Trend and abrupt analysis of Dongting Lake water level and its driving forces using Mann-Kendall approach

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Abstract. In order to quantitatively describe the evolution trend of Dongting Lake water level and its driving forces, the Mann-Kendall approach is used to determine the lake water level and its driving forces, including the discharge of the Yangtze River at Yichang hydrological station, three outlets, and four rivers. The results show that the annual runoff and the runoff from September to October of the Yangtze River, the annual runoff of the three outlets have a significant downward trend, especially after the impoundment of the large reservoirs on the middle and upper reaches of Yangtze River. The Yangtze River discharge has a sudden change during the impoundment period, while the annual runoff and the runoff from September to October of the four rivers showed an insignificant decrease trend. The lake water level at Chenglingji decreased during the impoundment period of the large reservoirs slowed down, especially in September and October, so we can see that the reservoir impoundment is an important factor that decreasing the water level of Dongting Lake.

1. Introduction
Dongting Lake is one of the only two existing river-connected lakes in the middle and lower reaches of the Yangtze River [1-2]. It is located on the south bank of Jingjiang River and connected to “three outlets” (Songzi, Taiping and Ouchi). The Yangtze River flows into the Dongting Lake through Three outlets, and merges with the “four rivers” (Xiangjiang, Zishui, Yuanjiang and Lishui) in the Dongting Lake basin (Figure 1).

Figure 1. Location map of the Dongting Lake.
After the lake regulating, the water back to the Yangtze River again through Chenglingji hydrological station. Dongting Lake plays an important role in flood regulation, biodiversity conservation, and water resource utilization [3]. However, since the beginning of 21st century, due to the lack of rainfall in the lake basin, the simultaneous impoundment of the reservoirs in the Yangtze River and its tributaries, the erosion of the river bed caused by the clean water release [4], the discharge of three outlets has been greatly reduced, and the water level of the Dongting Lake has remained extreme low level. The water level of the lake mouth Chenglingji is 2.08m lower than that before the impoundment of the reservoirs, besides it enter to the dry season one month earlier [5]. At the same time, the water quality of the lake deteriorates remarkably, and the decrease of water level leads to the increase of TN and TP, which is an important reason of water quality deterioration.

The variation of lake water level not only changes the water storage capacity and heat capacity, but also changes the hydrodynamic process, causing the chain reaction of environmental capacity and ecological process [6]. Once the regular water level was changed artificially, the scale and distribution of different types of water units in the lake will change accordingly [7]. If the natural wetland distribution pattern is broken, it will affect the flooding and exposure time of different types of wetlands, and then the vegetation. It also affect the habitat conditions of animals such as rare migratory birds and fish. So making sense of the variation trend of lake water level has been widely valued by scholars [8]. The water level variation of Dongting Lake is closely related to its driving forces (discharge of Yangtze River, three outlets and four rivers). Therefore, it is of great significance to study the trend of driving forces. In this paper, based on the water level of the representative site of Dongting Lake and the long-term flow data of the Yangtze River, three outlets and four rivers, the Mann-Kendall approach is used to analyze the water level of Dongting Lake and its driving forces.

2. Mann-Kendall trend and abrupt test method

The trend detection methods mainly include Spearman rank correlation coefficient, Daniel trend test method, moving average method, Mann-Kendall non-parametric test method. Mann-Kendall is a well-known non-parametric test that was introduced by Mann and developed by Kendall, the main advantage of the method is that the test not only requires the data to be normally distributed but also does not follow any specific statistical distribution. This is perhaps the most widespread method for trend analyzing in hydrological variables.

