The Impacts of Reservoirs on Runoff in the Upper Yellow River, China

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Abstract. River runoff is an important link in the water cycle that can be adversely affected by the construction of reservoirs. Based on the runoff data from 1950 to 2009 at eight stations in the upper Yellow River, this study investigated the impacts of the combined operation of Longyangxia Reservoir and Liujiaxia Reservoir on river runoff. The measured series of runoff data for the period after the commencement of combined operation of two reservoirs were restored by adjusting for water balance. The intra-annual characteristics of observed and restored runoff at Lanzhou station and Xiaheyan station were analyzed using Mann-Kendall test and wavelet analysis. There was a significantly downward trend in both runoff series, with abrupt changes in 1986 in the observed data and in 1989 in the restored data. Periodic oscillations in the observed and restored runoff series occurred at temporal scales of 3–5-year, 6–9-year, 14–19-year, and 22–27-year. The observed runoff series at Lanzhou station and Xiaheyan station had periodicities of 25-year, 16-year, 8-year, and 4-year. The restored runoff series at Lanzhou station had periodicities of 23-year, 8-year, and 4-year, and at Xiaheyan station had periodicities of 24-year, 4-year, and 8-year. The results show that the combined operation of Longyangxia Reservoir and Liujiaxia Reservoir contributed to the decreasing trend of river runoff, and led to runoff abrupt changes and alterations in the periodic variation.

1. Introduction

River runoff is a critical link in the water cycle. Strict monitoring and control are essential for the appropriate development, utilization, and management of river water resources. River runoff is affected by natural and anthropogenic factors, including climate change, land use, vegetative cover, etc. Therefore, it is important to regulate the operation of activities that impact river runoff1–2. There are increasing evidences that anthropogenic factors might have the major influence on the hydrological cycle and the temporal and spatial distribution of water resources3. Continued technological development have increased the ability of mankind to transform nature, and watershed processes, including river runoff, have been considerably affected by human activities4. Changes in river runoff inevitably affect the watershed ecosystem and, in turn, the social structure of communities in river basins. Runoff changes resulting from developments on the Yellow River have influenced social and economic development, industry and agriculture, and the standard of living of inhabitants of the Yellow River basin. The upper reaches of the Yellow River basin yield the majority of the runoff from the river and runoff from this region determines the continuity of water resources. The combined
operation of Longyangxia Reservoir and Liujiaxia Reservoir on the upper Yellow River influences the distribution of river water on an annual basis[5]. The operation of the reservoirs provides considerable benefits, such as supply of electricity, flood defense, irrigation, and so on. But at the same time, it has negative impacts on river runoff downstream of the reservoirs.

Many previous studies have investigated the impacts of the Longyangxia and Liujiaxia Reservoirs on downstream waters. Shen et al.[6] compared characteristics of water and sediment and investigated fluvial processes in the Inner Mongolia reaches of the Yellow River before and after the operation of the Longyangxia and Liujiaxia Reservoirs. Huang et al.[6] reported that the operation of the Longyangxia and Liujiaxia Reservoirs had important impacts on ice jam events in the Ningxia–Inner Mongolia reaches of the river. Zheng et al.[7] analyzed the impact of the reservoirs on the ecological basic flow of the Yellow River using a method for quantitative calculation of flow compensation benefits of cascade reservoirs. Ran et al.[8] investigated the impact of the reservoirs on the cross-section of the channel at the Toudaoguai gauging station. The channel cross-section was strongly influenced by the operation of the reservoirs upstream, and the impacts on the downstream waters extended beyond the Sanhuhekou gauging station. Fan et al.[9] looked at water discharge and suspended-sediment concentration at six hydrological stations on the Ningxia–Inner Mongolia reaches of the Yellow River during flood seasons from 1952 to 1986. There was a 40% decrease in sediment transport during flood periods as a result of impoundment in the Liujiaxia Reservoir, sediment-checking dams, and the deposition of soil in the study area.

The studies discussed above investigated fluvial processes, ice prevention, and ecological basic flow in the Ningxia–Inner Mongolia reaches of the Yellow River and considered the possible influences of the combined operation of the Longyangxia and Liujiaxia Reservoirs on water discharge and sediment load. However, few studies have analyzed the changes in runoff characteristics before and after the operation of the Longyangxia and Liujiaxia Reservoirs. Therefore, the present study aimed to investigate the influence of the combined operation of the Longyangxia and Liujiaxia Reservoirs on runoff in the upper reaches of the Yellow River. The runoff series for the period after the commencement of operation of the reservoirs was restored by altering water balance, and the restored and observed series at Lanzhou and Xiaheyan stations were compared. Trends in observed and restored annual runoff, including gradual and abrupt changes, were assessed using the Mann–Kendall test. Finally, multiple timescale characteristics of observed and restored annual runoff were identified using the multi-resolution function of a wavelet transform.

2. Data and methods

2.1. Study area

The Yellow River (Huanghe in Chinese language) is the second longest river in China, and the fifth longest river in the world. It originates on the Qinghai–Tibet Plateau, flows eastward through nine provinces of China, and empties into the Bohai Sea. The Yellow River is about 5,464 km long and drains an area of 752,443 km²[10]. The upper Yellow River extends from the source to the city of Hekouzhen. This part of the river is 3,472 km long and has an elevation difference of 3,496 m with an average channel gradient of about 1.01‰[8]. Since the founding of the People’s Republic of China in 1949, many reservoirs have been built along upper Yellow River. Of these, the Longyangxia and Liujiaxia Reservoirs have had the greatest effect on the downstream fluvial geomorphology[11].

