Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 14 No 8, 2706 doi: 10.2166/wcc.2023.044

Variation characteristics of Poyang Lake water area and its response to meteorological factors in the past 35 years

Feiyan Jiang, Runyuan Kuang*, Aoxin Xia, Qianyun Feng and Meng Zhou
School of Civil and Surveying & Mapping Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China
*Corresponding author. E-mail: rykuang@163.com

FJ, 0000-0001-8621-5202

ABSTRACT

The hydrological situation of Poyang Lake has undergone changes due to the influence of climate change and human activities. Its typical throughput and seasonal variation characteristics have attracted much attention. Research on the long-term hydrological variation of Poyang Lake needs to be enriched. Using remote sensing images from 1986 to 2020 and combining them with the Normalized Difference Vegetation Index (NDVI), this study extracts the water area of Poyang Lake and analyzes its variation characteristics. The results show that the water area of Poyang Lake has a consistent periodic variation with meteorological factors. Both the water area and meteorological factors have a main period of 18 m (months). Water area change points occurred in 2003, 2010, and 2016. In different research periods, there is a significant correlation between the water area and meteorological factor changes. Furthermore, the correlation between water vapor pressure and precipitation with the water area change is the strongest.

Key words: longtime series, NDVI, Poyang Lake water regime change

HIGHLIGHTS

- The change of the Poyang Lake water area in long time series was studied.
- The change of long-term meteorological factors was studied.
- The response relationship between the water area and meteorological factors was studied.
- Wavelet analysis and M-K mutation test were applied.
- Multi-source long time series remote sensing image application was applied.

INTRODUCTION

Inland water bodies such as rivers and lakes are an important part of global water resources. However, with the increase in pollution caused by industrial production, the problem of inland water pollution and spatial variation of water quality caused by climate change and human activities have become a major concern for scholars and governments. Rivers and lakes provide important water sources and habitats for aquatic organisms, regulate flow, and improve multiple ecological functions and regional microclimate. Changes in hydrology can reflect the combined effects of climate and human activities on the water cycle and the ecosystem (Yan *et al.* 2020). Poyang Lake is the largest freshwater lake in China. Since the 21st century, climate change and frequent human activities have caused changes in the water regime of Poyang Lake (Liu *et al.* 2020). The existing research shows that since 2003, the low water levels and extreme low water levels of Poyang Lake have occurred earlier and the duration of low water levels has been prolonged, which is closely related to the completion of the Three Gorges Dam (Yang & Liao 2017).

Zheng *et al.* used Landsat data, multi-spectral image vegetation classification, and principal components to analyze the impact of the completion of the Three Gorges Dam on the hydrological handover at the Poyang Lake estuary. The results showed that after the impoundment of the Three Gorges Dam, the dry season of Poyang Lake was prolonged, the flood season was shortened (Lyu *et al.* 2018), and the hydrological changes in the basin were obvious (Zheng *et al.* 2020). Sun & Ma used satellite altimetry data and MODIS data to invert the water level data of Poyang Lake and used the area and water level changes to simulate its water volume change, the linear relationship between the area and water level, and the water balance relationship to calculate the water volume interaction between Poyang Lake and the Yangtze River. The results showed that the Yangtze River mainstream has a certain backing effect on the water intrusion of Poyang Lake in the rainy season with increased precipitation (Sun & Ma 2020). Tian *et al.* extracted the water area of Poyang Lake from Landsat-8 images and Sentinel-1 images. A prediction model based on 45-day cumulative precipitation data was established. According to the verification of real data, it showed that the prediction model had a good effect on precipitation in the southwest of Poyang Lake, which verified the correlation between hydrological changes and precipitation changes in Poyang Lake (Tian *et al.* 2020). Liu *et al.* (2020), based on remote sensing data and DEM data, extracted the Normalized Difference Water Index (NDWI) of Poyang Lake, estimated the water volume information by using the dynamic storage capacity method, studied the long-term dynamic changes of the water volume of Poyang Lake from 1989 to 2018, and analyzed its driving factors and ecological effects. Zhang *et al.* (2019) used the Landsat image and the GaoFen (GF) image NDWI to extract the water body of Poyang Lake, combined with the time series data of the Hukou hydrological station in the Poyang Lake area, and established the relationship model between the water area and the water level in different periods of the year. The model can monitor the continuous change of lake water level and has important guidance and reference significance for drawing volume curves (Zhang *et al.* 2019). Wu *et al.* and Tian *et al.* used remote sensing images of Poyang Lake in the dry season and the flood season from 1980 to 2010 to extract its water area and explored the main driving factors affecting the change of the Poyang Lake water area. The results showed that the water area in the flood season and the dry season showed a decreasing trend. Human activities such as the construction of water conservancy projects in the upper reaches of the Yangtze River and the development of urbanization in the basin were the main driving factors for the reduction of water area in Poyang Lake during the flood season. Land use change caused by human activities was the main reason for the significant reduction of water area in Poyang Lake in the dry season (Tian *et al.* 2020; Wu *et al.* 2021). Liu *et al.* used the NDWI/Normalized Difference Vegetation Index (NDVI) joint method to extract the Poyang Lake water area of the Coastal Zone Imager (CZI) multi-spectral image of the HY-1C/D satellite and analyzed the time series of the Poyang Lake area. Combined with the water level data, the quantitative relationship between the water area and the water level of Poyang Lake was analyzed, and the flood risk area of Poyang Lake was identified. The results show that the water area of the Poyang Lake area has a high correlation with the water level, and the flood-prone areas are mainly located in the southeast and west regions of the lake (Liu *et al.* 2022). All of these studies have revealed the hydrological changes in the Poyang Lake water area and its influencing factors. There are many factors affecting the hydrological changes in Poyang Lake, mainly including meteorological factors, water from the Yangtze River, water from five rivers, and human activities. In order to analyze the long-term series of Poyang Lake water area regime changes and its response to meteorology, this paper used Advanced Very High Resolution Radiometer (AVHRR) images and Moderate-Resolution Imaging Spectroradiometer (MODIS) images to construct time series data of the Poyang Lake water area from 1986 to 2020 and combined the Mann–Kendall (M–K) mutation test, wavelet analysis, correlation analysis, and other methods to quantitatively analyze the water regime changes and its response to meteorology. This provides new technical support and policy recommendations for Poyang Lake water regime change research, regional ecological protection, and regional development and construction.