2.1. Mann-Kendall trend test

In this study, we use the Mann-Kendall to detect water level and discharge trend. Mann-Kendall test is also prior to other non-parametric trend tests due to its simplicity and wide range of applicability. Therefore, this method is the best candidate for comparison with a new method. For a given time series of \(n\) data points where the \(x_j\) symbolizes the data point at the time \(j\), the Mann-Kendall statistics (\(S\)) is defined as the summation of the number of positive differences minus the number of negative differences:

\[
S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \text{sgn}(x_j - x_i)
\]  

(1)

Where \(N\) is the length of the data set, \(x_i\) and \(x_j\) denote the data values at times \(i\) and \(j\). While a negative value of \(S\) indicates a decreasing trend, positive value indicates an increasing trend. Then, statistical significance of the trend is checked as follows.

The null hypothesis (\(H_0\)) is a stated assumption that data are independent and identically distributed random variables (no trend is present) and if \(N>10\), the statistic \(S\) is expected to be normal distribution with a mean of zero and variance which is calculated by:

\[
Var(S) = \frac{n(n-1)(2n+5)}{18}
\]  

(2)
Then, the standard $Z$ value of the test statistics can be calculated as:

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{\text{var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{(S+1)}{\sqrt{\text{var}(S)}} & S < 0 \end{cases} \quad (3)$$

The calculated standard $Z$ value is compared with the standard normal distribution table with two-tailed confidence levels ($\alpha = 10\%$, $\alpha = 5\%$ and $\alpha = 1\%$). If $|Z| > Z_{\alpha/2}$, the null hypothesis ($H_0$) is invalid. Otherwise, the $H_0$ hypothesis is accepted that the trend is not statistically significant, and there is no trend in the time series (trendless time series). In this study, 90% and 95% two-tailed confidence levels were used for the Mann-Kendall method.

Besides identifying whether a trend exists, the Kendall inclination is usually used to detect the monotonic trend [9-10]. The magnitude of trend can be defined as follows:

$$\beta = \text{median}\left(\frac{x_i - x_j}{i - j}\right) \quad (j < i) \quad (4)$$

Positive $\beta$ indicates an increased trend, and negative $\beta$ indicates a decreased trend.

2.2. Abrupt change test
Abrupt change denotes a fast transition from one status to another. It occurs when the hydrological data is forced to cross a threshold. The Mann-Kendall abrupt change test is one of the most effective methods for testing abrupt time series changes which can clarify the start time of the mutation [9]. The method is used to analyze the change points of water level and discharge in this study. For time series $X_n$ ($n$ is the length of the data set), the order series ($S_k$) is given as follows:

$$S_k = \sum_{i=1}^{k} r_i \quad (k = 2, 3, \cdots, n) \quad (5)$$

In which

$$r_i = \begin{cases} 1, x_i > x_j, & (j = 1, 2, 3, \cdots, n) \\ 0, x_i \leq x_j, & \end{cases}$$

Where $x_j$ and $x_i$ are the sequential data values, and the statistic ($UF_k$) is defined as:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}} \quad (7)$$

Where $UF_1 = 0$, $E(S_k)$ and $\text{Var}(S_k)$ are the average value and variance of $S_k$, which can be calculated by following equations:

$$E(S_k) = \frac{n(n-1)}{4} \quad (8)$$

$$\text{Var}(S_k) = \frac{n(n-1)(2n+5)}{72} \quad (9)$$

Then, $UB_k$ is calculated by repeating the above process in the order $x_n, x_{n-1}, \cdots, x_2, x_1$ of the time series which makes $UB_k = UB_k$ ($UB_i = 0$, $k = n, n-1, \cdots, 2, 1$). The significance level is $p = 0.05$.

3. Trend and abrupt analysis of driving forces
Studies have shown that the inflow of Yangtze River and four rivers into the lake is the main driving forces for the water level of Dongting Lake. Therefore, if we want to grasp the trend and reasons of the water level change at Chenglingji, we must first analyze the trend of the flow into the lake. The information used is as follows: (1) Annual runoff and mean runoff from September to October of Yangtze River at Yichang hydrological station from 1950 to 2010; (2) Diversion flow and division ratio at three outlets from 1955 to 2008; (3) Annual runoff and mean runoff from September to
October of four rivers from 1988-2008; (4) Annual water level and mean water in October at Chenglingji Station from 1987 to 2009. The location of each station is shown in Figure 1. The Mann-Kendall approach was used to analyze the trend of the above various water level and flow data, and the results are shown in Table 1.

