Decreased river runoff on the Mongolian Plateau since around 2000

Wenhua Qi · Xiaomei Hu · Hao Bai · Asadilla Yusup · Qinwei Ran · Hui Yang · Haijun Wang · Zurui Ao · Shengli Tao

Abstract

Context Mongolian Plateau is one of the largest contingent arid and semi-arid regions of the world. Rivers on the plateau provide vital water for millions of indigenous Mongolian people and numerous endangered wildlife, but are increasingly disturbed by climate change and human activities. Yet, long-term

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changes in river runoff across the plateau remain poorly studied due to data unavailability.

Objectives This study aimed to analyze the temporal trends in gauged river runoff on the Mongolian Plateau, identify drivers of the observed changes, and evaluate CMIP6 models' performance in simulating historical runoff changes across the plateau.

Methods We compiled possibly the largest database of long-term (20 - 71 years) river runoff for the plateau comprising measurements over 30 major rivers. Statistical analyses were conducted to assess trends in river runoff and correlations between runoff and climatic variables. Additionally, we applied the Budyko curve framework to identify the influence of human activities on river runoff in specific basins. Furthermore, we compared ground-measured runoff data with simulations from CMIP6 models to evaluate the ability of CMIP6 models to replicate runoff dynamics in typical arid and semi-arid regions.

Results We observed pervasive and abrupt reduction in runoff in 21 out of the 30 rivers within 5 years before or after the year of 2000. Variations in river runoff were most significantly caused by changes in total precipitation (TP). In particular, 27 rivers experienced abrupt TP changes around 2000, and there was a significant positive correlation between annual fluctuations in TP and river runoff for 18 rivers. In addition to climate factors, the influence of human activities was identified in certain basins. The CMIP6 simulations failed to capture the abrupt changes in

runoff occurred pervasively across the plateau around 2000.

Conclusions Around 2000, major rivers on the Mongolian Plateau, especially in Inner Mongolia, experienced runoff declines, primarily due to TP changes. Human activities like dam construction and water diversion further influenced local runoff. CMIP6 historical runoff simulations were inaccurate across the plateau, highlighting the difficulty of simulating river runoff in this critical region. Our study could contribute to a more comprehensive understanding of the water resource changes on the Mongolian Plateau, with direct implications for enhancing ecological conservation and management practice.

Introduction

The Mongolian Plateau is situated in central Asia, and is well-known for its arid and semi-arid climate (Neupert 1999; Bao et al. 2014). Water scarcity is a significant issue in this area due to the region's low precipitation (~380 mm/year) but high potential evaporation rate (~1200 mm/year) (Karthe et al. 2019). Rivers on the plateau provide valuable surface water resources for numerous lakes, the Eurasian grasslands, and indigenous herders (Tao et al. 2015). Also, an increasing number of rivers and their connected wetlands are being recognized as the Ramsar Convention of international importance (Table S1), providing vital habitat and water supply for endangered wildlife.

However, the plateau is experiencing rapid climate change, with a warming rate much higher than the global average (0.33 vs. 0.12°/decade; Wang et al. 2008; Karl et al. 2015). Previous studies have suggested that climate change is expected to accelerate water cycles (Milly et al. 2005; Oki and Kanae 2006; Dey and Mishra 2017), with a fundamental impact on the river runoff. For instance, Zhang et al. (2007) found that climate change is mainly responsible for the decrease in runoff of the Songhuajiang River Basin from 1950 to 2004. Yang et al. (2022) found that total precipitation (TP) was the main driving force impacting changes in runoff in the Northwest, Southwest, Yangtze, Southeast, and

Pearl River Basins, based on an analysis of 64 catchments in mainland China. Considering the rapid climate changes occurring on the Mongolian Plateau, it is expected that the river runoff in this region will change dramatically, with far-reaching impacts on local societies and ecosystems.

In addition to climate change, river runoff is subject to influences of human activities (Vorosmarty et al. 2000; Pekel et al. 2016; Wang et al. 2016; Dey and Mishra 2017). The Mongolian Plateau, unfortunately, is one of the global hotpots with intensive human activities such as mining, dam construction, water diversion, and irrigation. The plateau is the largest surface coal mining region in the world (Ma et al. 2021), but mining activities have been reported to destroy groundwater aquifers and over-consume river water, resulting into the dried-up of lakes and rivers (Tao et al. 2015). The area of irrigated croplands in Inner Mongolia increased from 0.66 million ha in the late 1970s to 3.03 million ha in 2010 (Tao et al. 2015). As of 2019, the irrigated croplands area on the Mongolian Plateau (including Mongolia and Inner Mongolia) had expanded to 12.49 million ha (FAO, Food and Agriculture Organization of the United Nations). To meet the water demand of the croplands, massive groundwater has been pumped out, numerous dams constructed, and river water diverted into croplands (Best 2019). Given such strong human disturbances, river runoff at certain regions on the plateau should have changed dramatically.

Nevertheless, there has been no study assessing the changes in river runoff across the entire Mongolian Plateau (Chen et al. 2018; Tong et al. 2018). Existing studies focused on individual river at the sub-basin level. Taking the Gen River in the Heilongjiang River Basin as an example, the average daily runoff experienced a gradual decline from 1985 to 2016, with an overall reduction speed of 57,300 m^3/year (Yue et al. 2020). In the Taoer River Basin, which is also part of the Heilongjiang River Basin on the plateau, the interplay of reduced precipitation and rising temperatures from 1958 to 2006 worsened drought conditions, resulting in a considerable decrease in runoff at the basin scale (Yin et al. 2012). In the Tabu River Basin in Inner Mongolia, measured runoff data from 2000 to 2018 showed a 41% reduction in annual runoff compared to the period of 1956–1999 (Li et al. 2021). However, these existing case studies differed largely in their time spans and analytic methods.

The lack of a comprehensive understanding of historic river runoff changes on the Mongolian Plateau hinders the implementation of water conservation practices.

This study provided the first comprehensive analysis of the temporal trend of runoff and its influencing factors on the entire Mongolian Plateau. We compiled a database of gauged river runoff consisting of measurements from 30 hydrological stations, possibly the largest among its kind for the Mongolian Plateau. With this database, we aim to (1) analyze the temporal trend in gauged river runoff on the Mongolian Plateau, and to (2) identify the drivers of observed runoff changes.

Besides, an additional analysis was conducted to assess the accuracy of the modelled historical river runoff by Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase 6 (CMIP6) models over the plateau (Eyring et al. 2016). With the intensifying of climate changes, CMIP6 simulations have been widely used to evaluate the impacts of climate change, including runoff, across the globe (Wang et al. 2022), but their accuracy of simulation in arid and semi-arid regions remains poorly quantified (Guo et al. 2022). We took our compiled runoff dataset for the Mongolian Plateau as a unique opportunity to validate the CMIP simulation in typical arid and semi-arid environmental settings. Thus, the third purpose of this study is to (3) assess the performance of CMIP6 models in simulating the historical changes in river runoff over the Mongolian Plateau. Our findings could contribute to a better understanding of the hydrological characteristics and their changes on the Mongolian Plateau, which are critical for water resource management and sustainable development in this environmentally-fragile region.

