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Identifying dominant component of runoff yield processes: a case study in a sub-basin of the middle Yellow River

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ABSTRACT

The effects of long-term natural climate change and human activities on runoff generation mechanism in the middle Yellow River Basin are long-standing concerns. This study analyzed the characteristics of hydro-climatic variables in the meso-scale Tuweihe catchment based on the observed data for the period 1956–2016 and a climate elastic method. The spatial distribution of dominant runoff processes (DRP) following land use changes in case of rainfall was identified. The results show significant decreasing trends in annual runoff, whereas slightly downward trends are identified for annual precipitation and potential evapotranspiration, 1984 is detected as the mutation year of the study period. The average contributions of climate change and human activities to the runoff reduction in the Tuweihe catchment were 33.2% and 66.8%, respectively. In general, the influences of human activities on runoff are applied mostly through the alteration of the catchment characteristics. The dominant runoff processes changes between 1980 and 2015 show significant effects of large-scale soil and water conservation measures in the Tuweihe catchment. We found that Hortonian overland flow (HOF) and fast subsurface flow (SSF1) were the two main processes in 1980 (30.3% and 34.4% respectively), but the proportion of HOF decreased by 9.6% in 2015. The proportions of saturation overland flow (SOF) and SSF have increased to varying degrees, which means that the catchment is more prone to generate subsurface flow processes. Consequently, under similar rainfall conditions, the runoff yield of flood events decreases in the second period.

Key words: climate change, dominant runoff processes, flood events, human activities, Middle Yellow River

HIGHLIGHTS

- Based on GIS to identify the spatial distribution map of the dominant runoff process in the watershed, it can be used as a starting point for the construction of a refined hydrological model in the future.
- Attribution analysis of the covariant phenomenon of the runoff law of storms and floods under changing conditions from the mechanism level.

1. INTRODUCTION

The annual runoff of many rivers in arid and semi-arid regions around the world has decreased significantly with climate change as well as intensified human activities in the last few decades (Gao *et al.* 2011). The Yellow River, considered the cradle of Chinese civilization, as the main source of water for the 107 million people in Northwest and North China. It is also known as the lifeline of the area along the Yellow River (Wang *et al.* 2006). However, since the 1960s, the runoff in the lower reaches of the Yellow River has continued to decrease, and even the phenomenon of zero-flow has occurred frequently until 2000s (Yang *et al.* 2004; Tang *et al.* 2008). The Yellow River zero-flow phenomenon, i.e., the flow downstream of the mainstream is zero, not only affects agricultural irrigation in the area along the Yellow River, but also leads to serious degradation of the ecological environment in the source area of the Yellow River, which has become the main sources that restrict the healthy development of the economy in the Loess Plateau (Zheng *et al.* 2007). Since the 1960s, large-scale artificial projects have been carried out along the Yellow River, such as reservoir construction, soil and water conservation, irrigation diversion etc., casting significant impacts on spatio-temporal distribution of runoff and sediment of the river (Gao *et al.* 2017). For instance, the Huayuankou Station, a hydrometric gauge that controls large (approximately 97% of the total) areas of the Yellow River basin, natural runoff showed a remarkable download trend during the period of 1952–1997 (Liu & Zheng 2004).

Numerous existing studies mainly focus on the analysis of the factors affecting the runoff changes in the Yellow River Basin, aims to quantitatively evaluate the impact of these factors. Wang *et al.* (2012a) suggest that human activities have been a dominant influencing factor in the runoff changes (accounts for 92.07%) for the whole Yellow River basin since the 1980s. Similarity, Miao *et al.* (2012) and Jia *et al.* (2017) also believe that vegetation restoration on the Loess Plateau has a greater contribution to the reduction of runoff than climate change. Nevertheless, Cuo *et al.* (2013) pointed out that changes in observed streamflow were caused primarily by climate change above Tang Nai Hai hydrometric station. These previous studies mainly used the observed hydrological data, soil and water conservation area and reservoir siltation data of the hydrometric gauges since the 1950s, to systematically carry out research on the law of streamflow change, driving factors and contribution rate of the Yellow River. The combination of different dominant runoff processes (DRP) leads to storm runoff in the watershed. However, due to the lack of in-depth understanding of the hydrological cycle mechanism, the diagnostic analysis on the causes and mechanisms of the Yellow River runoff variation are still insufficient. Understanding runoff generation mechanism as well as dominant runoff processes and their spatial distribution in a changing environment is of critical importance regarding the effectively manage water resources. The main objective is trying to explore the reasons for the decrease in runoff yield of the Yellow River from the perspective of the dominant runoff generation processes. Nowadays, GIS-based methods are generally applied to identify runoff processes, ranging from the plot scale to the meso-scale catchment (Hümann & Müller 2013). Four different DRPs are distinguished: Hortonian overland flow (HOF) due to infiltration excess, saturation overland flow (SOF) due to saturation excess, lateral subsurface flow (SSF) in the soil and deep percolation (DP) (Scherrer & Naef 2003). The middle reaches of the Yellow River basin are specially characterized by the huge thickness of loess, sparse precipitation, high rainfall intensity and low vegetation coverage. Therefore, most scholars believe that the underlying surface conditions in this area are poor and cannot effectively retain surface runoff, which is a typical area of HOF (Wang *et al.* 2011). However, driven by vegetation restoration and climate changes, the runoff generation processes in this area may have changed (Hu *et al.* 2020).

The Tuweihe catchment is located in the key area of the ecological restoration project, and is also in the ecologically fragile area of the desert-loess transitional belt of the Loess Plateau. In the past few decades, the underlying surface conditions of the basin have shown significant changes (Mu *et al.* 2007), which have changed the hydrological processes such as regional infiltration, evapotranspiration, and runoff. However, there are still knowledge gaps on the role of human activities altering the hydrological sequences of runoff discharge, regardless whether the effect is negative or positive. The overall objectives of this study were therefore: (1) to analyze the hydro-climatic characteristics of the Tuweihe catchment from 1956 to 2016, and detect sequence mutation point; (2) to reveal the leading factors affecting runoff changes, and quantitatively estimate the contribution rate of climate change and human activities on runoff changes; (3) to systematically investigate the variation characteristics of the dominant runoff processes and its impact on the runoff yield at the catchment scale. This study will potentially contribute to better understand the response law of runoff generation mechanisms in middle Yellow River basin under the background of changing environment, while also providing a stronger base for decision-making regarding water resources management of the loess plateau.

