Study on the characteristics of water level during the flood season in the Poyang Lake, China

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Abstract. Characteristics analysis on the water level in the Poyang Lake, China during the flood season in 1956-2012 are presented, including the trend test, abrupt change detection and periodic identification. The Mann-Kendall test and Spearman’s rho test were conducted with results showing no significant trend in both the flood season averaged WLs and monthly averaged WLs in the Poyang Lake. The sequential Mann-Kendall test and Pettitt test were carried out and showed no significant abrupt change in trend of WLs as well. Besides, the Morlet continuous wavelet transform was applied to identify the periodic characteristics in trend of WLs. The results indicated that there were three types scale of periodic component, in which the periodic oscillation in 35 years was the first main period of the annual flood season averaged WLs with basically two oscillations, while the periodic oscillation in 11 years and 5 years were the second and third main periods, respectively.

1. Introduction
Flood is one of the most common natural hazards worldwide which often lead to severe economic losses and damage to towns and farms, and under the strong influence of the East Asian monsoon, it is also the most frequently occurred natural disaster in China [1, 2]. The Yangtze River is widely known for its huge annual runoff volume and also floods frequently occurred especially in the middle and lower reaches. The Poyang Lake (115°49′E-116°46′E, 28°24′N-29°46′N) that well known as the largest freshwater lake in China is located in the north of the Jiangxi Province and at the southern bank of the middle reach of the Yangtze River as well. The Lake receives inflow from its five major tributaries, namely Ganjiang River, Fuhe River, Xinjiang River, Raohe River and Xiushui River, respectively. In the meantime, it also drains outflow through the waterway to the Yangtze River (Figure 1). Thus, it is a typical seasonal lake that has been described as “flooding like sea, drying like thread” [3]. Its drainage area of approximately 162225 km² occupies nearly 97.2% of territory area of the Jiangxi Province and 9% of the total drainage area of the Yangtze River Basin, respectively. Based on the observations derived from Hukou hydrological station where is located in the confluence of the Poyang lake and the Yangtze River, the annual averaged runoff volume of $1.512 \times 10^{11}$ m³ accounts for 16.9% of the annual averaged runoff volume measured at Datong station in the lower reach of the Yangtze River during 1950-2018. The Poyang Lake is planned as a vital place to store and regulate the flood volume for the middle and lower reaches of the Yangtze River, an essential source to provide water resource for the lower reach, as
well as an important component in ecosystem of the Yangtze River Basin. Therefore, researches on the characteristics of related issues in flood control for the Poyang Lake occupies an important place in the protection, regulation and utilization of the Yangtze River.

In this study, characteristics analysis were conducted on the water level (WL) in the Poyang Lake during the flood season in 1956-2012. Both the Mann-Kendall (MK) test and Spearman’s rho (SR) test were applied to investigate the trend characteristics in the WL data series observed during the flood season. To detect the abrupt change in trend of WLs, the sequential Mann-Kendall (SQMK) test and Pettitt test were also employed, respectively. Finally, the Morlet continuous wavelet transform (CWT) was used to identify the periodic characteristics.

Figure 1. Standard false color composite of Landsat 7 ETM+ and Landsat 8 OLI cloud free images (bands NIR, red, green) acquired during the flood season in 2019

2. Data sets and methods

2.1. Study area
The Poyang Lake is located in a typical subtropical monsoon climate region, with an annual mean temperature of 16-18°C and an annual mean precipitation of 1350-1800 mm. During the flood season, the lake covers an area of 3800 km², inundating the low-lying alluvial plains surrounding the lake and along large rivers flowing into it [4]. The Poyang Lake is commonly divided into southern and northern parts due to the presence of the Songmen Mountain, in which the southern part is the main lake area with relatively shallow water depth, and the northern part is a narrow waterway to the Yangtze River. The Poyang Lake is about 173 km in length from north to south and 74 km width from east to west, with the narrowest point of 2.8 km located in Pingfeng and a total shoreline of 1200 km. The terrain of lake bed inclines from east to west and from south to north, where is flat with elevation down to -8 m (a.m.s.l., Wusong datum) in the deep depth zone of the main lake area, and relatively narrow and deep in the waterway that in NNE direction and with elevation about 3-5 m lower than the former area. Dai et al.
[3] suggested that the Poyang Lake characterized by seasonal water level fluctuations could be divided into four distinct periods, namely the dry season (from December to March), rising period (from April to June, the rising season), flood season (from July to September, the peak period) and retreating period (from October to November).

