Research on Evolution Law of Runoff in Water Source Area and Water Receiving Area for Water Diversion Project

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Abstract. Against the background of climate change, exploring the runoff evolution law of water source area and water receiving area for the water transfer project is of great significance for compiling the water dispatching plan and safeguarding water safety of the basin. In this paper, the water diversion project from the Yangtze River to the Huaihe River is taken as the research object, and the runoff evolution of water source area and water receiving area under multiple time scales was studied by adopting various analysis methods such as mutation test, interannual trend and periodic oscillation. Results show that mutation years of annual runoff in Datong station were 1988 and 2003, while that in Lutaizi station were 1981 and 2010. Compared with multi-year mean runoff during the base period (1956-2022) in Datong station, multi-year mean runoff during 1956-1988, 1989-2003 and 2004-2022 changed by -2.2%, 7.0% and -1.7% respectively. When it comes to Lutaizi station, multi-year mean runoff during 1956-1981, 1982-2010 and 2011-2022 changed by -0.2%, 6.1% and -14.2% respectively in comparison with multi-year mean runoff during the base period. 56a and 42a were the first and second main periods of annual runoff in Datong station, while 28a and 10a were the first and second main periods of annual runoff in Lutaizi station. However, the variation period of the former were significant, while that of the latter were not significant.

Keywords: Runoff, Mutation test, Interannual trend, Morlet wavelet analysis, Inter-basin water diversion project

1 Introduction

The distribution of water resources in China is highly uneven, with a surplus in the south and a deficiency in the north, as well as more in the east and less in the west [1]. There is a significant mismatch between the distribution of population, economic development and water resources, and the scarcity of water resources has been a major constraint on economic and social development [2]. The inter-basin water

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transfer project serves as a crucial means to address the shortage of water resources [3]. By transferring water resources from basins with abundant water to those with scarce water, it facilitates the water cycle and enhances the meteorological conditions in the water transfer area, ultimately achieving rational allocation of water resources across basins and effectively addressing the issue of uneven spatial and temporal distribution of water resources [4].

The Yangtze-Huaihe River Water Diversion Project is a large-scale inter-basin water resources allocation project aimed at diverting water from the lower reaches of the Yangtze River to the middle reaches of the Huaihe River [5-7]. In recent years, affected by the monsoon climate, drought disasters have occurred frequently in the eastern monsoon region. In addition, due to the change of underlying surface and the influence of high-intensity human activities, the assumption of runoff consistency no longer exists, exacerbating the complexity of hydrological characteristics, compromising water resource security, and introducing uncertainties into water transfer planning [8, 9]. Consequently, investigating the runoff evolution in both water source and receiving areas of the water transfer project is crucial for planning and managing water resources within the basin and ensuring regional water supply security [10].

Using long-series monitoring data to analyze interannual trend, mutation test and periodic oscillation of runoff series is the basis for revealing the impact of climate change on runoff evolution [11]. Researchers have carried out extensive research on this topic. Parametric test and non-parametric test are commonly used methods for mutation analysis. The former mainly includes sliding t test, Gramer method, Yamamot method and ordered clustering method, while the latter mainly includes Mann-Kendall method, Pettitt method, Lepage method and R/S method [12]. In recent years, statistical methods for extracting runoff time series cycle have developed rapidly, from the periodogram, variance analysis to power spectrum, maximum entropy and wavelet analysis [13]. Based on these, this paper focuses on water source and receiving areas of the Yangtze River to Huaihe River project, the cumulative anomaly test, the orderly clustering test and the sliding t test were adopted to synthetically judge the mutation year, the linear trend and the sliding average methods were adopted to detect the interannual variation, the Morlet wavelet was adopted to detect the periodic variation. This research is valuable for providing technical support for exploring the runoff evolution in both water source and receiving areas, as well as formulating the water dispatching scheme for the water diversion project.

2 Research area and Data

2.1 Research area

The water supply scope of the Yangtze-to-Huaihe River Water Diversion Project involves 12 prefecture-level cities in Anhui Province and 2 prefecture-level cities in Henan Province [5]. It is estimated that by 2035 and 2040, mean annual water transfer concerning this water transfer project potentially reach 3.3 billion m^3 and 4.3 billion m^3, respectively with considering the planning scheme [7].

2.2 Data

The Datong station in the Yangtze River Basin and the Lutaizi station in the Huaihe River Basin were selected as the research stations, with the former station serving as the last runoff control station in the lower reaches of the Yangtze River and the latter station as the main control station in the middle reaches of the Huaihe River. These two hydrological stations adequately represent the inflow of the lower reaches of the Yangtze River and the middle and lower reaches of the Huaihe River [14, 15].

