Analysis on variation characteristics of the minimum flow at Datong Station under the influence of the Three Gorges Reservoir

Bo Yan1,2*, Liqiang Yao1,2, Longling Zhang3, Jiqiong Li1,4
1. Changjiang River Scientific Research Institute, Wuhan 430010, China;
2. Hubei Key Laboratory of Water Resources & Eco-Environmental Sciences, Wuhan 430010, China;
3. Pukou Water Affairs Bureau of Nanjing City, Nanjing 211800, China;
4. Wuhan Changjiang Kechuang Technology Development Co. Ltd, Wuhan 430010, China;
* correspondence: yanb@mail.crsri.cn

Abstract. As an important hydrological control station in the lower reaches of the Yangtze River, the Datong Station can provide guidance for regulating downstream water withdrawal activities by studying the characteristics of its changes during the dry season. This study selected the annual minimum flow index, applied linear trend method, Mann-Kendall method and wavelet analysis method to analyze its trend and periodic change characteristics, and analyzed the empirical frequency changes before and after the operation of the Three Gorges Reservoir, and obtained the following conclusions: The annual minimum flow series shows a significant increase trend, showing the characteristics of multi-period nesting in periodic changes, in which the first main period is 35-year. At the same frequency, the corresponding flow after the Three Gorges Reservoir operation was all larger than that before.

1. Introduction
The Yangtze River Basin spans the three major regions of Southwest China, Central China, and East China[1]. In 2017, the total population of the basin was 459 million, accounting for 33% of the country, and the urbanization rate reached 49%. The population density in the basin is relatively high, about 1.8 times the national average population density. The Yangtze River is an important support for national strategies such as the development of the Yangtze River Economic Belt and the integrated development of the Yangtze River Delta. It is a link connecting the Silk Road Economic Belt and the 21st Century Maritime Silk Road. The unique advantage of the two-way opening of the east and the west holds an important position in my country's economic and social development.

Datong Station is an important hydrological station on the lower reaches of the Yangtze River. Its runoff changes, especially in dry seasons, can affect the water withdrawal activities in the lower reaches of the Yangtze River (Jiangsu, Zhejiang, Shanghai), and play a key supporting role in economic development.

This study uses the annual minimum flow as an indicator to measure the change of runoff during the dry season, and studies the changes of Datong Station affected by the operation of the Three
Gorges Reservoir, with a view to providing basic support for studying the impact of the Three Gorges Reservoir on the lower reaches of the Yangtze River.

2. Study Area
The Yangtze River is the third largest river in the world and the largest river in China. It originates from the southwest side of Geladadong Snow Mountain, the main peak of Tanggula Mountain on the Qinghai-Tibet Plateau, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Shanghai and other 11 provinces (autonomous regions and municipalities directly under the Central Government) were injected into the East China Sea. The tributaries extend to 8 provinces (autonomous regions) including Guizhou, Gansu, Shanxi, Henan, Zhejiang, Guangxi, Guangdong, and Fujian. The basin area is about 1.8 million km², accounting for about 18.8% of China's land area[2].

Datong Station is an important hydrological station in the lower reaches of the Yangtze River. It is located in Meilong Town, Chizhou City, Anhui Province[3]. It has a history of more than 90 years. The station is located in the mainstream water system of the lower reaches of the Yangtze River, with a catchment area of about 1.7×10⁶ km² and a distance of 624 km from the estuary.

3. Data and Methodology

3.1. Data
This study collected daily runoff data from Datong Station from 1950 to 2018 to statistic the annual minimum flow series. The data comes from the Hydrological Yearbook of the Yangtze River Basin and has been checked for data consistency, reliability, and representativeness.

3.2. Methodology
In this study, the annual minimum flow was used to analyze the runoff changes in dry season at Datong Station and assess its changes affected by the operation of the Three Gorges Reservoir. The liner trend method[4], Mann-kendall (M-K) method[5] and wavelet analysis[6] were employed to evaluate the characteristics of runoff changes in dry season.

4. Results and Discussion

4.1. Analysis of the variation trend of the annual minimum flow
Analyzing linear trend of the annual minimum flow from 1950 to 2018, Figure 1 and Figure 2 show linear trend analysis and wavelet analysis, respectively. Figure 1 shows that based on the linear trend method, the annual minimum flow at Datong Station shows an increasing trend. The linear tendency amplitude increased by 489m³/s every 10 years. The M-K statistic is 4.99, which has passed the significance test at 95% confidence level, indicating that the increasing trend is significant.