The primary purpose of the Liujiaxia Reservoir is to provide hydroelectric power, with secondary purposes including flood control, ice prevention, and irrigation. Construction began in 1958, water storage commenced in October 1968, and the reservoir has been operating since November 1969. The Liujiaxia Reservoir is a yearly regulating storage reservoir with a storage capacity of 57×10⁸ m³ at the normal water level of 1,735 m and 64×10⁸ m³ at the check flood level of 1,738 m[12]. Xunhua, Hongqi, and Zheqiao hydrological stations control reservoir inflow, and Xiaochuan station controls outflow (Figure 1).
Figure 1. Location of the study area showing the upper Yellow River, the reservoirs, and the hydrological stations.

Construction of the Longyangxia Reservoir, the most upstream in the cascade of stations developed on the Yellow River, began in 1976 and water storage commenced in October 1986. Longyangxia Reservoir, with a storage capacity of $247 \times 10^8$ m$^3$ at the normal water level of 2,600 m and a storage capacity of $276.3 \times 10^8$ m$^3$ at the check flood level of 2,605 m, is a multi-year regulating storage reservoir\textsuperscript{[12]}. Tangnaihai hydrological station controls the reservoir inflow, and Guide station controls the outflow (Figure 1). Since 1986, the strategy of the combined operation of Longyangxia and Liujiaxia Reservoirs has been to provide better river management. The operation of the reservoirs regulates water discharge into the downstream fluvial system, and reduces the magnitude of flood peaks during the flood season while increasing the duration of mid- and low-discharge periods.

At Lanzhou station, 100 km downstream of Liujiaxia Reservoir, the average annual runoff from 1950 to 2009 was $308.54 \times 10^8$ m$^3$, accounting for 57.5% of the total runoff of the Yellow River. Xiaheyan station, 462 km downstream of Liujiaxia Reservoir, controls inflow into upper Yellow River desert wide river valley.

2.2. Data

Hydrological data on daily runoff at Tangnaihai, Guide, Xunhua, Xiaochuan, Lanzhou, and Xiaheyan stations in the mainstream of the upper Yellow River, as well as daily runoff data for Hongqi and Zheqiao stations in the main tributaries of the upper Yellow River basin, were acquired from the hydrological yearbooks of the People’s Republic of China. The data series used in this study are consistent and complete, with no missing data. The drainage areas and the data periods for each station are presented in Table 1, and the geographical location of these stations is shown in Figure 1.

Table 1. Detailed hydrological records of stations along the mainstream of the upper Yellow River and on tributaries in the upper Yellow River basin.

| Station name                     | Drainage area (km$^2$) | Data period   |
|----------------------------------|------------------------|---------------|
| Stations along the tributaries of the Upper Yellow River |                         |               |
| Hongqi station                   | 24,973                 | 1950–2009     |
| Zheqiao station                  | 6,843                  | 1950–2009     |
| Stations along the mainstream of the Upper Yellow River |                         |               |
| Tangnaihai station               | 121,972                | 1950–2009     |
| Guide station                    | 133,650                | 1950–2009     |
| Xunhua station                   | 145,459                | 1950–2009     |
| Xiaochuan station                | 181,770                | 1950–2009     |
| Lanzhou station                  | 222,551                | 1950–2009     |
| Xiaheyan station                 | 254,142                | 1950–2009     |
2.3. Methods

2.3.1. Mann–Kendall trend test. The Mann–Kendall (MK) test is a statistical method used to analyze trends and abrupt changes in time series. The advantages of the test are that it does not assume any distribution form in the data and it has similar power to its parametric competitors\textsuperscript{[13]}. The World Meteorological Organization recommends the MK test and it has been widely used to assess the significance of trends in hydro meteorological time series\textsuperscript{[14-17]}.

In the MK test, the null hypothesis $H_0$ states that the time series $(x_1, x_2, \cdots, x_n)$ is a sample of $n$ independent and identically distributed random variables. The alternative hypothesis $H_1$ of a two-sided test is that the distributions of $x_k$ and $x_j$ are not identical for all $k, j \leq n$ with $k \neq j$. The test statistic $S$ is given by:

$$ S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k) $$

with

$$ \text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} $$

When the sample size $n$ is $\geq 10$, the test statistic $S$ approximately obeys a normal distribution, which has a mean of zero, and the variance $\text{var}(S)$ is given by:

$$ \text{var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{q} t_i(t_i-1)(2t_i+5)}{18} $$

where $q$ is the number of tied groups; $t_i$ is the $i$th group; and $\Sigma$ denotes the summation over all ties. The standard normal variable $Z$ is computed as follows:

$$ Z = \begin{cases} (S-1) / \sqrt{\text{var}(S)} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ (S+1) / \sqrt{\text{var}(S)} & \text{if } S < 0 \end{cases} $$

supposing that the time series refers to no trend. In a two-sided test for trend, the null hypothesis $H_0$ is accepted if $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, where $\alpha$ is the significance level of the test. In this paper, $\alpha = 0.05$ is applied. Positive values of $Z$ indicate increasing trends while negative values of $Z$ indicate decreasing trends.

2.3.2. Sequential Mann–Kendall test. The sequential version of the MK test follows the method described by Gerstengarbe and Werner\textsuperscript{[18]} to test for the assumption of a trend in a sample $(x_1, x_2, \cdots, x_n)$ of the random variable $X$, based on the rank series $a_{ij}$ of the progressive and retrograde rows of this sample. The null hypothesis is that the sample under investigation shows no sign of a developing trend. The following test is done to prove or disprove this hypothesis. First an MK test statistic, $S_k$ is calculated as:

$$ S_k = \sum_{i=1}^{k} \sum_{j=1}^{i-1} a_{ij} \quad (k = 2, 3, \cdots, n) $$

where

$$ a_{ij} = \begin{cases} 1 & \text{if } x_i > x_j \\ 0 & \text{if } x_i \leq x_j \end{cases} \quad (j = 1, 2, \cdots, i) $$