METHODS

Study area

Poyang Lake is in the northern part of Jiangxi Province, which is located on the south bank of the middle and lower reaches of the Yangtze River (Guo *et al.* 2021). It receives water from the Ganjiang River, Fuhe River, Xin River, Rao River, and Xiushui River and connects to the Yangtze River through the lake emissary (Guo *et al.* 2021; Yang & Liao 2017). Poyang Lake is bounded by Songmen Mountain, which divides the lake into two parts: the north, which is the channel into the river; and the south, which is the main lake body, and covers an area of 3,150 km^2 (Yang & Liao 2017). The region has a typical subtropical monsoon climate, and the water area changes significantly with the seasons (Tian *et al.* 2021). The wet season is from June to September, and the dry season is from December to February. As the largest freshwater lake in China and one of the top 10 ecological function protected areas in China (Liu *et al.* 2011), Poyang Lake's hydrological regime change has always been a focus of attention for domestic and foreign researchers. Poyang Lake plays an important role in regulating the water level of the Yangtze River, conserving local water sources, and maintaining the ecological balance around it. Therefore, the study of the long-term changes in the Poyang Lake water area and its influencing factors is crucial for the ecological protection and ecological health of the Poyang Lake area.

This paper selected the Poyang Lake water area as the study area. In addition, this paper also used the precipitation, temperature, relative humidity, and water vapor pressure of 17 stations in the Poyang Lake Basin collected by the National Meteorological Science Data Center and the Ministry of Water Resources (https://data.cma.cn/) from 1985 to 2019. The scope and location of the study area are shown in Figure 1.

Data

In this paper, AVHRR LAC 1KM 1B dataset and Terra-MODIS dataset are used to extract and calculate the water area of the Poyang Lake area (data can be downloaded from www.avl, class.noaa.gov, and https://earthdata.nasa.gov). AVHRR LAC is the regional land cover data that has coverage time from 1985 to the present, with a time resolution of 1 day and a spatial resolution of 1.1 km.

Water body extraction method

According to the band setting of the AVHRR image, the band ratio method, specifically the NDVI method, is used in combination with the threshold method to extract the water body of the Poyang Lake area. The calculation formula of the NDVI is as follows:

$$NDVI = \frac{Band_{NIR} - Band_{Red}}{Band_{NIR} + Band_{Red}} \quad (1)$$

$Band_{NIR}$ represents the near infrared band; $Band_{Red}$ represents the red band.

The water body of the AVHRR image is extracted by using a combination of visual interpretation experience, superimposed image judgment, and reference to other scholars' research experience. Through repeated experiments to compare the extraction results, the water range of the Poyang Lake area in the AVHRR image can be determined. The water body of the MODIS

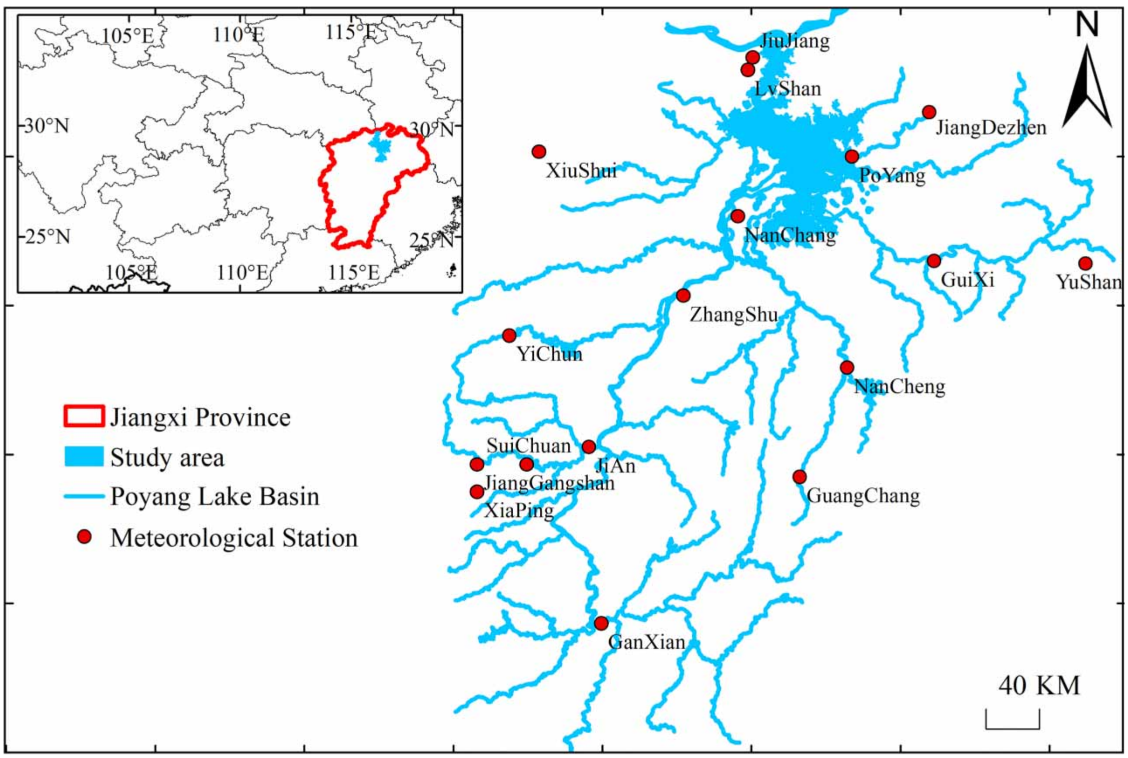

Figure 1 | Location of the study area.

image is obtained by comparing the water body pixel range with the ISODATA unsupervised classification. The water area extraction results obtained from the two datasets are compared with the existing research results and found to have a consistent trend in the change of water area in the Poyang Lake area.

