

Water Area Variation and ~~Response of~~ River–lake Interactions in the Poyang Lake from 1977–2021

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Abstract: Lake has an essential role in Earth's hydrologic cycle. The Poyang Lake, China's largest freshwater lake. Most previous research only used a brief time span of data for examination, or the analysis itself was not sufficiently thorough. In this study, using remote sensing imagery, hydrological data, meteorological data, and land use surveys, we investigated changes in the Poyang Lake water area from 1977–2021. In addition, we examined the relationship between the lake water area and potential impact factors and analyzed the influence of river–lake interactions on the lake water area. The results revealed a significant decrease in the Poyang Lake water area decreased significantly during the study period. Further, in the wet season, runoff, sediment, and precipitation significantly correlate with water area; in the dry season, sediment significantly correlates with a water area. Additionally, the Three Gorges Dam water impoundment situated in the upper reaches of the Yangtze River weakened and eliminated the block and reverse flow of the Yangtze River into the Poyang Lake, causing the water area to decrease toward the end of the wet season in 2005 and in the dry season in 2003. Changes in the lakebed elevation caused by sedimentation and anthropogenic activities have also accelerated the shrinkage of the water area. Overall, the results of this study indicate that variations in river–lake interactions are the primary cause of the significant changes observed in the Poyang Lake water area in the last five decades.

Keywords: The Poyang Lake, remote sensing image, climate change, anthropogenic influence, river–lake interaction

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1. Introduction

Lakes are natural reservoirs of water formed by the collection of stagnant water in surface depressions. The broad expanse of water and slow currents that are characteristic of lakes play an essential role in Earth's hydrologic cycle [1]. In addition, lakes provide water to surrounding areas and influence river flow regulation and groundwater levels. The ecosystems formed by lakes also provide an essential living habitat for a range of organisms. Therefore, it is essential to maintain a stable state of lakes to ensure ecological balance [2–4]. In recent years, Global warming and frequent human activity has substantially impacted major lakes, and their surrounding environments worldwide. Several scholars have analyzed the characteristics of global lake changes and have confirmed that changes to the lake area affect the overlying atmosphere and lake–air interactions, impacting the regional climate [5–7]. As a result of these impacts and the important role that lakes play in ecosystems and regional climate change stability, there is an urgent need to understand lake changes, which are occurring on a rapid scale.

Lake Poyang, the largest freshwater fluvial lake in China, is located in China's most important economic development region—The Middle-lower Yangtze Plain (Fig.1) As the

largest lake connected to the Yangtze River, Poyang Lake is an alternately inflow-outflow lake with complex hydrological relationships and unique rhythmic changes. In the flood season, Poyang Lake is a lake scenery when the Poyang Basin and Yangtze River flow combine creating the lake. In the dry season, Poyang Lake is a river landscape, Poyang Basin runoff flows through the lake berth into Yangtze River [8]. Hydrological monitoring revealed that the interval between the wet and dry season has decreased, seasonal drought events have intensified, and floods have occurred more frequently in the last 22 years. Dramatic changes in the lake's hydrological cycle have had negative environmental effects. Several scholars have recommended the construction of a dam at the estuary of the Poyang Lake to artificially regulate the interaction between the Yangtze River and Poyang Lake and decrease the severity of disaster events. However, there is a lot of debate about this idea. Opponents contend that climate change and human activity have significant impact on the Poyang Lake basin and that erecting dams would further worsen the effects of the broken hydrological connection [9–11] Therefore, having a comprehensive grasp of the changes and causes of the Poyang Lake is necessary. Monitoring lake water areas helps us more intuitively understand the true condition of lakes, especially big lake systems. Previous of Poyang Lake research largely used discontinuity and a limited data period to analyze, or the analysis component was not thorough enough.

In this study, historical images of the Poyang Lake from the last 40 years were used to extract water area data of wet and dry seasons. Combined with basin hydrology, meteorology, and land use data and using statistical methods, the impact of climate change and anthropogenic activities on the hydrological relationship of the Poyang Lake were studied. Based on this research, we propose a theoretical basis for the regulation of the Poyang Lake.

