Runoff characteristics and its sensitivity to climate factors in the Weihe River Basin from 2006 to 2018 (Postprint)

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Abstract

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Full Text

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Abstract: Exploring current runoff characteristics following the large-scale implementation of the Grain for Green (GFG) project and investigating their sensitivities to potential drivers are crucial for water resource prediction and management. Based on measured runoff data from 62 hydrological stations in the Weihe River Basin (WRB) from 2006 to 2018, this study analyzed the temporal and spatial runoff characteristics. Correlation analysis was used to investigate relationships between different runoff indicators and climate-related factors. Additionally, an improved Budyko framework was applied to assess the sensitivities of annual runoff to precipitation, potential evaporation, and other factors. The results showed that the daily runoff flow duration curves (FDCs) of all selected hydrological stations fell within three narrow ranges, with corresponding mean annual runoff spanning approximately 1.50 orders of magnitude, indicating substantial variation in runoff across different hydrological stations in the WRB. Trend analysis of runoff under different exceedance frequencies showed that runoff from the south bank of the Weihe River was more abundant and stable than that from the north bank. Runoff was unevenly distributed throughout the year, concentrated mainly in the flood season, accounting for more than 50.00% of annual runoff. However, the trend of annual runoff change was not obvious in most areas.

Correlation analysis revealed that rare-frequency runoff events were more susceptible to climate factors. In this study, daily runoff under 10%–20% exceedance frequencies, consecutive maximum daily runoff, and low-runoff variability rate showed strong correlations with precipitation, aridity index, and average runoff depth on rainy days. In comparison, daily runoff under 50%–99% exceedance frequencies, consecutive minimum daily runoff, and high-runoff variability rate exhibited weak correlations with all selected impact factors. Sensitivity analysis results suggested that the sensitivity of annual runoff to precipitation was always higher than that to potential evaporation. Runoff at approximately 87.10% of the selected hydrological stations was most sensitive to precipitation changes, while 12.90% were most sensitive to other factors.

The spatial pattern of the sensitivity analysis indicated that in relatively humid southern areas, runoff was more sensitive to potential evaporation and other factors, and less sensitive to precipitation.

Keywords: daily runoff; climate-related factors; precipitation; potential evaporation; correlation analysis; sensitivity analysis; Weihe River Basin

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Introduction

As an essential process of the hydrological cycle, changes in runoff play a vital role in the sustainable development of human society, the economy, and the living environment (Greve et al., 2014; Sun et al., 2016). In the past few decades, the runoff of 24% of the world's major rivers has experienced significant changes, most notably declining trends in Asia's large rivers (Li et al., 2020). Yang et al. (2022) reported that from 1965 to 2018, the runoff of the Haihe River Basin, Liaohe River Basin, and Yellow River Basin in China showed a significant downward trend, leading to a sharp decline in the supply of ecosystem services and severe damage to human well-being. Therefore, evaluating the influencing factors of runoff change is of great significance for the development and utilization of water resources, agricultural production, and economic development (Sun et al., 2013).

To improve the ecological environment, a series of ecological protection measures have been implemented in river basins (Ouyang et al., 2013). Among them, the Grain for Green (GFG) project has dramatically optimized land use structure and improved ecosystem services (Zeng et al., 2020). The study of Yang et al. (2022) showed that abrupt changes in runoff in many rivers occurred in the 1990s, indicating that the implementation of the GFG project can reduce runoff. However, climate change also drives the hydrological cycle, primarily through changes in precipitation and temperature (Xie et al., 2015). Under global warming, hydrological variables such as surface runoff, evapotranspiration, and precipitation change greatly (Nilawar and Waikar, 2018). Therefore, studying current runoff characteristics after the GFG project and investigating runoff responses to climate-related factors will help us profoundly understand the water resource situation.

The Weihe River Basin (WRB) is a typical transitional watershed between arid and semi-arid areas in China, and its water resources are susceptible to climate change (Song et al., 2007). Yang et al. (2014) found that climate factors could promote runoff in Northwest China. Qiu et al. (2022) found that the magnitude and frequency of extreme precipitation in the WRB have strengthened in the past 60 years and showed a strong aggregation mode. Additionally, in some areas, higher potential evapotranspiration and temperature will also intensify the hydrological cycle (Li et al., 2016; Miao et al., 2016). As the largest primary tributary of the Yellow River Basin (YRB), the Weihe River not only provides a huge amount of water for the YRB and irrigates the Guanzhong Plain in the lower reaches, but also maintains ecological balance and social and economic development in Northwest China (Zuo et al., 2015). Since the large-scale implementation of the GFG project, runoff in the WRB has experienced a dramatic decreasing trend (Gao et al., 2013; Chang et al., 2015).

The relationships between runoff and climate factors in the WRB are usually assessed by hydrological models or empirical statistical methods. Gao et al. (2013) used double-mass curves for the period 1932–2008 to quantify the contribution of precipitation to runoff change, and the results showed that the impact of precipitation on runoff decline accounted for only 17.20% before and after the transition year. Zhao et al. (2013) quantitatively evaluated the impacts of climate change and human activities on runoff in the WRB from 1958 to 2008 based on the Budyko curve method. They found that the decrease in annual runoff at most hydrological stations was due to reduced precipitation and increased potential evaporation. Li et al. (2019) applied the Soil and Water Assessment Tool (SWAT) model in the WRB and found that in the tributaries and upstream hydrological stations, from 1970 to 2016, the dominant factor of runoff reduction was climate change, which accounted for more than 90.00%.