M–K mutation test

The M–K trend test is a non-parametric statistical test method widely used in hydrological time series analysis. The M–K test can be used to determine whether there is a mutation in the time series data which, if there is, can determine the time of mutation. This method is commonly used in hydrological analysis, and in this specific case, the study uses it to determine the overall trend and point of change in the water area of the Poyang Lake area. The principle is as follows:

For data with time series Xn, constructing cumulative sample number sequence dk, $xj < xi(i \geq j \geq 1)$:

$$dk = \sum_{i=1}^{n} \gamma i(k = 1, 2, \ldots, n), \ \gamma i = \begin{cases} 1 & xi > xj \\ 0 & xi \leq xj \end{cases} \tag{2}$$

Assuming that the time series is independent and random, define statistics

$$\mathrm{UFk} = \frac{dk - E(dk)}{\sqrt{\mathrm{Var}(dk)}}, k = 1, 2, 3, \ldots, n \tag{3}$$

Of which, $\mathrm{UFk} = 0$, $E(dk)$, $\mathrm{Var}(dk)$ is the mean and variance of the cumulative count when $x_1, x_2, x_3, \ldots, x_n$ are independent of each other and have the same continuous distribution, there is

$$E(dk) = \frac{k(k-1)}{4}, \ \mathrm{Var}(dk) = \frac{k(k-1)(2k+5)}{72} \tag{4}$$

UFk means the standard normal distribution; it is a sequence of statistics $x_1, x_2, x_3, \ldots, x_n$ calculated by time series, again by time series x_n negative sequence $x_n, x_{n-1}, \ldots x_1$; repeat this process, multiply the result by -1 to get the sequence UB_k. Given the significance level α, viewing a normal distribution table, if $|\mathrm{UF}_i| > U\alpha$, it indicates that there is a clear trend change in the time series; if $\mathrm{UF}_k = \mathrm{UB}_k$, and $|\mathrm{UF}_k| < |U\alpha|$, then point k is the mutation point. This study takes $\alpha = 0.05$ and $U\alpha = \pm 1.96$.

Wavelet analysis

Wavelet analysis is a technique used to analyze time series data. It can identify different cycles and patterns within the data and reveal trends at various time scales. In this study, the Morlet wavelet analysis is used to examine the variation trend of the water area in Poyang Lake and the variation period of meteorological factors.

The basic principle of wavelet analysis is to use a set of wavelet function systems to represent the function of approximating a signal. Therefore, the wavelet function is the key to wavelet analysis. In the time series study of this paper, the data are mostly discrete, so it is necessary to use the discrete wavelet transform function (5), obtain the wavelet coefficient through the wavelet transform function (5), analyze the change characteristics of the time series data through the wavelet coefficient, and then integrate the square value of the wavelet coefficient in the b domain. The wavelet variance formula (6) can be obtained by the change process of the wavelet variance with scale a, which is called the wavelet variance diagram. The specific expressions are as follows:

$$Wf(a, b) = \frac{1}{\sqrt{a} \int_{-\infty}^{+\infty} f(t) \bar{\Psi} \left[\frac{t-b}{a} \right] dt} \tag{5}$$

$$\mathrm{Var}(a) = \int_{-\infty}^{+\infty} |Wf(a, b)|^2 db \tag{6}$$

where a is the time scale factor; b is the time position factor; $Wf(a, b)$ is wavelet coefficients; $\mathrm{Var}(a)$ is the wavelet variance; and $\bar{\Psi}[(t-b)/a]$ is the basis wavelet function.

Correlation analysis

Correlation analysis is a method used to measure the relationship between two or more variables. In this paper, the Pearson correlation coefficient and the Spearman correlation coefficient are used to analyze the possible correlation between changes in the Poyang Lake area and meteorological factors.

The Pearson correlation coefficient is used to evaluate the linear relationship between two continuous variables, and it is used to measure the linear correlation between two datasets. The datasets should be normally distributed, without outliers, and be continuous variables. Its expression is as follows:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (7)$$

In the formula, r is the correlation coefficient value, x_i and y_i are different values corresponding to x and y; $\bar{x}$ and $\bar{y}$ are the average values of x and y, respectively, and n is the number of variables.

The Spearman correlation coefficient is used to evaluate the monotonic relationship between two continuous variables. In the monotonic relationship, the variables tend to change together but not necessarily at a constant rate. When the dataset is seriously non-normally distributed, the variables are discontinuous, the outliers are greatly affected, and the Spearman correlation coefficient is selected. The expression is as follows:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \quad (8)$$

In the formula, r_s is the correlation coefficient value, d_t is the difference between the levels of each pair of samples in the two variables, and n is the number of variables.

RESULTS

Data processing

In this paper, 520 high-definition cloudless images from 1986 to 2003 were selected. The MODIS image is a three-level reflectivity 8-day composite product. MOD09Q1 has a time resolution of 8 days and a spatial resolution of 0.25 km (Xu *et al.* 2019). This paper selects 820 MODIS images from 2000 to 2020. The NDVI is calculated for both types of images, and the water body of the Poyang Lake area is extracted by thresholding. Finally, both of these images were used to reflect the change in the Poyang Lake region water area from 1986 to 2020. The images from 2001 to 2003 from the same year of the two datasets were selected for comparison. Because the resolution of the AVHRR image is lower than that of the MODIS image, the area extracted by MODIS is slightly larger than that extracted by AVHRR, but the changing trend of the two is roughly consistent, indicating that both images can accurately reflect the water area of the Poyang Lake area.

Variation of Poyang Lake water area

A total of 1,340 periods of the Poyang Lake water area from 1986 to 2020 were extracted using the NDVI and a threshold to reflect changes in the water area during this period. For the extracted water body area, the monthly average water body area was used to construct the monthly sequence data. Figure 2 shows a general map of the monthly sequence change of the water body area in the Poyang Lake water area over the past 35 years. The Poyang Lake water area is represented by a color scale, and the blank areas are those missing the image data.

From the multi-year average monthly water area changes, it can be seen that the maximum water area is concentrated in June–September each year, and the water area is smaller annually from December to February of the following year. Figure 3 shows the significant trend of annual changes in the water area in Poyang Lake. The water area starts to expand from April to May every year, with June to September being the wet season of the year. During this period, the water area remains high. From October, the water area begins to decline slowly and the low water level trend continues until March of the next year. Due to various factors, the wet and dry seasons in the Poyang Lake area are slightly different each year. In the wet

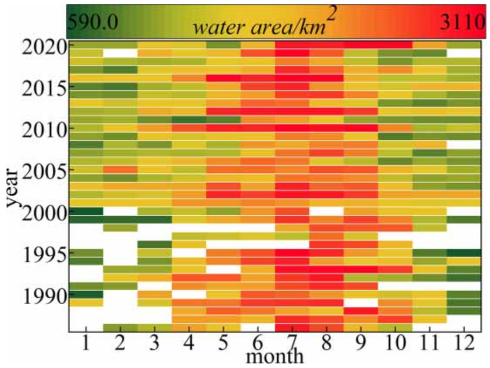

Figure 2 | 1986–2020 Monthly water area of Poyang Lake.