Based on monthly measured runoff data in Datong station and Lutaizi station from 1956 to 2022, the mutability, trend and periodicity of annual runoff were examined.

3 Research method

3.1 Mutation test methods

Cumulative anomaly test. The cumulative anomaly method is a method to judge the variation trend of runoff series by cumulative anomaly value [11]. For a given runoff series *x*, the cumulative anomaly value is calculated as follows:

$$x_t = \sum_{i=1}^{t} (x_i - x), t = 1,2, \ldots n \tag{1}$$

In the formula, x_t is cumulative anomaly value of a certain year, 10^8 m^3; x_i is annual runoff of the *i* year, 10^8 m^3; x is mean annual runoff, 10^8 m^3.

Ordered clustering test. The essence of the ordered clustering test to find the mutation point for runoff series is to locate the optimal segmentation point, which is achieved by minimizing the sum of squared deviations within the same classes. For a given runoff series *x*, the optimal segmentation point is determined as follows:

$$\begin{cases} minS_n(t) = V_t + V_{n-t} \\ V_t = \sum_{i=1}^{t} (x_i - x_t) \\ V_{n-t} = \sum_{i=t+1}^{n} (x_i - x_{n-t}) \end{cases} \tag{2}$$

In the formula, *t* is the most likely mutation point; $S_n(t)$ is the sum of square of total deviation; V_t, V_{n-t} are the sum of squares of deviations before and after the mutation point; x_t, x_{n-t} are mean value of the series before and after the mutation point.

Sliding t test. The sliding t test is to test the mutation by examining whether the difference between mean values of two samples series is significant. For a given runoff series *x*, the sample size is *n*, assuming that there is a reference point, the sliding t statistics is calculated as follows:

$$t = \frac{x_1 - x_2}{S_w \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \sim t(n_1 + n_1 - 2) \tag{3}$$

$$S_w = \sqrt{\frac{n_1 {S_1}^2 + n_2 {S_2}^2}{n_1 + n_1 - 2}} \tag{4}$$

Where x_1 and x_2 are sample series before and after the reference point; n_1 and n_2 are sample size before and after the reference point; x_1 and x_2 are mean value before and after the reference point; S_1^2 and S_2^2 are variance before and after the reference point.

3.2 Morlet wavelet analysis

Morlet wavelet can be taken to uncover the periodic variation in runoff series and accurately represent the changing trend across different time scales [13]. For a given time series, the continuous wavelet transform is calculated as follows:

$$W_f(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \varphi\left(\frac{t-b}{a}\right) dt \tag{5}$$

In the formula, $W_f(a,b)$ represents the coefficient obtained from the wavelet transform, $\varphi(t)$ denotes the Morlet mother wavelet function, φ is the complex conjugate of φ; a represents the time scale, which indicates the periodic scale of the wavelet; b denotes the translation factor, indicating the shift in time.

Runoff series are mostly discrete series, and the time series needs to be discretized. For example $f(k\Delta t)$, for the sampling time interval Δt, the calculation formula of the discrete wavelet transform coefficient is as follows:

$$W_f(a,b) = \frac{1}{\sqrt{a}} \Delta t \sum_{k=1}^{N} f(k\Delta t) \varphi\left(\frac{k\Delta t - b}{a}\right) \tag{6}$$

The wavelet coefficients derived from the wavelet transform of time series represent the projections of the sequences at various time scales and positions, which can be employed to describe the composition structure and multi-time scale variation characteristics of time series. In addition, aimed at showing the distribution of wave energy with taking time scale into account, the square of all wavelet transform coefficients in time domain is integrated to obtain the wavelet variance.

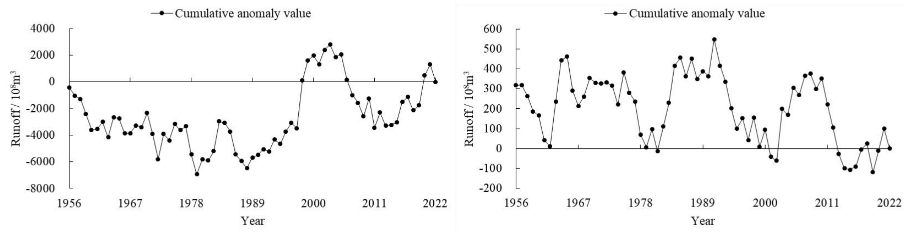
$$var(a) = \int_{-\infty}^{+\infty} \left|W_f(a,b)\right|^2 db \tag{7}$$

In the formula, $var(a)$ is the wavelet variance for time scale a.