Materials and methods

Study area

We focused on the key parts of the Mongolian Plateau, namely Inner Mongolia of China and the Republic of Mongolia, which together span an area of around 2.75 million km^2 (Fig. 1). Our study region extends from the Greater Khingan Mountains in the east to the Altai Mountains in the west, Yinshan Mountains in the south, and Sayan Mountains and Jablonov Mountains in the north. The topography in the study region gently slopes from west to east and includes mountainous terrain in the northwest, the arid Gobi Desert in the southwest, and extensive hilly grasslands in the central and eastern areas (Dulamsuren et al. 2005; Miao et al. 2015). The region is

Fig. 1 The location of the Mongolian Plateau and distribution of the hydrological stations compiled by this study. Hydrologic stations within the same brown circle are located in the same watershed. IDs 1–4 Heilongjiang River Basin; IDs 5–6 and 14: Inland River Basin; ID 7: Haihe River Basin; IDs 8–13: Liaohe River Basin; IDs 15–23: Yellow River Basin; ID 24: Heihe River Basin; IDs 25–29: Selenga River Basin; ID 30: Kharkhiraa River Basin
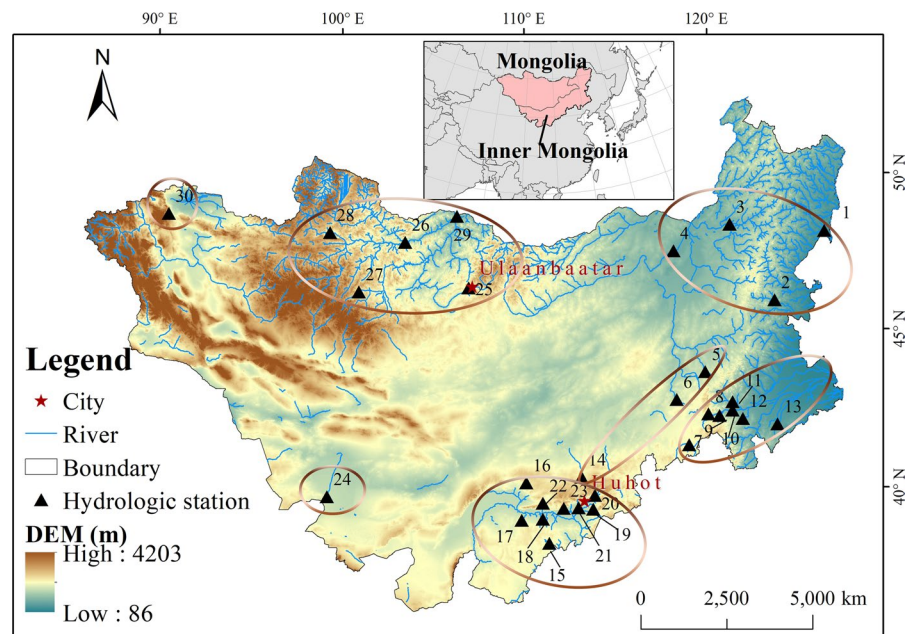
surrounded by high mountains and is far from the ocean, resulting in a typical continental climate with cold winters and hot summers. The monthly mean air temperatures range from -15.2 °C in January to 21.6 °C in July, with temperatures consistently below 0 °C from November to March (Liu et al. 2019). The region has a low annual precipitation of around 380 mm but high potential evaporation of around 1200 mm (Karthe et al. 2019). The total population of the Mongolian Plateau in the year of 2022 was 27.5 million (Inner Mongolia Autonomous Region Bureau of Statistics data, https://tj.nmg.gov.cn/; National Statistical Office of Mongolia data, https://www.nso.mn/mn).

Data and methods

River runoff data

A database of annual river runoff was built for the Mongolian Plateau with tremendous efforts. The runoff data were gathered from various sources, including literature and the hydrological yearbooks of China. In specific, we searched and gathered all the literature published in the past 20 years using key words "runoff", "river", and "Mongolian Plateau". Additionally, we gathered relevant statistical yearbooks and materials released by governments and related departments. Since we are interested in exploring the long-term changes in river runoff, we demand that each runoff time series should span at least 20 years and should extend into 2000s or even beyond. Finally, 30 hydrological stations with runoff time series met these criteria. 24 out of the 30 stations are located in Inner Mongolia, whereas 6 are situated in Mongolia (Fig. 1). The longest time span of 30 time series is 71 years. A detailed description of all hydrological stations and river runoff time series can be found in Table S2.

The units of runoff data differ among datasets and literature. We therefore unified the units into depth in millimeters (mm, Table S3). Firstly, we determined the precise location of each hydrological station based on its latitude and longitude, and employed basin maps, pertinent descriptions from the literature, and HydroBASINS data (https://www.hydrosheds.org/products/hydrobasins) to ascertain the basin's area; Secondly, we converted the units of various runoff data (e.g., 10^8 m³/s, m³/s, 10^8 m³) by adjusting for variations in basin size and the duration of measurement, ultimately expressing all annual runoff depths in millimeters (mm).

Climate data

We used the 'ERA5-Land' climate data with a time-resolution of 1 month (Hersbach et al. 2020) (https://cds.climate.copernicus.eu/). Monthly climate data were averaged across each river basin, and paired with the runoff time series. Monthly air temperature, precipitation, and potential evaporation at the basin level were then processed into annual mean temperature (AMT), annual precipitation (TP), and annual potential evaporation (PET).

Dam data

The locations of dams on the Mongolian Plateau were derived from Global Dam Watch (https://www.globaldamwatch.org/) (Mulligan et al. 2020). This database includes authentic digitized coordinates pinpointing the positions of dams, complemented by a worldwide map illustrating the watershed associated with each individual dam. According to the data description of Global Dam Watch, medium to large-scale dams (< 0.1 km³) were obtained from Google Earth, and large dams (≥ 0.1 km³) were sourced from openly accessible databases, research articles, grey literature, and online resources (Mulligan et al. 2020).

CMIP6 simulation data

Simulated runoff data from 26 CMIP6 Earth system models were used in this work (https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6). Since all the models simulated runoff modulus (kg/s/m²) at the basin scale, we converted the runoff modulus into annual runoff depth (mm). Table S4 provides a brief description of each model and its corresponding spatial resolution (Eyring et al. 2016). The spatial resolution of all models was unified to $0.01° \times 0.01°$ in ArcGIS software (version 10.2 ESRI, Redlands, CA, USA, http://www.esri.com/software/arcgis/arcgis-for-desktop) using Bilinear resampling.