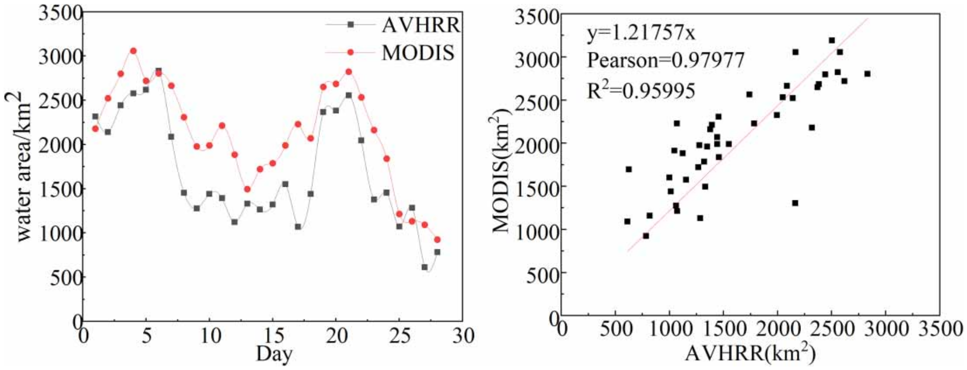

Figure 3 | AVHRR and MODIS contemporaneous image comparison.

year, the wet season starts earlier and the dry season starts later, with an extended period of ample flow. In dry years, the wet season starts later and the ample flow period is shorter, and the dry season lasts longer. The change in the Poyang Lake water area shows a pattern of flooding and drought cycles (Dai *et al.* 2014). During the study period, the longest duration of ample flow was in 2010, lasting from April to October of the same year, with the wet season lasting for 7 months and the ample flow continuing. This was followed by 1993, 1995, 2002, 2012, and 2016. The characteristics of the wet season in 1997, 2001, 2009, 2011, and 2018 were weak, with most of the months in the year being in a period of low water level. By comparing the characteristics of the wet and dry seasons in various years, it can be found that although the monthly sequence data before 2000 are missing, the trend of the wet and dry seasons suggests that the wet season in the Poyang Lake water area before 2000 lasted for a long time. The seasonal changes in the Poyang Lake water area after 2000 are still significant, but the duration of the wet season decreases significantly and the dry months increase.

Figure 4 shows the normal distribution and change of the maximum and minimum water area of Poyang Lake from 1986 to 2020. The minimum value of the water area fluctuated greatly before 2003, showing a trend of increase and decrease, and the minimum value of the water area decreased continuously from 2001 to 2006.

From the normal distribution curve of the multi-year water area, it can be seen that the water area in 1987, 1993, 1995, 2001, 2005, 2008, 2013, and 2015 generally showed a symmetrical normal distribution state. During these years, the water area changed smoothly, and there was no extremely dry or flooded hydrological situation. In 1989, 1992, 2007, 2010, 2011, 2014, and 2019, it was a serious non-normal distribution. In these years, extreme hydrological phenomena may occur. For example, in 2011, it was an obvious non-normal distribution, and for the whole year, the water area was low, which was an extremely dry year. In 2010 also, it was a non-normal distribution, and the annual water area was generally high, which was a wet year. Therefore, from 2010 to 2011, Poyang Lake experienced two years of drought and flooding.

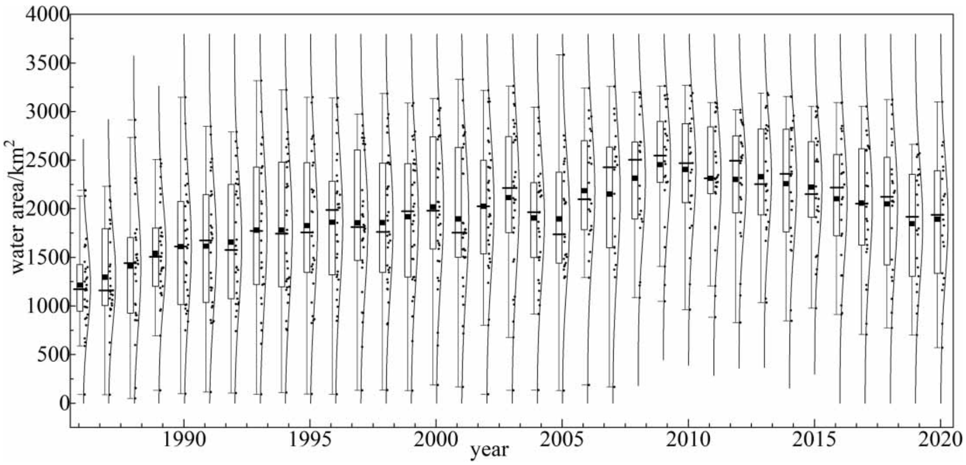

Figure 4 | 1986–2020 Normal distribution of the Poyang Lake water area.

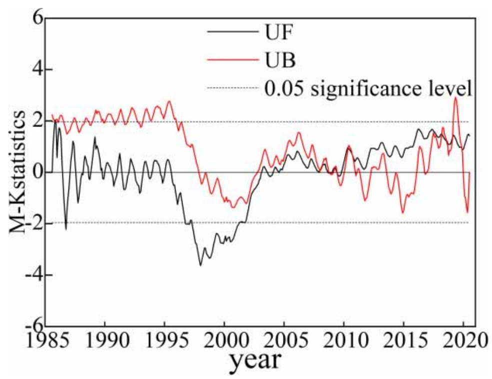

Figure 5 | 1986–2020 M–K mutation test results of the Poyang Lake water area.