Under the null hypothesis of no trend, the statistic $S_k$ is normally distributed with an expected value of $E(S_k)$ and the variance $\text{var}(S_k)$ as follows:
\[ E(S_k) = \frac{k(k-1)}{4} \]  
(7)

\[ \text{var}(S_k) = \frac{k(k-1)(2k+5)}{72} \]  
(8)

Under the above assumption, the definition of the statistic index \( UF_k \) is calculated as:

\[ UF_k = \frac{S_k - E(S_k)}{\sqrt{\text{var}(S_k)}} \quad (k = 2, 3, \cdots, n) \]  
(9)

\( UF_k \) follows a standard normal distribution. In a two-sided test for trend, the null hypothesis is rejected at the significance level of \( \alpha \) if \( |UF| \geq |U_{1-\alpha/2}| \), where \( U_{1-\alpha/2} \) is the value of the standard normal distribution with a probability of \( \alpha/2. \) A positive \( UF \) value denotes a positive trend and a negative value denotes a negative trend. In this paper, a significance level of \( \alpha = 0.05 \) is used.

The corresponding rank series for the so-called retrograde rows are similarly obtained for the restored sample \((x_0, x_0-1, \cdots, x_1)\). Following the same procedure as shown in equations (5)–(9), the statistical variables, \( S_k \), \( E(S_k) \), \( \text{var}(S_k) \), and \( UF_k \) will be calculated for the retrograde sample. The \( UF \) values calculated with progressive and retrograde series are named \( UF_k \) and \( UB_m \), respectively, in this paper. If the intersection point of the two lines \( UF_3 \) and \( UB_m \) \((k=1, 2, \cdots, n; m=1, 2, \cdots, n)\) is between the two confidence lines, it is then judged that an abrupt change has taken place at that point within the time series\(^{[19]}\).

2.3.3. Wavelet analysis. Wavelet analysis evolved from Fourier analysis and is mainly used for multiple-scale analysis of time series of earth surface processes, such as temperature, precipitation, and runoff\(^{[20]}\). In this paper, we use the continuous wavelet transform (CWT). The CWT of the signal can be defined as the following inner products:

\[ W_f(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \phi^*(\frac{t-b}{a}) dt \]  
(10)

where \( W_f(a, b) \) is the wavelet coefficient; \( a \) is the scale parameter used to stretch or compress the mother wavelet \( \phi_{a,b}(t) \) that is related to the frequency of the signal; \( b \) is the location parameter used to shift the mother wavelet \( \phi_{a,b}(t) \) to the time domain of the signal; the \( * \) indicates the complex conjugate of the wavelet function; and \( f(t) \) is the input signal.

The mother wavelet \( \phi_{a,b}(t) \) is defined as:

\[ \phi_{a,b}(t) = \frac{1}{\sqrt{a}} \phi\left(\frac{t-b}{a}\right) \]  
(11)

A number of wavelet forms including the Mexican hat wavelet, the Morlet wavelet, and the Mexican hat wavelet are used as the mother wavelet. Therefore, several factors need to be considered when choosing a mother wavelet for a particular application\(^{[21]}\). These include the following: (1) orthogonal or non-orthogonal; (2) complex or real; (3) width, which determines the balance between time and frequency resolution; and (4) shape, which should reflect the type of features present in the time series. In this paper, we selected a non-orthogonal mother wavelet, to allow for smooth and continuous variations in wavelet power spectrum, and a complex form, to allow for the derivation of phase or timing errors from the real and imaginary parts of the wavelet spectrum\(^{[22]}\). After some testing, the complex Morlet wavelet was chosen for the time series considered in this paper:

\[ \phi(t) = e^{-t^2/2} e^{i\omega_0 t} \]  
(12)

This implies that its Fourier transform \( \hat{\phi}(\omega) \) is defined by:

\[ \hat{\phi}(\omega) = \sqrt{2\pi} e^{-(\omega-\omega_0)^2/2} \]  
(13)

where \( \omega_0 \) is the nondimensional frequency and \( t \) is the nondimensional time parameter. The time/scale resolution is adjusted by \( \omega_0 \). For high values of \( \omega_0 \), the scale resolution increases, whereas time
resolutions decreases, and vice versa. Fourier frequency $f$ and wavelet scale $a$ are not direct reciprocals of each other. Instead, the result of wavelet analysis has to be rescaled with a factor depending on the mother wavelet \cite{23}. For the Morlet wavelet, the conversion reads:

\[
\frac{1}{f} = \frac{4\pi}{\omega_0 + \sqrt{2 + \omega_0^2}} \times a
\]  

(14)

For $\omega_0=6.2$, $a/f$ is approximately one \cite{24}.

In fact, hydrological time series are mostly discrete. Therefore, according to Liu et al. \cite{25}, equation (10)’s discrete wavelet expansion can be expressed as:

\[
W_f(a,b) = \frac{1}{\sqrt{a}} \Delta t \sum_{k=1}^{N} f(k\Delta t)\varphi^* \left( \frac{k\Delta t - b}{a} \right)
\]

(15)

where $\Delta t$ is the time interval of sampling and $N$ is the length of the time series.

The variation of $W_f(a,b)$ is depicted by a two-dimensional isogram, in which $a$ is denoted by the y-coordinate and $b$ is denoted by the x-coordinate. Therefore, the time series characteristics at different timescales can be analyzed and identified from the isograms.

Wavelet coefficients obtained by wavelet transform reflect the response of timescales to input signals. To better understand which timescale can best reflect the periodic regularity of an input signal, the wavelet variance must be determined. The wavelet variance is defined by:

\[
\text{var}(a) = \int_{-\infty}^{\infty} |W_f(a,b)|^2 \, db
\]

(16)

The extent of variance at corresponding timescales is used to represent the energy intensity of the time series. The bigger the wavelet variance is, the stronger the energy intensity of the timescale, and the more significant the period of the time series. Therefore, we can determine the main periods of time series by calculating wavelet variance.