We conducted a correlation analysis between our complied (ground-gauged) river runoff and the simulated runoff from each of the 26 CMIP6 models. Previous research has suggested that aggregating the

calculations from multiple CMIP6 models provides more accurate results than relying solely on simulations from a single model (Papalexiou et al. 2020; Srivastava et al. 2020). Thus, we also averaged the simulated runoff from the 26 models for each basin and quantified their temporal consistency with the compiled river runoff.

Non-parametric Mann–Kendall's test and Double-mass analysis

Theil–Sen Median trend analysis and the non-parametric Mann–Kendall's test (MK test) were used in this work to assess the trend of climatic variables and hydrological river runoff (Mann 1945; Kendall 1975; Liu et al. 2002). To detect whether there were abrupt changes in climatic variables and runoff, we used the MK test, which has been widely used to assess the significance of the trends in hydro-meteorological time series due to its robustness against non-normally distributed data (Serrano et al. 1999; Yue et al. 2020). The formula for calculating its statistics τ, variance σ^2 and standardized statistics Zs (M–K value) is as follows:

$$\tau = \frac{4P}{N(N-1)} - 1,$$

$$\sigma^2 = \frac{2(2N+9)}{9N(N-1)},$$

$$Z_s = \tau/\sigma.$$

In this formula, P is the total number of times that $x_i < x_j$ occurs across all recorded values in the study series, and N is the length of the series. The series has a significant trend if the Z_s statistic does not meet $-Z_{1-\alpha/2} \leq Z_s \leq Z_{1-\alpha/2}$ (α is the specified significance level); otherwise, the trend is not significant. The critical value is ± 1.96 when the significance level $\alpha = 0.05$ is given. If there were more than one abrupt changes in the river runoff time series, the one with the highest significance level was considered in our analysis.

In addition to Mann–Kendall's test, we performed double-mass (DM) analysis to identify the year of abrupt change in runoff. Double-mass analysis is a widely used method for quantifying trends and changes in a time series. The underlying principle of double-mass curve analysis asserts that if data values for two variables change proportionally over time, plotting the accumulation of one quantity against the accumulation of another during the same time period will result in a straight line (Zhan et al. 2011; Pirnia et al. 2019). We selected the year of abrupt change in runoff with the highest significance level, as determined by the Mann–Kendall's test. We then checked if the abrupt changes in runoff can be observed by an independent method, that is the DM analysis above detailed (Fig. S1).

Climatic influences on runoff changes

To account for the interaction between climatic variables (TP, PET, and AMT) and river runoff, a partial correlation analysis was conducted. Partial correlation can minimize the mutual influence of different climatic factors on runoff changes.

For climate variables correlated significantly ($P < 0.05$) with runoff, we further checked if the climate variables exhibited abrupt changes prior to the abrupt changes in river runoff. Toward this purpose, the same MK-test was conducted on climate time series, and the abrupt changes were compared with those of runoff.

Analysis of underlying surface parameters based on Budyko curve framework

We also used the Budyko curve framework to quantify the changes in the underlying surface parameters of the basins. This helps confirm the influence of human activities on the changes in runoff. Budyko (1974) proposed that the primary controlling factors for the long-term average annual evaporation from the land surface are the land surface water supply and atmospheric evaporative demand.

$$\frac{E}{TP} = f\left(\frac{PET}{TP}\right) = f(\varphi),$$

where E and PET represent actual annual evaporation and potential annual evaporation, respectively, in millimeters (mm); TP denotes annual average precipitation (mm).

Fu (1981) derived empirical formulas characterizing underlying surface features based on the Budyko hypothesis. In 2008, Yang et al. introduced the concept of available water supply into Budyko
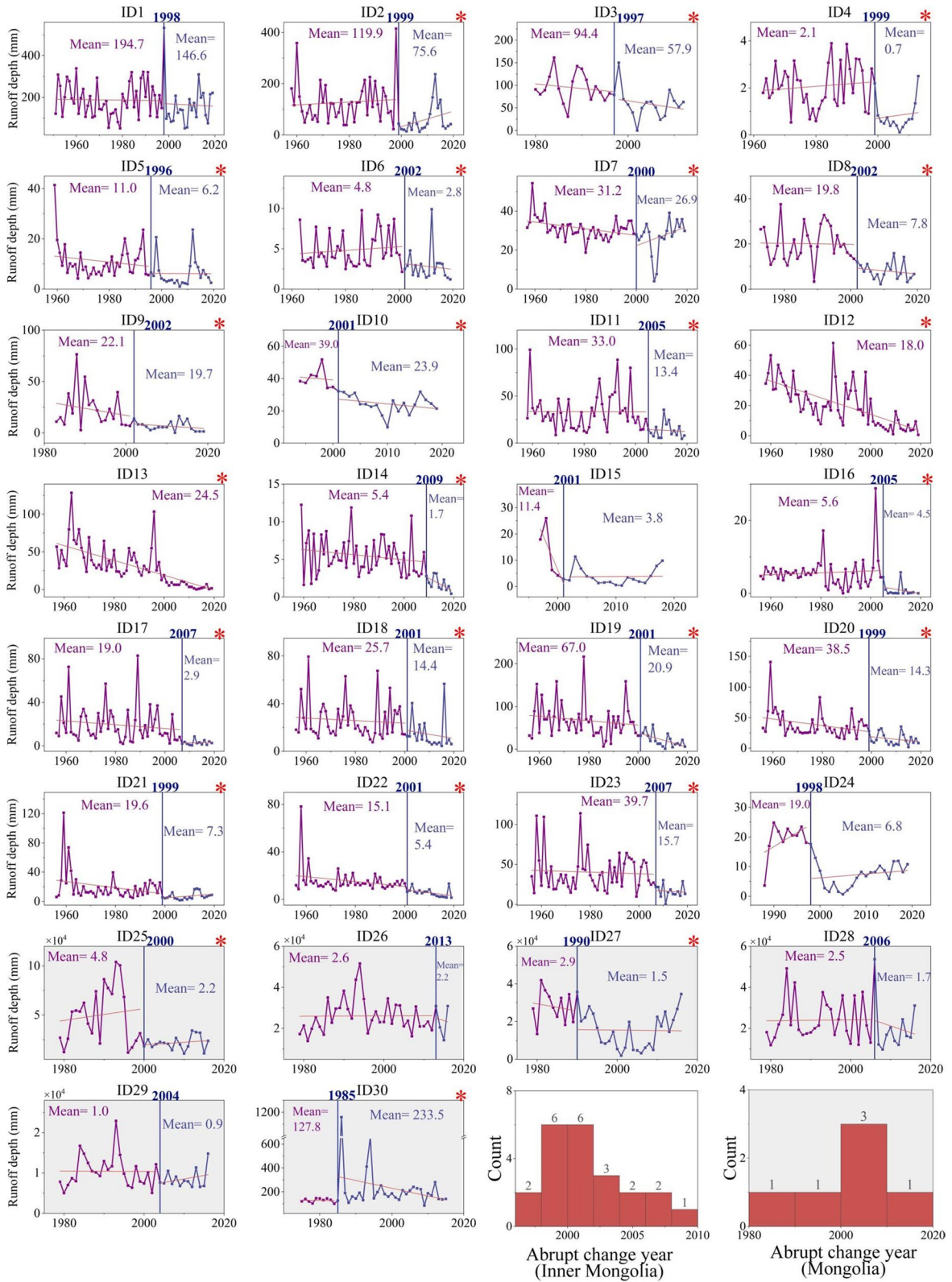
◄**Fig. 2** Long-term variations in river runoff on the Mongolian Plateau. The "*" symbol denotes that the river experienced a significant change in runoff ($P < 0.05$); the blue vertical line highlights the abrupt change year of runoff; the purple line and accompanying text illustrate the trend and average of runoff before the abrupt change, whereas the blue line and text depict the trend and average of runoff after the abrupt change. Red lines represent the corresponding fitted curves. The basins with white background are located in Inner Mongolia and those with a grey background located in Mongolia. The histograms in the bottom-right represent the frequency distribution of the years of abrupt change in the 30 river runoff time series in Inner Mongolia (white background) and Mongolia (grey background)