2. MATERIALS AND METHODS

2.1. Study area

The Tuweihe catchment covers an area of 3,294 km^2 on the northern Loess Plateau and is a first order tributary to the middle reaches of the Yellow River (109°41′-110°28′E, 38°10′-39°15′N). The river originates from the Jia county of Shaanxi Province, and the main stream of the Tuweihe catchment is 140 km long (Figure 1). Affected by the typical semi-arid continental climate, the mean annual precipitation of this basin is 401 mm (1956–2016), and the average annual temperature is 8.5 °C (Xu *et al.* 2006). Rainfall is strongly seasonal, with 76% falling between June and September, mainly as intense storms. Consequently, runoff is concentrated in the wet season, accounting for 82.6% of the annual total. The average annual runoff load at the hydrological gauging station (Gaojiachuan, 3,253 km^2) were 3.2×10^8 m^3 (97 mm/a) between 1956 and 2016. The elevation ranges from 675 m in the southeast to 1,409 m in the northwest.

Beginning in the 1960s, the country and local governments increased their investment in the desert forests of the Loess Plateau, and along with the active advancement of the industry's back-feeding agriculture and forestry policy, a large

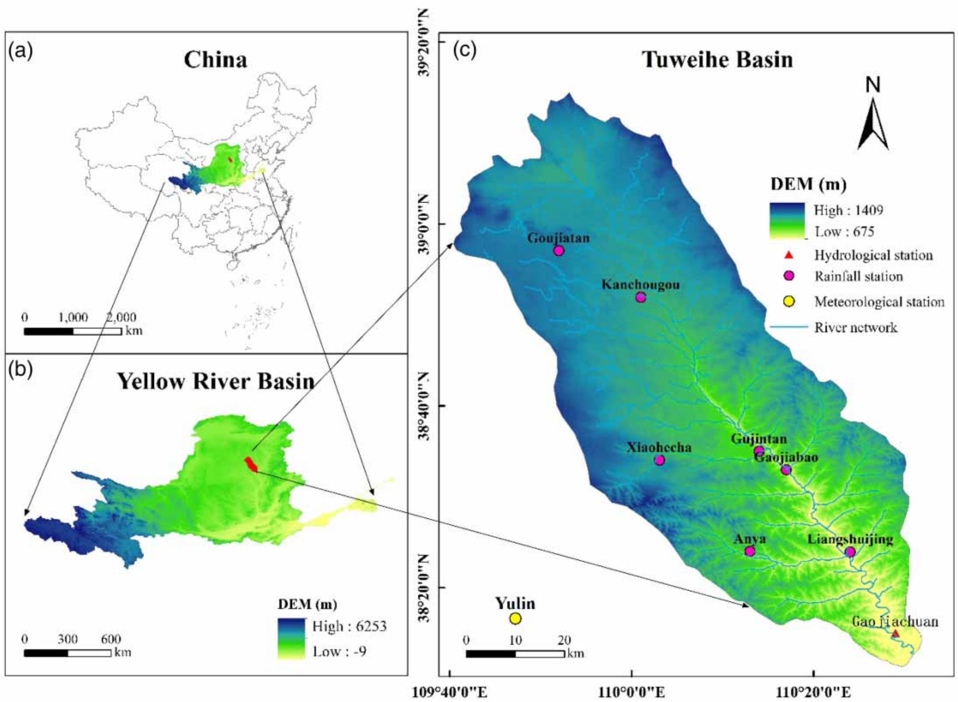

Figure 1 | Map of the Tuweihe catchment. (a) Inset map showing the location of the Yellow River basin in China. (b) Location of the Tuweihe catchment along the Yellow River basin. (c) Map of the Tuweihe catchment and the meteorological station and hydrological station.

number of soil and water conservation measures, mainly terraced fields and check-dams, have been implemented in the Tuweihe catchment. The area of water conservation measures at the end of each decade is shown in Table 1. While the vegetation coverage of the basin is improving as a whole, the runoff discharge of the catchment is declining (Mu *et al.* 2007). Nevertheless, during this period, no large-scale water fetching activities occurred in the basin, which makes it particularly important to take the Tuweihe catchment as an example to explore the influence of the greening process on the runoff generation in the Loess Plateau.

2.2. Data collection

The datasets used in this study were collected from different sources (Table 2). Hourly precipitation and runoff records from 1956 to 2016 for 8 stations were obtained from the 'People's Republic of China, Hydrological Data of the Yellow River Basin', published by the Yellow River Conservancy Committee (YRCC). Meteorological data were obtained from a surface climate data set (v 3.0; National Climate Centre of China Meteorological Administration, http://data.cma.cn/).

Geographical information used for the DRP identification mainly included topography, slope, lithology, soil and land use (Figure 2). The digital elevation data used was extracted from 30 m ASTER GDEM, provided by Geospatial Data Cloud site, Chinese Academy of Sciences (http://www.gscloud.cn/) and was used to generate topographic parameter (hillslope length and angle). The lithology map was obtained from the Food and Agriculture Organization (FAO). The soil information was provided by the Data Center for Resources and Environmental Science, Chinese Academy of Sciences (http://www.resdc.cn/). The land use scenarios for two years (1980 and 2015) were obtained from National Tibetan Plateau/Third Pole

Table 1 | Area statistics of soil and water conservation measures of the Tuweihe catchment

Measures	**1959**	**1969**	**1979**	**1989**	**1996**
Terrace (km^2)	1	10.8	31.3	45.5	66.5
Check-dams (km^2)	0.2	1.7	7.1	11.1	15.5

Table 2 | Overview of data for this study

Data	Time	Resolution	Data sources
Digital Elevation Model (DEM)	–	30 m	Geospatial Data Cloud site, Chinese Academy of Sciences
Soil map		1:1000000	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences
Lithology map	–	1:1000000	World Soil Database (FAO/IIASA/ISRIC2008)
Land-use map	1980 2015	1:100000 1:100000	National Tibetan Plateau/Third Pole Environment Data Center
Hydrological data	1956–2016	Daily	Yellow River Conservancy Committee
Meteorological data	1956–2016	Daily	National Climate Centre of China Meteorological Administration