Previous studies have focused on long-term changes in runoff and its driving factors in the WRB while ignoring current runoff characteristics. Additionally, there are significant spatial differences in the geographical characteristics and climate types across the entire WRB, which makes the response of hydrological regimes in different locations to climate change quite different (Huang et al., 2016). Existing studies primarily analyzed the sensitivity of runoff at the watershed outlet to potential influencing factors. However, they ignored detailed and systematic analysis of the relationship between climate variables (i.e., precipitation, evaporation, and other related parameters) and runoff characteristics throughout the entire WRB. In this study, several classical hydrological analysis methods were applied to analyze runoff characteristics and their sensitivities to climate factors in the WRB from 2006 to 2018. The aims of this study are to: (1) investigate the temporal and spatial variations in runoff characteristics at 62 hydrological stations in the WRB; (2) estimate the correlation between selected runoff characteristics and climate factors; and (3) calculate the sensitivities of annual runoff to precipitation, potential evaporation, and other factors based on an improved Budyko method.

Study Area

The WRB, located on the central Loess Plateau in northern China, was selected as the study area. The main Weihe River has a total length of 818 km and a drainage area of 1.35$×10^{4}$ km^2 [Figure 1: see original paper]. It originates north of the Niaoshu Mountains in Gansu Province and eventually flows into the Yellow River at Tongguan County, Shaanxi Province. The topography of the basin decreases from west to east, with elevation ranging from 243 to 3916 m. There are many tributaries of the Weihe River. The Jinghe River and Beiluo River are the first and second largest tributaries, respectively. Tributaries with a drainage area of more than 1.00$\times10^{3}$ km^2 include the Bangsha River, Jihe River, Heihe River, Fenghe River, and Bahe River in the south, and the Xinhe River, Sandu River, Hulu River, Niutou River, Qianhe River, Qishui River, Shichuan River, Jinghe River, and Beiluo River in the north (Zhou and Yan, 2014). The WRB is located in the transition area between arid and humid regions of China, with an average annual precipitation of 572 mm, characterized by uneven distribution with more precipitation in the south and less in the north. Runoff is also characterized by uneven regional distribution, considerable interannual variation, and uneven annual distribution. The GFG project was first piloted in Gansu, Shaanxi, and Sichuan provinces in 1999 and was fully launched nationwide in 2002. Therefore, the large-scale implementation of the GFG project in the WRB occurred after 2000.

Fig. 1 Topography, river networks, and hydrological stations of the Weihe River Basin (WRB)

Data Sources

To ensure temporal consistency and availability of runoff data measured by the selected hydrological stations, we chose 2006–2018 as the study period. Daily runoff and precipitation data from hydrological and meteorological stations were acquired from the Hydrological Year Book of the Yellow River Basin (the Ministry of Water Resources of the People's Republic of China, 2006–2018). Other observational daily meteorological data, including daily maximum and minimum air temperatures from 22 national meteorological stations, were derived from the National Meteorological Administration (http://www.cma.gov.cn/). The daily precipitation and temperature data were aggregated into monthly or annual values for subsequent calculation and analysis.

Runoff Characteristic Indices

Table 1 lists the 20 indices selected for this study along with their descriptions and calculations. These indices describe runoff characteristics from different aspects. Q1, Q5, Q10, Q20, Q50, Q80, Q90, Q95, and Q99 refer to runoff at 1%, 5%, 10%, 20%, 50%, 80%, 90%, 95%, and 99% exceedance frequencies, respectively. Among them, some are related to high-frequency runoff events (Q80, Q90, Q95, and Q99) and some to low-frequency runoff events (Q1, Q5, Q10, and Q20). Extreme consecutive daily runoff indices include maximum daily runoff (Max1), maximum runoff for 7 consecutive days (Max7), maximum runoff for 30 consecutive days (Max30), minimum daily runoff (Min1), minimum runoff for 7 consecutive days (Min7), and minimum runoff for 30 consecutive days (Min30). Additionally, there are indices showing low runoff variability rate (RQ95:Q50) and high runoff variability rate (RQ5:Q50). These runoff series can basically reflect the general hydrological characteristics of a watershed (Bassiouni and Oki, 2013).

Table 1 Description and calculation of runoff characteristic indices

Index	Description and calculation
Q1, Q5, Q10, Q20, Q50, Q80, Q90, Q95, and Q99	Daily runoff under different exceedance frequencies. The subscript represents the percentage of runoff exceedance probability.
Min1, Min7, and Min30	Consecutive minimum daily runoff. The subscript indicates the consecutive days.
Max1, Max7, and Max30	Consecutive maximum daily runoff. The subscript indicates the consecutive days.
RQ95:Q50 and RQ5:Q50	Low-runoff variability rate and high-runoff variability rate, respectively. Annual runoff is divided by the median annual runoff, providing an overview of how the flow duration curve changes over time.
RC	Ratio of annual runoff to precipitation, reflecting the average water production capacity of the basin during a certain period.
R	Annual runoff.