hypothesis. Utilizing dimensional analysis and mathematical derivation, they put forth an analytical expression known as the Mezentsev–Choudhury–Yang's function (Mezentsev 1955; Choudhury 1999; Yang et al. 2008), designed to be applicable across arbitrary time scales:

$$\frac{E}{TP} = \frac{\varphi}{[1 + \varphi^n]^{1/n}},$$

where n is the characteristic parameter of the underlying surface (reflecting human activities, vegetation coverage, soil properties, and other factors related with the conditions of the underlying surface), with a value range of $(0, +\infty)$ (Choudhury 1999; Li et al. 2013). A larger value of n or an increase in n can be viewed as a signal of heavier or augmented human influences on local hydrology (Xue et al. 2022).

Results

River runoff changes on the Mongolian Plateau

Among the 30 rivers of the Mongolian Plateau, only the Kharkhiraa River (ID 30) in the northwest showed a significant upward trend in runoff with a velocity of 1.51 mm/year (during the period from 1977 to 2015, $P < 0.05$, Fig. 2). All of the remaining 29 rivers showed a decreasing trend in discharge, and 23 of them had a significant trend ($P < 0.05$, Fig. 2). Importantly, the MK test revealed significant and abrupt changes in runoff in 21 out of the 28 rivers, with the abrupt changes observed within a timeframe of 5 years before or after the year 2000 (Fig. 2). The results of the DM analysis largely aligned with the

those of the MK test (Fig. S1). Out of the 28 rivers experiencing abrupt changes as determined by the MK test, 27 (96.4%) rivers underwent an abrupt decrease, while only one river (ID 30, in Mongolia) showed an abrupt increase in discharge.

A noticeable pattern emerges in the timing of abrupt change years for rivers in Inner Mongolia. As depicted in the histogram subset in Fig. 2, among the 22 rivers in the Inner Mongolia with abrupt changes, 19 (86.4%) experienced abrupt changes around the year 2000. All the rivers in the Heilongjiang River Basin (IDs 1–4), located in the northeastern part of Inner Mongolia, experienced abrupt decreases in runoff before the year 2000. Likewise, rivers in the Heihe River Basin (ID 24) also underwent abrupt decreases in runoff before the year 2000. The majority of rivers in the Yellow River Basin (IDs 15–23) and the Liao River Basin (IDs 8–13) experienced abrupt decreases after the year 2000. However, the timing of the abrupt changes of runoff did not show a clear pattern in Mongolia (IDs 25–30, histogram subset in Fig. 2).

Climatic influences on runoff

To identify the climatic factors responsible for the observed runoff changes, we first conducted partial correlation analyses between three climate factors (TP, AMT, and PET) and river runoff. We found that, the runoff changes in 19 rivers were significantly ($P < 0.05$) correlated with at least one climatic factor (Table 1). Changes in TP rather than AMT and PET had the greatest impact on the changes in river runoff (Table 1). Specifically, 18 out of 30 runoff time series had a significantly positive correlation ($P < 0.05$) with TP (Fig. 3). Although AMT and PET of all the 30 rivers showed significantly increasing trends ($P < 0.05$), only 3 and 2 of which, respectively, had a significant correlation with river runoff (Table 1; Figs. S1, S2).

For climate factors that correlated significantly ($P < 0.05$) with runoff, we further checked if they exhibited abrupt changes 5 years prior to the abrupt changes in river runoff. Notably, 27 rivers experienced abrupt changes in TP around 2000. In 8 of these rivers (subsets with a green background in Fig. 3), we observed that TP substantially correlated with runoff and that TP changed abruptly 5 years before the abrupt shift in runoff. Seven of these eight rivers were located in Inner Mongolia, and only one was located in Mongolia. In contrast to the widespread control of

Table 1 Partial correlations between runoff and TP, AMT and PET

IDs	TP	AMT	PET	IDs	TP	AMT	PET
1	0.59**	0.04	−0.51	16	0.27*	−0.09	0.15
2	0.64**	−0.08	−0.02	17	0.23	−0.15	−0.10
3	0.62**	0.07	−0.22	18	0.29*	−0.06	−0.08
4	0.31*	0.26	−0.28*	19	0.53**	−0.32*	0.23
5	0.49**	0.04	−0.01	20	0.15	−0.08	−0.16
6	0.43**	−0.11	0.03	21	0.19	0.00	−0.07
7	0.23	0.04	−0.08	22	0.37**	−0.22	0.15
8	−0.18	−0.04	−0.11	23	0.38**	0.00	−0.11
9	0.23	0.00	−0.25	24	−0.42*	0.16	−0.38*
10	0.11	0.24	−0.28	25	0.66**	0.35*	−0.04
11	0.35*	0.21	−0.18	26	0.28	0.34*	−0.25
12	0.04	−0.14	−0.21	27	0.44*	−0.15	−0.12
13	−0.02	−0.18	−0.07	28	0.43*	0.11	−0.18
14	0.31*	−0.14	−0.21	29	0.48**	0.10	−0.12
15	0.19	0.24	−0.18	30	0.28	0.12	0.00

TP total precipitation, *PET* potential evaporation, *ATM* average mean temperature

*Correlation at a significance level of 0.05, **correlation at a significance level of 0.01

TP, AMT displayed abrupt changes 5 years before the runoff shift in only one river, and we didn't identify any case where PET had significant correlations or exhibited abrupt changes 5 years before runoff changes (Figs. S2, S3).