4 Results and analysis

4.1 Runoff mutation

Considering that there are some mutation test methods and each method has its advantages and limitations, it is not appropriate to judge the mutation point of runoff series by a single method, and a variety of test methods should be adopted to comprehensively compare and judge the mutation year. In this paper, cumulative anomaly test method and ordered clustering test method were used to preliminarily judge the mutation year, and sliding t test was adopted for verification. Firstly, the cumulative anomaly method was employed to detect the mutation year in Datong station and Lutaizi station, and the cumulative anomaly value was shown in Fig. 1.

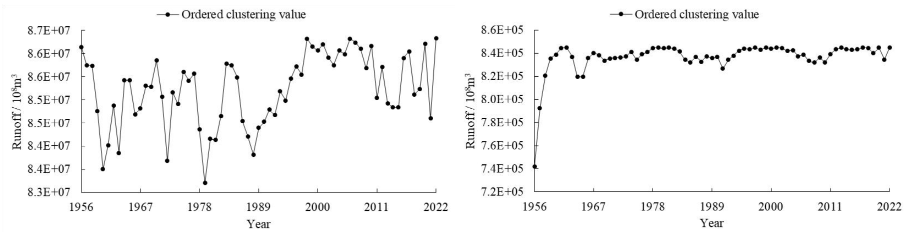


(a) Datong station (b) Lutaizi station

Fig. 1. The cumulative anomaly test of annual runoff.

According to Fig. 1, the cumulative anomaly value of annual runoff in Datong station showed a decreasing trend during 1956-1979 and 2003-2011, and showed an increasing trend during 1988-2003 and 2011-2021, indicating mutation years judged by the cumulative anomaly test may be 1979, 1988, 2003 and 2011. Similarly, the cumulative anomaly value of annual runoff in Lutaizi station showed a decreasing trend during 1965-1981, 1991-2002, 2010-2019, and showed an increasing trend during 1981-1991, 2002-2010, indicating that mutation years may be 1981, 1991, 2002 and 2010.

Secondly, the ordered clustering test is used to detect mutation years, and the sum of squared deviations was shown in Fig. 2.



(a) Datong station (b) Lutaizi station

Fig. 2. Ordered clustering test of annual runoff.

There are multiple minimum points concerning the sum of squared deviation curve of annual runoff in Datong station, and corresponding years were 1960, 1972, 1979, 1988, 2003 and 2015, respectively, showing that mutation years judged by ordered clustering test may be 1960, 1972, 1979, 1988, 2003 and 2015. Similarly, mutation years of annual runoff in Lutaizi station judged by ordered clustering test may be 1964, 1975, 1991 and 2010.

Clearly, mutation years determined by the cumulative anomaly test and ordered clustering test were not in agreement. For instance, at the Datong station, 1979, 1988, and 2003 were identified as mutation years by both tests, while 2011 was identified only by the cumulative anomaly test, and 1960, 1972, and 2015 were identified only by the ordered clustering test. Therefore, adhering to the principle of majority, the sliding t-test was utilized to assess the significance of mutation years derived from two methods. Mutation years initially identified by both tests were established as the base year, and the mean and variance of two series were calculated separately to obtain the statistic t, whose significance was then evaluated. Assuming n_1=n_2=5 and a significance level of α=0.05, the critical value $t_{0.05}$=±2.366. Results of the significance test for mutation years based on the sliding t-test were presented in Table 1.

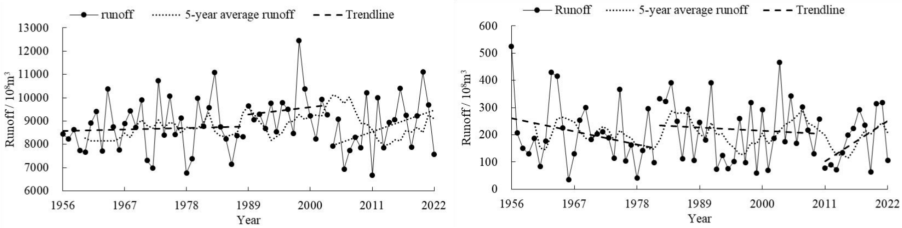
Table 1. The significance test of runoff mutation years based on the sliding t test.