Table 1. Results of the statistical tests for Chenglingji water level and its driving forces.

| Item                      | Sample size                      | Mann-Kendall trend test | Trend  | Significance |
|---------------------------|----------------------------------|-------------------------|--------|--------------|
| Chenglingji Water level   | Mean annual water level from 1960-2008 | 3.0859 ***             | increase | significant   |
|                           | Mean water level in October from 1987-2009 | -2.958*                | decrease | significant   |
|                           | Annual runoff from 1950-2010      | -1.8109**              | decrease | significant   |
|                           | Runoff of Yangtze River from 1950-2010 | -1.9026**              | decrease | significant   |
|                           | Flow diversion from 1955-2005      | -6.6765***             | decrease | significant   |
|                           | Flow diversion from 1955-2005      | -7.6149***             | decrease | significant   |
|                           | Annual runoff from 1988-2008      | 1.1122                  | increase | non-significant |
|                           | Mean runoff from September and October from 1988-2008 | -0.70027              | decrease | non-significant |

Notes: *, **, *** respectively pass the 90%, 95%, 99% significance test.

3.1. Trend of runoff of Yangtze River at Yichang hydrological station

It can be seen from Table 1 that the annual runoff statistics of Yichang hydrological station $Z=-1.8109$ passed the significant test of 90% and 95% confidence, but did not pass the 99% significance test, indicating the annual runoff of Yichang station has downward trend, but the downward trend is not particularly significant. It can be seen from Figure 2 that the annual runoff of Yangtze River at Yichang hydrological station reached a maximum of 575.1 billion m$^3$ in 1954, and reached a minimum of 284.7 billion m$^3$ in 2006. The runoff statistics from September to October $Z=-1.9026$. According to Figure 3, the runoff from September to October is similar to the annual runoff change trend, and there is a decreasing trend.

![Figure 2. Trend and abrupt test of annual runoff at Yichang hydrological station.](image1)

![Figure 3. Trend and abrupt test of runoff in September and October at Yichang hydrological station.](image2)

The Mann-Kendall method was used to analyze the annual runoff sequence at Yichang hydrological station and the September-October runoff sequence. The results are shown in Figure 2. It can be seen that most of the statistical $UF$ is less than zero, which also confirms that the annual runoff is generally decreasing. The jumping points are 1959, 1961, 1972 and 2001 respectively. The average annual flow difference is -1521m$^3$/s, 1172m$^3$/s, 2253m$^3$/s, and -1764m$^3$/s; while the mean runoff from September to October is slightly different from the annual runoff sequence jump point, the jump occurs in 1959, 1998, 2003, year 2006. The reason is that the 1959 Yangtze River basin suffered from a drought in a hundred years, especially in July and August, the rainfall in many areas was less than 1/4 of the same period. The Yangtze River had the lowest water level in the same period in history. In
1998, although the Yangtze River basin occurred extraordinary floods, but the duration is mainly concentrated in the flood season from June to August, which has less impact on the runoff of the whole year, and the flow of Yichang station has increased from September to October. Three Gorges Reservoir stored water to 135.0 m in 2003, and 156.0 m in 2006 respectively, which caused the decrease of the discharge during the impoundment. Therefore, it can be considered that the impoundment of the Three Gorges Reservoir is an important reason for the decrease of the runoff sequence from September to October.

3.2. Trend of division flow and division ratio of three outlets
Jingjiang three outlets divide water into Dongting Lake through Songzi River, Hudu River and Ouchi River respectively. Division ratio means the ratio of the three outlets flow to the annual average runoff of the Yangtze River at Zhicheng hydrological station. Division ratio is an important parameter which tokens the characteristic of connectivity between the Yangtze River and the Dongting Lake, and directly affect the changes between the relationship between Dongting Lake and lakes.