The Y axis in each subset represents the standardized values of river runoff and TP, employing max–min normalization. The vertical gray and green lines indicate the years of abrupt change in runoff and TP, respectively. The strength (R^2) and significance (P) of the correlation between river runoff and TP were labeled within each subset. Subsets with green backgrounds indicate that TP correlated significantly ($P < 0.05$) with runoff and TP displayed abrupt changes 5 years before the abrupt shift in runoff.

Human impacts on runoff

In addition to the widespread control of TP on river runoff changes, human activities also exerted profound influences on river runoff. First, dam construction largely altered the localized river runoff. Numerous large-scale dams (≥ 0.1 km^3) can be found in the Liao River Basin (IDs 8–13) and Yellow River Basin (IDs 15–23, Fig. 4a). Only river ID 11 in the Liao River Basin showed a significant positive correlation between runoff and TP ($P < 0.05$), whereas other basins showed no significant correlation (Table 1; Fig. 3). Rivers in the Yellow River Basin experienced abrupt changes in runoff during 1999–2007 (Fig. 2),

but most rivers (IDs 15, 17, 20, 21) showed no significant correlation with any climate factor (Table 1).

Apart from dam construction, it is worth pointing out that the water diversion project also largely influenced the river runoff, which was the most evident in the Heihei River Basin (ID 24). In order to restore and rebuild the damaged downstream ecosystems of the Heihe River Basin, the Heihe River "97" Water Separation Scheme was implemented in July 2000. Water began flowing into the downstream areas of the Heihe River, including the East and West Juyan Lakes, in July 2002 (Xi et al. 2007). The runoff of river ID 24 showed a fluctuating upward trend after 2000 (Fig. 2). Note that in this river basin, TP showed an increasing trend around 2000, but PET and AMT also increased strongly at the same time (Figs. S1, S2), and PET in this region was 3 times higher than TP after 2000. Thus, the increase in river runoff cannot be entirely attributed to the increase in TP.

The green dots in (a) represent dams with a capacity < 0.1 km^3, while the red dots represent dams with a capacity ≥ 0.1 km^3 (data from Mulligan et al. 2020). The volumes of the transferred shown in (b) water were obtained from the Heihe River Basin Authority within the Yellow River Conservancy Commission under the Ministry of Water Resources (Qiao et al. 2007).

To further quantify the influences of climatic and human factors on runoff change, the Budyko curve framework was used to analyze the spatial and
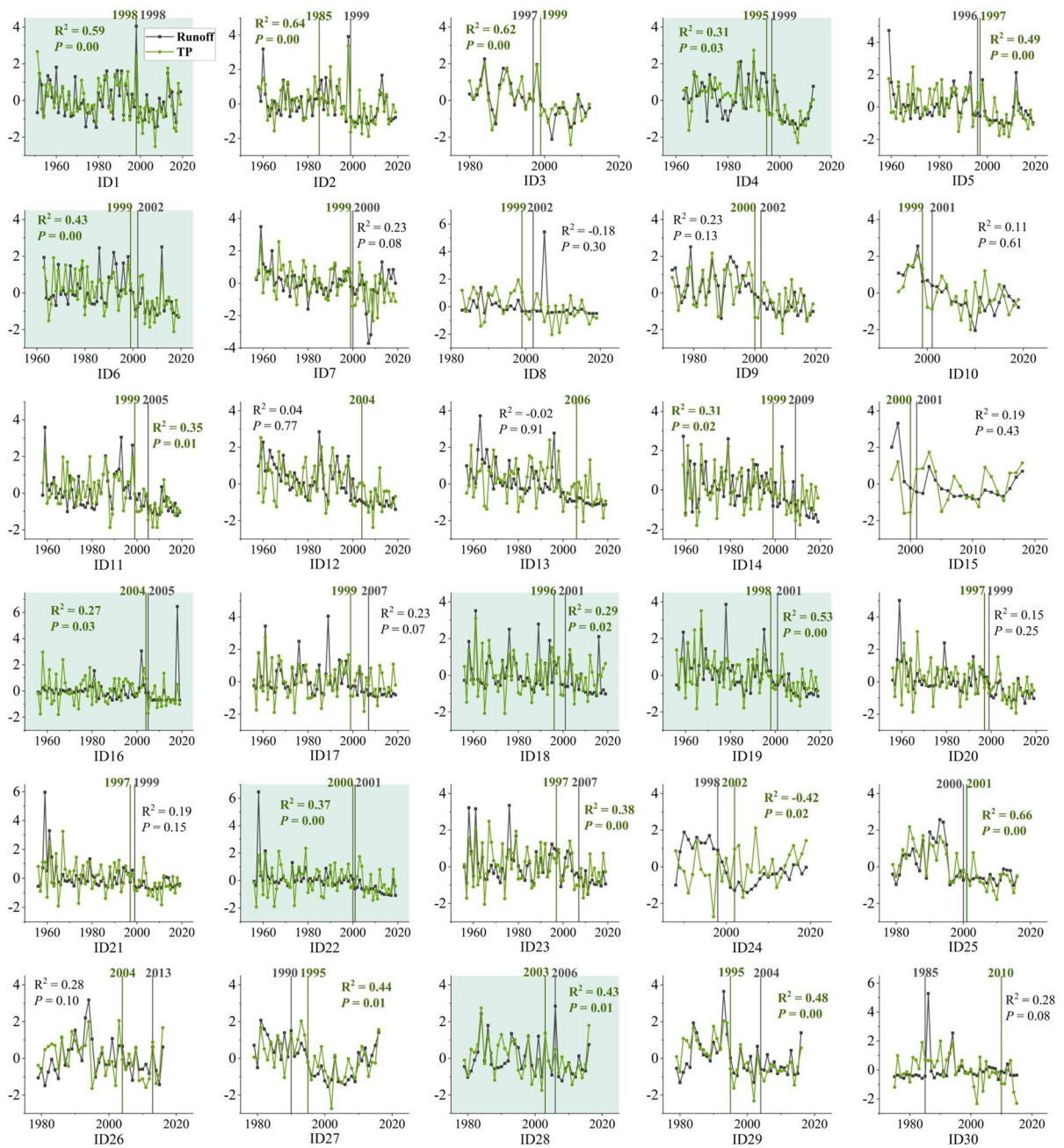
Fig. 3 Time series of river runoff (colored in gray) and TP (colored in green) for the 30 Mongolian rivers

temporal patterns of the underlying surface parameters (namely, n) of the basins. The results indicated that the values of n were the lowest in basins where runoff significantly correlated with at least one climatic factor (namely Basins 1–6, 11, 14, 16, 18, 19, and 22–29). In contrast, n values were the highest in basins where runoff showed no significant correlation with any climatic factor (namely Basins 7–10, 12, 13, 15, 17, 20, 21 and 30), and has further increased after the years of abrupt change in runoff (Fig. 5f). This suggests pronounced and increased human impacts in such basins.