<table>
<tr><th rowspan="2">Station</th><th colspan="2">Mutation year</th><th rowspan="2">Statistic t</th><th rowspan="2">Pass the significance test</th></tr>
<tr><th>Cumulative anomaly test</th><th>Ordered clustering test</th></tr>
<tr><td rowspan="7">Datong</td><td>—</td><td>1960</td><td>-2.096</td><td>No</td></tr>
<tr><td>—</td><td>1972</td><td>-1.324</td><td>No</td></tr>
<tr><td colspan="2">1979</td><td>-1.938</td><td>No</td></tr>
<tr><td colspan="2">1988</td><td>-3.795</td><td>Yes</td></tr>
<tr><td colspan="2">2003</td><td>3.117</td><td>Yes</td></tr>
<tr><td>2011</td><td>—</td><td>-1.685</td><td>No</td></tr>
<tr><td>—</td><td>2015</td><td>-1.493</td><td>No</td></tr>
<tr><td rowspan="6">Lutaizi</td><td>—</td><td>1964</td><td>0.918</td><td>No</td></tr>
<tr><td>—</td><td>1975</td><td>1.278</td><td>No</td></tr>
<tr><td>1981</td><td>—</td><td>-2.342</td><td>Yes</td></tr>
<tr><td colspan="2">1991</td><td>2.175</td><td>No</td></tr>
<tr><td>2002</td><td>—</td><td>-1.531</td><td>No</td></tr>
<tr><td colspan="2">2010</td><td>2.911</td><td>Yes</td></tr>
</table>

It follows that if mutation years of annual runoff in Datong station were 1988 and 2003, the statistic t was greater than the significant level, indicating that 1988 and 2003 were mutation years. Similarly, mutation years of annual runoff in Lutaizi station were 1981 and 2010, which have passed the significance test of 0.05 level.

4.2 Interannual trend

The linear trend line and the moving average method were employed to examine the interannual variation trend, and the *F* significance test was carried out on the linear regression equation of trend line. The interannual variation trend was shown in Fig. 3, and its significance test were shown in Table 2.



(a) Datong station (b) Lutaizi station

Fig. 3. The inter-annual variation trend of annual runoff.

Table 2. The significance test of runoff variation trend

Station	Period	Runoff (10^8 m^3)	Rate	F_α	F	Pass the significance test
Datong	1956-2022	8863	—	3.989	0.983	No
	1956-1988	8667	-2.20%	4.16	0.078	No
	1989-2003	9482	7.00%	4.667	0.186	No
	2004-2022	8716	-1.70%	4.451	2.951	No
Lutaizi	1956-2022	206.6	—	3.989	0.57	No
	1956-1981	206.1	-0.20%	4.26	1.938	No
	1982-2010	219.2	6.10%	4.21	0.201	No
	2011-2022	177.2	-14.20%	4.965	3.28	No

The significance level α=0.05 was selected. At this time, the molecular degree of freedom was 1, the denominator degree of freedom was n, and its significance level was $F_\alpha=F_{0.05}$. According to the correlation coefficient R^2 of the trend line, the significance test $F= R^2/((1- R^2)/(n-2))$ was calculated. If $F>F_{0.05}$, it was indicated that the trend line changed significantly. Otherwise, the change was not significant.

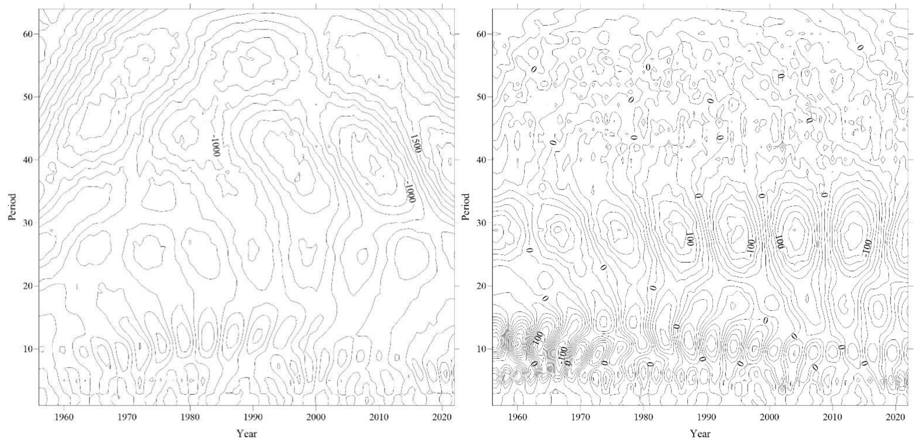
From Fig. 3 and Tab. 2, annual runoff in Datong station showed an upward trend during 1956-1988, 1989-2003 and 2004-2022, but the significance test statistics F were all smaller than F_α, indicating that the change trend was indistinctive in these periods. Similarly, annual runoff in Lutaizi station showed a downward, downward and upward trend during 1956-1981, 1982-2010 and 2011-2022, respectively, but the trend failed to test the significance of 0.05 level, indicating that the change trend was indistinctive in these periods.

