Effects of climatic variability and human activity on runoff in the Loess Plateau of China

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ABSTRACT

The Loess Plateau in north-central China has a long history of human activities. As a result of climate change, deforestation and sparse vegetative cover, the region suffers from water shortages and severe soil erosion, significantly influencing efforts for sustainable social development. In order to understand the impacts of climatic variability and human activities on runoff and other hydrological factors in this region, the Luoyugou catchment and its paired catchments (Qiaozidong and Qiaozixi) were selected. Statistical analysis indicated precipitation did not vary significantly whereas the annual runoff decreased from 1986 to 2008, with an abrupt change in 1994. Actual evapotranspiration (AET) increased slightly but not significantly. A comparison of runoff in the paired catchments showed land use changes reduced runoff by more than 38% under the same rainfall conditions. Human activities were the strongest contributor to changes in runoff and AET, at 67% and 90% respectively, while the remaining contributor was climate variation. The influence of various human activities on runoff is quite different, and soil-water conservation initiatives have a greater impact on runoff (about 41%). Thus, human activities were the primary reason for the reduction in runoff in the study catchment compared to climate. Greater emphasis should be given to afforestation and soil-water conservation measures.

Keywords: runoff, climate change, human activities, Loess Plateau

RÉSUMÉ

Le Plateau de Loess situé dans le centre-nord de la Chine est depuis longtemps marqué par les activités humaines. En raison du changement climatique, du déboisement et d'un couvert végétal clairsemé, la région subit des périodes de sécheresse et une érosion des sols importante, ce qui entrave grandement les efforts en vue d'un développement social durable. Pour évaluer les conséquences de la variabilité climatique et des activités humaines sur le ruissellement et les autres facteurs hydrologiques de la région, on a jumelé trois bassins hydrographiques soit celui de Luoyugou et ses témoins les bassins Qiaozidong et Qiaozixi pour y mener une étude. Les analyses statistiques ont révélé que le ruissellement avait diminué entre 1986 et 2008, avec un changement marqué en 1994, bien que les précipitations n'aient pas varié de façon significative. L'évapotranspiration réelle (EtR) a connu une hausse légère, mais pas significative. Une comparaison du ruissellement dans les bassins jumelés à l'étude a démontré que les changements d'affectation territoriale ont réduit de plus de 38 % le ruissellement dans les mêmes conditions pluviométriques. Les activités humaines constituaient le facteur le plus important de changement du ruissellement ainsi que l'EtR, soit, respectivement, de 67 % et de 90 %, le changement climatique expliquant le reste de cette variation. L'influence des différentes activités humaines était très inégale et les projets de conservation de l'eau et des sols avaient la plus grande influence sur le ruissellement (environ 41 %). Les activités humaines représentaient donc la principale cause de réduction du ruissellement dans le bassin sous étude par rapport au climat. Il faudrait donc mettre davantage l'accent sur le reboisement de terres en friche et sur les mesures de conservation de l'eau et des sols.

Mots clés : ruissellement, changement climatique, activités humaines, Plateau de Loess

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Introduction

Climate change and human activities are key factors considered responsible for changes in hydrological dynamics of water catchments (Asbjornsen *et al.* 2011). Climate change has resulted in the rise of atmosphere temperatures and modified the pattern of precipitation and evapotranspiration, which has directly led to altered regional hydrological cycles (Li *et al.* 2008). Climatic variables, especially rainfall, largely determine the runoff volume of a catchment (Wang *et al.* 2009). Changes in land use and land cover also causes significant impacts on hydrology by affecting the characteristics of runoff, evapotranspiration, sediment, soil moisture, infiltration and groundwater recharge (Gabris *et al.* 2003). Current hydrologic models and statistical methods are usually applied to study the effects of climate variations and human activities on catchment hydrological processes (Chen and Chen 2004). Traditional statistical methods require data from long-term monitoring, which are often not available. More importantly, these methods lack a physical basis and decrease the degree of computational precision (Zhan *et al.* 2011). Hydrological models also require considerable data that may be unavailable, such as spatial data representing landscape structure and catchment properties.