Fig. 4 Typical human
disturbance on river runoff
on the Mongolian Plateau.
a Distribution of dams on
the Mongolian Plateau,
and **b** cumulative water
transferred from the Heihe
River to the East and West
Juyan Lake between 2000
and 2005
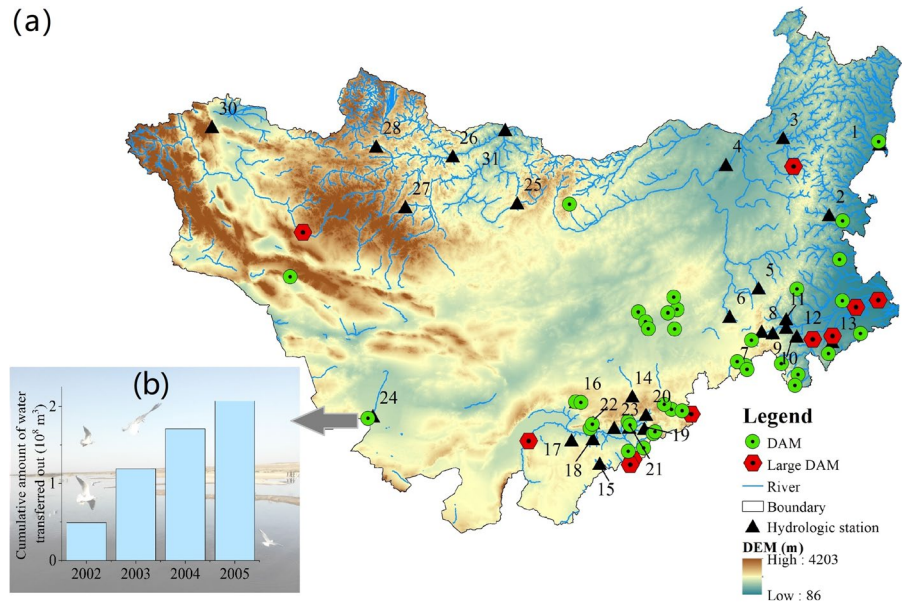
Fig. 5 Fitted curves of the
aridity index (PET/TP) and
evapotranspiration ratio (E/
TP) before and after the
abrupt changes in runoff
based on Budyko curve
framework. The colorful
legend on the right repre-
sents the density of points
(basins). *PET* potential
evaporation, *TP* precipita-
tion, *E* actual evaporation.
a, **b** All basins (IDs 1–30),
c, **d** basins where runoff
significantly correlated with
at least one climatic factor,
and **e**, **f** basins showed
runoff showed no signifi-
cant correlation with any
climatic factor
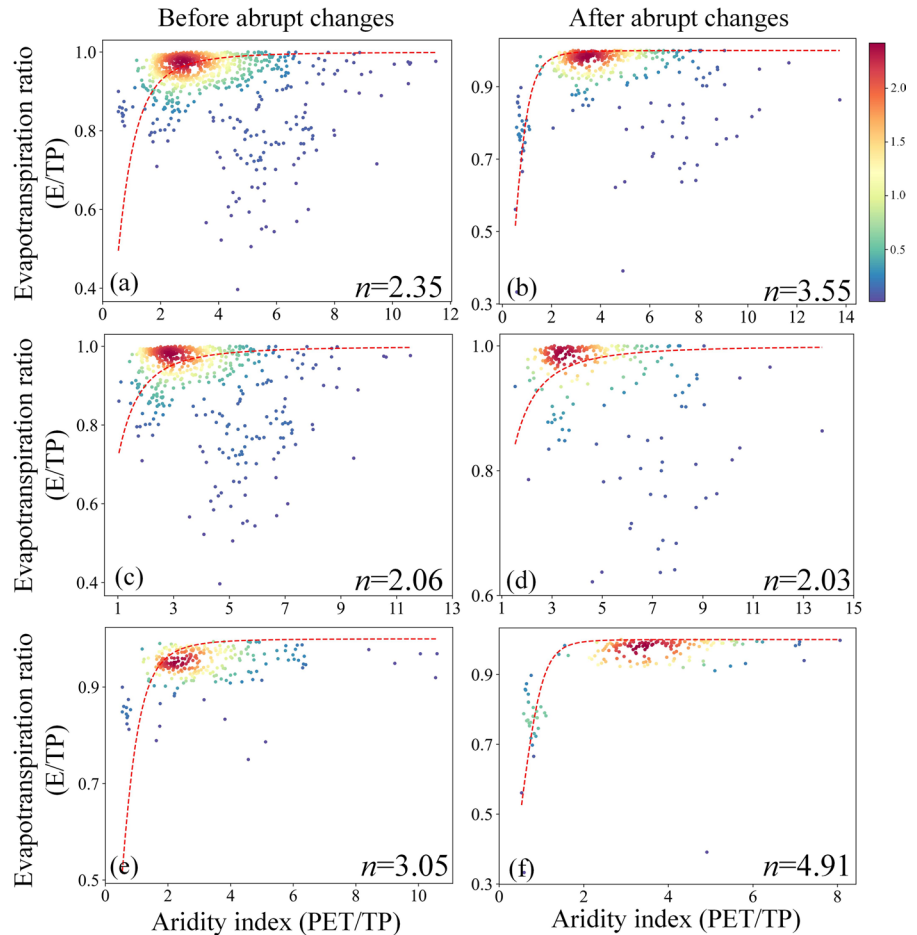
Comparison between measured runoff and CMIP6 data

The runoff simulated by the CMIP6 models (averaged across models) showed no significant correlation ($P < 0.05$) with the measured runoff at various hydrological stations. The correlation coefficients (R^2) were generally lower than 0.2 (Fig. 6). In contrast to the measured runoff time series which generally showed decreasing trends (Fig. 2), only five basins (IDs 14, 16, 19–21) exhibited a decreasing trend according to the simulated historical runoff.

Further inspecting the correlations between measured runoff and simulated runoff by each of the 26 models, we found that out of the 780 correlations (26 models×30 basins), only 55 showed a significant correlation ($P < 0.05$, Table S5). Among them, the performance of the CESM2 and CMCC-ESM2 models was relatively better, both showing a significant correlation ($P < 0.05$) with measured runoff time series in 5 out of 30 basins (Table S5).

Regarding abrupt changes in runoff (Fig. 6), only four runoff time series (IDs 3, 6, 18, and 25) simulated by CMIP6 models showed abrupt changes. These changes occurred within the first 2–3 years of simulated runoff time series, thus did not coincident with the abrupt change observed in the measured runoff data from hydrological stations (Fig. 6).