2.2. Data sets

Data sets employed in this study included time series of daily averaged WL derived from the observations at four hydrological stations such as Tangyin (TY), Duchang (DC), Xingzi (XZ) and Hukou (HK) of the Poyang Lake during the main flood season period (April - September) in 1956-2012, which were mainly provided by the Bureau of Hydrology, Changjiang Water Resources Commission and Hydrology Bureau of Jiangxi Province. And all the WLs were measured relative to the Wusong datum. The locations of the four hydrological stations are shown in Figure 1. It can be seen that the TY station is located nearly in the center of the Poyang Lake, and the DC station is near the inlet of the waterway to the Yangtze River, which are representative stations less affected by the discharge from the five major tributaries or the high WL in the Yangtze River. The XZ station and HK station are located in the waterway to the Yangtze River, from which the observations can be applied to identify the characteristics of WL influenced from both the Poyang Lake and the Yangtze River. Besides, missing data were interpolated with the correlations among stations derived from the available WL data.

2.3. Methods

2.3.1. Trend test and abrupt change detection method

In this study, trend analysis was conducted by applying the MK test and SR test, which are both rank-based non-parametric methods. Yue et al. [5] examined the power of both the MK test and SR test to detect monotonic trends in hydrological series and showed that the two tests become similarly more powerful as sample size increases. The MK test is proven to be little sensitive to outliers and can provide the main advantage in distribution free, for which it is commonly used for the assessment of significance of trends in many hydrologic and climatic time series [6]. In the MK test, the positive test statistics indicates an increase trend, whereas the negative test statistics indicates a decrease trend, which is similar to the SR test. The detail description and criteria of the MK test and SR test can be found in Rahman et al. [7].

The non-parametric SQMK test and Pettitt test were also employed to detect the abrupt change in trend of time series. The SQMK test can be used to detect an approximate beginning point of significant trends. And the Pettitt test is more sensitive to breaks in the middle of a time series [8]. The detail description and criteria of the SQMK test and Pettitt test can be found in Sabzevari et al. [9].

2.3.2. Periodic inspection method

The Morlet mother wavelet was employed for the CWT to analyze the periodic characteristics of time series data. Both the CWT and discrete wavelet transform are the main types of wavelet transforms which are used for applications based on study purpose. The Haar, Meyer, Morlet and Daubechies mother wavelets are commonly used in hydrometeorological studies. The CWT can be used for mapping the periodic characteristics of non-stationary signals. Thus, the CWT in a time-frequency representation of signal $f(t)$ can be expressed by the following equation:

$$W_f(a,b)=\frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\overline{\psi}_{a,b}(\frac{t-b}{a})dt$$

Where $W_f(a,b)$ is the wavelet transform coefficients; $a$ is the scale parameter, $b$ is the translation parameter; $\psi(t)$ is the mother wavelet function, namely the Morlet wavelet that used in this study. $\overline{\psi}_{a,b}$ is the complex conjugate function of $\psi_{a,b}$. $t$ is the time. Hence, $W_f(a,b)$ can be obtained by continuously varying the scale and the position parameter, respectively, which is to select the different
portions of the signal and analyze the different scale variations [10]. The detailed transform expressions can be found in Adarsh et al. [11]. Most observed hydrometeorological time series data are discrete, and the signal can be expressed as \( f(k\Delta t) \) \((k=1, 2, ..., N)\), in which \( \Delta t \) is the sample interval. The above wavelet transform Equation (1) can be discreted as:

\[
W_j(a,b) = \frac{1}{\sqrt{a}} \sum_{k=1}^{N} f(k\Delta t) \tilde{\psi}_{a,b}(k\Delta t - b)
\]  

Besides, it should be noted that the critical values of \( \pm 1.96 \) at 0.05 significance level were set criteria in this study.

3. Results and discussion

3.1. Basic characteristics analysis

The characteristic monthly averaged WLs during the flood seasons of 1956-2012 in the Poyang Lake are presented in box-plots of Figure 2 and Table 1. For example, the mean value of the flood season averaged WLs at TY was 16.06 [16.02, 16.10] m (the range represents 95% confidence intervals, CIs), while the mean value of the monthly averaged WLs during April - September was 14.28 [14.24, 14.33] m, 15.23 [15.15, 15.30] m, 16.22 [16.13, 16.30] m, 17.77 [17.68, 17.87] m, 16.79 [16.69, 16.89] m and 16.01 [15.91, 16.10] m, respectively. The mean value of the flood season averaged WLs at HK was 15.40 [15.34-15.47] m, while the mean value of the monthly averaged WLs during April - September was 12.03 [11.92, 12.15] m, 14.07 [13.95, 14.19] m, 15.85 [15.74, 15.96] m, 17.81 [17.70, 17.92] m, 16.79 [16.67, 16.91] m and 15.80 [15.67, 15.92] m, respectively.