An alternative method proposed by Milly and Dunne (2002) to describe the first-order effect of changes in precipitation and potential evapotranspiration on runoff has attracted wide attention. It may be used to study hydrological responses to changes in climate and land use and enables the separation of the effect of climate on runoff from that of land use changes caused by human activities (Li *et al.* 2010). In order to further analyze the effect of land use changes on runoff and evapotranspiration, a paired catchments approach and separation evaluation methods have been used in this study.

The Loess Plateau in north-central China covers approximately 400 000 km² and is the world's largest. "Loess" refers to fine-grained, wind-deposited, yellowish alluvium soil. The region is highly erosion-prone and the most vulnerable ecological environment in the country. It is characterized by its

unique gullied landscape. According to hydrological records, approximately 90% of the sediment of the Yellow River comes from the Loess Plateau (Tang and Chen 1990). Since the latter half of the 20th century, this region has experienced a warming and drying trend (Liu *et al.* 2006). In addition, severe ground-water exploitation has accelerated water shortages caused by climate variations and human activities. This has had a significant negative impact on the social and economic development in this region. Therefore, it is imperative to understand and quantify the influence and relative importance of climate variations and human activities.

Luoyugou, a typical catchment on the Loess Plateau, was selected as the study area. It is vulnerable to climate changes and has been affected by human activities over the past 30 years. With a worsening water crisis, it has become important to assess the impact of climate variation and human activities on hydrological factors and to use this information to develop strategies for ecological restoration and sustainable regional development. Therefore, the purpose of this study is to separate the effects of climate variability and human activities on runoff and AET in a typical loess catchment. Specifically, the following will be addressed: (1) to detect trends and changes in precipitation (P), potential evapotranspiration (PET), runoff (R) and actual evapotranspiration (AET); (2) to estimate the contribution of climate change and human activities on the change of R and AET; (3) to understand the influence of different forms of human activities on runoff variation.

Materials and Methods

Study area

The Luoyugou catchment and its paired watersheds of Qiaozidong and Qiaozixi, located south of Tianshui City, Gansu Province in northwestern China, have an area of approximately 73 km². The area is part of the third sub-region of the Loess Plateau. The gully system is feather-shaped and ranges from 1200 to 1895 m in elevation (Fig. 1). Average temperatures are above 10°C and the area has a continental monsoon climate, changing from semi-arid to semi-humid over the year with an annual precipitation of approximately

Fig. 1. Location of watersheds under study.

Table 1. The main characteristics of the nested watersheds

Name	Area (km ²)	Is there artificial disturbance?	Length of Watershed (km)	Slope in Gully (%)	Relative height difference (m)	Annual erosion modulus from 1986 to 2004 (t/km ²)	Vegetation cover of 2004 (%)	Main land use types of 2004
Qiaozidong	1.27	YES	2.13	20.75	377	2310.4	39.86	Forest (58.8%) and orchards (28.9%)
Qiaozixi	1.10	NO	2.22	21.47	377	4270.6	21.79	Orchards (38.3%) and sloping land (36.4%)

550 mm. More than 60% of the year's rainfall is during the June to September monsoon season. Soil types are mount gray loamy, loess gray, and loess loamy soils (Yu *et al.* 2009). The Qiaozidong watershed is a half-scallop shape with an area of 1.27 km², and the Qiaozixi watershed has a feathering pattern over an area of 1.10 km². There are no control measures for soil and water conservation in Qiaozixi. Qiaozidong has controls and has similar natural conditions to Qiaozixi. The main characteristics of Qiaozidong and Qiaozixi are listed in Table 1.

Land use data

Four satellite images (Landsat TM 1986, 1995, 2001, 2008) were obtained from Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS). Using ArcGIS9.3, land use structure and land cover change of the Luoyugou catchment were obtained through overlay analysis for the four study periods: 1986, 1995, 2001 and 2008.

Hydrological data

Annual runoff data were available from the hydrological station and precipitation was measured by nine automatic rain gauges located within Luoyugou. Air temperature and other meteorological factors including relative humidity, solar radiation and wind speed were measured at a local meteorological station one km outside the study watershed. Potential evapotranspiration (PET) was calculated with meteorological data for the period using the Penman-Monteith equation (Allen *et al.* 1998).