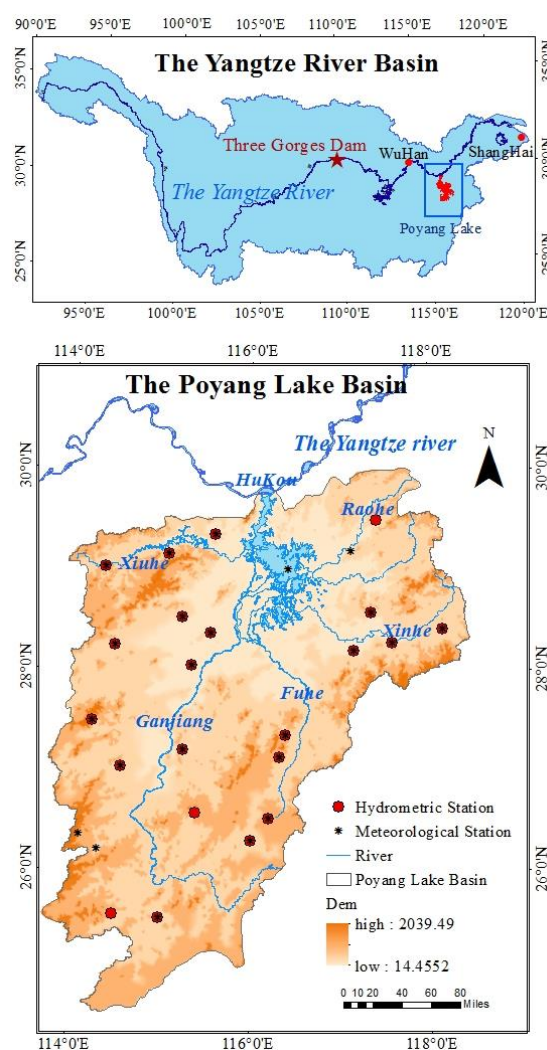


Figure 1. Poyang Lake Basin.

2. Study Area and Data

2.1. Study area

We considered of a portion of the Poyang Lake Basin as the study area, which occurs in the south bank of the middle Yangtze Proper and connects with the Yangtze River (28°22'–29°45' N and 115°47'–116°45' E); the basin covers an area of 162225 km². The Poyang Lake Basin is characterized by five rivers, namely the Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui Rivers; these rivers flow into the Poyang Lake. Upon inflow storage, the lake water flows into the Yangtze River via the estuary of the lake, which in turn receives the Yangtze River runoff (Shankman, Keim, and Song 2006).

The Poyang Lake Basin is characterized by a subtropical monsoon climate, with intense solar radiation. Due to the highly variable precipitation in the basin, the seasonal variation of runoff into the lake of the five major rivers is substantial, with the precipitation received during this period accounting for 75% of the annual precipitation. During the dry season, from November–February, the area of the lake shrinks and the lakebed remains bare.

2.2. Data collection

Remote Sensing images were obtained for the Poyang Lake Basin during the dry season, as this period is characterized by cloudless skies, from the Landsat series (MSS, TM,

ETM+, OLI) for the 1977–2021 period (Fig. 2) and downloaded from the United States Geological Survey (USGS, website at <https://earthexplorer.usgs.gov/>). Only high-quality images with a suitable extraction effect were selected, and the extraction results passed visual inspection. Overall, 328 images were screened by excluding missing data from 1980, 1982, 1985, 1994, and 2009. In addition, historical high-resolution satellite images of the Poyang Lake obtained by the USGS (December 13, 1967) were compared with earlier periods characterized by less anthropogenic disturbance. Visual inspection showed that the extraction results were accurate.

We selected runoff, sediment and land use to represent the effects of human activity, and precipitation and evaporation to represent the effects of the climate. Runoff and sediment data were obtained from the actual measurements of hydrological stations in the Poyang Lake Basin and Lake Estuary (Fig. 1), recorded in the Hydrology Data Yearbook and published by the Ministry of Water Resources and Power, PRC (runoff data distribution period: 1977–2020; sediment data distribution period: 1980–2020). Temperature and precipitation data of the Poyang Lake Basin were also obtained from meteorological stations (Fig. 1) and downloaded from the China Meteorological Data Network for the 1977–2020 period (<http://data.cma.cn/>). Finally, land use data for the Poyang Lake Basin were obtained from the China National Land Use Database and classified using a secondary classification system for the following years: 1980, 1995, 2000, 2005, 2010, 2015, and 2020. All measured data used in this study were verified and rated as good quality.