Mutation test of the Poyang Lake water area

The M–K test was carried out on the monthly data of the Poyang Lake water area from 1986 to 2020. The results (Figure 5) showed that the Poyang Lake water area fluctuated significantly over the 35-year period. The sudden change point in the water area occurred in 2003. Before 2003, the water area showed a significant downward trend. After 2003, the changing trend tended to be gradual and showed a non-significant upward trend. In this paper, the monthly average of the Poyang Lake water area for the past 35 years was used for the M–K test. The time series is more intensive and can be more finely analyzed to study the changes in the Poyang Lake water area. Wang *et al.* used the average annual Poyang Lake water level for the past 60 years to conduct the M–K test. The results showed that the average annual water level showed an upward trend during 1980–2008, while the average water level in the past 5 years (2009–2014) showed an overall downward trend, but it was not significant (Wang *et al.* 2017). Compared to the test of the average annual water level of Poyang Lake, this study shows that the water area changed steadily from 1985 to 1995, showing a slight upward trend. From 1995 to 2000, the water area showed a significant downward trend, followed by a sharp rise after 2000, and a significant upward trend from 2000 to 2005. In 2010 and 2016, there were also mutations. Although the water area has been showing a decreasing trend in recent years, in 2010 and 2016, Poyang Lake Basin flooded (Zhang *et al.* 2022). The two mutations may be related to the flood during these two years.

Mutation test of the meteorological factor

The monthly series data of precipitation, temperature, relative humidity, and water vapor pressure in the Poyang Lake Basin were obtained by averaging the meteorological data of 17 stations in the basin. The mutation test was performed on the monthly sequence data from January 1986 to November 2019, and Figure 6 is obtained. The changes in precipitation and relative humidity had some similar trends before 2000. Temperature and water vapor pressure showed similar trends overall. Precipitation showed a non-significant upward trend before 2002 ($p > 0.05$), a sudden change around 2002, a non-significant decline from 2002 to 2010, a sudden change around 2014, and a non-significant upward trend after 2014. Relative humidity showed a non-significant upward trend from 1987 to 1992 ($p > 0.05$), and a mutation occurred around 1995. It fluctuated between 1995 and 2003, showing a significant downward trend from 2005 ($p < 0.05$). After the mutation in 2018, it turned into a non-significant upward trend. The variation trends of air temperature and water vapor pressure UF curves were highly similar, but their monthly variations were different. During the study period, temperature showed a non-significant increasing trend, water vapor pressure changed in 2003, and showed a non-significant decreasing trend from 2003 to 2014.

Wavelet analysis of the Poyang Lake water area

The wavelet variance analysis of the monthly sequence of the Poyang Lake water area from 1986 to 2020 was conducted, and the periodic law of the water area change of Poyang Lake in the past 35 years was obtained. The wavelet variance diagram (Figure 7) shows that the wavelet variance of the Poyang Lake water area has four peaks at 18, 30, 68, and 96 m, respectively. The main cycle of the Poyang Lake water area change is 18 m (m represents month) in the past 35 years, indicating that it oscillates strongly around 18 m. Secondary periods are 30, 68, and 96 m, respectively. The periodic regularity of the water area around 225 m (2005)–325 m (2013) is poor. There are several complete periodic changes in other time scales, indicating

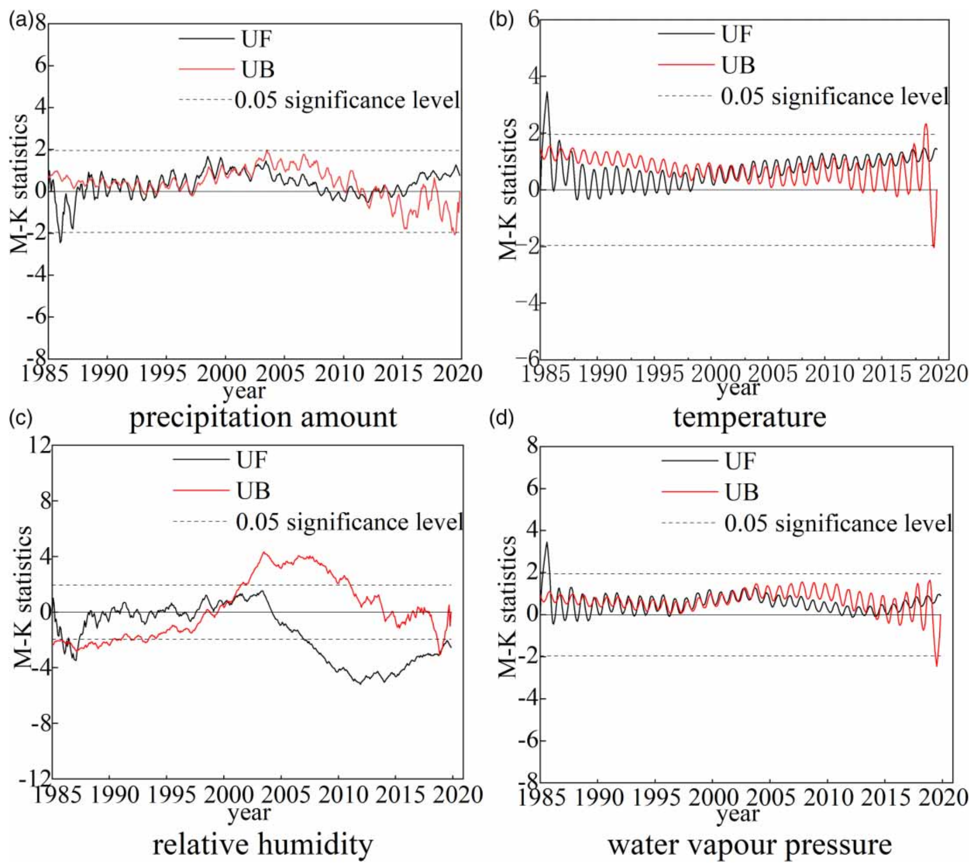

Figure 6 | Meteorological factor M–K analysis. (a) precipitation amount, (b) temperature, (c) relative humidity, (d) water vapor.