3. Results and discussion

3.1. Analysis of reservoir operation

The monthly variation in the storage volume of the Liujiaxia Reservoir from 1969 to 1986, before the completion of the Longyangxia Reservoir, is shown in Figure 2a. The storage period for the Liujiaxia Reservoir was from June to October and the annual storage volume was $28.7 \times 10^8$ m$^3$, with peak storage of $10.5 \times 10^8$ m$^3$ in September. The discharge period was from November to May of the following year and the annual discharge volume was $28.1 \times 10^8$ m$^3$, with peak discharge of $6.4 \times 10^8$ m$^3$ in January. The variation in annual water storage for Liujiaxia Reservoir from 1969 to 1986 is shown in Figure 2b. The largest storage volume during that period was $10.5 \times 10^8$ m$^3$ in 1969, in the early days of the reservoir’s operation. The volume represented 12.9% of the annual runoff at Xunhua station (the storage control station), 10.5% of the annual runoff at Lanzhou station, and 10.8% of the annual runoff at Xiaheyan station. The largest discharge volume was $17.2 \times 10^8$ m$^3$ in 1986. Over the whole period, the proportion of water storage of Liujiaxia Reservoir to the annual runoff at Xunhua station was between 0.04% and 12.9%. Regulation of the reservoir’s storage and discharge affected the annual water distribution downstream, the volume of floodwater decreased, and the water volume in the non-flood season increased.

The monthly variation in storage volume of the two reservoirs separately and combined from 1987 to 2009 is shown in Figure 3a. The storage period for Longyangxia Reservoir was from June to October, with an annual storage volume of $47.2 \times 10^8$ m$^3$. The annual discharge volume from November to May of the following year was $38.8 \times 10^8$ m$^3$. 


The operation of the Liujiaxia Reservoir changed after the Longyangxia Reservoir commenced operation in 1987. The combined operation of the two reservoirs increased the amplitude of storage and discharge volumes. The combined storage volume from June to October was $5.28 \times 10^8$ m$^3$, with peak storage of $15.9 \times 10^8$ m$^3$ in July. The combined discharge volume from November to May of the following year was $4.40 \times 10^8$ m$^3$. There was little variation in the monthly discharge volume but the highest discharge of $9.1 \times 10^8$ m$^3$ occurred in May. The annual storage/discharge for the two reservoirs separately and combined between 1987 and 2009 is shown in Figure 3. In the early years of the operation of Longyangxia Reservoir, there were several years with large storage volumes. In 1987, 1988, and 1989 the storage volumes were $4.54 \times 10^8$ m$^3$, $1.24 \times 10^8$ m$^3$, and $7.75 \times 10^8$ m$^3$, respectively, representing 25.7%, 7.5%, and 23.6% of the annual runoff at Tangnaihai station (the storage control station of Longyangxia Reservoir). The largest storage and discharge volumes for the period were $9.32 \times 10^8$ m$^3$ in 2005 and $4.82 \times 10^8$ m$^3$ in 2006, respectively, representing 36.6% and 34.1% of the annual runoff at Tangnaihai station. Over the whole period, the proportion of water storage of Longyangxia Reservoir to the annual runoff at Tangnaihai station was between 3.1% and 34.1%. The combined storage volume of the two reservoirs in 1987, 1988, and 1989 was $3.74 \times 10^8$ m$^3$, $2.77 \times 10^8$ m$^3$, and $8.02 \times 10^8$ m$^3$, respectively, representing 21.1%, 16.8%, and 24.5% of the annual runoff at Tangnaihai station, 16.2%, 11.5%, and 20.6% of the annual runoff at Lanzhou station, and 16.2%, 11.5%, and 20.6% of the annual runoff at Xiaheyan station. Over the whole period, the proportion of combined water storage in the Liujiaxia and Longyangxia Reservoirs to the annual runoff at Tangnaihai, Lanzhou, and Xiaheyan stations was between 2.1% and 40.2%, between 1.4% and 31.4%, and between 1.5% and 35.5%, respectively. The combined operation of Longyangxia and Liujiaxia Reservoirs considerably altered the natural runoff processes and the annual water distribution at Lanzhou and Xiaheyan stations downstream. The volume of floodwater reaching the stations decreased, and the volume of water reaching the stations in the non-flood season increased.
3.2. Analysis of trends in runoff

In this paper, the runoff series for Lanzhou and Xiaheyan stations were restored in terms of water balance using the following formula:

\[ Q = Q_0 + (Q_1 - Q_2) + (Q_3 - Q_4) + \Delta Q \]  

(17)

where \( Q \) is the restored daily runoff; \( Q_0 \) is the observed daily runoff; \( Q_1 \) and \( Q_2 \) are the inflow and outflow of Longyangxia Reservoir; \( Q_3 \) and \( Q_4 \) are the inflow and outflow of Liujiaxia Reservoir; and \( \Delta Q \) is a correction value.

The runoff characteristics of observed and restored series are presented in Table 2 and Table 3. The observed and restored runoff series were analyzed to determine the effects of reservoir operation on runoff.