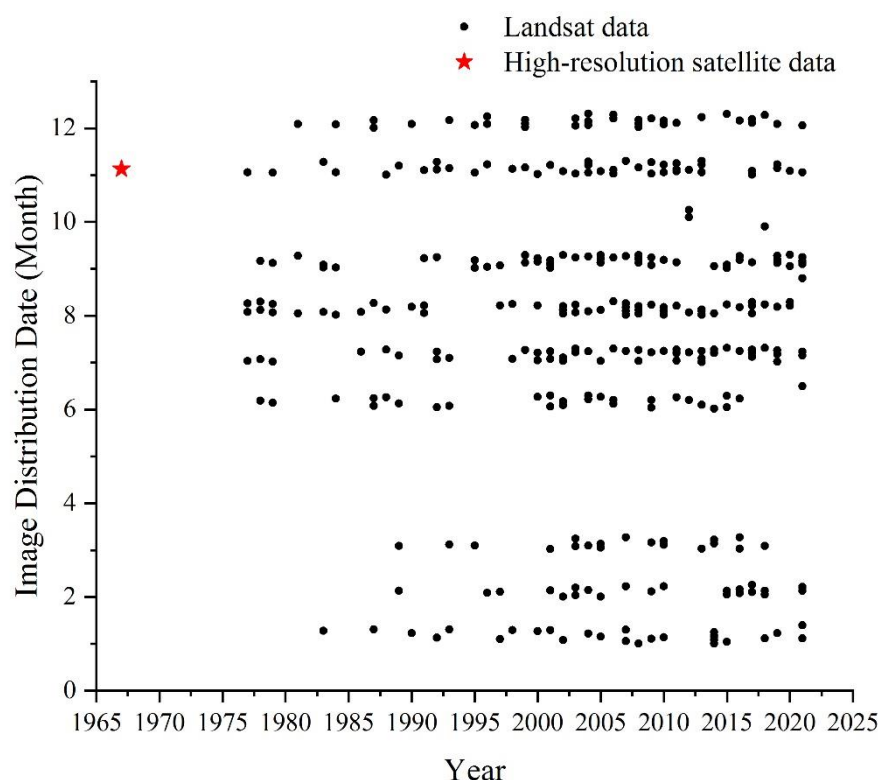


Figure 2. Remote sensing temporal data distribution.

3. Methods

3.1. Extraction Method of Water Area

The multi-band pixel value comparison method was used to extract water information and calculate the water area. In addition, the spectral characteristics of the water images were used to set thresholds, extract lake water data, and calculate the mean area of the annual wet and dry seasons [16]. The result was consistent with the pixel values of

adjacent pixels. After manual visual verification, the extracted water data were deemed accurate.

3.2. Statistical Analysis

The Mann–Kendall mutation test was used to detect the change-point year of data and the Mann–Kendall trend method was used to identify temporal trends in the data series. In addition, an exert correlation analysis was used to investigate the relationship between water area and impact factor, including the net outflow of the lake, sediment discharge, rainfall, and temperature [17,18]. Finally, the cross-tabulation matrix and change in terms of the percent of the landscape was used to assess the total change of land categories [19]. The results of the image comparisons revealed the characteristics and influencing mechanisms of water area change in the Poyang Lake Basin.

4. Results

4.1. Trends and Change Point of Lake Water Area

From 1977–2002, the water area from in the wet season displayed a significant downward trend (MK trend test $Z = -1.67$, passing the 95% test), with an annual decrease rate of -9.14 km^2 (Fig. 3). The largest lake area recorded for this period was 4662.05 km^2 in 1998, and the smallest was 2139.37 km^2 in 2006. The MK mutation test showed that the change-point year was 2005, post which, the declining rate of the water area increased.

In the dry season of the 1977–2021 period, the lake water area showed a notable downward trend (MK test $Z = -3.09$, passing the 99% test), with a decrease rate of $-17.52 \text{ km}^2/\text{a}$. The largest area recorded was 3202.91 km^2 in 1997 and the smallest area was 775.41 km^2 in 2019. In addition, the MK mutation test showed that the change-point year was 2003, post which, the declining rate of the water area increased (Fig. 3).

