

Variation Characteristics of Temperature, Precipitation, and Runoff and Their Interrelationships in the Baiyangdian Basin Postprint

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Abstract

Using the Mann-Kendall trend test, abrupt change test, and wavelet analysis method, we analyzed the variation trends, abrupt change points, and periodic variations of temperature and precipitation at 7 meteorological stations and runoff at 3 typical hydrological stations in the Baiyangdian Basin from 1957 to 2012, and investigated the response relationship between runoff and precipitation as well as temperature, aiming to provide basic data support for ecological environment protection and rational water resources utilization in this region. The results show that the annual mean temperature in the study area exhibited an increasing trend, which became more pronounced after 1988, wherein the temperature increases in winter and spring contributed significantly to the temperature rise; precipitation changes were relatively complex, showing an overall fluctuating decreasing trend, wherein summer precipitation exhibited the largest reduction magnitude, reaching $1.72 \text{ mm} \cdot \text{a}^{-1}$. Directly impacted by temperature rise and precipitation, runoff at typical stations showed a significant decreasing trend, and exhibited a negative correlation with temperature and a significant positive correlation with precipitation variation at the interannual scale; at the intra-annual scale, it exhibited significant positive correlations with both temperature and precipitation variations. Summer runoff exhibited the largest reduction magnitude, decreasing at rates of $0.85 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, $0.72 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, and $0.66 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$ at Fuping, Daomaguan, and Zijingguan stations, respectively. The periodic variations of all three indicators were relatively pronounced, wherein the fluctuation variations of runoff and precipitation were basically consistent, indicating that the response of runoff to precipitation was particularly prominent. Runoff variation was influenced not only by temperature and precipitation, but also by various other factors such as water conservancy project construction and diverse agricultural measures.

Full Text

Preamble

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Variation Trend and Response Relationship of Temperature, Precipitation and Runoff in Baiyangdian Lake Basin

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Abstract: As the largest freshwater lake in the North China Plain, Baiyangdian Lake serves as a critical hydro-confluence for flood prevention, sedimentation mitigation, irrigation, water supply, and maintenance of ecological balance in the region. Since the 1960s, surface runoff into Baiyangdian Basin has continuously declined, water quantity has greatly reduced, and lake-drying events have become more frequent due to climate change and human activities. This decreasing water quantity has diminished the lake's ecological function, further affecting regional socio-economic development and ecological security. Using observed daily temperature and precipitation data from seven meteorological stations and monthly runoff data from three typical hydrological stations for the period 1957-2012, this study analyzes change characteristics in temperature, precipitation, and runoff in the Baiyangdian Lake Basin. The cumulative anomaly method, Mann-Kendall test, and Morlet wavelet analysis were employed to determine trends and abrupt changes in mean annual temperature, precipitation, and runoff. The results show that the climate in the study area has a significant warming trend with an abrupt temperature increase since 1988, particularly driven by rising temperatures in winter and summer. Annual precipitation showed a decreasing trend with obvious fluctuation; the decrease in summer precipitation ($1.72 \text{ mm} \cdot \text{a}^{-1}$) was higher than in other seasons. Increasing temperature combined with decreasing precipitation has aggravated dry and hot climatic conditions and lake-drying in the region. Runoff showed an obvious decreasing trend due to the combined effects of temperature and precipitation. There was a negative correlation between runoff and temperature and a positive correlation between runoff and precipitation at the annual scale. At the seasonal scale, runoff was positively correlated with both temperature and precipitation.

Summer runoff at Fuping, Daomaguan, and Zijingguan hydrological stations decreased by $0.85 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, $0.72 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, and $0.66 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, respectively. The intervals of change in mean annual temperature, precipitation, and runoff were obvious, with fluctuations in runoff and precipitation being consistent, suggesting that the response of runoff to precipitation was more prominent. Runoff change was influenced not only by temperature and precipitation but also by other climatic factors, water conservancy projects, agricultural practices, and local geological conditions. Future studies should further analyze the effect of each factor on runoff to comprehensively understand the driving mechanisms in the basin.

Keywords: Precipitation; Air temperature; Runoff response; Mann-Kendall test; Cumulative anomaly method; Morlet wavelet analysis; Baiyangdian Lake Basin

Water resources are the source of life and an indispensable material resource for human survival and development, playing a vital role in sustainable socio-economic development. The hydrological cycle serves as a crucial regulatory and controlling process, acting as an important link connecting the geosphere, biosphere, and atmosphere. Runoff is a fundamental component of the hydrological cycle and a basic element of water balance. As the primary indicator characterizing water resource abundance, runoff represents water resources that can be developed and utilized over the long term. Therefore, scientific understanding of the hydrological cycle process, with runoff as its main manifestation, is a prerequisite for rational water resource utilization.