Note: Q1, Q5, Q10, Q20, Q50, Q80, Q90, Q95, and Q99 refer to runoff at 1%, 5%, 10%, 20%, 50%, 80%, 90%, 95%, and 99% exceedance frequencies, respectively; Min1, Min7, and Min30 refer to minimum runoff for 1, 7, and 30 consecutive days, respectively; Max1, Max7, and Max30 refer to maximum runoff for 1, 7, and 30 consecutive days, respectively; RQ95:Q50 and RQ5:Q50 refer to low runoff variability rate and high runoff variability rate, respectively; RC refers to runoff coefficient; R refers to annual runoff; "/" denotes dimensionless.

Precipitation- and Evaporation-Related Indicators

To explore which climate factor is most closely related to runoff characteristics, we selected several indicators and their combinations for correlation analysis (Table 2). Among climate factors, precipitation is the most active climatic factor in the natural water cycle process, and many precipitation-related factors play essential roles in hydrological processes (Chang et al., 2015). Temperature mainly affects the hydrological process by influencing evaporation. Due to the strong seasonality of precipitation and evaporation, precipitation seasonality (Psi) and potential evaporation seasonality (Ep_{si}) were calculated to express their seasonal characteristics. In addition, precipitation and evaporation usually affect runoff through joint action, so their combination was considered. Among the eight selected indicators, three were related to precipitation (annual precipitation, Psi, and average rain depth), two to evaporation (annual potential evaporation and Ep_{si}), two to the combination of precipitation and potential evaporation (aridity index and seasonal correlation between water supply and demand (CORR)), and one to temperature.

Table 2 Climate-related characteristics selected to estimate the runoff characteristics

Predictor	Calculation
Annual precipitation (P)	
Precipitation seasonality (Psi)	Psi is calculated as follows (Walsh and Lawler, 1981): $\Psi = \frac{1}{P}\sum_{i=1}^{12}\left\|P_i - \frac{P}{12}\right\|$ where i refers to the month; and P_i is the monthly precipitation (mm).
Average rain depth (α)	Mean precipitation during rainy days (mm/d).
Annual potential evaporation (Ep)	Ep is calculated by a modified version of the Hargreaves (Droogers and Allen, 2002): $Ep = 0.76 \times 0.0013 \times RA \times (T_{av} + 17.8) \times (TD - 0.0123P)^{0.408}$ where T_{av} is the average of the mean maximum temperature and minimum temperature for each month (°C); TD represents the difference between the average maximum temperature and minimum temperature per month (°C); and RA represents the extraterrestrial radiation (MJ/($m^2 \cdot d$)), which were acquired from the Food and Agriculture Organization (FAO) of the United Nations.
Potential evaporation seasonality (Ep_{si})	Ep_{si} is calculated as follows (Walsh and Lawler, 1981): $\Psi_{Ep} = \frac{1}{Ep}\sum_{i=1}^{12}\left\|Ep_i - \frac{Ep}{12}\right\|$ where Ep and Ep_m are the annual and monthly potential evaporation (mm), respectively.
Aridity index ( )	$\phi = \frac{Ep}{P}$

Predictor	Calculation
Seasonal correlation between water supply and demand (CORR)	CORR is the correlation coefficient between monthly precipitation and annual potential evaporation (Petersen et al., 2012).
Average annual temperature (TA)	$$TA = \frac{1}{12}\sum_{i=1}^{12}(T_i + 274.15)$$ where T_i is the monthly mean air temperature of the ith month (°C).

Note: "/" denotes dimensionless.

Flow Duration Curve (FDC) Method

Flow duration curve (FDC) indicates the relationship between the magnitude and frequency of daily, weekly, monthly, or yearly runoff for a specific watershed without considering temporal continuity, providing the percentage of time that a flow is equaled or exceeded in the entire time series (Cigizoglu and Bayazit, 2015). FDC is widely used in hydropower engineering design, water resource supply, irrigation planning, verification of hydrological model results in data-sparse areas, and analysis of regional hydrological characteristics (Vogel and Fennessey, 1994). Based on long time-series daily flows, FDC is one of the most effective methods for analyzing runoff distribution characteristics and variation in a basin (Gao et al., 2015). FDC was applied in this study to comprehensively and graphically reflect the variation characteristics of watershed runoff during the entire study period.

Correlation Analysis

Regression analysis was adopted to evaluate the correlation between runoff values and potential climatic factors listed in Table 2. The choice of linear, exponential, or power functions depends on the determination coefficient (R^2). The fitting equation corresponding to the maximum R^2 is considered the optimal time series distribution.

Trend Test

The Mann-Kendall (MK) test is a nonparametric method (Mann, 1945; Kendall, 1990). Because this method does not require samples to follow a specific distribution and the results are not easily disturbed by outliers, MK test is widely used for trend detection in hydrological series (Wen et al., 2019). Gao et al. (2017) introduced the principle and application of this method in detail. In this study, MK test was used to detect trends in observed runoff series at different gauges in the WRB.