![Figure 2](image.png)

Figure 2. The box-plots of monthly averaged WLs during the flood season in 1956-2012

| Time series       | TY         | DC         | XZ         | HK         |
|-------------------|------------|------------|------------|------------|
| Flood season      | 16.06      | 16.02-16.10| 15.69      | 15.65-15.73| 15.66      | 15.61-15.71| 15.40      | 15.34-15.47|
| April             | 14.28      | 14.24-14.33| 13.48      | 13.42-13.55| 12.90      | 12.82-12.97| 12.03      | 11.92-12.15|
| May               | 15.23      | 15.15-15.30| 14.80      | 14.72-14.88| 14.67      | 14.58-14.76| 14.07      | 13.95-14.19|
| June              | 16.22      | 16.13-16.30| 16.00      | 15.91-16.08| 16.05      | 15.97-16.14| 15.85      | 15.74-15.96|
| July              | 17.77      | 17.68-17.87| 17.54\*    | 17.45-17.63| 17.73      | 17.65-17.82| 17.81      | 17.70-17.92|
| August            | 16.79      | 16.69-16.89| 16.53      | 16.44-16.62| 16.70      | 16.60-16.79| 16.79      | 16.67-16.91|
| September         | 16.01      | 15.91-16.10| 15.73      | 15.64-15.83| 15.85      | 15.75-15.95| 15.80      | 15.67-15.92|

\* Data when reverse surface slope occurred in the waterway to the Yangtze River are shown in bold.

It can be seen that the monthly averaged WLs were the highest in July during the flood season, under the combination of both the lake-flood and river-flood. And the WLs at TY were relatively higher than...
those observed at other stations, and they presented as TY > DC > XZ > HK in most time during the flood season especially when lake-flood dominated. However, for outlet flow was retarded by the high WL in the Yangtze River when river-flood dominated during July and August, the water surface slope tended to be reversed frequently in the waterway to the Yangtze River. Besides, that the WLs at XZ were higher than those at DC and HK can also be observed, during June before the river-flood dominated period and September after the river-flood dominated period as well. This may be due to the fact that discharge flow in the Yangtze River was insufficient to maintain the retarding effect and then the WL receded at HK.

3.2. Trend analysis and abrupt change detection

The MK and two-tailed SR trend test results of characteristic WLs in the flood seasons during 1956-2012 in the Poyang Lake are shown in Table 2. It can be seen that there was no significant trend in the flood season averaged WLs during 1956-2012 at TY, DC, XZ or HK. However, the flood season averaged WLs increased slightly overall. Similar results can be drawn from the trend tests on the monthly averaged WLs during the flood season. It is noteworthy that a statistically significant decrease trend in the monthly averaged WLs of May was detected at 0.10 significance level.

The SQMK and Pettitt test results of characteristic WLs are shown in Figure 3 and Table 3, respectively. The detailed SQMK analysis is limited to the abrupt change detection in trend of the monthly averaged WLs in July, which started to rise from 1965-1966 and crossed the critical line at 0.05 significance level in 1996-1997. After the monthly averaged WLs reached the peak in 1998, the trend was reversed to decrease gradually. However, there were two crossing points located between the significance levels and thus no definite abrupt change could be identified. The Pettitt test also indicated that the flood season averaged WLs and monthly averaged WLs both increased slightly during the major period but no significant abrupt change occurred.