Table 2. Runoff characteristics at Lanzhou station in the upper Yellow River basin in various decades.

| Data period | Observed runoff | Restored runoff |
|-------------|-----------------|-----------------|
|             | Mean (10^8 m^3/year) | Standard deviation (10^8 m^3/year) | Coefficient of variation | Anomaly percentage (%) | Mean (10^8 m^3/year) | Standard deviation (10^8 m^3/year) | Coefficient of variation | Anomaly percentage (%) |
| 1950–1959   | 314.30          | 56.58           | 0.180          | 1.87            | 314.30           | 56.58           | 0.180          | 1.87            |
| 1960–1969   | 357.43          | 87.72           | 0.245          | 15.85           | 361.04           | 84.81           | 0.235          | 15.46           |
| 1970–1979   | 317.97          | 60.37           | 0.190          | 3.06            | 318.55           | 60.28           | 0.189          | 1.87            |
| 1980–1989   | 333.91          | 70.84           | 0.212          | 8.22            | 348.93           | 72.42           | 0.208          | 11.58           |
| 1990–1999   | 260.08          | 36.96           | 0.142          | −15.71          | 260.50           | 44.10           | 0.169          | −16.70          |
| 2000–2009   | 267.57          | 33.37           | 0.125          | −13.28          | 272.93           | 61.96           | 0.227          | −12.72          |
| 1950–2009   | 308.54          | 67.67           | 0.219          | −              | 312.71           | 71.95           | 0.230          | −              |

Table 3. Runoff characteristics at Xiaheyan station in the upper Yellow River basin in various decades.

| Data period | Observed runoff | Restored runoff |
|-------------|-----------------|-----------------|
|             | Mean (10^8 m^3/year) | Standard deviation (10^8 m^3/year) | Coefficient of variation | Anomaly percentage (%) | Mean (10^8 m^3/year) | Standard deviation (10^8 m^3/year) | Coefficient of variation | Anomaly percentage (%) |
| 1950–1959   | 311.47          | 57.57           | 0.185          | 4.70            | 311.47           | 57.57           | 0.185          | 3.25            |
| 1960–1969   | 354.83          | 91.82           | 0.259          | 19.27           | 358.44           | 89.00           | 0.248          | 18.82           |
| 1970–1979   | 309.26          | 60.18           | 0.195          | 3.96            | 309.84           | 60.21           | 0.194          | 2.71            |
| 1980–1989   | 325.15          | 75.98           | 0.234          | 9.30            | 340.18           | 77.21           | 0.227          | 12.77           |
| 1990–1999   | 241.83          | 36.07           | 0.149          | −18.71          | 242.25           | 43.81           | 0.181          | −19.69          |
| 2000–2009   | 242.41          | 31.85           | 0.131          | −18.51          | 247.77           | 61.69           | 0.249          | −17.86          |
| 1950–2009   | 297.49          | 73.22           | 0.246          | −              | 301.66           | 77.24           | 0.256          | −              |

As shown in Table 2, the mean annual runoff at Lanzhou station for 1950–2009 was 308.54×10^8 m^3 with a standard deviation of 67.67×10^8 m^3. On a decadal scale, runoff was highest in the 1960s and lowest in the 1990s. In the 1990s and 2000s runoff was 15.71% and 13.28% less than average annual runoff, respectively. The restored average annual runoff at Lanzhou station was 321.71×10^8 m^3, 4.17×10^8 m^3 more than the average of the observed series, which indicates that the reservoir operation decreased the downstream runoff. The restored runoff series also showed a decreasing trend in the 1990s, which indicates that operation of the reservoir could not reverse the decreasing trend. From 1960 to 1989, the runoff at Lanzhou station was mainly affected by the operation of the Liujiaxia Reservoir and the early years of the combined operation of Liujiaxia and Longyangxia Reservoirs. The coefficients of variation of the observed series for each of the three decades from 1960 to 1990 are larger than those of the corresponding restored series, indicating that the discrete degrees of variation in the observed series are larger than those in the restored series. In the 1990s and 2000s, the runoff at Lanzhou station was mainly affected by the combined operation of the Liujiaxia and Longyangxia Reservoirs. The coefficients of variation for the observed series for both of the decades from 1990 to
2009 are smaller than those of the corresponding restored series, which indicates that the discrete degrees of variation in the observed series are smaller than those in the restored series. Similar findings were observed for runoff at Xiaheyan station (Table 3).

The results of the MK trend test of annual runoff in the upper Yellow River are shown in Table 4. Both the observed and restored runoff series for Lanzhou and Xiaheyan stations show a decreasing trend. The results indicate a decreasing trend in observed and restored runoff series for the stations on the upper Yellow River, significant at the 95% confidence level. The Z-statistics of the observed and restored runoff series for Lanzhou station are −2.72 and −2.44, respectively, and for Xiaheyan station are −3.56 and −3.12, respectively. The Z-statistics of the observed runoff series are smaller than those of the restored series, indicating an obvious decreasing trend. Moreover, as shown in Figure 4, according to the linear trend rate the observed and restored runoff at Lanzhou station decreased by 14.11×10^6 m^3 and 12.38×10^6 m^3 per 10 years, respectively, and at Xiaheyan station by 18.43×10^6 m^3 and 16.70×10^6 m^3 per 10 years, respectively. The average 10-year decreases in observed runoff are smaller than the decreases in restored runoff, which indicates that operation of the reservoirs contributed to the decreasing trend in runoff.

The results show that the decrease in runoff volume, in terms of trend and amplitude, in the upper Yellow River basin was related to the combined operation of the Longyangxia and Liujiaxia Reservoirs.

### 3.3. Analysis of abrupt changes in runoff

The results of the analysis of abrupt changes in runoff (when \( \alpha=0.05(U_{1-\alpha/2}=±1.96) \) in the MK test) are shown in Figure 4. The observed runoff at Lanzhou station showed a decreasing trend during 1950–1963 and 1971–1980 and an increasing trend during 1964–1970 and 1981–1987, but neither trend was significant at the 95% confidence level (Figure 4a). After 1988, the observed runoff decreased, and the decreasing trend became significant at the 95% confidence level. The \( UF_{k} \) and \( UB_{m} \) curves have two crossover points, between 1986 and 1989, between the critical lines of the 95% confidence level, which indicates that the observed series for Lanzhou station underwent an abrupt change during those years. The average observed runoff was 334.48×10^6 m^3/year during 1950–1986 and 266.82×10^6 m^3/year during 1987–2009, a total decrease of 20.23% (Table 5). However, the average observed runoff was 329.41×10^6 m^3/year during 1950–1988 and 269.78×10^6 m^3/year during 1989–2009, a total decrease of 18.10% (Table 5). Therefore, the abrupt change occurred once, and probably in the earlier year of 1986. As shown in Figure 4c, the trend at Xiaheyan station was similar, with an abrupt change between 1986 and 1989. Again, we consider that the abrupt change occurred in 1986.