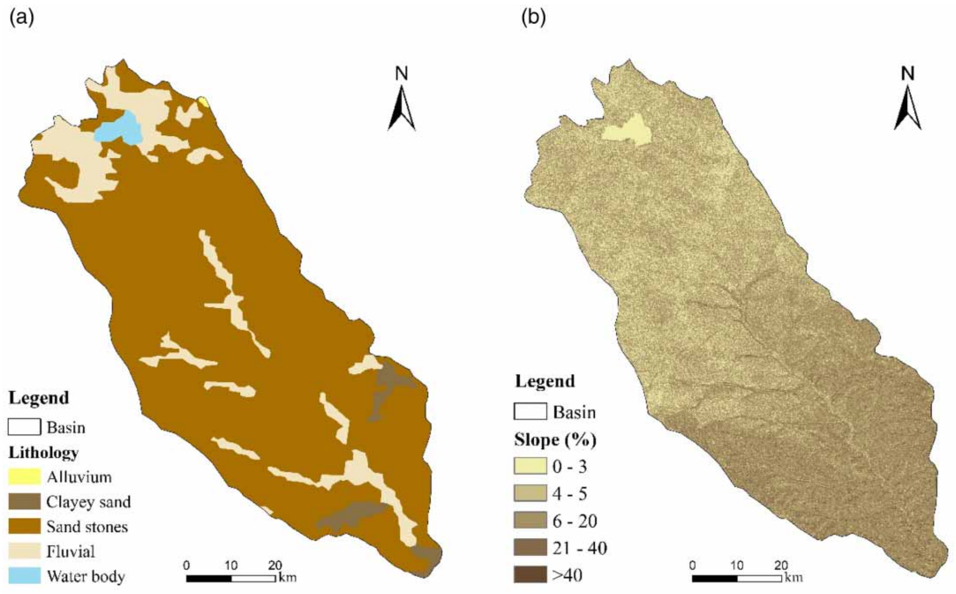

Figure 2 | Spatial patterns of: (a) lithology; (b) topographic slope of the Tuweihe catchment.

Environment Data Center (http://data.tpdc.ac.cn/en/), which is the first certified data repository in China. Six land use types were divided: farmland, forest, grassland, water body, urban area and bare land.

2.3. Methodology

2.3.1. Potential evapotranspiration

The catchment's potential evapotranspiration from 1956 to 2016 was calculated using the Penman-Monteith formula, recommended by the International Food and Agriculture Organization (FAO) (Pereira *et al.* 2015). The method is considered as a standard approach to calculate E_0, which reads:

$$E_0 = \frac{0.408\Delta(R_{net} - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where E_0 is the potential evaporation (mm/d); Δ is the saturation vapor pressure curve slope (kPa/°C); R_{net} is the net radiation (MJ/(m^2·d)), which is the sum of solar shortwave radiation and ground longwave radiation; G is the soil heat flux (MJ/(m^2·d)); γ is the psychrometric constant (kPa/°C); T is the daily mean air temperature at 2 m height (°C); u_2 is the wind speed at 2 m height (m/s); e_s is the average saturated vapor pressure (kPa); e_a is the actual vapor pressure (kPa). All the above parameters can be calculated from the average air pressure, wind speed at a height of 10 m, maximum temperature, minimum temperature, average relative humidity and sunshine duration.

2.3.2. Trend test on hydro-climatic data

Trend testing is of great importance for understanding the dynamics and variations of runoff, precipitation, and other variables over a long period. For this purpose, the wildly used non-parametric Mann–Kendall test (Mann 1945; Kendall 1975) was applied in this research. First the M-K test statistic is given as follows:

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

$$UF = \frac{S_k - E[S_k]}{\mathrm{Var}[S_k]} (k = 1, 2, \ldots, n) \tag{3}$$

where x_i and x_j represent the values in years i and j, $i > j$, n is the record length of the series, and sgn $(x - x_j)$ is a characterization of the function. $E(S_K)$ and Var (S_K) represent the mean and variance of S_K, respectively.

Then the time series order is reversed (*i.e.*, $x_n, x_{n-1}, \ldots, x_1$) and the above process is repeated to compute statistical variables *UB*. Finally, we draw curves of *UF* and *UB*, and if the two curves have an intersection point in the confidence level, then it can be considered as a mutation point. Researchers believe that after the hydrological sequence is significantly affected by climate change or human activities, the stability of its distribution sequence will be disturbed or destroyed, showing a certain degree of phase or trend. Therefore, according to the detected runoff mutation point, the research period can be divided into base period and mutation period. The base period watershed is in a natural state, means that the runoff is only affected by climate change. However, in the mutation period, human activities may have a significant impact on the runoff change.

2.3.3. Estimating the relative impact of climate change and human activities on runoff

For a certain watershed, the total changes (ΔR, mm) of runoff are synthetic production of climate change (ΔR_C, mm) and human activities (ΔR_H, mm), it can be calculated from the difference between the measured runoff before and after the mutation point. Therefore, to quantitatively distinguish the impact of climate change and human activities on runoff, only one factor should be quantified, and the effect of the other factor can be calculated by formula (5). Based on long-term water balance assumptions and the Budyko hypothesis (Budyko *et al.* 1974), the evapotranspiration (E_a) is a function of the dryness index ($\phi = E_0/P$). Then the contribution of climate change to runoff can be derived by calculating the elastic coefficient of runoff on precipitation and potential evaporation, which is expressed as:

$$\Delta R = \Delta R_C + \Delta R_H \tag{4}$$

$$\Delta R_C = \Delta R_P + \Delta R_E = \varepsilon_P \frac{\bar{R}}{\bar{P}} \Delta P + \varepsilon_{E_0} \frac{\bar{R}}{\bar{E}_0} \Delta E_0 \tag{5}$$

$$\varepsilon_P + \varepsilon_{E_0} = 1 \tag{6}$$

$$\varepsilon_P = 1 + \frac{\phi F'(\phi)}{1 - F(\phi)} \tag{7}$$

where ΔR_P, ΔR_E are contributions of rainfall and potential evapotranspiration to runoff, respectively. ε_P, ε_{E_0} are dimensionless parameters which represent elastic coefficients of runoff on precipitation and potential evapotranspiration, respectively; $\bar{P}$, $\bar{R}$ and $\overline{E_0}$ are multi-year average of precipitation (mm), runoff depth (mm) and potential evapotranspiration (mm) of the study basin; $F(\phi)$ and F' (ϕ) can be calculated by the following Budyko forms (Ol'dekop 1911; Pike 1964; Budyko *et al.* 1974; Fu 1981; Zhang *et al.* 2001) (Table 3).

Table 3 | Five commonly used forms of F(ϕ) and F′(ϕ) based on the Budyko hypothesis

Forms	F(ϕ)	F′(ϕ)
Ol'dekop	$\phi\tanh(1/\phi)$	$\tanh(1/\phi) - 4/[\phi\ (e^{-1/\phi} + e^{1/\phi})^2]$
Budyko	$[\phi\tanh(1/\phi)\ (1 - e^{-\phi})]^{0.5}$	$0.5[\phi\tanh(1/\phi)\ (1 - e^{-\phi})]^{0.5} \times [(\tanh(1/\phi) - \mathrm{sech}^2(1/\phi)/\phi)\ (1 - e^{-\phi}) + \phi\tanh(1/\phi)\ e^{-\phi}]$
Turc-Pike	$(1 + \phi^{-2})^{-0.5}$	$1/\phi^3\ [(1 + (1/\phi)^2)^{1.5}]$
Fubaopu	$1 + \phi - (1 + \phi^{\alpha})^{1/\alpha}$	$1 - (1 + \phi^{\alpha})^{1/\alpha - 1}\phi^{\alpha - 1}$
Zhang	$(1 + \omega\phi)/(1 + \omega\phi + 1/\phi)$	$(\omega + 2\omega/\phi - 1 + 1/\phi^2)/(1 + \omega\phi + 1/\phi)^2$

Note: α and ω are parameters of each formula. $\alpha = 2.2$ and $\omega = 1$.