Figure 2 shows that the wavelet analysis of the minimum flow at Datong Station, which has periodic variation on three levels, concluding the large scale of 49–64a, the mesoscale of 20–48a, and the small scale of 5–18a (Fig.2a). At the large scale of 49–64a, the oscillation signal is weak, showing quasi-two oscillations of dry-abundant alternation. At the mesoscale of 20–48a, there exist quasi-three oscillations of abundant-dry alternation. The periodic variations were stable before 1990, and the period stability was weakened after 1990, but still showing obvious periodicity. At the small scale of 5–18a, the oscillation tends to be obvious after 1970s, and the oscillation amplitude is not large.

the wavelet variance figure (Figure 2b) shows that there are 4 obvious peaks, which correspond to the time scales of 35-year, 56-year, 44-year, and 13-year, respectively. Among them, the largest peak corresponds to the 35-year time scale, indicating the strongest periodic oscillation, which is the first main period of the annual minimum flow series. The 56-year time scale corresponds to the second peak, which is the second main period. The 44-year and 13-year time scales correspond to the third and forth main period, respectively.

Figure 2c and 2d show the wavelet analysis of the first and second main periods. It can be seen
from the figures that at the 35-year time scale, the average variation period of the annual minimum flow is about 23 years, having experienced three periods of abundant-dry variation. At the 56-year time scale, the average variation period is about 35 years, having experienced two periods of abundant-dry variation.

Figure 1 Annual minimum flow variation of Datong Station from 1950 to 2018

Figure 2 Wavelet analysis of annual minimum flow at Datong Station

(a) Real part contours of wavelet coefficients
(b) Wavelet variance
(c) Wavelet real part process of the first main period (35-year time scale)
(d) Wavelet real part process of the second main period (56-year time scale)
4.2. Analysis of ranking of annual minimum daily flow

Collecting daily flow of Datong Station over 83 years from 1923 to 1925 and 1929 to 2018, the annual minimum daily flow was ranked from small to large, to clarify the minimum daily flow variation of Datong Station.

Due to the long sequence, Table 1 only lists the top five minimum daily flow, the minimum daily flow from 2003 to 2018 and their ranking. Figure 3 shows that the annual minimum daily flow at Datong Station fluctuated around 8000m$^3$/s before 2000, which has increased after 2000, and the minimum daily flow has been above 10,000m$^3$/s since 2008. Table 1 shows that the No.1 minimum daily flow over the years was 6040m$^3$/s, which appeared in January 1923, and the 2nd to 5th minimum daily flow was 6300m$^3$/s (February 1963), 6470m$^3$/s (January 1979), 6500m$^3$/s (January 1957), 6660m$^3$/s (February 1959), respectively. Since the Three Gorges operation in 2003, the minimum daily flow of Datong Station in 2004 was 8380 m$^3$/s, only ranking the 33rd, and that of the remaining years were all at 59th and beyond. After experimental water storage of the Three Gorges Reservoir in 2008, the annual minimum daily flow at Datong Station has been above 10,000m$^3$/s.

Figure 3 The changes of annual minimum daily flow at Datong Station

| Ranking | Annual minimum daily flow (m$^3$/s) | Occurring time (year/month) |
|---------|-----------------------------------|-----------------------------|
| 1       | 6040                              | 1923/1                      |
| 2       | 6300                              | 1963/2                      |
| 3       | 6470                              | 1979/1                      |
| 4       | 6500                              | 1957/1                      |
| 5       | 6660                              | 1959/2                      |
| ...     | ...                               | ...                         |
| 33      | 8380                              | 2004/2                      |
| ...     | ...                               | ...                         |
| 59      | 9650                              | 2006/1                      |
| 60      | 9730                              | 2005/1                      |
| ...     | ...                               | ...                         |
| 66      | 10000                             | 2007/1                      |
| ...     | ...                               | ...                         |
| 68      | 10300                             | 2008/1                      |
| 69      | 10400                             | 2003/12                     |
| 70      | 10400                             | 2014/2                      |
| ...     | ...                               | ...                         |
| 73      | 10900                             | 2009/1                      |
| 74      | 10900                             | 2013/12                     |
| ...     | ...                               | ...                         |
| 76      | 11300                             | 2015/2                      |
| 77      | 11400                             | 2010/1                      |
| 78      | 11400                             | 2012/1                      |
4.3. Analysis of minimum daily flow empirical frequency variation

The empirical frequency method was used to analyse the change of annual minimum daily flow at Datong Station before and after the Three Gorges Reservoir construction. Considering that the annual minimum daily flow series after the construction of the Three Gorges Reservoir were relatively short, which cannot meet the requirements of the specification for more than 30 years, and the historical flow series were not investigated and analyzed, the analysis results are for reference only.