As the largest freshwater lake wetland in the North China Plain, Baiyangdian Lake is an important water conservancy hub that plays significant roles in flood mitigation, water storage for irrigation, microclimate regulation, and maintenance of ecological balance. The Baiyangdian Basin belongs to the Daqing River system of the Haihe River Basin. Since the 1960s, under the strong interference of climate conditions and human activities, surface runoff into Baiyangdian Basin has continuously decreased, water resources in the lake area have substantially reduced, and lake-drying phenomena have occurred frequently. The increasing water demand has led to large volumes of domestic sewage and industrial wastewater inflow, seriously threatening the water environment. The reduction in water quantity and deterioration of water quality in the Baiyangdian Basin have diminished its ecological function, thereby affecting the region's socio-economic development and ecological security.

In recent years, research on climatic factors and runoff changes in the Baiyangdian Basin has achieved certain results. Numerous researchers have investigated climate factor variations, runoff changes and driving mechanisms, and water cycle processes in the basin [3-7]. Liu et al. [3] found that annual runoff in the Baiyangdian Basin showed a decreasing trend with strong persistence. Zhou et al. [4] analyzed changes in mountainous runoff and their driving factors, con-

cluding that rising temperatures and decreasing precipitation were the main causes of runoff reduction, and that expansion of industrial, agricultural, and mining land areas might also contribute to runoff decline. Wang et al. [5] analyzed climate factor changes in the basin, noting a significant warming trend and obvious precipitation decrease, and predicted that the future climate of Baiyangdian would continue to develop toward warmer and drier conditions. Hu et al. [6] analyzed and simulated the water cycle mechanism, finding that annual runoff in the upstream water source area showed a decreasing trend dominated by human activities. However, these studies analyzed climate factors and runoff separately rather than conducting unified analyses, lacking examination of the response relationship between them. Therefore, based on previous research, this study selected hydrological observation data from three stations (Fuping, Daomaguan, and Zijingguan) in the upstream areas of rivers flowing into Baiyangdian, along with temperature and precipitation data from seven meteorological stations. Using wavelet analysis, Mann-Kendall trend and abrupt change tests, and cumulative anomaly methods, we conducted a comprehensive analysis of trend changes, abrupt changes, periodicity, and runoff response to climate change in the basin, aiming to provide a foundation for ecological protection and rational water resource utilization.

1. Study Area Overview

The Baiyangdian Basin (Fig. 1) belongs to the Daqing River system of the Haihe River Basin, located between 113°39'–116°11' E and 38°4'–40°4' N, with a drainage area of 31,200 km² across Hebei Province, Shanxi Province, and Beijing. The terrain slopes from high in the northwest to low in the southeast, with elevation ranging from 0 to 2,784 m, forming mountainous, plain, and depression areas from west to east. The basin has a temperate monsoon continental semi-humid and semi-arid climate with distinct seasons: dry and rainless springs, hot and rainy summers, crisp autumns, and cold dry winters. The annual mean temperature ranges from 7.3 to 12.7°C, and the multi-year average precipitation is 564 mm. Precipitation distribution is extremely uneven within the year, with 70%–80% concentrated in June–August, mostly in the form of heavy rain. Spatially, precipitation is higher on the windward slopes of the western mountainous area and lower on the leeward slopes and plain areas.

This study used daily meteorological data from seven national basic meteorological stations in and around the Baiyangdian Basin from 1957 to 2012, including daily precipitation, mean temperature, daily minimum temperature, and daily maximum temperature. Meteorological data were provided by the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>). Runoff data comprised monthly and annual mean runoff series from three typical hydrological stations in the basin: Zijingguan (1957–2012), Daomaguan (1957–2012), and Fuping (1960–2012). Missing data were interpolated using multiple regression with neighboring data. Runoff data were primarily obtained from the Hydrological Yearbook “Hydrological Data of Haihe River Basin, Volume 3, Book

4, Daqing River System.” The distribution of meteorological and hydrological stations is shown in Fig. 1.