Runoff Sensitivity Coefficient Based on the Budyko Framework

Based on the Budyko framework (Budyko, 1974), Fu's function (Fu, 1981) stated that the average annual balance between evaporation and runoff could be presented as follows:

$$\frac{E}{P} = F(\phi, \omega) = 1 - \frac{R}{P}$$

where E refers to actual evaporation (mm); P represents precipitation (mm); R represents runoff (mm); F is an analytical equation representing the evaporative fraction (E/P) or runoff ratio (R/P); is aridity index; and ω is a parameter that represents all other factors affecting the average annual distribution of precipitation (such as soil type, vegetation, and topography).

Rewriting Equation 1, whereby aridity index is replaced by potential evaporation/precipitation (Ep/P) (Berghuijs et al., 2017):

$$\frac{R}{P} = 1 - F\left(\frac{Ep}{P}, \omega\right) = 1 - \left[\frac{Ep}{P} \cdot \left(1 + \frac{Ep}{P}\right)^{\omega - 1}\right]^{\frac{1}{\omega}}$$

The elasticity coefficient refers to the ratio of the growth rate of two interrelated indicators over a certain period (Zhang and He, 2016). The absolute elasticities of runoff to precipitation, potential evaporation, and other factors were obtained by deriving the partial differential expressions for each factor:

$$\varepsilon_{R,P} = \frac{\partial R/R}{\partial P/P} = \frac{1 + \omega\phi}{\omega(1 + \phi)} \cdot \left(\frac{1 + \phi}{1 + \omega\phi}\right)^{\frac{\omega - 1}{\omega}}$$

$$\varepsilon_{R,Ep} = \frac{\partial R/R}{\partial Ep/Ep} = -\frac{\phi(1 + \omega\phi)}{\omega(1 + \phi)} \cdot \left(\frac{1 + \phi}{1 + \omega\phi}\right)^{\frac{\omega - 1}{\omega}}$$

$$\varepsilon_{R,\omega} = \frac{\partial R/R}{\partial \omega/\omega} = -\frac{\ln(1 + \omega\phi) - \ln(1 + \phi)}{\omega} \cdot \left(\frac{1 + \phi}{1 + \omega\phi}\right)^{\frac{\omega - 1}{\omega}}$$

where ω represents other factors; _R,P, _R,Ep, and _R,ω are the absolute sensitivities of runoff to precipitation, potential evaporation, and other factors, respectively.

To assess the relative importance of each influencing factor, the relative sensitivity of runoff to these three factors is calculated as follows:

$$\theta_x = \frac{|\varepsilon_{R,x}|}{|\varepsilon_{R,P}| + |\varepsilon_{R,Ep}| + |\varepsilon_{R,\omega}|}$$

where _x is the relative sensitivity of runoff to precipitation, potential evaporation, and other factors. _x can vary from close to zero (i.e., almost unaffected by that specific factor) to close to one (i.e., almost completely affected by that specific factor).

Exceedance Frequency for Daily Runoff

Figure 2 [Figure 2: see original paper] shows the flow duration curves (FDCs) of daily runoff for 62 hydrological stations in the WRB during 2006–2018. The FDCs of the selected hydrological stations fell within three narrow bands with mean annual runoff values of 3.43–13.33 mm, 20.92–109.30 mm, and 229.03–507.25 mm, represented by red, green, and blue lines, respectively. The results depicted significant variability in runoff across different areas of the WRB. Among them, the green curves accounted for the highest proportion, showing that runoff variability at most stations was in the middle range. Between Q20 and Q80, the slopes of FDCs were relatively gradual. The value of Q50 varied from 0.00 to 0.79 mm. For high-frequency runoff events (Q90, Q95, and Q99) and rare-frequency runoff events (Q1, Q5, and Q10), the FDCs of each station decreased as the percentage of exceedance increased. It can be seen that in the upstream area of each tributary, including the main stem of the Weihe River, Hulu River, and Malian River in the northern Jinghe River Basin, runoff was low. The high-runoff areas were mainly located on the south bank of the WRB, including the Bahe River, Laohe River, Fenghe River, and Shitou River.

Fig. 2 (a) Flow duration curves (FDCs) of daily runoff in the WRB with three distinct ranges of mean annual runoff (MAR); (b) Spatial distribution of hydrological stations with different ranges of MAR. Red, green, and blue sites represent 6, 45, and 11 of the 62 stations, respectively, where MAR varied from 3.43 to 13.33 mm, from 20.92 to 109.30 mm, and from 229.03 to 507.25 mm, respectively.

Trend of Daily Runoff at Different Exceedance Frequencies

We divided the WRB into 62 subintervals based on the selected hydrological stations. The area controlled by a single hydrological station was designated as one interval, and the area between adjacent hydrological stations upstream and downstream was designated as another interval. During the study period, the variation trends of Q95, Q50, and Q5 in different intervals are shown in Figure 3 [Figure 3: see original paper]. For high-frequency runoff events (Q95), 17 subintervals showed significant upward trends, located at the source of the

WRB, the middle and lower reaches of the Jinghe River Basin, and the middle reaches of the Beiluo River Basin; 2 subintervals showed a downward trend, while other subintervals showed no significant trend. For intermediate-frequency runoff events (Q50), nine subintervals showed a significant upward trend, most located in the Jinghe River Basin; two subintervals showed a downward trend, while others showed no trends.