Discussion

Climate-dominated sudden reduction in runoff

This study found that most major rivers on the Mongolian Plateau experienced an abrupt reduction in river runoff around 2000 (Fig. 2). To the best of our knowledge, this is the first comprehensive evaluation on the change in river runoff for the entire plateau. Our finding is realizable and supported by previous case studies conducted with uneven spatial or temporal coverages. For instance, an analysis with a large amount of runoff measurements from hydrological stations revealed a significant decline in measured runoff from 1965 to 2016 in China, and the decline was more severe in China's northern regions (part of the Mongolian Plateau included) than southern regions (Zhang et al. 2022). Ren et al. (2002) observed a declining trend in river runoff in

northern China, including the Liaohe River (IDs 8–13 of this study), Yellow River (IDs 15–23), and Heihe River (ID 24). In the Yellow River Basin, Yang et al. (2020) identified a rapid reduction in runoff during recent decades, with one also occurred around 2000. Similarly, Yue et al. (2020) noted a downward trend in runoff in the Heilongjiang region (IDs 1–4), with abrupt changes occurring in around 2000 (1997 and 1999). Our study, together with the previous case studies, suggested that the sudden reduction in river runoff might be pervasive in Asia's northern arid and semi-arid regions.

Climate change is widely considered to have a substantial influence on the hydrological cycle (Oki and Kanae 2006; Zhao et al. 2015). Evidence from historical records of precipitation, streamflow, and drought indices all indicate a widespread increase in aridity globally (Dai 2011, 2013). Consistent trends have been observed in this study, with most rivers showing an increasing trend in AMT and PET (Figs. S1, S2), while TP showed a declining trend over the past 30 years (Fig. 3). We quantified the relationship between annual runoff and TP for each of the river basin, and found significant positive correlations ($P < 0.05$, Fig. 3). In addition, TP in many regions exhibited similar abrupt changes as river runoff, highlighting the critical role of precipitation in controlling river runoff in arid and semi-arid regions (Yue et al. 2020).

Another reason for the abrupt decreases in runoff around the year of 2000, could be the extreme climatic events occurred to the plateau. Since 2000, the frequency and magnitude of extreme climatic events have increased on the Mongolian Plateau compared to those recorded in the few decades prior (Fernández-Giménez et al. 2012; John et al. 2013). Tong et al. also observed a significant and abrupt change in the occurrence of drought on the Mongolian Plateau starting in 1999. In particular, Mongolia's successive 1999–2002 dzuds and droughts were the worst ever observed over the past 50 years (Tachiiri et al. 2008). Thus, the abrupt changes in river runoff are consistent with the increased frequency and intensity of extreme climatic events on the Mongolian Plateau.

Human disturbances on river runoff

In addition to climatic factors, human activities are an important driving force behind the runoff changes on
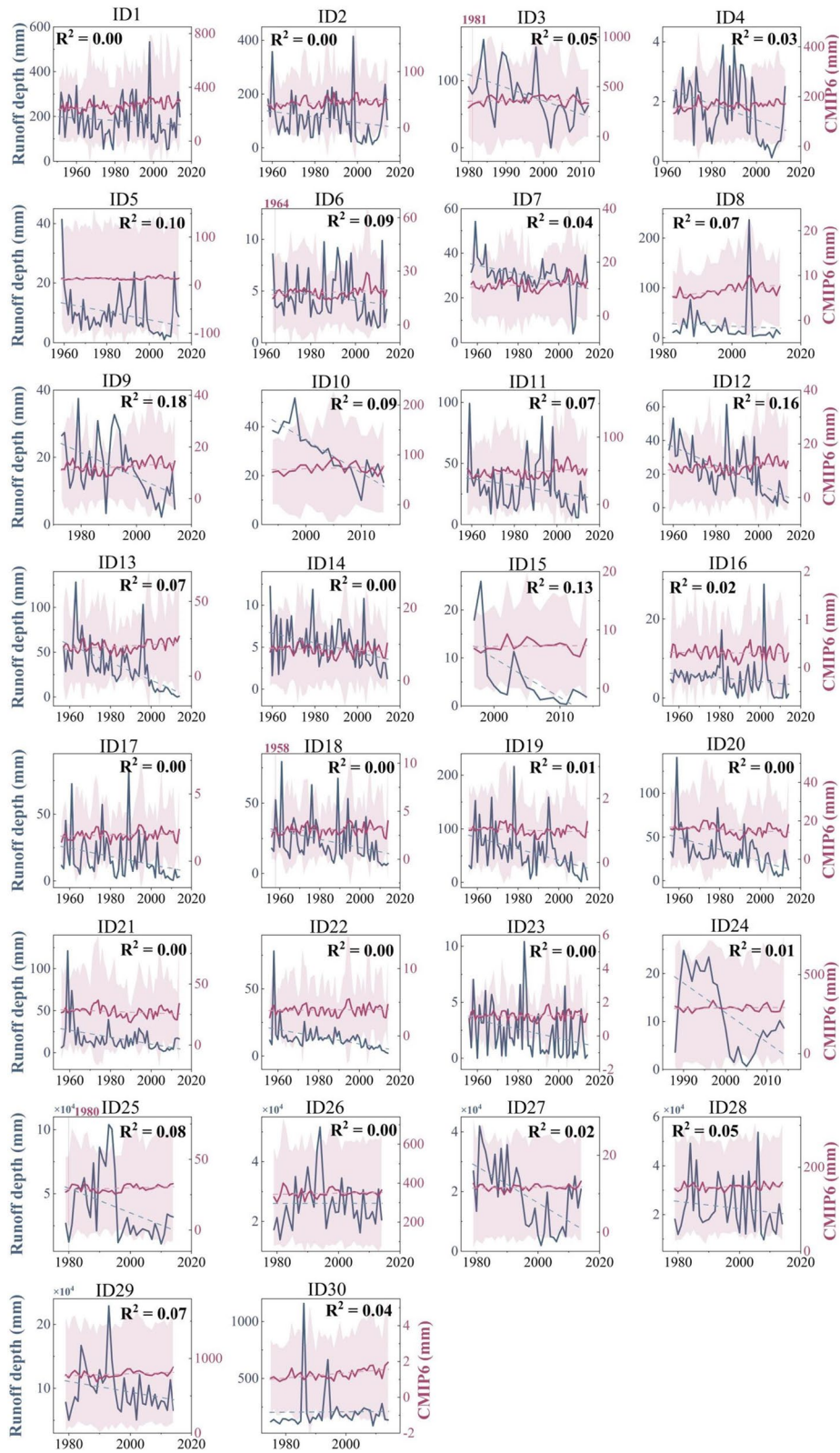
◄**Fig. 6** Comparisons between measured river runoff and CMIP6 simulated runoff. In each subset, the blue solid line and dashed line represent the observed actual runoff and its fitted trend, respectively. The red solid line and dashed line represent the simulated historical runoff by CMIP6 models and its fitted trend, respectively. The shaded pink area indicates the variations (standard deviation) in simulated runoff of the 26 models. The red vertical lines in some subsets (IDs 3, 6, 18, and 25) represent the year of abrupt change in the historical runoff simulated by CMIP6