| Time series | TY MK | SR | Trend | DC MK | SR | Trend | XZ MK | SR | Trend | HK MK | SR | Trend |
|-------------|-------|----|-------|-------|----|-------|-------|----|-------|-------|----|-------|
| Flood season | 0.38  | 0.43 | +    | 0.12  | 0.07 | +    | 0.09  | 0.13 | +    | 0.20  | 0.29 | +    |
| Apr.        | 0.78  | 0.84 | +    | -0.43 | -0.43 | -    | -0.63 | -0.52 | -    | -0.10 | -0.09 | -    |
| May.        | -1.69 | -1.70 | -    | -1.85 | -1.89 | -    | -1.74 | -1.79 | -    | -1.62 | -1.62 | -    |
| Jun.        | 0.05  | 0.06 | +    | -0.42 | -0.35 | -    | -0.28 | -0.19 | -    | -0.17 | -0.12 | -    |
| Jul.        | 0.64  | 0.66 | +    | 0.59  | 0.58  | +    | 0.65  | 0.62  | +    | 0.65  | 0.60  | +    |
| Aug.        | 1.37  | 1.28 | +    | 1.26  | 1.14  | +    | 1.30  | 1.19  | +    | 1.34  | 1.20  | +    |
| Sept.       | 0.46  | 0.46 | +    | 0.32  | 0.33  | +    | 0.34  | 0.37  | +    | 0.38  | 0.41  | +    |
3.3. Periodic inspection

The Morlet CWT results of the normalized flood season averaged WLs during 1956-2012 in the Poyang Lake are shown in Figure 4. Figure 4(a) and Figure 4(c) are the wavelet coefficient contour maps at TY and HK, respectively. Figure 4(b) and Figure 4(d) are the wavelet variance plots at TY and HK, respectively.

Table 3. The Pettitt test characteristic statistics of WLs during 1956-2012

| Time series   | TY | DC | XZ | HK |
|--------------|----|----|----|----|
|               |    |    |    |    |
| Flood season  |    |    |    |    |
| Apr.          |    |    |    |    |
| May           |    |    |    |    |
| Jun.          |    |    |    |    |
| Jul.          |    |    |    |    |
| Aug.          |    |    |    |    |
| Sept.         |    |    |    |    |

| t     | p  | Shift | t     | p  | Shift | t     | p  | Shift |
|-------|----|-------|-------|----|-------|-------|----|-------|
| 1972  | 0.40 | +   | 1972  | 0.51 | +   | 1972  | 0.49 | +   | 1972  | 0.44 | +   |
| 1974  | 0.09 | +   | 1974  | 0.42 | +   | 1974  | 0.50 | +   | 1979  | 0.44 | +   |
| 2006  | 0.13 | +   | 2006  | 0.09 | +   | 2006  | 0.11 | +   | 2006  | 0.15 | +   |
| 1969  | 0.81 | +   | 1978  | 0.84 | +   | 1969  | 0.82 | +   | 1969  | 0.75 | +   |
| 1988  | 0.28 | +   | 1988  | 0.31 | +   | 1988  | 0.28 | +   | 1988  | 0.28 | +   |
| 1979  | 0.17 | +   | 1979  | 0.22 | +   | 1979  | 0.21 | +   | 1979  | 0.19 | +   |
| 1978  | 0.37 | +   | 1978  | 0.43 | +   | 1978  | 0.42 | +   | 1978  | 0.39 | +   |
In these contour maps, that real part of wavelet coefficient is positive denotes the WL is above the average, whereas that real part is negative denotes the WL is below the average. In Figure 4(a) and Figure 4(c), there were three types scale of periodic component, namely 23-41 years, 9-15 years and 4-8 years. As the 23-41 years scale that occupied almost the entire time domain, basically two oscillations with the alternately high and low flood season averaged WLs can be seen. As the 9-15 years scale, typical five oscillations were stable before 2004. However, as the 4-8 years scale, stable five oscillations and the other two oscillations can be detected before and after 1999, respectively. Figure 4(b) and Figure 4(d) both show three obvious peaks and indicate the relatively strong periodic oscillations in 35 years, 11 years and 5 years, which is also in accordance with the results from Figure 4(a) and Figure 4(c). Thus, the periodic oscillation in 35 years was the first main period of the annual flood season averaged WLs, while the periodic oscillations in 11 years and 5 years were the second and third main period, respectively.

4. Conclusions
The study presents characteristics analysis on WL in the Poyang Lake during the flood season in 1956-2012. The monthly averaged WLs were the highest in July during the flood season, and those at TY were relatively higher. The water surface slope tended to be reversed frequently in the waterway to the Yangtze River when river-flood dominated during July and August. The MK test and two-tailed SR test results both indicate that there was no significant trend in the flood season averaged or monthly averaged WLs during 1956-2012 at TY, DC, XZ or HK, though the averaged WLs increased slightly in most time domain. The SQMK test and Pettitt test results both show no significant abrupt change in trend of averaged WLs. And in the Morlet CWT results, three types scale of periodic component were identified, in which the periodic oscillation in 35 years was the first main period of the annual flood season averaged WLs with basically two oscillations.
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