3.1. Mann-Kendall (MK) Trend Test

The MK test is widely used for trend detection in hydro-meteorological variables, including temperature, precipitation, and runoff [8-9]. This method does not require samples to follow a specific distribution and can directly test variable trends [10-13]. The test statistic Z is calculated as:

$$Z = \frac{\sum_{j=1}^{n-1} \sum_{k=j+1}^n (x_j - x_k)}{\sqrt{\frac{n-1}{3} \left(\sum_{j=1}^{n-1} \text{VAR}(x_j) + \sum_{k=2}^n \text{VAR}(x_k) \right)}}$$

where n is the sample size, and x_j and x_k are values in the time series.

A positive Z value indicates an upward trend, while a negative value indicates a downward trend. When $|Z| \geq Z_{\alpha/2}$, the variable shows a significant upward or downward trend at significance level α , where the critical value $Z_{\alpha/2}$ can be obtained from standard normal distribution tables.

When a sample trend is significant, the slope b is typically used to represent the long-term monotonic trend of the series, calculated as:

$$b = \frac{\sum_{i=1}^n x_i - n \bar{x}}{\sum_{i=1}^n i - \frac{n(n+1)}{2}}$$

where x_i and x_j are sample values in years i and j , respectively. When $b > 0$, the series has an upward trend; when $b = 0$, no trend exists; when $b < 0$, the series has a downward trend.

3.2. Mann-Kendall (MK) Abrupt Change Test

For a time series x with n samples, construct a rank sequence [12,14]:

$$R_i = \text{rank}(x_i)$$

where S_k is the cumulative count of the number of times that the value at time i is greater than the value at time j .

Under the assumption of random independence in the time series, define the statistic for the forward sample sequence:

$$U_F = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}}$$

where $E(S_k) = \frac{k(k+1)}{2}$, and $E(S_k)$ and $\text{Var}(S_k)$ are the mean and variance of the cumulative count S_k , respectively.

Repeat the above process using the inverse order of the time series x , while making $U_{Fk} = -U_{Bk}$ ($k = n, n-1, \dots, 1$) and $U_B = 0$.

3.3. Cumulative Anomaly Method

The cumulative anomaly method [12] is a commonly used approach for visually judging change trends through curves. For a series x , the cumulative anomaly at a given time i is calculated as:

1, 2, Δ

By calculating the cumulative anomalies for all n time points, a cumulative anomaly curve can be plotted for trend analysis.

3.4. Wavelet Analysis

Wavelet analysis, developed based on Fourier analysis, can reveal not only the scales of climate series changes but also their temporal positions. It has been widely applied in analyzing variation characteristics of hydro-meteorological elements [15-17]. The discrete form of wavelet transform is:

$(,)$ $f a b (,)$ are wavelet coefficients; $ψ$ is the mother wavelet, which is a dual-window function with both a frequency window and a time window; a is the frequency parameter; b is the time parameter; Δt is the sampling interval; and n is the sample size.

Discrete wavelet transform expands a one-dimensional signal in both time and frequency directions, enabling the creation of two-dimensional images with time parameters on the horizontal axis and frequency parameters on the vertical axis. This allows analysis of how cycles of different lengths evolve over time and identification of significant periods in the series.

Wavelet variance can more accurately diagnose which period has the strongest oscillation. The wavelet variance is:

$var()$

4. Results and Analysis

4.1. Interannual Variation and Abrupt Change Analysis

The interannual variations of mean annual temperature from seven meteorological stations, annual precipitation, and annual runoff from three hydrological stations (Fig. 2 [Figure 2: see original paper]), along with abrupt change detection (Fig. 3 [Figure 3: see original paper]), reveal that the multi-year average temperature in the Baiyangdian Basin from 1957-2012 was 11.36°C. The highest annual mean temperature occurred in 2007 (12.84°C), and the lowest in 1969 (9.83°C). The MK trend test yielded a statistic $Z = 6.01$ for mean annual temperature, exceeding the $\alpha = 0.05$ significance level, indicating a very significant warming trend (Fig. 2a). The MK abrupt change test identified the abrupt change year around 1991 (Fig. 3a), which passed the $\alpha = 0.05$ significance requirement. The temperature anomaly also shows continuously increasing values, indicating rising mean annual temperature, with anomalies becoming predominantly positive after 1991 and increasing at a faster rate than before (Fig. 4a [Figure 4: see original paper]).