2.3.4. GIS-based basin scale identification of dominant runoff processes

Different runoff processes generate storm runoff in the watershed (Naef *et al.* 2002). During a flood event, according to the water flow pathways, the runoff processes were denoted as the 'Hortonian Overland Flow' (HOF), 'Saturation Overland Flow' (SOF), 'Fast Subsurface Flow' (SSF) or interflow, and 'Deep Percolation' (DP) (Scherrer & Naef 2003). The overview of the above four runoff processes is given in Table 4, where numbers 1–3 represent the lag time in the reaction to precipitation. However, considering the uneven spatial distribution of meteorological elements and underlying surface conditions of the watershed, several runoff processes may occur at one site simultaneously. The dominant runoff processes (DRP) being that which contributes most to runoff (Schmocker *et al.* 2007).

The formation process of runoff is complicated and influenced by factors such as topographic slope, geological conditions and land use types, etc. Slope reflects the degree of steepness of the ground. Flat areas with a gentle slope can hold rainfall, allowing rainfall to infiltrate and reduce the formation of surface runoff, while on steep slopes, runoff yield will be high due to the rapid migration of surface runoff. The permeability of geological conditions determines the rate of water penetration into the ground. Where the geology is highly permeable, the infiltration rate of surface water is high and it is easy to generate underground runoff, while in places where the geology is impenetrable, the watershed is more prone to produce other types of surface runoff or rapid subsurface flow according to the slope. Based on the so-called process decision scheme proposed by Scherrer & Naef (2003), Müller *et al.* (2009) applied Geographic Information System (GIS) to developed a simplified but highly accurate method to identify DRP, which combines the analysis of topography, geological information and land use types. The method can be described as follows: The first step is to calculate the slope and classify it, in accordance with the original decision scheme to determine dominant runoff processes with DEM. Second, the permeability of the underlying lithology was classified. Finally, the permeability layer is intersected with slope and land use to generate a map of dominant runoff processes (DRP). The above steps are executed on the ArcGIS 10.4 platform. The assumed DRP dependency for arable, grass and forest land regarding slope and permeability is given in Table 5 and serves as the basis for identifying DRP. In addition to these previously defined criteria, some other assumptions have to be made and applied in the analysis. Due to sealed soil surface forms impervious ground, the DRP of the urban areas and bare land are assumed to be HOF, independent of permeability and slope according to the method of Scherrer & Naef (2003). Furthermore, the riparian zone is

Table 4 | An overview of the different runoff processes in flood events

Process	Type	Abbreviation	Intensity of runoff process
Overland flow processes	Hortonian	HOF	Immediate Hortonian overland flow due to infiltration hindrance
	Saturation	SOF1	Immediate saturation overland flow due to soil saturation
		SOF2	Saturation overland flow due to slowly saturating soils
		SOF3	Delayed overland flow due to very slowly saturated soils
Subsurface flow processes	Lateral flow	SSF1	Subsurface flow
		SSF2	Delayed subsurface flow
		SSF3	Strongly delayed subsurface flow
	Vertical flow	DP	Deep percolation

Table 5 | Dependency of the DRP on the slope and permeability of the substratum for grassland, arable land and forest

Slope (%)	Impermeable substratum Grass and arable land	Impermeable substratum Forest	Permeable substratum Grass, arable land and forest
0–3	D_{SOF3}	D_{SOF3}	D_{DP}
3–5	D_{SOF2}	D_{SSF3}	D_{DP}
5–20	D_{SSF2}	D_{SSF2}	D_{DP}
20–40	D_{SSF1}	D_{SSF2}	D_{DP}
>40	D_{SSF1}	D_{SSF1}	D_{DP}

easily saturated due to the relatively moist soil, which tends to generate fast reacting saturation overland flow (SOF1) on both sides of the stream network (Liang & Xie 2001).

3. RESULTS AND DISCUSSION

3.1. Temporal trends of hydro-climatic variables

The annual variations of runoff, precipitation and potential evapotranspiration in Tuweihe catchment during the period 1956–2016 were illustrated in Figure 3(a). In the past 60 years, particularly after the 1980s, the runoff sequence exhibited a significant reduction. To quantify the magnitudes of decreases in hydro-climatic variables, long-term Mann–Kendall test was examined in this study. The annual precipitation and annual potential evapotranspiration series both present a certain decline trend but not significant, while the annual runoff series shows a significant downward trend and passed the 0.05 significance level. This result is in good agreement with those of previous research employed in the study area, such those of Xu (2011), Wang *et al.* (2012b) and Zhou *et al.* (2015). As shown in Figure 3(b), the year 1984 was detected as a mutation point at the 0.05 significance level for annual runoff. This is almost consistent with the implementation time of the 'Special Management Plan for Soil and Water Conservation in the Loess Plateau Region of the Yellow River Basin' (beginning in 1983). According to the mutation point detection results, the study period was divided into two sub-periods: Period I: 1956–1984 (before the mutation point) and Period II: 1985–2016 (after the mutation point). Compared with the Period I, the annual runoff and annual precipitation of the basin decreased by 36.3% and 7%, respectively (Table 6). The annual changes in potential evapotranspiration are very small and can be ignored. Based on the above analysis, although the runoff has undergone significant change around 1984, the climate change is not significant, namely, human activities may have exerted an important role in this process.