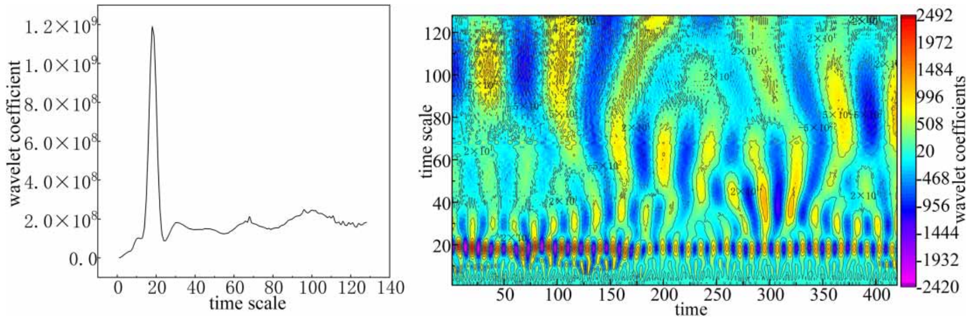

Figure 7 | 1986–2020 Wavelet analysis results of the water area of Poyang Lake. (a) precipitation amount, (b) temperature, (c) relative humidity, (d) water vapor.

that the seasonal variation of the Poyang Lake water area is obvious. During the study period, the 18 m contour of the main period is dense and the signal is strong, indicating that the periodic variation of Poyang Lake is stable (Xie *et al.* 2022).

DISCUSSION

Wavelet analysis of the meteorological factor

The monthly sequence data of 17 meteorological stations are analyzed by wavelet analysis, and the wavelet variance map and the contour map of complex wavelet coefficients are obtained (Figure 8). In the wavelet variance diagram of precipitation, the main period of precipitation on the time scale is about 18 m, and there are also sub-periods of 68 and 80 m. The main periodic variation of precipitation is consistent with the temperature, relative humidity, and water vapor pressure, all around 18 m. In addition to the main period of about 19 m, there are several sub-periods with larger time scales, such as 26 and 52 m. The

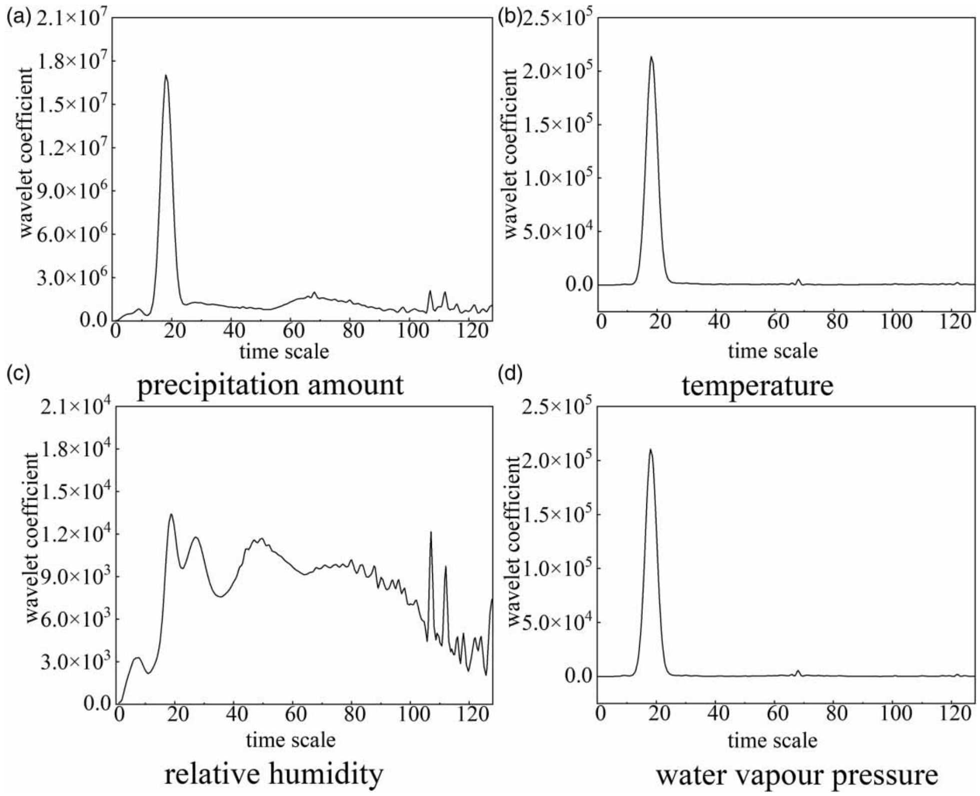

Figure 8 | Meteorological factor wavelet variance. (a) precipitation amount, (b) temperature, (c) relative humidity, (d) water vapor.

periodic scale change of relative humidity is similar to that of precipitation in the range of 100–128 m. The periodic variation of air temperature and water vapor pressure is highly consistent, and the main period is 18 m.

It can be seen from the contour map of the wavelet coefficient (Figure 9) that the main period of precipitation, air temperature, relative humidity, and vapor pressure is 18 m, which changes intensively and stably, and is highly consistent with the high–low change pattern of the Poyang Lake water area. The precipitation also has a relatively stable change in the sub-periodic scale of around 60 m and around 100 m. The sub-periodic variation scales of relative humidity and precipitation at 60 and 100 m also have similar consistency in the wavelet coefficient contour map, which are all three complete cycles of high–low alternation. There is a high degree of consistency between the periodic changes in temperature and water vapor pressure, as can be seen from the wavelet coefficient contour map of the two. Overall, the periodic alternations between meteorological factors are significant and stable, with global consistency.

Poyang Lake water area and meteorological factor correlation analysis

According to the seasonal variation characteristics of the Poyang Lake water area, the correlation between the change in the Poyang Lake water area and meteorological factors was divided into five time periods: the whole year (January–December), the wet season (May–September), the dry season (November–March of the next year), before the wet season (January–April), and after the wet season (October–December). A different correlation coefficient was used for the different research periods. The Pearson correlation coefficient was used for the variables for the year-round study period and the Spearman correlation coefficient was used for the variables for the other study periods. From the perspective of the annual research period, there is a strong significant correlation between the water area and temperature and water vapor pressure, a moderate correlation between the water area and precipitation, and a weak correlation between the water area and relative humidity. From the perspective of the wet season, the strongest correlation is the water vapor pressure, which has a significant moderate correlation at the 0.05 level. From the perspective of the dry season, the strongest correlation is precipitation, which has a stronger correlation at 0.05 level than that in the wet season, which is related to the seasonal variation of the water area of Poyang Lake with precipitation. From the point of view before the wet season, there is a significant correlation between water vapor pressure and precipitation and the water area, which is related to the expansion of the Poyang Lake area before the