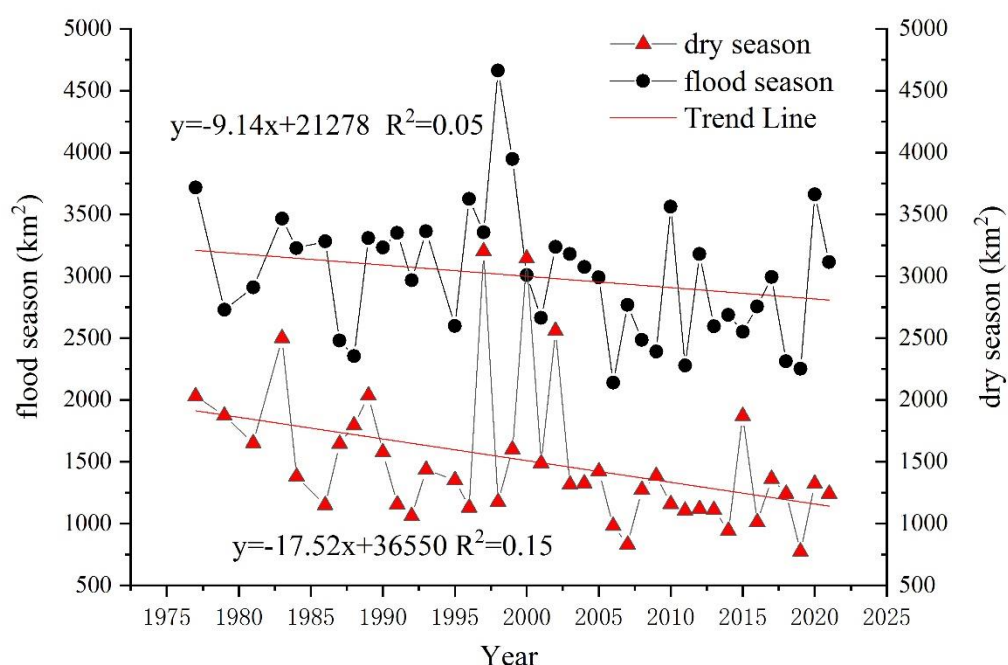


Figure3. Characteristics of water area variation in the Poyang Lake during 1977–2021.

4.2. Analysis of Lake Water Area Impact Factor

The Poyang Lake is a classical river-connected drain lake. Figure 4 indicates the complex hydrological relationships that exist in this lake. The hydrological factors considered in this study were runoff, precipitation, evaporation, lakebed, and water utilization. Groundwater was not considered, as the complexity of the exchange relationship of this resource is beyond the scope of this research. In the analysis, inflow and net outflow were used to express the influence of runoff, with net outflow indicating the total runoff of the rivers into the lake minus the runoff from the lake estuary. Selected sediments were analyzed to investigate variations in the lakebed, and land use was studied to investigate the water utilization.

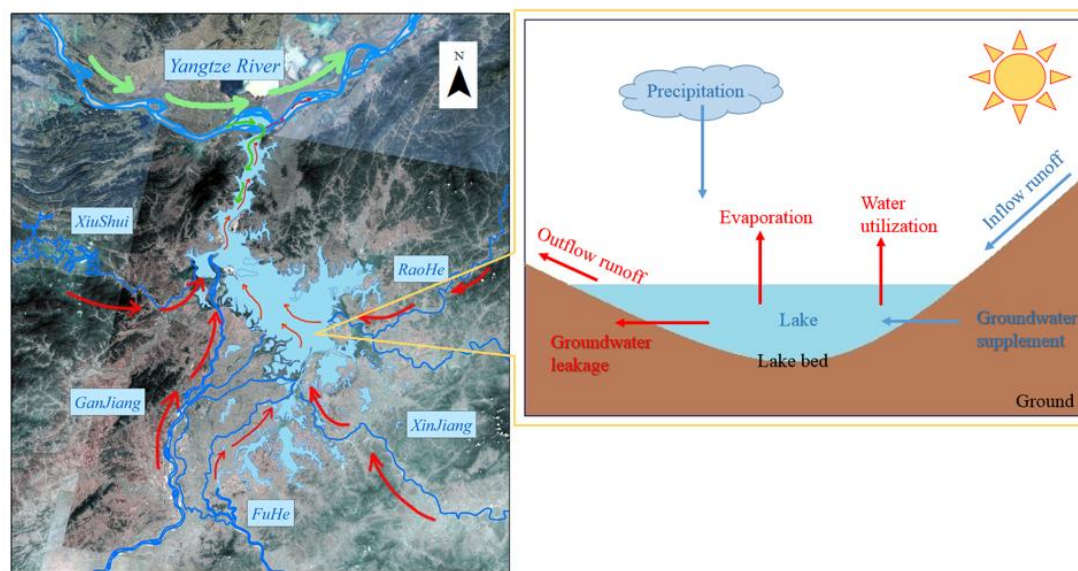


Figure 4. Hydrological relationship diagram of the Poyang Lake.