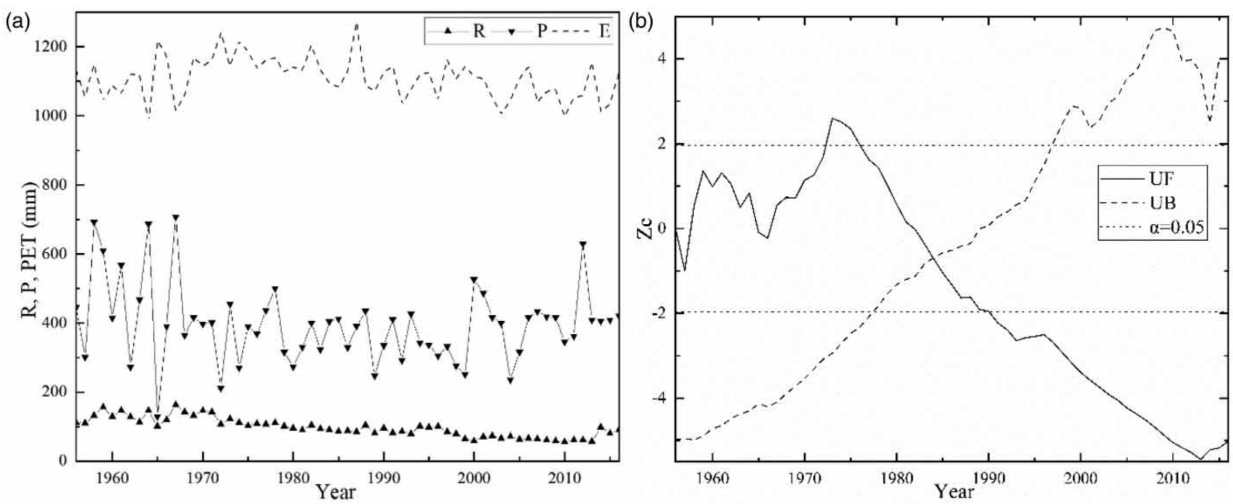

Figure 3 | Long-term variation of hydro-climatic factors (a) and mutation point of annual runoff (b) in Tuweihe catchment.

Table 6 | Variation of hydro-climatic factors around the mutation point in Tuweihe catchment

Variables	Z_c	Significant	Mean value (mm)		Change (%)
			1956–1984	1985–2016	
P	0.296	*ns*	430.1	400.2	– 7.0%
E_0	0.995	*ns*	1,128.7	1,099.1	– 2.6%
R	5.018	**	125.7	80.1	– 36.3%

Note: The asterisks ** represent the statistical significance at 5% level.

Table 7 | Separating the effects of climate change and human activities by climate elasticity method

Variables	Ol'dekop	Budyko	Turc-Pike	Fubaopu	Zhang	Average
ε_P	2.64	3.07	2.84	2.63	2.58	2.75
ΔR_C (mm)	−14.7	– 16.3	– 15.6	– 14.7	– 14.5	– 15.16
ΔR_H (mm)	– 30.90	– 29.30	– 30.00	– 30.90	– 31.10	– 30.44
ΔR_C (%)	32.2	35.7	34.2	32.2	31.8	33.2
ΔR_H (%)	67.8	64.3	65.8	67.8	68.2	66.8

The impact of climate change and human activities on runoff change based on Budyko hypothesis is represented in Table 7 The results manifest that the elasticity coefficients of runoff to precipitation estimated by using five functions are very close, with an average value of 2.75. It also indicates that the method applied in this study has good performance and can explain the influence of each variable on runoff variation. The contribution rate of climate change and human activities to runoff change is 31.8%–35.7% and 64.3%–68.2%, with the average values of 33.2% and 66.8%, respectively. Similar findings were revealed in other studies. Applying the residual analysis based on double mass curves (RA-DMC), Kong *et al.* (2016) revealed that human activities have become the dominant factor in the change of net runoff for the entire Yellow River Basin, and its contribution rate to the change of net runoff is as high as 91.7%, showing overall consistency. Also based on the Budyko framework, Shen *et al.* (2017) quantified attribution of runoff changes in 224 catchments across China, and found that changes in climate accounted for 19% of runoff reduction in some catchments of the Yellow River Basin. Additionally, Wang *et al.* (2010) adopted the variable infiltration capacity (VIC) model to distinguish the causative factors of the changing hydrological process in a sub-basin of the middle Yellow River. Comparatively speaking, the hydrological simulation method is designed to restore the natural runoff during the mutation period, so that the natural runoff in this period is consistent with the observed runoff during the baseline period. However, the elastic coefficient method calculates the sensitivity of runoff to precipitation and evaporation based on the water balance equation and Budyko framework, which requires lower time scale of data. These two methods of different principles and calculation scales have obtained relatively consistent results, but the results of this paper further show that since the 1980s, the impact rate of human activities on runoff reduction in the middle Yellow River basin has increased significantly.

3.2. Land use changes

Figure 4 shows the land use information of the Tuweihe catchment in 1980 and 2015, and the changes in various land-use types are calculated in Table 7. Grassland is the most common evenly distributed land-use type in the Tuweihe catchment, showing an increase of 9.73%. Farmland and urban areas are located mainly in the lower and middle-stream area of the basin, showing decreases and increases of −0.29% and 1.81%, respectively. The bare land is concentrated in the middle and upper reaches of the northwest, and the rate of change is the largest among all types, with a decrease of 11.30%, corresponding to a remarkable coverage increase in the grassland. Forest land is primarily found along the river network, showing an increase of 0.13%. However, the area of water body has hardly changed over the years. We believe that the large-scale soil and water conservation measures in the Tuweihe catchment (such as grass-planting, afforestation, creation of level terraces, and building check dams, etc.) were responsible for the decreased unused regions. In addition, urban areas showed a stepwise

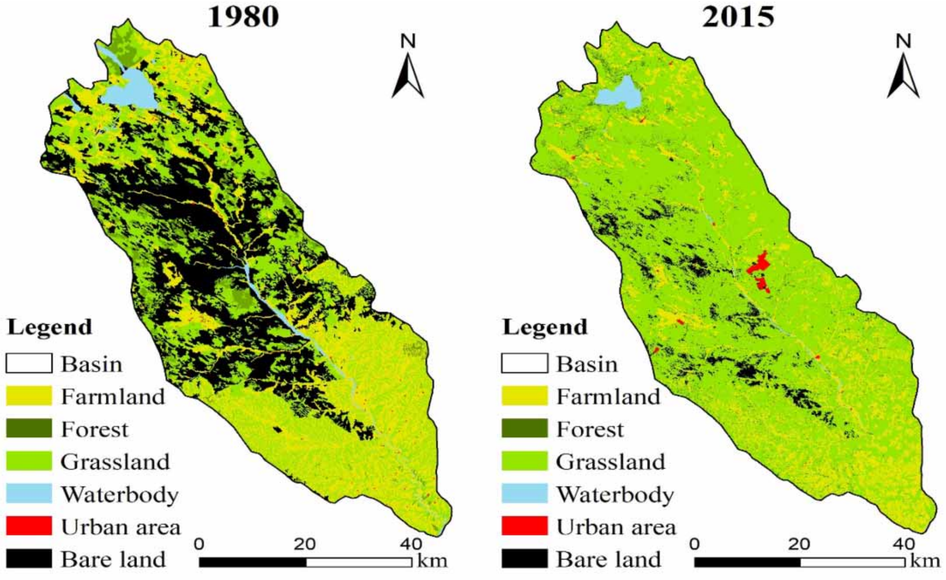

Figure 4 | Land use changes in the Tuweihe catchment.

increase from 3.4 km^2 in 1980 to 62.9 km^2 in 2015. Hence, the population and urbanization grew rapidly over the past four decades. The increasing urban area and reduction in bare land may explain the extension of grassland due, to some degree, to the movement of local farmers and the abandonment of farmland. Changes in the underlying surface are mainly affected by human activities (Table 8).