Over the past 57 years, the maximum annual precipitation was 811.43 mm in 1959, and the minimum was 299.66 mm in 1965, giving an extreme value

ratio of 1.71. Annual precipitation showed an overall decreasing trend with an average reduction rate of approximately $1.87 \text{ mm} \cdot \text{a}^{-1}$, though the trend was not significant due to internal fluctuations (Fig. 2b). The MK test statistic $Z = -1.61$ did not meet the $\alpha = 0.05$ significance level. The MK abrupt change test found no obvious abrupt change points in annual precipitation during the 57-year period (Fig. 3b).

Three typical hydrological stations—Fuping, Daomaguan, and Zijingguan—were selected to analyze annual runoff changes. The maximum runoff volume was $17.7 \times 10^3 \text{ m}^3$ in 1963, and the minimum was $2.38 \times 10^3 \text{ m}^3$ in 2007, with an extreme value ratio of 6.44 (Fig. 2c, d). The MK trend test yielded $Z = -4.76$, passing the $\alpha = 0.001$ significance level, indicating a strong decreasing trend with an average annual reduction of $0.11 \times 10^3 \text{ m}^3 \cdot \text{a}^{-1}$. The MK abrupt change test suggested possible abrupt change years around 1984, 1985, 1986, 1987, and 1994, but only the years before 1984 met the $\alpha = 0.05$ significance level (Fig. 3c). The runoff anomaly also shows inconsistent changes before and after 1984 (Fig. 4c).

To further analyze the relationships between runoff and temperature/precipitation, cumulative anomaly analyses were performed for temperature, precipitation, and runoff from the three stations for 1957–2012 (Fig. 4). The cumulative temperature anomaly was predominantly negative, showing a decreasing then increasing trend with a turning point in 1991 (Fig. 4a), indicating a shift from low to high temperatures. The precipitation cumulative anomaly was mainly positive, with a significant fluctuation in 1996. Before 1996, it showed a wavy upward trend, after which it declined rapidly to the present (Fig. 4b). The runoff cumulative anomalies at Daomaguan and Zijingguan were positive, showing consistent trends of increase–stable fluctuation–decrease, while Fuping station showed significant fluctuations. However, all three stations showed decreasing trends after 1984, indicating runoff values were generally below average (Fig. 4c). Both annual precipitation and runoff experienced growth–stable–decline trends, suggesting a significant positive response of runoff to precipitation. The opposite trends between mean annual temperature and runoff indicate a certain negative response.

Pearson correlation analysis further revealed significant positive correlations between annual runoff at each station and annual precipitation, as precipitation directly affects runoff generation. Significant negative correlations existed between runoff and mean annual temperature, as rising temperatures increase evaporation and reduce runoff. However, during 1996–2012, runoff and precipitation were not significantly correlated because precipitation showed a fluctuating upward trend while runoff continued to decline. During this period, temperature increases remained significant, suggesting that runoff reduction was mainly caused by temperature rise.

In addition to meteorological factors, water conservancy projects and agricultural practices also affect basin water resources. The abrupt change years in runoff were close to the timing of national rural land reforms. The early 1980s

marked the beginning of China's land reform, which stimulated farmers' enthusiasm and increased agricultural production through extensive agricultural activities. However, with basically unchanged cultivated land area and water production efficiency, increased agricultural output led to increased agricultural water consumption [18], explaining the runoff reduction beginning around 1980.

Furthermore, three large reservoirs were built upstream of Baiyangdian–Xidayang, Wangkuai, and Angezhuang (Longmen Reservoir has dried up)—primarily for flood control and power generation. With decreasing precipitation year by year, flood control became unnecessary, but reservoir storage also continuously decreased. Currently, Xidayang Reservoir mainly supplies water for the Tanghe Irrigation District and Baoding City; Wangkuai Reservoir focuses on water quality management (Class I-II) and currently supplies water to Beijing; Angezhuang Reservoir has vigorously developed tourism, which may affect water quality. Reservoir construction has disrupted natural water circulation paths, causing substantial water loss through evaporation and seepage [19], also contributing to runoff reduction.

4.2. Interdecadal Variation

The decadal and intra-annual differences in precipitation, temperature, and runoff in the study area are substantial (Fig. 5 [Figure 5: see original paper]). Monthly temperature distribution within the year is stable, with winter averages below 0°C and other months above 0°C; maximum temperatures occur in July. Decadally, monthly mean temperatures show an upward trend with accelerated warming after the 1990s, consistent with the interannual temperature changes and the detected abrupt change year of 1991 (Fig. 5a). Intra-annual precipitation distribution is uneven: from November to March of the following year, low temperatures correspond to low precipitation, accounting for only 7.8% of annual precipitation. Starting in April, precipitation increases with rising temperatures, reaching maximum values in July–August, demonstrating obvious characteristics of concurrent rainfall and heat. Since the 1960s, monthly precipitation has shown a clear decreasing trend only in July–August, with complex changes in other months, indicating that precipitation variation is influenced not only by temperature but also by human activities and other climatic factors (Fig. 5b).