For rare-frequency runoff events (Q5), three subintervals showed significant upward trends, and two showed a downward trend. In general, runoff on the south bank of the Weihe River was more stable than that on the north bank, and high-frequency runoff events showed more variability than intermediate- and rare-frequency runoff events.

Fig. 3 Spatial distributions of runoff trends under high-frequency runoff events (Q95; a), intermediate-frequency runoff events (Q50; b), and rare-frequency runoff events (Q5; c)

Seasonal Distribution of Annual Precipitation and Runoff

Taking the observed runoff at Linjiacun, Xianyang, and Huaxian stations located in the upper, middle, and lower reaches of the main stream of the Weihe River, respectively, Zhangjiashan station in the Jinghe River Basin, and Zhuangtou station in the Beiluo River Basin as examples, and taking the sum of observed runoff at Huaxian and Zhuangtou stations as the total runoff of the whole WRB, the monthly distribution of precipitation and runoff was analyzed (Table 3). For the selected hydrological stations, monthly precipitation and runoff were distributed unevenly and mainly concentrated in the flood season (June–September) (Table 3). Precipitation in the flood season accounted for more than 60.00% of the average annual precipitation. Runoff from June to September accounted for approximately 50.00% of the total flow volume. The results revealed the nonuniformity of the annual distribution in the WRB.

Table 3 Distribution of monthly precipitation and runoff in the Weihe River basin (WRB)

Station	Hydrological element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Proportion in flood season (%)
Linjiacun	Precipitation	6.75	12.36	28.45	42.01	67.83	79.81	125.67	117.11	129.45	51.22	19.95	3.34	67.8
	Runoff													50.2
Xianyang	Precipitation	6.38	9.91	23.41	36.78	60.26	54.16	103.21	100.87	105.06	47.98	20.56	3.67	62.3
	Runoff													51.4
Huaxian	Precipitation	4.36	8.85	17.37	36.79	59.82	50.17	90.58	79.21	98.98	43.32	26.11	4.48	58.7
	Runoff													52.1
Zhangjiashan	Precipitation	6.48	9.48	23.07	34.05	47.83	56.15	88.88	75.76	95.82	38.58	18.12	3.34	61.2
	Runoff													49.8
Zhuangtou	Precipitation	4.20	8.80	13.24	29.63	50.93	54.05	87.05	77.34	82.67	42.42	20.36	2.19	58.9

Station	Hydrological element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Proportion in flood season (%)
	Runoff													48.6
Total	Precipitation	5.64	9.88	21.11	35.85	57.34	58.87	99.08	90.06	102.40	44.70	21.02	3.40	60.8
	Runoff													50.4

Trend Analysis of Annual Runoff in Different Subintervals

The annual runoff trend analysis in the WRB is shown in Figure 4 [Figure 4: see original paper]. Regions with significantly increasing inflow were distributed in the middle and upper reaches of the Beiluo River Basin, the upper reaches of the Jing River, and the south bank of the Weihe River. Regions with significantly decreasing inflow were distributed in the lower reaches of the Beiluo River and the upper reaches of the Weihe River. In most regions, runoff showed no significant trend during the study period.

Fig. 4 Spatial distributions of annual runoff trends in different subintervals

Climate-Related Factors on Runoff Variability

Taking the total runoff of the WRB, the effects of climate-related factors on runoff variability were analyzed. Table 4 lists the R^2 values between runoff characteristics and precipitation- and evaporation-related control factors. According to the average R^2 values sorted from high to low, the three principal factors affecting runoff were precipitation, aridity index, and runoff depth in rainy days, while the three least important influencing factors were precipitation seasonality, potential evaporation seasonality, and potential evaporation. In general, factors related to precipitation had the greatest impact on runoff, while factors related to evaporation were less informative. Each influencing factor performed differently toward every runoff characteristic index. The most important influencing factors for rare-frequency daily runoff events (Q1, Q5, Q10, and Q20), consecutive maximum daily runoff events (Max1, Max7, and Max30), and high streamflow variability (RQ5:Q50) were precipitation, aridity index, and runoff depth in rainy days. Influencing factors identified as important for runoff coefficient were precipitation and annual average temperature. However, no significant influencing factors were detected for intermediate- and high-frequency runoff events (Q50, Q80, Q90, Q95, and Q99), minimum consecutive daily runoff (Min1, Min7, and Min30), and low streamflow variability rates (RQ95:Q50).