Compared with multi-year mean runoff during the base period 1956-2022, multi-year mean runoff in Datong station changed by-2.2%, 7.0% and -1.7% during 1956-1988, 1989-2003 and 2004-2022, indicating that 1989-2003 was the wet season, with multi-year mean runoff 948.2 billion m^3. Similarly, compared with multi-year mean runoff during the base period, multi-year mean runoff in Lutaizi station changed by -0.2%, 6.1% and -14.2% during 1956-1981, 1982-2010 and 2011-2022, indicating that 2011-2022 was the dry season, with multi-year mean runoff 17.72 billion m^3.

4.3 Periodic oscillation

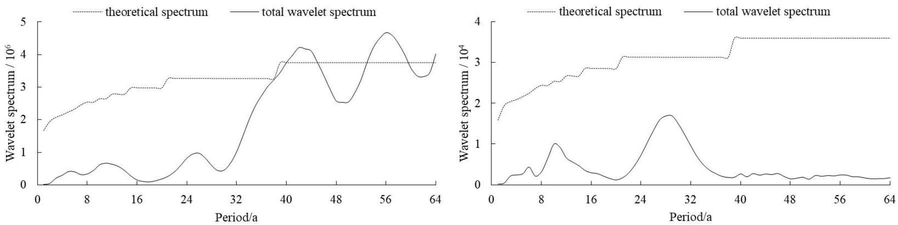
Morlet wavelet was employed to detect the variation period of annual runoff in Datong station and Lutaizi station. Real contour of wavelet coefficients and overall wavelet power spectrum were shown in Fig. 4 and Fig. 5.

From Fig. 4, it follows that annual runoff in Datong station had periodic oscillations about 56a, 42a, 26a, 11a and 5a, and the maximum peak appeared in 56a, which was the first main period of runoff. 42a was the second main period of runoff, followed by 26a, 11a, 5a short period, corresponding to the third, fourth, fifth main periods. Similarly, annual runoff in Lutaizi station had periodic oscillations of about 28a, 10a and 6a, corresponding to the first, second and third main periods, respectively.



(a) Datong station (b) Lutaizi station

Fig. 4. Wavelet coefficient contour map of annual runoff.



(a) Datong station (b) Lutaizi station

Fig. 5. Wavelet coefficient contour map of annual runoff.

From Fig. 5, it follows that if the wavelet power spectrum during a certain time scale was greater than the theoretical spectrum, it meant that the variation period concerning this scale was significant. In the wavelet power spectrum of annual runoff in Datong station, the variation periods of 56a and 42a passed the significance test of 0.05 level, while remaining variation periods failed to test the significance. Similarly, the variation periods of 28a, 10a and 6a judged by the wavelet power spectrum of annual runoff in Lutaizi station failed to test the significance of 0.05 level, indicating that variation periods of annual runoff in Lutaizi station were not significant.

5 Conclusion

Based on monthly measured runoff data in Datong station in the Yangtze River Basin and Lutaizi station in the Huaihe River Basin during 1956-2022, an analysis was conducted to examine the mutability, trend, and periodicity of annual runoff. The methods employed to determine mutation year of runoff included the cumulative anomaly method, ordered clustering test method, and sliding t-test method. The interannual variation trend of runoff was analyzed by moving average method and linear trend line. The periodic variation of runoff was analyzed by the Morlet wavelet model. The primary conclusions of this research are as follows:

(1) The abrupt change years of annual runoff in Datong station were 1988 and 2003, while that in Lutaizi station were 1981 and 2010, and above years all passed the significance test of 0.05 level.

(2) Compared with multi-year mean runoff during the base period, multi-year mean runoff in Datong station changed by -2.2%, 7.0% and -1.7% during 1956-1988, 1989-2003 and 2004-2022, while that in Lutaizi station changed by -0.2%, 6.1% and -14.2% during 1956-1981, 1982-2010 and 2011-2022. 1989-2003 was the wet season of runoff in Datong station, 2011-2022 was the dry season of runoff in Lutaizi station.

(3) The first and second main periods of annual runoff in Datong station were 56a and 42a, respectively, with significant variation periods. In contrast, the first and second main periods of annual runoff in Lutaizi station were 28a and 10a, respectively, but the variation periods were not significant.

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