Runoff distribution within the year at the three typical hydrological stations is extremely uneven, showing obvious single-peak patterns with clear boundaries between flood and non-flood seasons. Runoff at Fuping, Daomaguan, and Zijinguan stations increases rapidly starting in June, peaks in August, and recedes quickly from October. Runoff is concentrated in June–October, accounting for 78%, 61%, and 62% of annual runoff, respectively, with July–September accounting for 61%, 48%, and 49%. This is mainly related to uneven intra-annual precipitation distribution, as precipitation is concentrated in June–September, peaking in July, suggesting a approximately one-month lag between maximum precipitation and maximum runoff. Decadally, with climate warming and precip-

itation reduction, the intra-annual runoff distribution has changed accordingly. Although the timing of maximum runoff has remained unchanged, the magnitude has decreased significantly. Compared with the 1960s, 1970s, 1980s, and 1990s, the maximum monthly runoff in the 2000s decreased by 85%, 78%, 75%, and 60% at Fuping station (Fig. 5c), 83%, 70%, 63%, and 50% at Daomaguan station (Fig. 5d), and 87%, 74%, 66%, and 67% at Zijingguan station (Fig. 5e). Based on MK abrupt change test results, the abrupt change years for annual runoff at the three stations were basically consistent with those for combined runoff.

4.3. Monthly and Seasonal Interannual Variation Analysis

To further examine intra-annual variations in temperature, precipitation, and runoff, trend tests were conducted for monthly and seasonal changes.

Monthly temperature changes show that t values for all 12 months were positive and passed the 95% confidence level test, indicating significant warming trends (Fig. 6a [Figure 6: see original paper]). Seasonal mean temperature sequences also showed significant warming trends at 95% confidence, with the most pronounced warming in winter ($0.57^{\circ}\text{C} \cdot (10\text{a})^{-1}$) and the smallest in summer ($0.33^{\circ}\text{C} \cdot (10\text{a})^{-1}$) (Fig. 6b). Monthly and seasonal precipitation changes were more complex than temperature, indicating frequent fluctuations. The values for July ($0.85 \text{ mm} \cdot \text{a}^{-1}$) and August ($1.30 \text{ mm} \cdot \text{a}^{-1}$) were the largest negative values, showing the greatest reduction, with August passing the 95% confidence test. Although February–April and October–December did not pass the confidence test, their negative t values indicated decreasing precipitation, while May, June, and September showed positive t values with increasing precipitation, with May passing the 95% confidence test (Fig. 6c). Seasonal precipitation t values were negative in summer and winter and positive in spring and autumn, with both summer and winter passing the 95% confidence test. Summer showed the largest decrease at $1.72 \text{ mm} \cdot \text{a}^{-1}$ (Fig. 6d).

For monthly runoff trends, t values for all 12 months at the three stations were negative and passed the 95% confidence test (except April, May, and June at Fuping station), indicating significant decreasing trends, most pronounced in June–October. The maximum reduction occurred in August, with decreases of $0.54 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, $0.33 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, and $0.34 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$ at Fuping, Daomaguan, and Zijingguan stations, respectively (Fig. 6e). Seasonal runoff distribution showed decreasing trends for all seasons (except spring at Fuping station), all passing the 95% confidence test. Summer showed the largest decreases: $0.85 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, $0.72 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$, and $0.66 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{a}^{-1}$ at the three stations, respectively (Fig. 6f). These results reflect an overall decreasing runoff trend, most pronounced in summer.

In summary, temperature in the Baiyangdian Basin shows a significant upward trend, while precipitation and runoff show decreasing trends. Winter and spring warming contributed most to temperature increase, while summer warming was

much smaller. Summer precipitation and runoff showed the largest decreases, constituting the main reason for intra-annual reductions. Intra-annual temperature and precipitation changes have significant positive correlations with runoff formation, while interannual temperature changes show significant negative correlations with interannual runoff changes, and positive correlations with interannual precipitation.