Data Analysis

The study involved: (1) statistic analytical methods including nonparametric Kendall's trend test (Hirsch *et al.* 1982), moving t-tests, double-mass curve analysis and Normalization Method ($y = (x - \text{MinValue}) / (\text{MaxValue} - \text{MinValue})$) from Baidubaike (Baidu, Inc. [undated]) to detect trends of runoff and climatic variables; (2) a paired catchment approach to explore the effects of human activities on runoff; (3) multi-year average water balance model and separation evaluation method to determine the rates of change in climate and human activities on runoff and AET, respectively.

Multi-year average water balance model

To estimate the impact of climate change and human activities on runoff, a change in observed mean annual runoff ΔQ^{tot} may result from climate variability ($\Delta Q^{\text{-clim}}$) and

human activities ($\Delta Q^{\text{-ha}}$) (Li *et al.* 2007, Zhang *et al.* 2009). Therefore ΔQ^{tot} may be estimated by the following:

$$[1] \quad \Delta Q^{\text{tot}} = \Delta Q^{\text{-clim}} + \Delta Q^{\text{-ha}}$$

ΔQ^{tot} is differences of annual mean runoff between two periods at the "inflection point", as follows:

$$[2] \quad \Delta Q^{\text{tot}} = \bar{Q}_2 - \bar{Q}_1$$

where $\bar{Q}_1$ and $\bar{Q}_2$ are average annual runoff of the two periods before and after the "inflection point".

Changes in precipitation and potential evapotranspiration may lead to changes in the water balance (Li *et al.* 2007). A change in mean annual runoff ($\Delta Q^{\text{-clim}}$) may be determined by (Milly and Dunne 2002):

$$[3] \quad \Delta Q^{\text{-clim}} = \beta \Delta P + \gamma \Delta E_0$$

where ΔP and ΔE_0 are changes in precipitation (P) and potential evapotranspiration (PET); β and γ are the reflection of runoff to precipitation and PET. According to Zhang *et al.* (2001), long-term average evapotranspiration and sensitivity coefficients may be estimated by:

$$[4] \quad \frac{E}{P} = \frac{1 + w(E_0 / P)}{1 + w(E_0 / P) + (E_0 / P)^{-1}}$$

$$[5] \quad \beta = \frac{1 + 2x + 3wX^2}{(1 + x + wX^2)^2}$$

$$[6] \quad \gamma = -\frac{1 + 2wX}{(1 + x + wX^2)^2}$$

where E is the actual evapotranspiration with a common unit of mm; x is the index of dryness and equal to E_0/P ; w is a integrative parameter related to vegetation type and calculated by weighting the area with each land type.

Separation evaluation method

Separation evaluation was used to examine the impacts of climatic variability and land use change on AET. It is critical to determine the inflection point in the evapotranspiration

record using double-mass curve analysis (DMC) of Bonat *et al.* 1997. By plotting the accumulation of two quantities the slope of the straight line will represent the constant of proportionality between the two quantities. An inflection point is a point on a curve at which the curvature or concavity changes sign from plus to minus or minus to plus. An inflection point in the slope indicates that factors other than precipitation affect AET. According to the inflection point of the curve, the study is divided into two periods, the “base period” influenced slightly by human activities and the “compared period” marking significant changes in land use by human activities and takes the inflection point as the cut-off to reflect the effect of land use change on AET. The method after Wang 2006 and Wang, G.Q. *et al.* 2008 is:

$$[7] \Delta S' = Q_{s2} - Q_{s1} = \Delta S_1 + \Delta S_2$$

$$[8] \Delta S_1 = Q_{s2} - Q'_{s2}$$

$$[9] \Delta S_2 = Q'_{s2} - Q_{s1}$$

where ΔS is the total change in AET, Q_{s1} and Q_{s2} represent the AET in the base period and compared period, and ΔS_1 and ΔS_2 are changes in AET by human activities and precipitation, respectively. Q'_{s2} is the simulation AET based on the P - AET curve.