4.2.1. Changes in the Lake Flow

Figure 5 indicates the increasing trend characterizing the annual inflow of the Poyang Lake from 1977–2020. However, the MK trend test indicated that the increasing trend was insignificant ($Z = 1.10$). In addition, the MK mutation test showed that the change point was in 1992 and 2003. The Pearson Analysis was used to test the relationship between the lake area and inflow, and indicated wet and dry season coefficients of 0.38 and 0.08, respectively. The correlation coefficient in the wet season passed the 99% level test.

Figure 6 also indicates a net increasing trend for the annual net outflow of the Poyang Lake from 1977–2020. The MK trend test confirmed that the increasing trend was lower than the inflow runoff (coefficient = 0.54). In addition, the MK mutation test revealed that the change point was insignificant, and the results of the Pearson Analysis revealed correlation coefficients between lake area and runoff of 0.09 and 0.48 in the dry and wet seasons, respectively. This indicates a correlation between the lake area and net outflow of > 99%. Results demonstrated that flood season lake areas have an associative relationship with the lake flow.

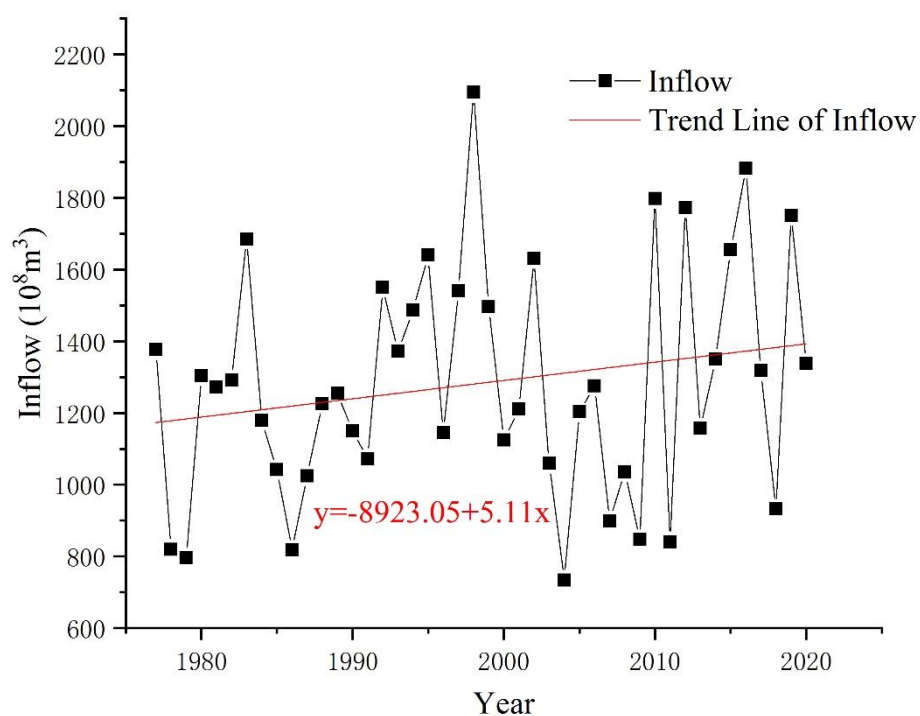


Figure5. Characteristics of inflow in the Poyang Lake during 1977–2020.

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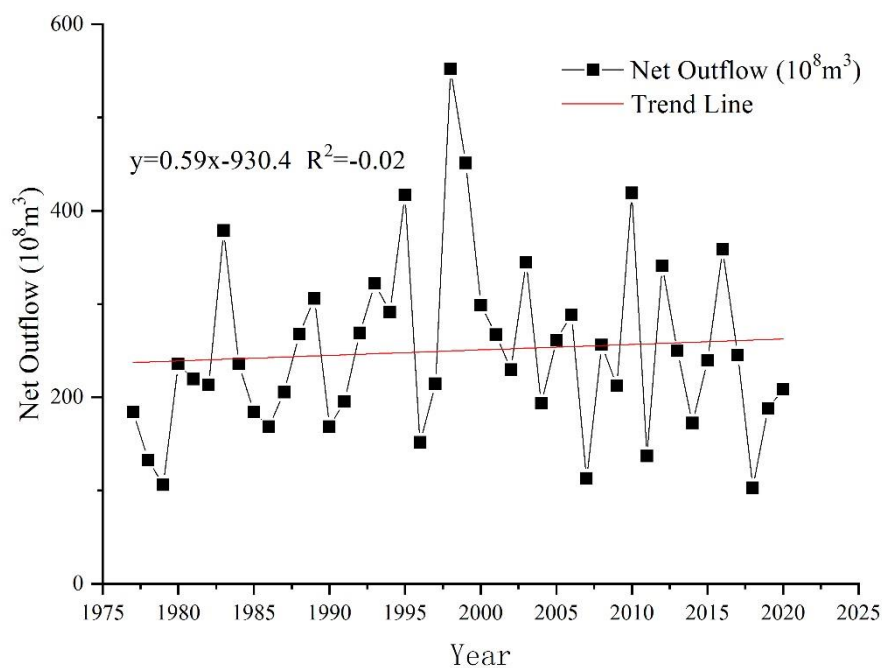