Table 4 R^2 values between runoff characteristics and climate-related factors

Index	P	Psi	α	Ep	Ep_{si}		CORR	TA
Q1	0.72+	0.06+	0.64+	0.07+	0.08+	0.75+	0.15+	0.05+

Index	P	Psi	α	Ep	Ep_{si}		CORR	TA
Q5	0.72+	0.22+	0.70+	0.08+	0.12+	0.22+	0.19+	0.15+
Q10	0.78+	0.16+	0.63+	0.71+	0.75+	0.45+	0.50+	0.19+
Q20	0.68+	0.14+	0.32+	0.40+	0.22+	0.05+	0.38+	0.46+
Q50	0.06+	0.06+	0.58+	0.69+	0.45+	0.19+	0.42+	0.34+
Q80	0.22+	0.22+	0.81+	0.09+	0.05+	0.46+	0.22+	0.34+
Q90	0.18+	0.18+	0.35+	0.17+	0.15+	0.34+	0.11+	0.20+
Q95	0.66+	0.15+	0.48+	0.13+	0.19+	0.20+	0.05+	0.06+
Q99	0.75+	0.04+	0.18+	0.04+	0.50+	0.06+	0.28+	0.05+
Max1	0.71+	0.08+	0.62+	0.08+	0.38+	0.26+	0.35+	0.09+
Max7	0.40+	0.12+	0.07+	0.15+	0.42+	0.35+	0.09+	0.12+
Max30	0.69+	0.75+	0.08+	0.19+	0.22+	0.09+	0.12+	0.15+
Min1	0.09+	0.17+	0.71+	0.46+	0.11+	0.05+	0.15+	0.15+
Min7	0.17+	0.13+	0.40+	0.34+	0.05+	0.28+	0.19+	0.50+
Min30	0.13+	0.04+	0.69+	0.20+	0.15+	0.26+	0.46+	0.38+
RQ95:Q50	0.04+	0.08+	0.09+	0.06+	0.19+	0.35+	0.34+	0.42+
RQ5:Q50	0.08+	0.12+	0.12+	0.05+	0.50+	0.09+	0.20+	0.22+
RC	0.15+	0.19+	0.15+	0.15+	0.38+	0.46+	0.34+	0.34+
R	0.19+	0.50+	0.19+	0.46+	0.42+	0.34+	0.20+	0.06+

Note: P, annual precipitation; Psi, precipitation seasonality; α, average rain depth; Ep, annual potential evaporation; Ep_{si}, potential evaporation seasonality; , aridity index; CORR, seasonal correlation between water supply and demand; TA, average annual temperature. Different fitting functions were considered here. “Lin”, “exp”, “log”, and “pow” represent linear, exponential, logarithm, and power functions, respectively. Only the values of R^2 with the strongest correlation are displayed. “/” denotes $R^2<0.05$; “+” and “–” indicate positive and negative relationships between runoff characteristics and climate-related factors, respectively.

Spatial Hydroclimatic Characteristics

The spatial distribution characteristics of the average runoff ratio, aridity index, and other factors during 2006–2018 are shown in Figure 5 [Figure 5: see original paper]. Different values were graded by natural discontinuities in ArcGIS 10.2. The runoff ratio in most areas of the WRB was 0.05–1.00, accounting for approximately half of the total hydrological stations. The aridity index was concentrated in 1.30–1.50, matching the climate conditions in the arid and semi-arid areas of the WRB. The spatial distribution characteristics of aridity index and runoff ratio were opposite. The runoff ratio was usually small in places with high aridity index, such as the northern WRB. Other factors showed characteristics of being high in the north and low in the south of the Weihe River.

Fig. 5 Distribution of spatial hydrological and climatic characteristics in the study area based on the Budyko framework. (a–c) Spatial pattern of the runoff ratio, aridity index, and other factors, respectively; (d–f) Values of the runoff ratio, aridity index, and other factors at different hydrological stations, respectively.

Spatial Pattern of Absolute Runoff Elasticities

Based on the obtained aridity index and other factors (Fig. 5), we depicted the spatial distribution of runoff sensitivities to precipitation, potential evaporation, and other factors in Figure 6 [Figure 6: see original paper]. Stations with runoff sensitivity to precipitation (_R,P) greater than 1.00 accounted for about 93.55% of the observed stations, suggesting that the change in runoff caused by precipitation was always equal to or larger than the change in precipitation itself. The average value of _R,P was 3.85, indicating that a 10.00% increase in precipitation would lead to a 38.50% increase in runoff. Generally, relatively humid regions (aridity index < 1.20) have lower _R,P values (e.g., the southern region of the basin). The WRB is a typical arid and semi-arid transitional zone in China, and runoff in this area has a far higher sensitivity to precipitation changes. In addition, _R,P always exceeded the absolute sensitivity of runoff to potential evaporation (_R,Ep), suggesting that the percentage change in runoff caused by precipitation was greater than that caused by potential evaporation. Compared with precipitation, potential evaporation has an opposite effect on runoff. The average _R,Ep was –2.85, indicating that a 10.00% increase in potential evaporation would lead to a 28.50% decrease in runoff. Runoff in relatively humid areas showed higher sensitivity to potential evaporation than in arid regions. The elasticity of runoff to other factors (_R,ω) was similar to that to _R,Ep, with a mean value of –2.16. Li et al. (2021) proved that other factors were significantly correlated with climatic and artificial factors. _R,ω was generally lower in dryland regions (e.g., the north of the Beiluo River and Jinghe River Basin) and higher in relatively humid areas (e.g., the south of the WRB). The sensitivity analysis showed that precipitation could promote runoff, while potential evaporation and other factors inhibited runoff.

Fig. 6 Absolute sensitivities of runoff to precipitation (_R,P; a), annual potential evaporation (_R,Ep; b), and other factors (_R,ω; c) in the WRB. (d–f) Values of _R,P, _R,Ep, and _R,ω at different hydrological stations, respectively.