Results and Discussion

Average annual precipitation in the Luoyugou catchment was 528 mm, ranging from 322 mm to 810 mm. Annual precipitation showed a slight decrease of 0.08 mm per year (Fig. 2A). Combined with the result of nonparametric Kendall's trend test and moving t-test, no inflection point was detected in the precipitation record (Fig. 3A and Fig. 4A).

Under the influence of human activities and warmer and drier climates, annual runoff showed a significant decreasing trend with a mean value of 20 mm (Fig. 2A). Nonparametric Kendall's trend test indicated that the change in annual runoff occurred in 1992 (Fig. 3B). Combined with the moving t-test (Fig. 4B), one inflection point in 1994 was identified. With this result, the annual runoff study period may be divided into two parts: a base period (1986–1994) and a compared period (1995–2008).

Annual potential evapotranspiration showed a slight increase (Fig. 2B). No change points occurred in the study period (Fig. 3C and Fig. 4C). Annual evapotranspiration from the water balance model (Zhang *et al.* 2001) showed a slight increase from 1986 to 2008 (Fig. 2B). Using Kendall's trend test and moving t-test, no break point was found in the AET record (Fig. 3D and Fig. 4D).

Land use changes

According to national land use classification combined with land use on hills and gully regions of the Loess Plateau, land use was categorized into seven types: sloping farmland, terrace, forest, grassland, orchard, river and settlements.

Based on ArcGIS 9.3, land use in different periods was obtained (Table 2). Sloping farmlands, terraces and forests, accounting for over 80% of the total area in the study period,

Fig. 2A. Changes in precipitation and runoff from 1986 to 2008.

Fig. 2B. Changes of PET and AET from 1986 to 2008.

dominated the area. Large-scale (about 75%) sloping farmlands were converted to terraces from 1986 to 1995. Policy and economic impacts were the driving force behind the extreme land use change (Madelene and Chen 2006). Forested lands increased by over 28% compared with 1986 levels, which coincide with the Slope Land Conversion Program in the Loess Plateau (Ma *et al.* 2008). Orchards increased after 2001 by 106%. This expansion was due to local farmers planting cherry trees to improve their incomes. River and settlement areas changed little over the study period. From 1986 to 1995, forest, grassland and terrace areas increased at a relative high rate while sloping farmland decreased. The decrease in runoff in the 1990s onwards is possibly due to changes in land use observed during the same period.

Effects of climate variations and human activities on runoff

Fig. 5 compares runoff modulus for the paired catchments (Qiaozidong and Qiaozixi) under similar rainfall conditions. Runoff in Qiaozixi is significantly lower than in Qiaozidong although rainfall levels are the same. The runoff modulus is reduced from 12% to 79% with an average reduction of 38%. This reduction is most likely due to land use changes and vegetation cover.

Fig. 3. Nonparametric Kendall's trend test of P (**A**), R (**B**), PET (**C**) and AET (**D**). Dark line C1; grey lines C2; dotted line significance level at 0.05.

Fig. 4. Moving t-test of P (**A**), R (**B**), PET (**C**) and AET (**D**). Dotted line represents significance level at 0.05.

Table 2. Area and percentage of land use types in Luoyugou watershed

Land type	1986		1995		2001		2008	
	Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)	Area (km ²)	Percentage (%)
Slope farmland	49.23	67.63	11.23	15.43	11.18	15.36	9.49	13.04
Terrace	3.09	4.25	39.05	53.65	39.03	53.62	39.76	54.62
Forest	7.89	10.84	9.97	13.70	10.06	13.82	10.13	13.92
Grassland	6.76	9.29	6.63	9.11	6.59	9.05	5.05	6.94
Orchard	2.07	2.84	2.17	2.98	2.18	2.99	4.27	5.87
River	1.06	1.46	1.06	1.46	1.06	1.46	0.84	1.15
Settlements	2.69	3.70	2.69	3.70	2.69	3.70	3.25	4.46
Total	72.79	100.00	72.79	100.00	72.79	100.00	72.79	100.00

Fig. 5. Comparison on runoff in single rainstorm.