The results of the MK trend test for annual runoff are shown in Table 4. The results indicate a decreasing trend in observed and restored runoff series for the stations on the upper Yellow River, significant at the 95% confidence level. The Z-statistics of the observed and restored runoff series for Lanzhou station are −2.72 and −2.44, respectively, and for Xiaheyan station are −3.56 and −3.12, respectively. The Z-statistics of the observed runoff series are smaller than those of the restored series, indicating an obvious decreasing trend. Moreover, as shown in Figure 4, according to the linear trend rate the observed and restored runoff at Lanzhou station decreased by 14.11×10^6 m^3 and 12.38×10^6 m^3 per 10 years, respectively, and at Xiaheyan station by 18.43×10^6 m^3 and 16.70×10^6 m^3 per 10 years, respectively. The average 10-year decreases in observed runoff are smaller than the decreases in restored runoff, which indicates that operation of the reservoirs contributed to the decreasing trend in runoff.

### Table 4. Results of Mann–Kendall trend tests for annual runoff.

| Station name | Data period | Critical value | Z-statistics | Significant trend |
|--------------|-------------|----------------|--------------|------------------|
|              |             |                | Observed runoff | Restored runoff | Observed runoff | Restored runoff |
| Lanzhou      | 1950–2009   | (−1.96,1.96)   | −2.72         | −2.44           | Decreasing      | Decreasing      |
| Xiaheyan     | 1950–2009   | (−1.96,1.96)   | −3.56         | −3.12           | Decreasing      | Decreasing      |

The results show that the decrease in runoff volume, in terms of trend and amplitude, in the upper Yellow River basin was related to the combined operation of the Longyangxia and Liujiaxia Reservoirs.

### 3.3. Analysis of abrupt changes in runoff

The results of the analysis of abrupt changes in runoff (when \( \alpha=0.05(U_{1-\alpha/2}=±1.96) \) in the MK test) are shown in Figure 4. The observed runoff at Lanzhou station showed a decreasing trend during 1950–1963 and 1971–1980 and an increasing trend during 1964–1970 and 1981–1987, but neither trend was significant at the 95% confidence level (Figure 4a). After 1988, the observed runoff decreased, and the decreasing trend became significant at the 95% confidence level. The \( UF_{k} \) and \( UB_{m} \) curves have two crossover points, between 1986 and 1989, between the critical lines of the 95% confidence level, which indicates that the observed series for Lanzhou station underwent an abrupt change during those years. The average observed runoff was 334.48×10^6 m^3/year during 1950–1986 and 266.82×10^6 m^3/year during 1987–2009, a total decrease of 20.23% (Table 5). However, the average observed runoff was 329.41×10^6 m^3/year during 1950–1988 and 269.78×10^6 m^3/year during 1989–2009, a total decrease of 18.10% (Table 5). Therefore, the abrupt change occurred once, and probably in the earlier year of 1986. As shown in Figure 4c, the trend at Xiaheyan station was similar, with an abrupt change between 1986 and 1989. Again, we consider that the abrupt change occurred in 1986.

### Table 5. Analysis of abrupt changes in annual runoff at stations in the upper Yellow River.

| Station name | Series | Change point | Pre – T \(^{-}\) (10^6 m^3/year) | Post – T \(^{-}\) (10^6 m^3/year) | Change \(^{-}\) (%) |
|--------------|--------|--------------|-------------------------------|-------------------------------|------------------|
| Lanzhou      | Observed | 1986–1987   | 334.48                        | 266.82                        | −20.23           |
| Lanzhou      | Observed | 1988–1989   | 329.41                        | 269.78                        | −18.10           |
| Lanzhou      | Restored | 1987–1988   | 333.96                        | 276.01                        | −17.35           |
| Lanzhou      | Restored | 1989–1990   | 335.70                        | 266.72                        | −20.55           |
| Xiaheyan     | Observed | 1986–1987   | 329.31                        | 246.31                        | −25.20           |
| Xiaheyan     | Observed | 1988–1989   | 323.64                        | 248.94                        | −23.08           |
| Xiaheyan     | Restored | 1987–1988   | 328.46                        | 255.37                        | −22.25           |
| Xiaheyan     | Restored | 1989–1990   | 329.98                        | 245.01                        | −25.75           |

\(^{1}\) Average value before the abrupt change, \(^{2}\) Average value after the abrupt change, \(^{3}\) Change between Pre – T\(^{-}\) and Post – T\(^{-}\)
Figure 4. Results of the Mann–Kendall trend test and linear regression analysis of annual runoff at Lanzhou and Xiaheyan stations.

The runoff series for Lanzhou station after water balance was restored is shown in Figure 4b. The restored series for Lanzhou station shows a decreasing trend during 1950–1963 and 1972–1981 and an increasing trend during 1964–1971 and 1982–1990, but neither trend was significant at the 95% confidence level. After 1991, the restored series decreased continuously, and the decreasing trend became significant at the 95% confidence level after 2000. The $UF_k$ and $UB_m$ curves have two crossover points, between 1987 and 1990, between the critical lines of the 95% confidence level,
which indicates an abrupt change at Lanzhou station occurred during those years. The average restored runoff was 333.96×10^8 m^3/year during 1950–1987 and 276.01×10^8 m^3/year during 1988–2009, a total decrease of 17.35% (Table 5). However, the average observed runoff was 335.70×10^8 m^3/year during 1950–1989 and 266.72×10^8 m^3/year during 1990–2009, a total decrease of 20.55% (Table 5). Therefore, the abrupt change occurred once, and probably in 1989. As shown in Figure 4d, there was also an abrupt change in the restored series for Xiaheyan station in 1989. Compared with the restored runoff series, the abrupt change in the observed series occurred three years earlier, which indicates that the reservoir operation had a definite effect on the downstream runoff.

