for water resource management. Taking the Jing River catchment as an example, the effects of climate change and land surface alteration on runoff for the whole catchment ZJS and two sub-watersheds (YJP and YLP) between 1961 and 2010 were investigated in this study using the elasticity method. Reductions in runoff were detected for all of the hydrological stations. The runoff was found to be most sensitive to P, followed by ET_0, the land surface conditions (described by the parameter n in the Choudhury–Yang equation), and spatiotemporal variations in the sensitivity coefficients. The degree of runoff has become more sensitive to climate change in YJP and ZJS but less sensitive to climate change in YLP, and it has become more sensitive to land surface alteration in all three. The decrease in P was the dominant factor in the runoff reduction in the three catchments, but its effects were largely offset by the increase in n in YLP. The variation in n has become the dominant factor in runoff change in ZJS and YJP in recent years, which suggests that land surface alteration due to soil conservation measures, including biological measures (i.e. the improvement of vegetation coverage) and engineering measures (i.e. construction of terraces and check dams), is becoming more important in runoff change.

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