Table 3. Contribution rate of climate change and land-use changes on runoff

Period	<i>P</i> (mm)	<i>E</i> ₀ (mm)	<i>Q</i> (mm)	ΔQ^{tot} (mm)	ΔQ^{cliz} (%)	ΔQ^{ha} (%)
1986–1994	541.1	1032.72	35.14	15.14	33.10	66.90
1995–2008	606.05	1073.15	20.10			

In order to analyze the impacts of climate variation and land use changes on runoff, runoff was divided into two parts according to the inflection point of the runoff record: a baseline period (1986–1994), representing runoff under more natural conditions and a compared period (1995–2008), representing runoff under the impact of climate change and human activities. Based on equations 1, 2 and 3, the effects of climate change and human activities on runoff were calculated. The model parameter *w* was determined according to 1986 land use data. Table 3 shows the results calculated by the multi-year average water balance model and indicates that cli-

mate change accounts for 33% of the observed change in mean annual runoff and human activities for 67%.

General linear regression analysis showed that runoff was positively correlated with *P* ($R^2 = 0.35$, $p = 0.003 < 0.05$) and negatively correlated with *T* ($R^2 = 0.30$, $p = 0.006 < 0.05$) (Fig. 6). From the size of the correlation coefficient, the interaction of *P* and *T* influences the reduction of runoff while precipitation has a greater influence on runoff compared to temperature. Normalization method applied to further analyze the impact of *P* and *T* on runoff found that changes in runoff and rainfall were similar, which indicates the change of precipitation had a greater influence on runoff than temperature (Fig. 7).

Effect of different forms of human activities on runoff

The above results demonstrate that human activities exert a dominant influence upon runoff decline in the Luoyugou watershed compared to climate. In order to analyze the effect of different forms of human activities, data including land use, water conservancy projects and annual water consumption during the period of 1986–2008 were collected from the Water Resources Bureau of Tianshui City.

Effect of the Slope Land Conversion Program on decreasing runoff

In the Luoyugou watershed, especially after 1990, large-scale sloping farmlands were converted to terraces and forests. According to the data (Table 2), sloping land, a major source of sediment yield, decreased by 39.7 km² and areas of forest and terraces increased by 2.2 km² and 36.7 km² from 1986 to 2008, respectively. Based on related research (Liu 1978, Wu and Pei 2002), the mean stream flow of sloping land area was about 80% higher than that of terraces and 37% lower than that of the sloping land area in the Loess Plateau. Using the data above and eq. 10, decreases in runoff can be attributed to about 30% of the Slope Land Conversion Program in the Luoyugou watershed. The formula is:

$$[10] S = \sum_{i=1}^n A_i \times I_R$$

where S is the contribution ratio of the effect of the Slope Land Conversion Program on runoff, A_i the area of terrace or forest transferred from the sloping area over the study period, and I_R the intercept capacity of terrace or forest on runoff compared with the sloping land.

Impacts of soil and water conservation measures on runoff

Implementation of soil and water conservation measures change land cover and alter underlying surface conditions and have direct or indirect impacts on runoff over the past 23 years (Li 2003, Hou *et al.* 2006). Soil and water conservation projects consisted largely of soil-retaining dams, small reser-

voirs and water cellars. One soil-retaining dam and three small reservoirs have a total storage capacity of 300 m³. In addition, there are over 735 water cellars with a total water storage capacity of 14 720 m³. Control areas account for 45% of the watershed with an effective irrigation area of 32.8 km². With a retention of 90%, reduced runoff due to conservation measures accounts for about 41% of the total runoff.

Effect of variations of annual water consumption on runoff

No major industrial or irrigation facilities exist in the Luoyu-gou watershed, hence water consumption by industry and agricultural irrigation was not considered. Therefore, the increase of domestic water consumption from natural precipitation and groundwater is the key point to consider. Domestic water consumption (W) is calculated as:

$$[11] W = (N_U \times Q_U + N_R \times Q_R + N_{SL} \times Q_{SL} + N_{LL} \times Q_{LL}) \times 365$$

where W is the domestic water consumption; N_U and N_R represent urban and rural populations; Q_U and Q_R are average water demands of urban and rural populations per person per day (l/p/d); N_{SL} and N_{LL} the number of small livestock (pigs, sheep, chickens) and large livestock (cattle, horses, mules, donkeys); Q_{SL} and Q_{LL} the average water demand of small livestock and large livestock per head per day (l/p/d).