3.3. Identification of dominant runoff processes

The spatial distribution of the DRP from 1980 to 2015 in the meso-scale Tuweihe catchment are shown in Figure 5, and the changes of DRP in different land use types are exhibited in Figure 6. We found that the DRP map was dominated by lateral flow (34.4–39.3% for SSF1) and Hortonian overland flow (20.7–30.3% for HOF). It can be speculated that considerable amount of precipitation flow rapidly into the river network along the ground surface thereby contributing to river runoff recharge in the study area. The area of DP remained basically stable. Meanwhile, the stream network (so-called 'riparian' zones) tends to produce fast reacting saturation overland flow (SOF1, accounting for 3.2–4.3%) due to the higher soil moisture content, and the rest of the processes show a relatively dispersed distribution.

However, with the implementation of large-scale soil and water conservation measures in the basin, which resulted in the grass area increased rapidly. Previous studies found that vegetation changes can significantly affect runoff generation processes: During the growth and development of plant roots, it can increase the macro porosities in the soil, and more water penetrates into the ground through the pores, thereby increasing the soil water content, which is conducive to the generation of soil flow and saturated surface runoff (Walker *et al.* 1993; Loch 2000). From 1980 to 2015, the proportion of HOF

Table 8 | Land use classification statistics of the Tuweihe catchment

	1980		2015		Change	
Land-use types	**Area (km^2)**	**Percent (%)**	**Area (km^2)**	**Percent (%)**	**Area (km^2)**	**Percent (%)**
Farmland	930	28.23	920.6	27.95	– 9.4	– 0.29
Forest	102.4	3.11	106.8	3.24	4.4	0.13
Grassland	1,186.7	36.03	1,507.1	45.75	320.4	9.73
Water body	79.2	2.40	76.6	2.33	– 2.6	– 0.08
Urban area	3.4	0.10	62.9	1.91	59.5	1.81
Bare land	992.3	30.12	620	18.82	– 372.3	– 11.30

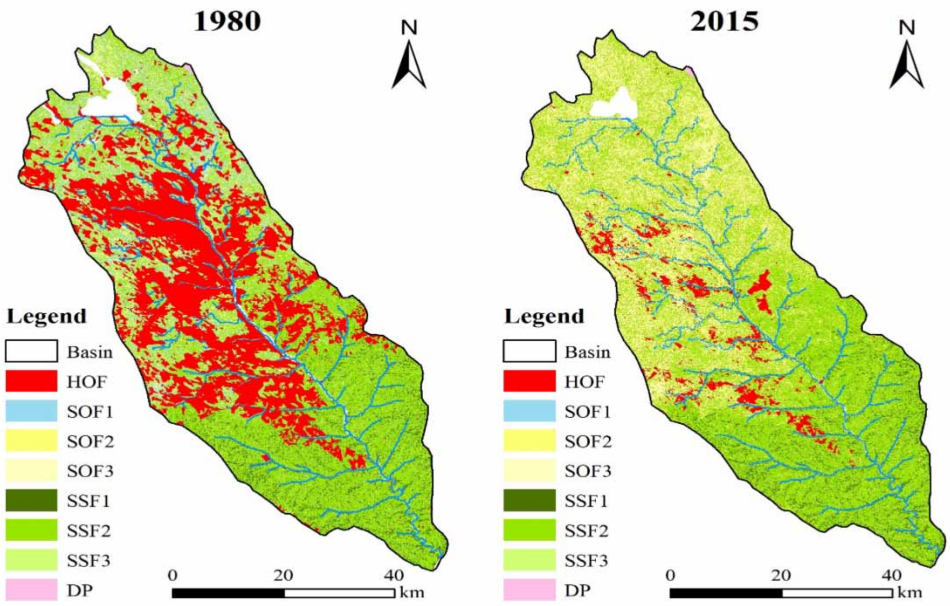

Figure 5 | Dominant runoff processes map of the Tuweihe catchment.

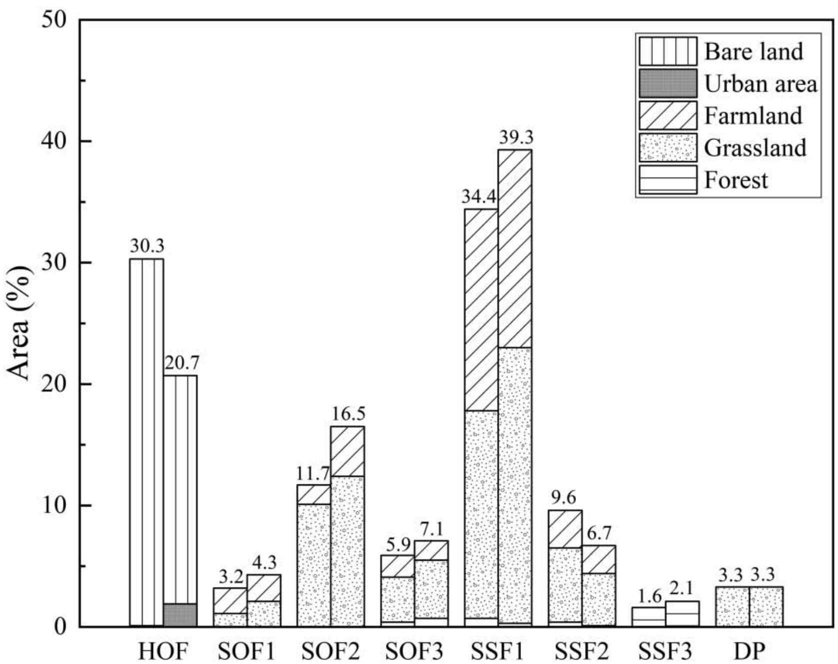

Figure 6 | The DRP changes and land use in these areas of the Tuweihe catchment in 1980 and 2015.

changes the most among DRP types, with a decrease of 9.6%, while the proportion of SOF and SSF both increased to varying extents.