It can be seen from Table 1 that the flow diversion and division ratio statistics Z have passed the 99% significance test, indicating that the flow diversion and division ratio have a significant downward trend. Figure 4 also confirms this result. The average runoff of the three outlets in 1955-2005 was 89.9 billion m$^3$, and the diversion ratio was 19.5%. It can be seen from Figure 5 that the division ratio tends to decrease year by year. For example, the annual runoff of 1946-1966 (before Jingjiang artificial cutoffs) is 134.4 million m$^3$, and the division ratio is 29.2%; The runoff is 101.4 billion m$^3$ from 1967-1972 (cutting), the division ratio is 23.3%; the annual runoff from 1973-1980 (after artificial cutoffs) is 85 billion m$^3$, the division ratio is 18.6%; the annual runoff from 1981-2002 (after Gezhouba Reservoir operation) is 68.7 billion m$^3$, the division ratio is 14.7%; in 2003-2005 (after operation of the Three Gorges Reservoir), the annual runoff is only 57.8 billion m$^3$, and the division ratio is 13.5%.

The Mann-Kendall method was used to analyze the division flow and division ratio from 1955-2005 respectively. It shows that the statistic $U_F$ is mostly less than zero, indicating that the division flow and division ratio are generally in a downward trend. In 1975, the only sudden change point is that the time period is in the Jingjiang main stream cutting period, and the Jingjiang hydraulic gradient increases, resulting in a rapid decrease in the flow of the three outlets.

Figure 4. Trend and abrupt test of annual runoff at three outlets.

Figure 5. Trend and abrupt test of division ratio at three outlets.

3.3. Trends of runoff of four rivers
The four rivers is an important part of the water resources of Hunan Province. The total drainage area in Hunan Province is 128,800 km$^2$. The flow of four rivers into the lake accounts for about 60% of the total amount of water in the lake. The average annual water intake of the lake is 166.9 billion m$^3$, which plays an important role in maintaining the lake water level.

It can be seen from Table 1 that the annual runoff statistics of four rivers from 1988 to 2008 Z =1.1122, indicating that the flow has an increasing trend, but the trend is not significant; and the runoff statistics from September to October of 1988-2008 Z =-0.70027, showing an insignificant decrease trend. Figure 6 shows that the annual runoff of the four rivers is generally increasing, with no abrupt changes. Figure 7 shows that the annual runoff of the September-October period of the four rivers
occurred in 1993, 2001 and 2003. According to historical observations, the sudden change is closely related to the decrease of rainfall in the autumn of that year.

4. Trend of Dongting Lake water level at Chenglingji hydrological station

4.1. Analysis of the trend of water level at Chenglingji hydrological station

It can be seen from Table 1 that the water level statistics $Z$ of Chenglingji is 3.0859, which indicates that the water level in the whole period of 1960-2008 is on the rise, but from each stage, the water level in the 1960s and 1980s is generally low. In the early 1980s and early 21st centuries, the water level was high. The important reason was that sedimentation caused the lake basin to rise. Since 2000, especially since the Three Gorges Reservoir impounded in 2003, the water level has shown a significant downward trend (Figure 8). The lake water level in October showed a stable fluctuation trend before 2000, and a sudden change occurred in 2003, after which the water level continued to decrease (Figure 9). According to the flow analysis of the four rivers, there is no significant change in the annual runoff of the four rivers and the runoff from September to October, and the water level at Chenglingji from September to October has shown a significant downward trend after 2000. At the same time, the flow of the Yangtze River at Yichang Station from September to October has shown a significant downward trend. It can be said that the main driving forces of the water level change in Dongting Lake is not the change of flow in its own tributary, but the simultaneous impoundment of the large reservoir in the middle and upper reaches of Yangtze River. It should be seen that the impoundment of the reservoirs is one of the most important reasons that cause the change of the Dongting Lake water level.