Water consumption cited by Ma and Zheng (2006) and Wang, Z.Y. *et al.* (2008) is shown in Table 4. Watershed population and livestock numbers are listed in Table 5 (Wu 2010). Based on 2008 data, an analysis of annual water consumption by humans and livestock shows domestic consumption in 2008 was 4.7×10^5 m³, equivalent to 6.5 mm of runoff, which accounts for approximately 29% of the runoff depth in 2008.

Effects of climate change and human activities on evapotranspiration

Fig. 8 shows that the rainfall evapotranspiration double cumulative curves are nearly straight lines, which suggests that differences between the base period (1986–1998) and the compared period (1999–2008) were small. Based on equations 7, 8 and 9, the effects of climate change and human activities on evapotranspiration were calculated. Table 6 shows that human activities account for 91% of the total evapotranspiration while rainfall accounts for only 9%. Reforestation, the Slope Land Conversion Program, constructing dams and other measures increased vegetative

Fig. 6. The relationship between runoff and precipitation, temperature in watershed.

Fig. 7. Changes process of precipitation, temperature and runoff normalized.

Table 4. The average water demand on the watershed

Year	Urban (l/p/d)	Rural (l/p/d)	Big livestock (l/head/d)	Small livestock (l/head/d)		
				Pig	Sheep	Chicken
1985	50	15	45	28	42	3
2008	87	30	45	28	42	3

Fig. 8. Double mass curve of annual AET and annual rainfall in the watershed.

cover and reduced surface runoff and increased evapotranspiration.

Conclusion

The Loess Plateau region in northwestern China, an area with some of the highest sediment yields in the world, has experienced severe water shortages and soil erosion due to the combined impacts of climate change and human activities during the past decades (Wang, S.P. *et al.* 2008, Xin *et al.* 2011). From 1986 to 2008, large-scale sloping farmlands changed into terraces and forest in the study basin. Land use change by

human activities effects on watershed hydrology are neither spatially nor temporally uniform because of its coupling with climate variability (Li *et al.* 2007, Zhang *et al.* 2009). It is important for watershed management and ecological restoration decisions to understand the water yield regime due to human activities from a watershed given a specific climate condition. Therefore, contributions of climatic variability and human activities to that of annual runoff and actual evapo-

transpiration in the Luoyugou watershed were evaluated using a multi-year average water balance model and separation evaluation method, respectively. The impacts of different forms of human activities on changes in runoff were also evaluated. Our analysis indicated that annual runoff showed a statistically significant decreasing trend ($p = 0.02$), although precipitation had no significant change (Fig. 2A). This study revealed that the contribution of human activities to the variation in runoff and AET was about 67% and 91%, respectively, while the remaining was due to climate changes. The implementations of soil and water conservation measures were identified as the strongest contributors (41%) for the change in runoff under different human activities from 1986 to 2008, compared with the slope land conversion program (30%) and increased domestic water

consumption (29%). Therefore, it is inferred that human activities are the main driving force of runoff decrease over the Luoyugou watershed in the past 23 years.

The approach used in this study simply determined contributions of changes for climate change and different forms of human activities to runoff and other hydrological factors, providing quantitative information for stakeholders and decision-makers to make better choices for land and water resource planning and management. More importantly, from the perspective of prevention and control of soil erosion, more attention should be paid to afforestation and soil-water conservation measures for the purpose of reducing soil erosion.

Table 5. Populations and breeding industry structure statistics

Year	Rural	Urban	Cattle	Horses	Mules	Donkeys	Pigs	Sheep	Chickens
1985	13398	3350	515	77	1108	390	2600	3100	11700
2008	15386	5129	642	75	1257	392	4286	1896	19685

Table 6. Impact of human activities and rainfall variation to evapotranspiration

Period	ΔS (10^4 t)	ΔS_1 (10^4 t)	Contribution (%)	ΔS_2 (10^4 t)	Contribution (%)
1986–1998					
1999–2008	102.99	93.73	91.0	9.25	9.0

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