the Mongolian Plateau. As shown in Table 1, the temporal runoff of 11 out of 30 basins (36.7%) did not exhibit significant correlation with any climate factor. It is noteworthy that the values of the underlying surface parameters in these basins were higher compared to other basins, and they increased further after the year of abrupt change in runoff (Fig. 5), suggesting augmented human interventions on runoff change. Case studies conducted across the Mongolian Plateau have also revealed human-induced runoff reduction. For instance, Liu et al. (2002) found that over 60% of the decrease in flow in the Yellow River Basin can be attributed to human activities. Zhang et al. (2007) revealed significant declines in runoff in the Liao River Basin from 1950 to 2004, with human activities reported the primary driving force. In the case of the Heihe River Basin, runoff showed a significant decrease from 1956 to 2005, with human activities explaining over 70% of the runoff reduction (Zhang et al. 2007). Human activities, such as dam and reservoir construction (Döll et al. 2009; Best 2019), irrigation and groundwater extraction (Aeschbach-Hertig and Gleeson 2012), and ecological restoration projects (Wu et al. 2020; Yang et al. 2020), directly or indirectly impact the water cycle through processes like infiltration, retention, and evaporation.

With the continuous development of the economy and society, dam construction has led to rapid transformations in river channels (Best 2019). The number of global hydroelectric power stations has seen a significant increase during past decades, with a 55.0% growth in gigawatt capacity (Hennig and Magee 2017; Best 2019; Wu et al. 2023). On a global scale, dams have reduced the river discharge into oceans or inland lakes by a magnitude of 0.8% (Döll et al. 2009). Rivers in northern China, one of the areas most affected by the combination of dam construction and human water use, have seen significant reductions in river discharge (Döll et al. 2009). In the

Liaohe River Basin, only one river showed a significant positive correlation with TP. In the Yellow River Basin, most rivers did not show significant correlation with any climatic factor (Table 1). The presence of numerous large dams (Fig. 4), particularly in the Liaohe River Basin and Yellow River Basin implied that while climate change may play a role in runoff variation, its impact may be overshadowed by the primary influence of dam construction.

Furthermore, the impact of irrigation and groundwater extraction on regional water resources cannot be ignored. Widespread activities such as irrigation and groundwater extraction have exacerbated water scarcity in arid or semi-arid regions, leading to further depletion of rivers (Wu et al. 2023). Due to water extraction, global discharge into oceans and inland water systems have decreased by 2.7% relative to natural conditions (Döll et al. 2009). Asia exhibits high rates of agricultural water withdrawal, with nearly 84.0% of water withdrawals in this region allocated for agricultural purposes, compared to the global average of 71.0% (Ragab and Prudhomme 2002).

According to FAO data, the cultivated land area on the Mongolian Plateau showed a steady increase, reaching 12.49 million ha in 2019, which has led to a continuous rise in agricultural water usage (Aeschbach-Hertig and Gleeson 2012). The central and western regions of Inner Mongolia face water scarcity due to low rainfall and high evaporation. However, from 2003 to 2010, an average of 200 million m^3 water was diverted annually into croplands or mining sites through man-made water canals (Ding 2013). Unsustainable mining practices and agricultural irrigation activities have been reported as the main factors contributing to the dried up of lakes and associated upstream rivers (Tao et al. 2015).

Inaccuracy of CMIP6 simulations on the Mongolian Plateau

Given the increasing atmospheric aridity over the twenty first century, CMIP6 simulations have been widely used to study the changes in runoff and climatic aridity at both global and regional scales (Huang et al. 2016; Wang et al. 2022; Fang et al. 2022). CMIP6 models are also a powerful tool for projecting future river runoff changes (Eyring et al. 2016; Cook et al. 2020). However, this study revealed that the simulated runoff from CMIP6 was inaccurate

on the Mongolian Plateau. Consequently, cautions should be given when using CMIP6 models for predicting future river runoff changes for this critical region.

One reason for the inaccuracy of CMIP6 model in our study region could be the complex and diverse terrain of the Mongolian Plateau which poses a challenge for accurate modeling of hydrological processes (Yang et al. 2014). In a location with complex topography and scant meteorological data, precipitation and temperature patterns are challenging to be accurately assimilated into models (Ahmed et al. 2014). Besides, geographical and soil characteristics in the plateau also exhibit large spatial variability, adding to the difficulties for CMIP6 models to accurately capture their intricate dynamics.

Moreover, the scarcity of high-quality observational data on the Mongolian Plateau exacerbates the challenges for modelling river runoff. The lack of comprehensive and long-term runoff observations hampers the validation and calibration of models, posing challenges to assess the accuracy and reliability of the predicted runoff simulations. Future efforts should be directed towards enhancing the observational network of river runoff, ensuring better validation and calibration of model outputs, especially in arid and semi-arid regions.

Limitations of analysis

In order to restore the ecological environment, China has been implementing the 'Grain to Green' revegetation program across northern China since 1999 (Feng et al. 2016). Due to the lack of specific information about the implementation of the policy in specific regions, this article was unable to conduct a quantitative analysis of the policy's impact on runoff changes in Inner Mongolia (part of the Mongolian Plateau). However, many studies have already demonstrated, especially in the Yellow River Basin, that the implementation of the policy has exerted a significant impact on runoff. Regional net primary productivity (NPP) has been estimated to increase by 9.3 ± 1.3 g C/m^2/year during 2000–2010 in Loess Plateau (Feng et al. 2016). According to Farley et al. (2005), conversion from cropland to grassland and shrubland could cause reduction in runoff by 44% and 31%, respectively, and the reduction may be the most pronounced in dry regions. The primary cause of the reduction in runoff is that the regional water cycle has intensified, as evidenced by the significant increase in evapotranspiration (Mo et al. 2017; Yang et al. 2020). Vegetation restoration and afforestation have contributed to this increase in evapotranspiration, resulting in a decrease in the ratio of river runoff to annual precipitation (Feng et al. 2016; Wu et al. 2020; Yang et al. 2020).

Conclusion

In conclusion, this study comprehensively quantified the spatial pattern and driving forces of river runoff changes across the Mongolian Plateau. We found that, around the year of 2000, most of the major rivers on the Mongolian Plateau witnessed a decline in runoff, especially in Inner Mongolia. Total precipitation (TP) had a greater impact on the observed abrupt runoff changes than other meteorological factors. Against the backdrop of precipitation-induced runoff changes, human activities such as dam construction and water diversion projects also caused substantial changes in runoff at the local scale. Such results highlight the importance of considering both climate and human factors when analyzing water resource changes on the Mongolian Plateau. Moreover, we found that the CMIP6 historical runoff simulations were inaccurate over the plateau, suggesting that large-scale circulation and climate models should be improved and their results should be interpreted with cautions on the Mongolian Plateau, and possibly also in other arid and semi-arid regions of the world.

Declarations

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