Relative Sensitivity of Runoff to Precipitation, Potential Evaporation, and Other Factors

The relative sensitivities of runoff to precipitation (_P), potential evaporation (_{Ep}), and other factors (_ω) are shown in Figure 7 [Figure 7: see original paper]. For 87.10% of the selected hydrological stations, precipitation was always the most critical contributor to runoff changes (_P > _{Ep} and _ω), while other factors were the dominant factor for the remaining 12.90% of stations (_ω > _P and _{Ep}). There was no area where potential evaporation accounted for the largest proportion.

Fig. 7 Relative sensitivities of runoff to precipitation (_P), potential evaporation (_{Ep}), and other factors ($\_\omega$) at different hydrological stations

Impact of Climate-Related Factors on Runoff Variability

Runoff is highly variable across different intervals of the study area, which may be related to local differences in soil texture, landform, runoff mechanism, watershed size, and river network density (Rossi et al., 2016). For a specific watershed, landform and soil properties are relatively stable over short periods, and vegetation cover does not change significantly. Therefore, meteorological elements have become essential factors affecting hydrological processes (Liu et al., 2016). Among them, precipitation plays a vital role in the hydrological cycle. Correlation analysis results showed that precipitation-related factors greatly impacted runoff change (Table 4). To more clearly show the relationship between daily runoff and daily precipitation, we constructed FDCs for daily precipitation at 62 meteorological stations (Fig. 8 [Figure 8: see original paper]). Because there are many days with no rainfall in a year, the diagram was drawn only for rainy days. There was substantial overlap among precipitation events when mean annual runoff varied across 3.00 orders of magnitude (Fig. 2), suggesting that precipitation among stations was relatively stable.

Fig. 8 FDCs for daily precipitation of 62 meteorological stations in the WRB

The shape of the curves showed that precipitation has a strong consistency with rare-frequency runoff events, indicating that the influence of extreme precipitation events on rare-frequency runoff was more potent than that on intermediate- and high-frequency runoff events. High-frequency runoff events, such as Q95 and Q99, are usually regarded as base flow (Beck et al., 2015), which is relatively stable and not easily affected.

Daily precipitation can also be described by the proportion of wet to dry days representing rain frequency (f) and average precipitation depth on rainy days (α) (Rossi et al., 2016). Based on the resulting values, we transformed mean annual precipitation, α, and f into grid maps by the Kriging method in ArcGIS 10.2 (Hevesi et al., 1992) (Fig. 9 [Figure 9: see original paper]). The results showed that areas with high mean annual precipitation were sometimes related to large α (e.g., high α in the middle Beiluo River), high f (e.g., high f in the Hulu River), or both (e.g., south bank of the Weihe River), illustrating that mean annual precipitation is affected by extreme weather conditions. Precipitation in the south and east of the WRB was more abundant than that in the north and west. Combined with the spatial distribution of runoff characteristics, this may explain why runoff was greater in the south than in the north, and more in the east than in the west (Fig. 5).

However, Rossi et al. (2016) found that rainfall variability played a secondary role in runoff variability. The most important driving force for daily runoff variation may be the nonlinear transformation from precipitation to runoff, rather than daily rainfall statistics. Additionally, precipitation also influences runoff generation by affecting soil water content, vegetative cover, evapotranspiration, etc. (Rodriguez-Iturbe, 2000).

Figure 9f shows the spatial distribution of other climate-related factors. In higher altitude areas, CORR was high, while potential evaporation and annual temperature were low. Potential evaporation was large in the northern WRB, but annual temperature was not the highest. Based on correlation analysis results (Table 4), CORR, potential evaporation, and annual temperature had poor correlations with runoff. Potential evaporation and annual temperature had adverse effects on runoff, while CORR had positive effects.

The temporal variations in precipitation and potential evaporation are usually considered the leading causes of runoff and evaporation changes over time (Greve et al., 2014). Evaporation is a term balancing input precipitation, which may strongly affect the conversion of precipitation into runoff at a daily scale to adjust runoff variability (Samain and Pauwels, 2013). Aridity index, calculated from precipitation and potential evaporation, determines the spatial distribution of precipitation to runoff and evaporation (Budyko, 1974; Greve et al., 2014). In general, various climate factors are interrelated and interact with each other, leading to runoff variation. With the advancement of global warming, atmospheric water content will increase, which will further intensify the Earth's water cycle (Huntington et al., 2016). Consequently, the spatiotemporal distribution of runoff would be affected (Zhang and Dong, 2013).

Fig. 9 Spatial distribution of mean annual precipitation (MAP; a), mean precipitation in rainy days (α; b), the ratio of wet to dry days (f; c), the seasonal correlation between water supply and demand (CORR; d), mean annual potential evaporation (Ep; e), and average annual temperature (TA; f) in the WRB

Explanations for Temporal and Spatial Variabilities of Runoff

In the WRB, the difference in runoff on a temporal scale was not significant, but it showed distinct regional characteristics in space. Runoff from southern and western rivers was more abundant and stable than that from northern and eastern rivers (Figs. 2 and 3). The reasons for this may be explained as follows.