4.2. Analysis of factors affecting water level Change at Chenglingji hydrological station

There are three main reasons that affecting the reduction of the Chenglingji water level in October: (1) The precipitation in the middle and upper reaches of the Yangtze River is reduced. Generally, the rainfall is random, the annual rainfall is unlikely to be less or more than normal. However, the year with less rainfall after August will increase the low water level when it is combined with other water level reduction factors. (2) Humans activity. It mainly includes sand mining and waterway management. Human activities such as sand mining have actually been formed, and their impact on water level reduction will not change. It is a long-term phenomenon, but it can be controlled after
taking necessary measures; (3) Impoundment of the large reservoirs in the middle and upper reaches of Yangtze River. According to the operation plan, the reservoir group storage period is mainly concentrated in September and October. These reservoirs will store water after the flood season every year, which will inevitably affect the downstream flow and the water level of the Dongting Lake.

5. Conclusions
The Mann-Kendall approach was used to analyze the change trend of the water level and its driving forces at Chenglingji hydrological station. The main conclusions are as follows:

1) The annual runoff of Yangtze River at Yichang station showed an overall downward trend, but the downward trend was not particularly obvious; the runoff from September to October showed an overall downward trend. The impoundment of TGR in 2003 and 2006 caused the decrease of the flow. Therefore, it can be considered that the impoundment of the reservoirs is an important reason for the decrease of the runoff from September to October; the division flow and division ratio of the three outlets have a significant downward trend; the flow of four rivers has an increasing trend, but the trend is not significant.

2) The water level of Dongting Lake at hydrological station from 1961-2008 has been increasing. However, since the Three Gorges Reservoir impounded in 2003, the water level showed a significant downward trend, while the water level in October changed suddenly, and then the water level continued to decrease, indicating that reservoir impoundment is an impoundment reason that lower the lake water level.

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References
[1] Li ZW, Nie XD, Zhang Y, et al. 2016 Assessing the influence of water level on schistosomiasis in Dongting Lake region before and after the construction of Three Gorges Dam. Environmental Monitoring and Assessment 188(1)
[2] Yang B, Liao DX, Li JB, et al. 2014 Relationship between water level and wetland ecosystem health state in east Dongting Lake Resources and Environment in the Yangtze Basin 23(8)
[3] Wang H, Zhang ZZ, Song DP, et al. 2015 Water and sediment transport mechanisms in a large river-connected lake Water and Environment Journal 29(3)
[4] Cheng JX, Xu LG, Wang XL, et al. 2018 Assessment of hydrologic alteration induced by the Three Gorges Dam in Dongting Lake, China River Research and Applications 34(7)
[5] Yuan Y, Zhang C, Zeng G, et al. 2016 Quantitative assessment of the contribution of climate variability and human activity to streamflow alteration in Dongting Lake, China Hydrological Processes 30(12)
[6] Liang J, Yu X, Zeng GM, et al. 2014 A hydrologic index based method for determining ecologically acceptable water-level range of Dongting Lake Journal of Limnology 74(1)
[7] Huang Q, Sun ZD, Opp C, et al. 2014 Hydrological Drought at Dongting Lake: Its Detection, Characterization, and Challenges Associated With Three Gorges Dam in Central Yangtze, China Water Resources Management 28(15)
[8] Coops H, Beklioglu M, Crisman TL 2003 The role of water-level fluctuations in shallow lake ecosystems–workshop conclusions Hydrobiologia 506(1-3)
[9] Xu M, Kang S, Wu H, et al. 2018 Detection of spatio-temporal variability of air temperature and precipitation based on long-term meteorological station observations over Tianshan Mountains, Central Asia Atmospheric Research 203
[10] Chen Y, Guan Y, Shao G, et al. 2016 Investigating Trends in Streamflow and Precipitation in Huangfuchuan Basin with Wavelet Analysis and the Mann-Kendall Test Water 8(3)