4.4. Periodic Variation

Wavelet analysis reveals obvious periodic changes in mean annual temperature, precipitation, and runoff (Fig. 7 [Figure 7: see original paper]). In the temperature wavelet analysis (Fig. 7a), wavelet coefficient contours alternate between $[-0.5, 0.5]$, with positive values indicating higher temperatures and negative values indicating lower temperatures. Contours show dense positive-negative phase changes at 4-5 a, 8-10 a, and 14-15 a time scales. This is reflected in wavelet variance, which shows extreme values at 4.5 a, 8.0 a, and 14.0 a, with 14.0 a being the first main period and 4.5 a and 8.0 a being secondary periods. The precipitation wavelet analysis (Fig. 7b) shows contours varying between $[-1, 1]$, with positive values indicating wet periods and negative values indicating dry periods. Dense positive-negative phase changes occur at 2-5 a, 8-10 a, and 13-15 a time scales. Wavelet variance shows extreme values at 2.5 a, 4.5 a, 8.0 a, and 13.0 a, with 13.0 a being the first main period. The runoff wavelet analysis (Fig. 7c) shows phase changes basically consistent with precipitation, indicating that runoff experienced multiple wet-dry alternations corresponding to precipitation fluctuations. Wavelet variance shows main periods of 2.5 a, 4.5 a, 8.0 a, and 14.0 a, with 8.0 a being the first main period. These results demonstrate that precipitation has direct impacts on runoff, with basically consistent fluctuation cycles and a certain lagged response in runoff to precipitation changes, related to underlying surface conditions.

5. Conclusions and Discussion

Based on trend analysis, abrupt change analysis, and periodicity analysis, this study examined changes in temperature, precipitation, and runoff in the Baiyangdian Basin from 1957-2012. The results show that mean annual temperature has an obvious upward trend with 1991 as the abrupt change year, after which warming accelerated. Annual precipitation shows an overall decreasing trend with large interannual fluctuations, reflecting influences from monsoon climate, sea level pressure, Pacific sea surface temperature, atmospheric circulation, solar activity, and greenhouse gases, with large spatial and temporal differences [3]. This suggests the basin's climate is gradually developing toward warmer and drier conditions. Annual runoff shows a strong decreasing trend with an average reduction of $0.11 \times 10^3 \text{ m}^3$, causing continuously decreasing inflow to the lake area and exacerbating lake-drying phenomena. This is mainly influenced by the warming and drying climate, while expansion of industrial and agricultural land increasing water consumption

and reservoir construction increasing evaporation are also important causes of continuous runoff reduction, requiring quantitative analysis in future research.

Since the 1960s, monthly mean temperatures have shown an upward trend, most pronounced in winter ($0.57^{\circ}\text{C} \cdot (10\text{a})^{-1}$), with overall warming accelerating after the 1990s, consistent with the temperature abrupt change year. Decadal precipitation changes in July–August show significant decreasing trends, constituting the main reason for intra-annual precipitation and runoff reduction, while other months show complex changes, indicating precipitation is influenced by temperature, agricultural practices, and water conservancy projects. Flood season runoff shows significant decreasing trends, while non-flood season runoff also decreased but with much smaller magnitude, making the single-peak intra-annual distribution less prominent.

In conclusion, significant temperature increases and gradual precipitation and runoff decreases have become the main development trends in the study area, further intensifying warming-drying conditions and lake-drying in the Baiyangdian Basin. Regarding specific response relationships: First, wavelet analysis reveals nested structures of multiple time scales for mean annual temperature, precipitation, and runoff, with weaker periodicity in temperature but strong consistency between precipitation and runoff cycles, indicating prominent runoff response to precipitation. Second, temperature and precipitation changes are basically consistent with runoff change trends, though runoff is affected by different factors at intra-annual versus interannual scales. At annual scales, rising temperature increases evapotranspiration, reducing runoff generation, while decreasing precipitation further reduces runoff, indicating significant negative correlation between interannual temperature and runoff changes and positive correlation with precipitation. At monthly and seasonal scales, summer runoff increases are mainly influenced by concurrent rainfall-heat climate characteristics, while decreases in other months are mainly related to rapid precipitation reduction, indicating significant positive correlations between intra-annual temperature/precipitation changes and runoff formation.

In reality, runoff change is influenced not only by temperature and precipitation but also by other climatic factors, human activities, and underlying surface condition changes. The impacts of these factors on basin runoff require further research to comprehensively understand the driving mechanisms.

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