### 3.4. Analysis of runoff periods

The foundation of period analysis is data standardization, because data standardization can eliminate interference and better show volatility and periodicity in time series data. The detailed formula is as follows:

\[
x'_i = \frac{x_i - \bar{x}}{\sigma}
\]

where \(x'_i\) is the standard sequence value of the \(i\)th year; \(x_i\) is the sequence value; \(\bar{x}\) is the average value; and \(\sigma\) is the standard deviation.

After standardization of the observed and restored runoff series data for Lanzhou and Xiaheyan stations, we generated contour maps of wavelet coefficients real part (Figure 5).

![Contour maps of wavelet coefficients real part](image)

Figure 5. Contour maps of wavelet coefficients real part of the observed and restored runoff series for Lanzhou (a and b) and Xiaheyan (c and d) stations.

The vertical intercept of the wavelet coefficients real part contour map reflects the oscillation intensity at the same time point on different timescales. The horizontal intercept reflects the oscillation intensity at different time points on the same timescale. As shown in Figure 5a, inter-annual (<10-year), and the decadal (>10-year) timescales of changes in the runoff series for Lanzhou station after commencement of the combined operation of Longyangxia and Liujiaxia Reservoirs were 3–5-year, 6–9-year, 14–19-year, and 22–27-year. The oscillation periodicity before 1970 was 14–19-year and 3–5-year, from 1970 to 1990 it was 22–27-year, 14–19-year, and 6–9-year, and after 1990 it was 22–27-year and 3–5-year. The results show that wet and dry changes over small timescales nest into larger timescales, reflecting multi-timescales and local variations in the runoff series. As shown in Figure 5c,
the timescales of changes in the runoff series for Xiaheyan station after commencement of the combined operation of Longyangxia and Liujiaxia Reservoirs were 3–5-year, 6–9-year, 14–19-year, and 22–27-year, indicating that the observed periodicity of changes in the runoff series for Xiaheyan and Lanzhou stations display synchronism. As shown in Figure 5b, the timescales of the restored runoff series for Lanzhou station were 3–5-year, 6–9-year, 14–19-year, and 22–27-year. The oscillations at 22–27-year, 14–19-year, 6–9-year, and 3–5-year timescales appeared since the 1980s, in 1950–1978, in 1968–1993, and over the whole period (with less energy than the three previous timescales), respectively. Similarly, as shown in Figure 5d, the timescales of the restored runoff series for Xiaheyan station were 3–5-year, 6–9-year, 14–19-year, and 22–27-year. The oscillations at 22–27-year, 14–19-year, 6–9-year, and 3–5-year timescales appeared since the 1980s, in 1950–1978, 1968–1993, and over the whole period (with less energy than the three previous timescales), respectively.

To analyze the main periodicity of the runoff series for Lanzhou and Xiaheyan stations before and after the combined operation of the Longyangxia and Liujiaxia Reservoirs, a wavelet variogram was generated (Figure 6). The variogram reflects the wave energy distribution with the changing timescales, and determines the main periodicity in runoff series.

![Wavelet variance curves of the runoff series for Lanzhou and Xiaheyan stations.](image)

As shown in Figure 6, the main periodicities of the observed runoff series for Lanzhou station were 25-year, 16-year, 8-year, and 4-year, and the main periodicities of the restored series were 23-year, 8-year, and 4-year. The main periodicities of the observed runoff series for Xiaheyan station were 25-year, 16-year, 8-year, and 4-year, and the main periodicities of the restored series were 24-year, 4-year, and 8-year. The comparison shows that the main periodicities of the observed runoff series for Lanzhou and Xiaheyan stations are similar and have good synchronism. However, there is a difference in the main periodic order between observed and restored runoff series. There are three main periods for the restored runoff series for Lanzhou and Xiaheyan stations, one less than for the observed runoff series, which indicates that the combined operation of the Longyangxia and Liujiaxia Reservoirs had some effect on the periodicity of runoff in the downstream Yellow River.

3.5. Discussion

3.5.1. Evaluation of the restored results. To test the rationality of the restored runoff series, we took the runoff series for Tangnaihai station (the storage control station of the Longyangxia Reservoir) as a reference that is less affected by human activity, and analyzed the trends, abrupt changes, and periodicity of runoff at that station. As shown in Figure 7, the runoff series Z-statistic for Tangnaihai station was −1.33, which was not significant at the 95% confidence level. This indicates that the downward trend in the runoff series for Tangnaihai station was not obvious. There was a decreasing trend during 1950–1963 and 1996–2009 and an increasing trend during 1964–1995, with an abrupt change occurring in 1993. The average observed runoff was 209.68×10^8 m^3/year during 1950–1993
and 172.85×10^8 m³/year during 1994–2009, a total decrease of 17.56%. The abrupt change in the restored runoff series for both Lanzhou and Xiaheyan stations occurred in 1989, which is similar to the change at Tangnaihai station. Therefore, we consider the restored runoff series to be reasonable. As shown in Figure 8, the timescales of the observed runoff series for Tangnaihai station were 3–5-year, 6–9-year, 14–19-year, and 24–27-year. The oscillations at 24–27-year, 14–19-year, 6–9-year, and 3–5-year timescales appeared since the 1980s, in 1950–1978, 1968–2009, and 1950–1980 (with less energy than the three previous timescales), respectively. As shown in Figure 9, the main periodicities of the observed runoff series for Tangnaihai station were 26-year, 8-year, and 17-year. Therefore, the periodicity of the restored runoff series for Lanzhou and Xiaheyan stations and Tangnaihai station are similar.