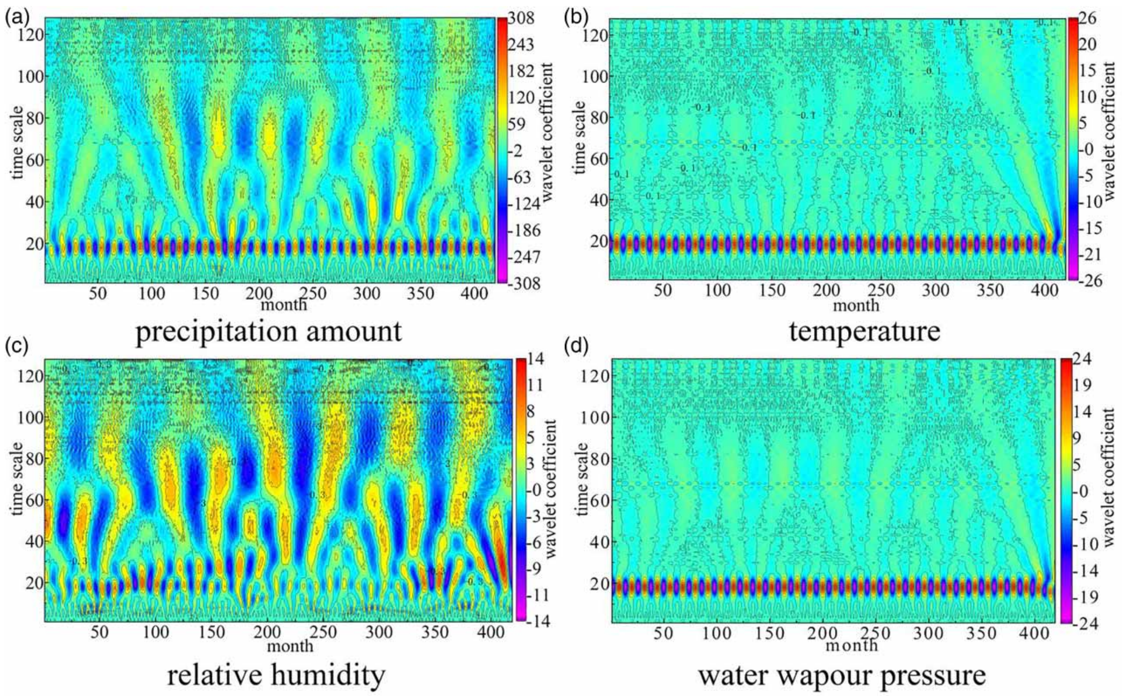

Figure 9 | Meteorological factor wavelet coefficient real component equivalent. (a) precipitation amount, (b) temperature, (c) relative humidity, (d) water vapor.

Table 1 | Correlation between the water surface area of the Poyang Lake and meteorological factors

Period	Coefficient	Temperature	Water vapor pressure	Precipitation	Relative humidity
Yearly	Pearson	0.71234**	0.75936**	0.47795**	0.25855**
	Spearman	0.71916**	0.76082**	0.49401**	0.24044**
Wet	Spearman	0.34214*	0.4468**	0.12789**	0.14473**
Dry	Spearman	0.20325**	0.37307**	0.51217**	0.43636**
Wet before	Spearman	0.42943**	0.49776**	0.58881**	0.2994**
Wet after	Spearman	0.37364**	0.53851**	0.46909**	0.46497**

The two-tailed significance test * represents a significant correlation at the 0.05 level and ** represents a significant correlation at the 0.01 level.
0.8–1.0 strong correlation, 0.6–0.8 strong correlation, 0.4–0.6 moderate correlation, 0.2–0.4 weak correlation, 0.0–0.2 very weak correlation or no correlation.

wet season. After the wet season, the correlation coefficient of water vapor pressure, precipitation, and relative humidity increased, indicating that the decrease in the Poyang Lake water area after the wet season was related to the decrease in precipitation, water vapor pressure, and relative humidity (Table 1).

The water quantity of Poyang Lake is mainly affected by three aspects: the first is the supporting effect of the Yangtze River on Poyang Lake, the second is the interaction effect of the five rivers on Poyang Lake, both of which are related to the runoff into the lake. The third is the recharge effect of precipitation on Poyang Lake. Precipitation is the main factor affecting runoff, and it is also the main factor affecting the change of the water area in most research periods. The correlation between precipitation before and after the wet season has increased. The precipitation increased before the water area of Poyang Lake reached the ample flow value, and the water area began to expand before the wet season. The change in water area during this period is mainly affected by precipitation. During the wet season, the water quantity of Poyang Lake is not only affected by precipitation, but also by water from the Yangtze River and the five rivers. The amount of lake water increases and the water area increases, so the response of the influencing factors of precipitation weakened. After the wet season, precipitation decreases, and runoff also decreases. The five rivers and the Yangtze River no longer have a replenishment effect, and the water area is mainly affected by precipitation. Therefore, the response factors of precipitation increase again. From the response relationship between meteorological factors, the response of relative humidity and precipitation to the change in water area has a consistency of change in the coefficient. The same temperature and vapor pressure also have these characteristics.

CONCLUSION

As an important part of the water cycle, the dynamic change characteristics of lakes are affected by meteorological factors, river–lake interaction, and human activities, and the hydrological situation is complex. In this paper, the long time series multi-source remote sensing image data are used to quantitatively and qualitatively analyze the water area change of Poyang Lake in the past 35 years. It provides a research basis for consolidating and improving the ecological environment quality of Poyang Lake, continuously improving the regulation and storage capacity of Poyang Lake, and comprehensively building a healthy, stable, and complete ecosystem around the lake basin. The results show that the use of the NOAA AVHRR image and the MODIS image can realize the long time series change monitoring of the Poyang Lake water area. The main research conclusions are the following:

(1) The water area change of Poyang Lake has an obvious seasonal wet and dry change process. The wet season is from May to September every year, and the water area usually reaches its peak in July every year. The length of the wet season is closely related to precipitation, so the interannual variation of the wet season has a small fluctuation. The minimum water area month of the year usually occurs in December, and the maximum water area can be four times the minimum. During the study period of this paper, the water area of Poyang Lake had a trend of expansion in the dry season. From 1986 to 2000, the wet and dry seasons changed steadily. In 2000, the dry season began to extend. From 2000 to 2020, the dry season was significantly extended. This is related to the increase in human activities and reservoir impoundment.