3.4. Effects of DRP changes on flood characteristics

The boxplots of the peak discharge and lag time of the Tuweihe catchment at different stages are shown in Figure 7. We found a greater variability of peak flow in period I (1956–1984) than in period II (1985–2016). The maximum and median were

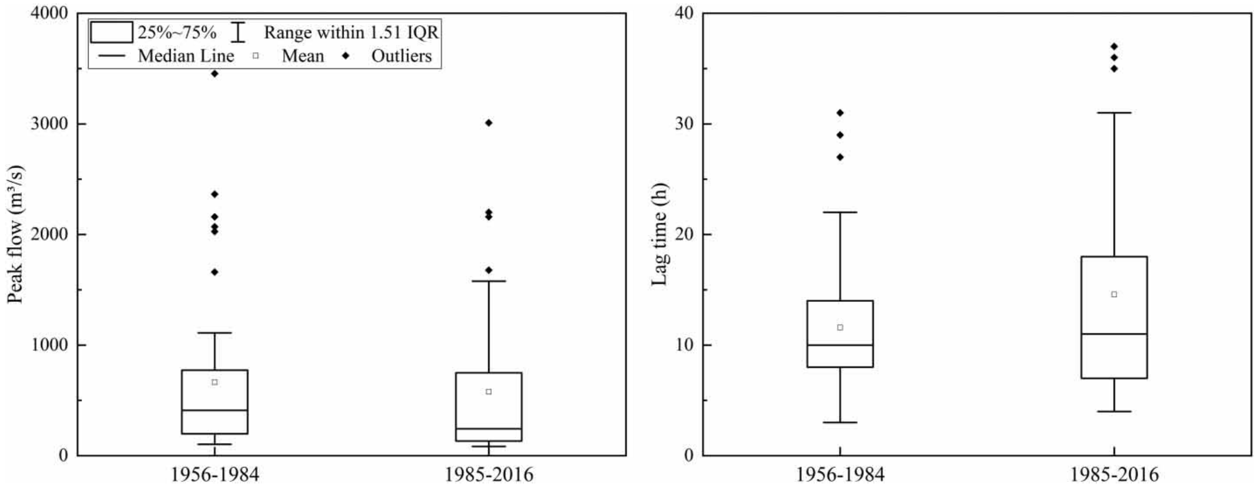

Figure 7 | Boxplots of the peak flow (left) and lag time (right) of the Tuweihe catchment.

higher in the first period, while the minimum was slightly lower in the second period. This indicates a reduction in runoff yield of the catchment under rainfall events. The 75th percentile of lag time in 1985–2016 was almost more than half than that before. The longer lag time in the second period can be explained by the change of DRP, that is, the appearance of SOF and SSF has increased, and it has suffered a strong retarding effect in the process of confluence.

We selected 8 flood events with different precipitation levels in two periods and divided into four groups. Then analyzed and compared the corresponding flood characteristics of similar rainfall events. The peak flow and runoff produced by the same magnitude of rainfall have decreased apparently. The overall attenuation of the peak flow is larger than that of the runoff depth, which are 34.8–84.8% and 7.1–79.7%, respectively (Figure 8, Table 9). In addition, the flood process line shows a distinct flattening phenomenon after the mutation point. The reason is that although the rainfall level and spatial distribution are extremely similar, the dominant runoff process may have altered from overland flow processes to other types.

For a specific watershed, different runoff components in the process of confluence, due to different media and flow paths, cause different regulation and storage effects, and different time to reach the outflow section of the basin, resulting in the flood process of the basin presents different fluctuation characteristics and shapes. For example, overland flow processes are less affected by regulation and storage, which is generally characterized by fast convergence velocity, large peak discharge, and the flood process presents steep rises and falls with good symmetry; while subsurface flow processes are greatly affected by regulation and storage, and generally exhibits slow velocity. The process line rises and falls slowly and has poor symmetry. Under the similar rainfall conditions, the Tuweihe catchment is more prone to generate lateral subsurface flow and saturation overland flow from 1956 to 2015, which consequently decreases the runoff yield of this flood event. This conclusion has been confirmed by many studies (Miao *et al.* 2011; Li *et al.* 2018) and is consistent with the conclusion of this article. In addition, as the thickness of the litter in the forest increases, the surface roughness is increased, and the confluence time of the runoff is increased, causing most of the surface runoff to return to the atmosphere in the form of evaporation. In addition, the increase in vegetation coverage can effectively increase the interception of precipitation by the vegetation canopy, and the intercepted precipitation will return to the atmosphere in the form of evaporation, thereby reducing the amount of precipitation reaching the ground. Hence, from the perspective of water resources, if the planning department prefers to reduce the pressure on flood control in the basin, it should control the continuous increase in the area of construction land in the future, and make the land converted from farmland into forest; if it focuses on solving the contradiction between the supply and demand of water resources in the basin. According to the current development trend, the area of construction land in the future should be increased, and the land that has been converted from farmland will mostly become grassland.

Besides, the clay content is an important index which is closely related to soil hydraulic properties, such as the saturated hydraulic conductivity. Figure 9 presents the spatial patterns of key landscape properties that have significant nexus on the runoff generation processes. In general, high clay content indicates low hydraulic conductivity, which can be confirmed by the obtained average hydraulic conductivity values (Li *et al.* 2012). The Tuweihe catchment has generally low clay content, with the internal heterogeneity showing some systematic trends (clay content values generally ascend with increasing stream