Since the Three Gorges Reservoir operation in 2003, the downstream natural runoff has been changed. To compare and analyze the empirical frequency variation of the minimum daily flow at Datong Station before and after the Three Gorges Reservoir construction, the design low water flow before and after the Three Gorges Reservoir operation were analyzed using 2003 as the node. The data series before the Three Gorges construction is from 1950 to 2003. The empirical frequency analysis needs to be based on the continuous low-water measured data of the long series, the data sequence after the Three Gorges construction is only 15 years from 2004 to 2018, which cannot meet the requirements of the long data series. Therefore, the minimum daily flow and the sub-minimum daily flow was used in this section.

Using the P-Ⅲ curve for line-fitting analysis, table 2 shows the low water flow analysis results at different frequencies before and after the Three Gorges Reservoir operation. It can be seen that in the frequency analysis results obtained by using the annual minimum daily flow series, the average value after the Three Gorges Reservoir operation was 2595m$^3$/s larger than that before the operation. Comparing the low water flow at different frequencies, the corresponding flow after the operation at the same frequency is larger than that before the operation. When the frequency is 95% (that is, low water occurs once in 20 years), the low water flow at Datong Station was 6528m$^3$/s before the Three Gorges Reservoir operation, and it was 9027m$^3$/s after the operation, which increases by 2499m$^3$/s. When the design frequency is 99% (that is, low water occurs once in 100 years), the low water flow at Datong Station was 5928m$^3$/s before the Three Gorges operation, and it was 8421m$^3$/s after the operation, which increases by 2493m$^3$/s. The low water flow occurring once in 100 years after the Three Gorges Reservoir operation equaled to that occurring once in 2 years before the operation. The results show that based on the empirical frequency curve of the minimum daily flow at Datong Station, the low water flow at Datong Station has increased after the Three Gorges Reservoir operation, and the low water risk of Datong Station has been reduced.

| Statistical period | Average (m$^3$/s) | Cv  | Cs  | Empirical frequency(%) |
|-------------------|------------------|-----|-----|------------------------|
|                   |                  |     |     | 50   | 75   | 80   | 90   | 95   | 97   | 99   | 99.9 |
| 1950~2003         | 8537             | 0.16| 0.56| 8410 | 7560 | 7366 | 6889 | 6528 | 6309 | 5928 | 5368 |
| 2004~2018         | 11132            | 0.13| 0.61| 10985| 10093| 9891 | 9397 | 9027 | 8805 | 8421 | 7869 |

5. Conclusions

(1) The annual minimum flow at Datong Station has shown a significant increasing trend, the linear tendency amplitude increases by 489m$^3$/s every 10 years. The annual minimum daily flow has increased after 2000, and the annual minimum flow has benn above 10,000m$^3$/s since 2008, and the historical rankings are all late in sorting (sorted from small to large).
(2) Analyzing the empirical frequency of the annual minimum daily flow at Datong Station before and after the Three Gorges Reservoir operation, the average after 2003 was 2595 m³/s larger than that before 2003. At the same frequency, the corresponding flow after 2003 was all larger than that before 2003. The low water flow occurring once in 100 years after 2003 equaled to that occurring once in 2 years before 2003.

(3) When analyzing the changes after the operation of the Three Gorges Reservoir, the time series used is from 2004 to 2018. The series is too short to meet the analysis needs, so the annual minimum flow and the sub-minimum flow are used for analysis, so the final results may have slight errors.

Acknowledgments
This work is funded by the National Key R&D Program of China (2017YFC0405400), the CRSRI Open Research Program (CKWV2019766/KY), the National Natural Science Foundation of China (U2040206, 41890822), National Public Research Institutes for Basic R&D Operating Expenses Special Project (CKSF2017061/SZ, CKSF2019433).

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