![Figure 7](image1.png)

Figure 7. Results of Mann–Kendall trend test and linear regression analysis of annual runoff for Tangnaihai station.

![Figure 8](image2.png)

Figure 8. Contour map of wavelet coefficients real part of the observed runoff series for Tangnaihai station.

![Figure 9](image3.png)

Figure 9. Wavelet variance curve of the runoff series for Tangnaihai station.

3.5.2. Evaluation of the runoff trends and abrupt changes. The Z-statistics on the MK test of the observed runoff series for Lanzhou and Xiaheyan stations were smaller than those of the restored series, but both were significant at the 95% confidence level. The results show a significant decreasing trend in both observed and restored runoff series, and indicate that reservoir operation could have
contributed to the decreasing trend. Further, abrupt changes in the observed runoff series for both Lanzhou and Xiaheyan stations occurred in 1986, and in 1989 in the restored series, which suggests that the effects of the Liujiaxia Reservoir were not obvious, but after the Longyangxia Reservoir was built, the effect of the combined operation of the two reservoirs led to clear changes in annual runoff, reflected in the abrupt change observed in the analysis.

In addition, the influence factors to runoff variation trend and sudden change of Lanzhou and Xiaheyan stations also include a series of regional soil conservation practices with general planning (such as afforestation, grass-planting, creation of level terraces, and building check dams, etc.)\textsuperscript{[26]}, diverted water resources for irrigation, and others will participate in the atmospheric cycle by evapotranspiration. These human activities changed the local micro-topography, increased the ability of intercepting precipitation, and consequently delayed and reduced the runoff, but this paper emphatically study the combined effects of Longyangxia and Liujiaxia reservoirs, other factors are not considered.

3.5.3. \textit{Causes of periodic variation}. The analysis identified periodicities on two timescales in the observed and restored runoff series for Lanzhou and Xiaheyan stations, annual variations (3–5-year and 6–9-year) and decadal variations (14–17-year and 23–27-year). These periodic variations may be related to air-sea interactions, the motion of celestial bodies, and medium-long wave period of sunspot activity. The period of the Southern Oscillation is 3–7-year, generated by air-sea interactions with the same 3–7-year periodicity\textsuperscript{[27]}. The period of runoff at this timescale may be influenced by the Southern Oscillation signals. The period of solar oscillation is 5–6-year, the sunspot period is 9–11-year, and Hill’s period is 22-year\textsuperscript{[28]}. All these cycles are related to solar activity. The periods are the similar to the annual and decadal periodic variation in the runoff series, which suggests that the variability in the runoff series is related to solar activity. In addition, movement of the Earth’s poles is an important cycle that affects precipitation in Western China\textsuperscript{[28]}. This cycle has a periodicity of about 7-year, similar to the 6–9-year period in observed and restored runoff series. This solar cycle leads to changes in the Earth’s centrifugal force, and to changes in the atmospheric circulation, air quality, moisture transport, and hydrographic processes\textsuperscript{[29]}. The periodic variation in the observed and restored runoff series is the result of an interaction between external factors that affect the climate (including solar activity, the motion of the Earth and celestial bodies, and movement of the Earth’s crust) and internal factors in the climate system (such as atmospheric circulation). According to wavelet variance, the main periodic order of the observed and restored series is different, which indicates that the combined operation of the two reservoirs affects the periodicity of the runoff. However, further long-term research is required to better understand the mechanisms involved.

4. Conclusions
Based on runoff data from 1950 to 2009 for eight stations on the upper Yellow River, the effects of the combined operation of the Longyangxia and Liujiaxia Reservoirs on runoff of the upper Yellow River were analyzed. The runoff series after the commencement of operation of the reservoirs was restored by adjusting water balance. The monthly variation in the storage volume before and after the combined operation were analyzed, the results show that regulation of the reservoir’s storage and discharge affected the annual water distribution downstream, the volume of floodwater decreased, and the water volume in the non-flood season increased.

The Z-statistics of MK trend test of the observed and restored runoff series for Lanzhou station are $-2.72$ and $-2.44$, respectively, and for Xiaheyan station are $-3.56$ and $-3.12$, respectively. The Z-statistics of the observed runoff series are smaller than those of the restored series, indicating an obvious decreasing trend. The abrupt changes in the observed and restored runoff series were in 1987 and 1990, respectively. The abrupt changes in the observed runoff series occurred three years earlier. These results suggest that the combined operation of the Longyangxia and Liujiaxia Reservoirs contributed to the decreasing trend and caused an abrupt change in runoff. Wavelet transform analyses on the observed and restored runoff series for Lanzhou and Xiaheyan stations indicate that the
significant periodicities were inter-annual (3–5-year, and 6–9-year) and the decadal (14–19-year, and 22–27-year). Wavelet analysis identified four main periodicities of 25-year, 16-year, 8-year, and 4-year in the observed runoff series, but three in the restored series (The Lanzhou station had periodicities of 23-year, 8-year, and 4-year, and at Xiaheyan station had periodicities of 24-year, 4-year, and 8-year). These results suggest that the combined operation of the Longyangxia and Liujiaxia Reservoirs affected the periodicity of changes in runoff.

In this paper, the effect of the combined operation of the Longyangxia and Liujiaxia Reservoirs on the downstream area of the Yellow River is demonstrated by quantitative analysis of the rules and characteristics of the abrupt and periodic changes in runoff. However, the reasons for runoff changes are complex and related to many factors including reservoir operation, vegetation, topographic features, rainfall, and evaporation. Future studies using different methods are needed to compare and complement the results of our study.

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