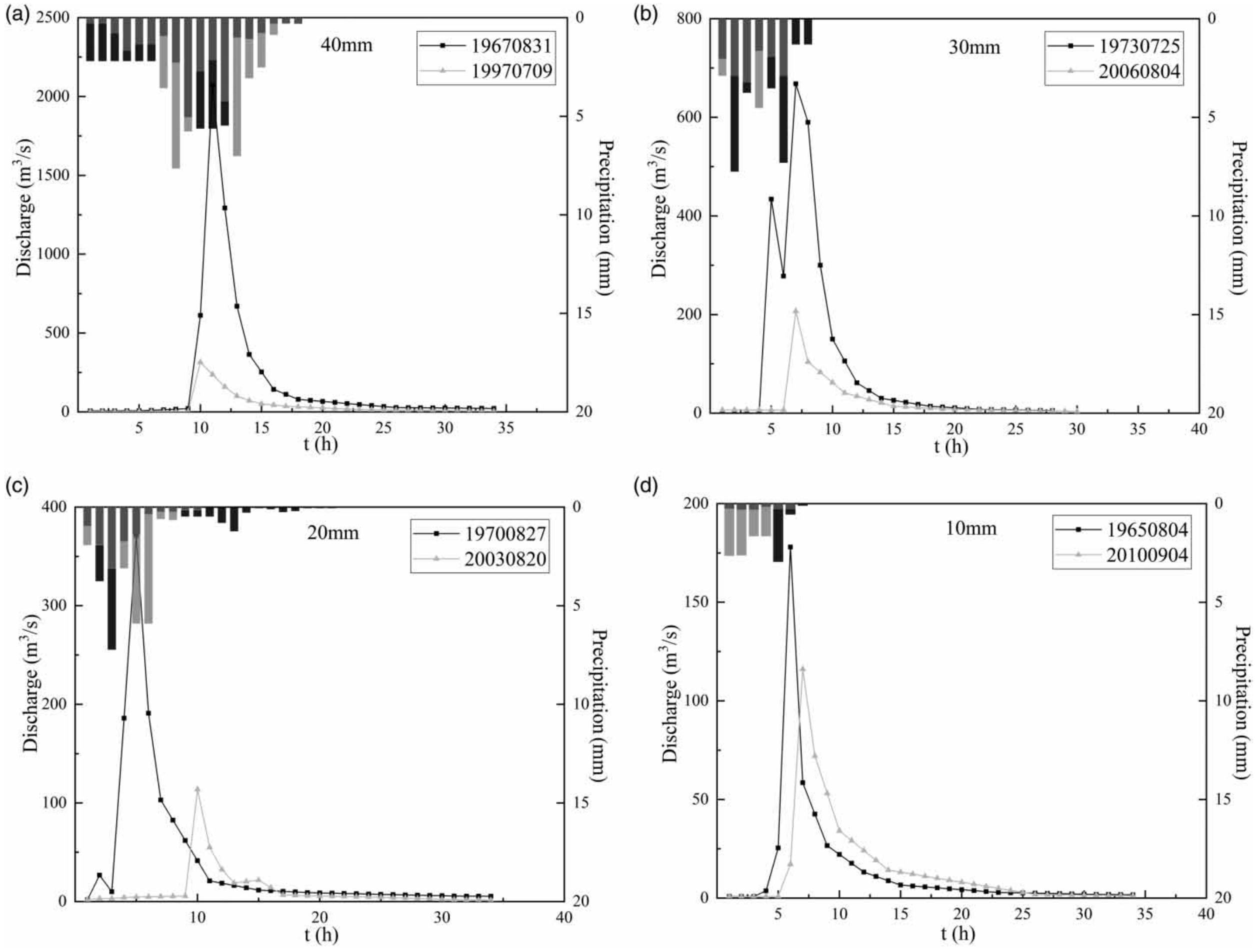

Figure 8 | Comparative analysis of similar rainfall events.

Table 9 | Analysis of flood characteristics with similar rainfall occurred in two periods

Groups	Flood events	Rainfall (mm)	Rainfall duration (h)	Max rainfall intensity (mm/h)	Peak flow		Runoff depth	
					(m³/s)	Change (%)	(mm)	Change (%)
40 mm	19670831	41.9	18	13.4	2,070	84.8	17.2	79.7
	19970709	45.9	18	13.9	315		3.5	
30 mm	19730725	28.6	8	13.2	668	69.0	7.9	67.1
	20060804	33.2	6	9.9	207		2.6	
20 mm	19700827	20.3	21	8.2	371	69.3	3.4	64.7
	20030820	23.5	12	8.8	114		1.2	
10 mm	19650804	12.6	7	5.1	178	34.8	1.4	7.1
	20100904	9.1	6	6.2	116		1.3	

order). In Tuweihe catchment, it is in the upper reaches of the watershed, away from the outlet, that the lower clay content values are exhibited. During a storm event, precipitation is more prone to trapped into these areas, so this part of the runoff will not flow all the way to the channels, but will re-infiltrate into the soil or directly evaporate instead. The re-infiltrated part will increase soil water storage, i.e., increase soil moisture or water table depth. In the dry season when the evaporation is water-limited, the increased soil water storage will lead to an increase in evaporation due to increased available water. In

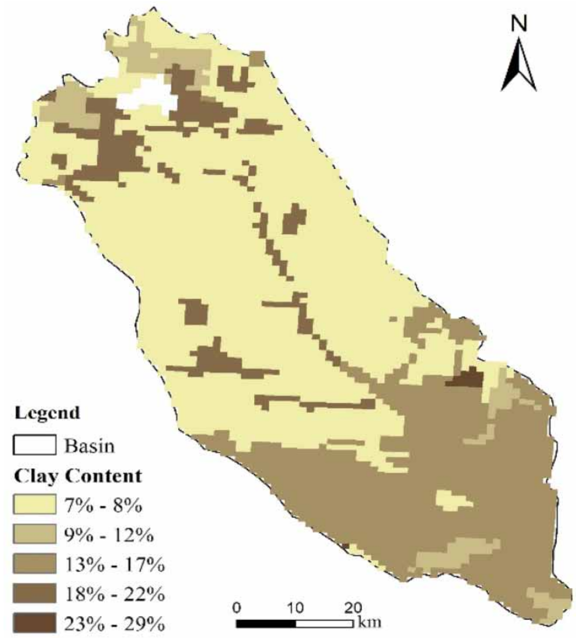

Figure 9 | Spatial patterns of clay ratio of the upper 40 cm soil layer.

the wet season, however, when the evaporation is energy-limited, the increased soil water storage will contribute to an increase in the saturation area, which leads to an increase of subsurface runoff generation or saturation overland flow during subsequent rainfall events. Thus, hydraulic conductivity may have the net effect of trapping the HOF and redistributing the bulk of this stored water to evaporation during the dry season, or to SSF and SOF in the wet season. As shown in Figure 5, in the Tuweihe catchment, the generation of HOF runoff has been significantly reduced and probably transformed into SOF2 and SSF1, i.e., the total volume of runoff generation is decreased.

4. SUMMARY AND CONCLUSIONS

In this study, the impacts of land-use and climate changes on water yield in the Tuweihe catchment of the Chinese Loess Plateau have been investigated by the combined use of statistical tests, elastic coefficient, and land-use maps. The Mann–Kendall test showed that annual runoff yield in the Tuweihe catchment during the period 1956–2016 decreased significantly, whereas a slight decreasing trend was detected for annual precipitation; potential evapotranspiration showed an inapparent increasing trend. The year 1984 was detected as significant mutation points for annual runoff, whereas no significant change point was detected in annual precipitation and potential evapotranspiration.

The effects of land-use and climate changes on water and sediment yields were assessed by using the Budyko hypothesis and five frameworks. The human activities decreased 66.8% of the water yield, whereas the climate change effect 33.2%. It can be concluded that human activities had greater impact on the water yield. The DRP maps between 1980 and 2015 show that the HOF and SSF1 were the two main runoff processes, which account for 34.4–39.3% and 20.7–30.3%, respectively. Moreover, peak flow attenuation and peak time lag effects were detected during recent years. Showing that under the significant effects of large-scale water and soil conservation measures in 1960s, the Tuweihe catchment is more prone to generate lateral subsurface flow and saturation overland flow. This study highlights the importance of identifying the DRP under changing environments and to explore how DRP transform may affect the runoff yield in the middle Yellow River, which provided greater insights into the comprehensive runoff generation responses at the watershed scale. However, this study identified the spatial distribution of DRP in case of normal rainfall events but not rainstorms, and its combined effects are particularly sophisticated. We also expect to further refine the research on the response of DRP changes to extreme climatic conditions in future research.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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