(2) The temporal variation of the Poyang Lake water area has a main period of 18 m time scale, as well as secondary periods of 30, 68, and 96 m. The periodic variation of the water area is consistent with the main cycle of precipitation, water vapor pressure, temperature, and relative humidity, indicating that there is a responsible relationship between the water area

and meteorological factors. There is also a similarity and response relationship between the mutation point of water area changing trend and precipitation.

(3) During the study period of this paper, there is a significant correlation between the water area of Poyang Lake and precipitation, water vapor pressure, temperature, and relative humidity. Water vapor pressure and precipitation are the main factors affecting the change in the water area. The correlation of various factors in different research periods has changed, either increased or decreased, which indicates that the change in the water area is not only affected by various meteorological factors but also by human activities and the interaction between rivers and lakes.

With the continuous development of social economy in the Poyang Lake area and the further development of water conservancy and hydropower in the upper reaches of the Yangtze River, Poyang Lake is experiencing new changes. Therefore, it is necessary to conduct more in-depth research to explore the causes and consequences of water regime changes in Poyang Lake. For example, Poyang Lake quantifies the changes in the relationship between rivers and lakes, considers the changes in climate factors, the impact of large-scale water conservancy projects on the water regime changes, and identifies the primary and secondary contradictions to carry out the targeted research, so as to provide new research ideas for protecting the ecosystem and economic development policies in the Poyang Lake area.

FUNDING

The work was supported by the National Natural Science Foundation of China (41101322) and the Science and Technology Research Project of the Education Department of Jiangxi Province (GJJ160617).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Dai, X., Wan, R. R., Yang, G. S. & Wang, X. 2014 Hydrological rhythm change of Poyang Lake and its relationship with water exchange between rivers and lakes. *Journal of Geographical Sciences* **34** (12), 1488–1496.

Guo, Z. T., Huang, F., Guo, L. D. & Wu, Y. 2021 Causes and countermeasures of hydrological situation evolution of Poyang Lake. *Journal of Yangtze River Academy of Sciences* **38** (6), 27–31.

Liu, C., Tan, Y., Lin, L., Tao, N. & Tan, H. 2011 Effects of water level change in Poyang Lake on migratory bird habitat. *Lake Science* **23** (1), 129–135.

Liu, H., Zheng, L., Jiang, L. & Liao, M. 2020 Forty-years water body change of Poyang Lake and its ecological impact based on Landsat and HJ-1 A/B observations. *Journal of Hydrology* **589** (3), 125161.

Liu, J. Q., Ye, X. M. & Yun, C. 2022 Study on the relationship between water area and water level of HY-1C/D satellite CZI image for flood risk analysis of Poyang Lake. *Journal of Central China Normal University (Natural Science Edition)* **56** (3), 505–512.

Lyu, T. Y., Chen, J. R. & Ren, S. S. 2018 Analysis of water level variation characteristics of Poyang Lake after the operation of the Three Gorges Project. *Journal of Water Resources and Hydraulic Engineering* **29** (5), 41–45.

Sun, F. D. & Ma, R. H. 2020 Remote sensing monitoring of dynamic changes in hydrological characteristics of Poyang Lake. *Journal of Geographical Sciences* **75** (03), 544–557.

Tian, H., Wang, J., Pei, J., Qin, Y., Zhang, L. & Wang, Y. 2020 High spatiotemporal resolution mapping of surface water in the southwest Poyang Lake and its responses to climate oscillations. *Sensors* **20** (2 of 17), 4872.

Tian, B. Q., Wu, C. X. & Mu, X. M. 2021 Long time series analysis of water area change characteristics and driving factors of Poyang Lake in flood season. *Study on Soil and Water Conservation* **28** (4), 212–217.

Wang, R. F., Li, Z. P. & Zhao, G. Z. 2017 Hydrological evolution characteristics of Poyang Lake in recent 60 years. *Journal of Tropical Geography* **37** (4), 512–521.

Wu, C. X., Tian, B. Q. & Gao, P. 2021 Analysis of water area change characteristics and driving factors of Poyang Lake in dry season in recent 40 years. *Soil and Water Conservation Journal* **35** (3), 177–184, 189.

Xia, X., Wu, Q. & M. X. 2012 Research progress on the impact of global climate change on surface water environmental quality. *Advances in Water Science* **23** (1), 124–133.

Xie, S. Y., Kuang, R. Y. & Song, Z. H. 2022 Variation characteristics of water area of Poyang Lake and its response to meteorological factors. *China Rural Water Conservancy and Hydropower* **477** (7), 103–109.

Xu, Y., Liu, W., Song, J., Yao, Y. & Gu, L. 2019 Dynamic monitoring of the lake area in the middle and lower reaches of the Yangtze River using MODIS images between 2000 and 2016. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **11** (12), 4690–4700.

Yan, L., Long, D., Bai, L., Zhang, C., Han, Z., Li, X., Wang, W., Shen, S. & Ye, Y. 2020 A review of water resources stereoscopic monitoring based on multi-source information. *Remote Sensing* **24** (7), 787–803.

Yang, P. J. & Liao, Z. 2017 Summarization of studies on the relationship between rivers and lakes in the Poyang Lake Basin. *China Rural Water Conservancy and Hydropower* **413** (3), 65–67, 74.

Zhang, W., Cui, C. L., Li, L. Y., Jia, Y. & Meng, L. 2019 Monitoring and analysis of water surface area of Poyang Lake based on long time series remote sensing data. *Journal of Hydrology* **39** (3), 29–35 + 21.

Zhang, M. Y., Deng, P. X. & Wang, L. Z. 2022 Quantitative analysis of the influence of confluence jacking of Poyang Lake on water level of Hankou in Yangtze River. *Journal of Lake Sciences* **34** (5), 1712–1722.

Zheng, L., Xu, J. & Tan, Z. 2020 A thirty-year Landsat study reveals changes to a river-lake junction ecosystem after implementation of the Three Gorges Dam. *Journal of Hydrology* **589**, 125185.

Zhu, L., Xing, H., Hou, D., Feng, Y., Yang, F. & Qiu, P. 2021 A long-term analysis of spatiotemporal change and driving factors on Poyang Lake during 1987-2019. *Environmental Studies* **30** (5), 4389–4399.

First received 28 January 2023; accepted in revised form 31 May 2023. Available online 13 June 2023