First, there are differences in geological and geomorphic conditions. The north bank of the Weihe River is densely distributed with river networks, most of which flow through the hilly and gully areas of the Loess Plateau and Guanzhong Plain. The role of loose loess soil and sparse vegetation in the distribution and regulation of precipitation on the Loess Plateau makes annual runoff in this region smaller, but interannual variation larger (Bai et al., 2020). The alluvial plain of the Weihe River is very flat with a high degree of water conservancy development, belonging to a low water-yield area (Wu et al., 2022). The tributaries on the south bank originate from the northern foot of the Qinling Mountains, with short sources, rapid flow, steep rise and fall of the river, and good conditions for runoff production and confluence, such as the Qingjiang River, Heihe River, Laoyu River, Dayu River, and Luofu River. Coupled with small rainfall loss and abundant recharge, the south bank of the Weihe River was considered a high water-yield area in the WRB (Gao and Feng, 2019; Wu et al., 2022). The southern WRB covers an area of 1.48\$×10ˆ{6}\$ km^2, with total self-produced water resources of 3.84\$×10ˆ{9}\$ m^3, accounting for approximately half of the total water resources in the Guanzhong area, which provides water for life, production, and ecology (Gao and Feng, 2019).

Second, there are different intensities of human activities. The intensity of human activities on the south bank of the Weihe River is weak, and the degree of development and utilization of water resources is relatively lower. The nonagricultural population accounts for only approximately 10% of the total population in the region, and per capita regional Gross Domestic Product (GDP), local fiscal revenue, and urban and rural residents' income are lower than the average level of Shaanxi Province (Gao and Feng, 2019). For the north bank, the population of the Guanzhong Plain is about 2.0\$×10$^{\{7\}, thelocalpopulationdensityisashighas 800/km}${2}\$, and the population urbanization rate is about 60.00% (Jia and Yang, 2017). Sustained population growth, urban scale expansion, and industrial structure upgrading all create large water demands (Gao et al., 2013; Zhan et al., 2014; Wang et al., 2019). Additionally, the Guanzhong Plain has a long history of irrigation, which is the principal form of water consumption. Irrigation water on the Guanzhong Plain accounted for 48.65% of total water consumption in 2019 (Shaanxi Province Department of Water Resources, 2019).

Since the 1970s, a large-scale GFG project has been implemented in the WRB, which has significantly changed land use/land cover conditions and improved the regional ecological environment (Li et al., 2017; Jiang et al., 2021). By increasing soil surface roughness, slowing runoff speed, increasing infiltration, and intensifying evaporation, runoff was restrained (Yang et al., 2021). Compared with the south bank, the GFG project has been implemented more widely in the loess area on the north bank and has achieved more significant results (Zhang et al., 2018).

Some researchers have proposed that excessive vegetation restoration may be a poor choice in arid and semi-arid areas because local precipitation conditions are not considered, which exacerbates water resource shortages to a certain extent (Jiang et al., 2019). In this study, annual runoff entered a relatively stable low-flow period, with no significant trend from 2006 to 2018. For seasonal distribution, runoff usually accounts for a large proportion in the flood season with abundant rainfall, which is consistent with most studies (Gao et al., 2013; Xie et al., 2022). The runoff coefficient of the basin was relatively low during the study period, varying from 0.05 to 0.11, which is smaller than in existing studies (Feng et al., 2016), suggesting that the ability of precipitation to transform into runoff is weakened. Therefore, large-scale vegetation restoration programs need effective and sustainable management.

Conclusions

Based on measured daily runoff and meteorological data from 62 gauges in the WRB from 2006 to 2018, we analyzed runoff characteristics and correlations between runoff characteristic indicators and climate-related factors. The modified Budyko framework was applied to evaluate the sensitivities of runoff to precipitation, potential evaporation, and other factors. The main findings are as follows:

1. Under different exceedance frequencies, runoff at different hydrological stations in the WRB varied greatly. The FDCs of the selected 62 hydrological stations fell within three narrow bands, with mean annual runoff spanning approximately 1.50 orders of magnitude. Runoff on the south bank of the Weihe River was more abundant and stable than that on the north bank, which is the primary water source of the WRB.
2. Precipitation-related factors had more influence on runoff characteristics than evaporation-related factors. In this study, rare-frequency runoff events (Q1, Q5, Q10, and Q20), consecutive maximum daily runoff (Max1, Max7, and Max30), and the ratio of high-runoff variability (RQ5:Q50) were strongly related to precipitation, aridity index, and average precipitation depth on rainy days, while high-frequency runoff events (Q50, Q80, Q90, Q95, and Q99), consecutive minimum daily runoff (Min1, Min7, and Min30), and the ratio of low-runoff variability (RQ95:Q50) had little correlation with the influencing factors.
3. Compared with potential evaporation and other factors, runoff was more sensitive to precipitation. In this study, runoff at 87.10% of the hydrological stations was most sensitive to precipitation, while the remaining 12.90% was dominated by other factors. Aridity index is an important factor affecting runoff characteristics. In places with lower aridity index, such as the south bank of the WRB, runoff was more sensitive to potential evaporation and other factors than to precipitation. Potential evaporation and other factors had adverse effects, while precipitation had positive effects on runoff. In general, runoff change is comprehensively affected by various factors.

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