Figure6. Characteristics of net outflow in the Poyang Lake during 1977–2020.

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4.2.2. Changes in the Poyang Lake sediment

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From 1980–2020, the total sediment received from the five major rivers into the Poyang Lake showed a significant downward trend (Fig. 7), with a decrease rate of $-33.5 \text{ km}^2/\text{a}$ (MK trend test $Z = -1.67$, $> 95\%$); however, the change point was not significant. A Pearson Analysis was used to determine the correlation between the annual sediment and area in the wet and dry seasons. The results revealed coefficients of 0.29 and 0.26 in the wet and dry season, respectively, with both coefficients at the 95% confidence level. These results demonstrate a close association between the lake area and lake sediment.

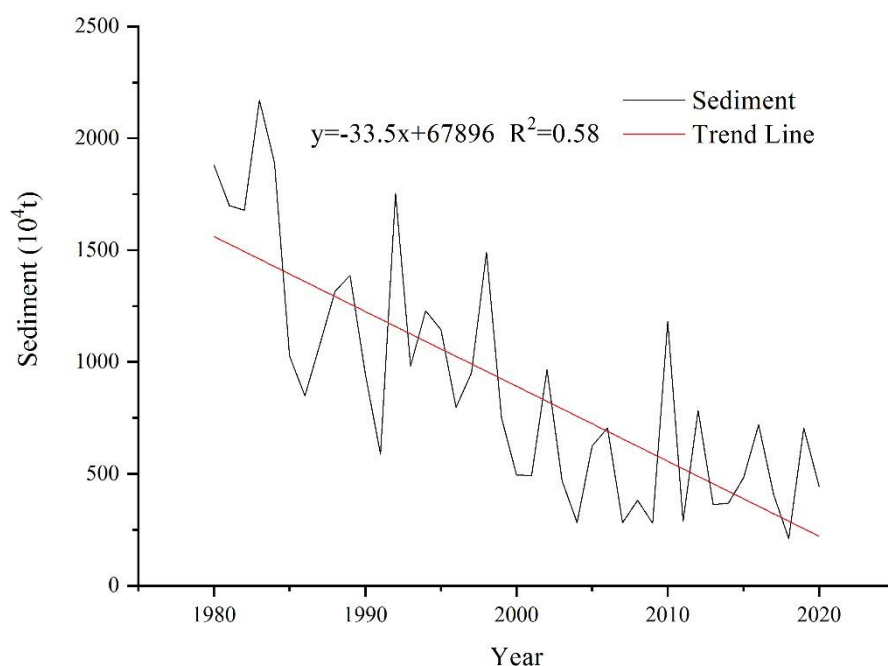


Figure 7. Characteristics of sediment in the Poyang Lake estuary during 1980–2020.

4.2.3. Changes in the Evaporation and Precipitation in the Poyang Lake

From 1977–2020, the evaporation rate during the dry season showed an insignificant increasing trend ($Z = 0.56$), whereas evaporation during the wet season showed a significant downward trend ($Z = -2.14$), with a decrease rate of $4.62 \times 10^{-1} \text{ mm/a}$ and change point in 1992. In addition, the Pearson Analysis test indicated no correlation between evaporation and lake area. The correlation coefficients were 0.11 and 0.06 in the dry and wet seasons, respectively (Fig. 8).

From 1977–2020, the wet season precipitation was characterized by an insignificant downward trend ($Z = -0.41$), whereas dry season precipitation significantly increased ($Z = 2.48$) (Fig. 9). The correlation coefficient of flood season precipitation and area was 0.31 at a 99% confidence level. In the dry season, the correlation coefficient was insignificant.

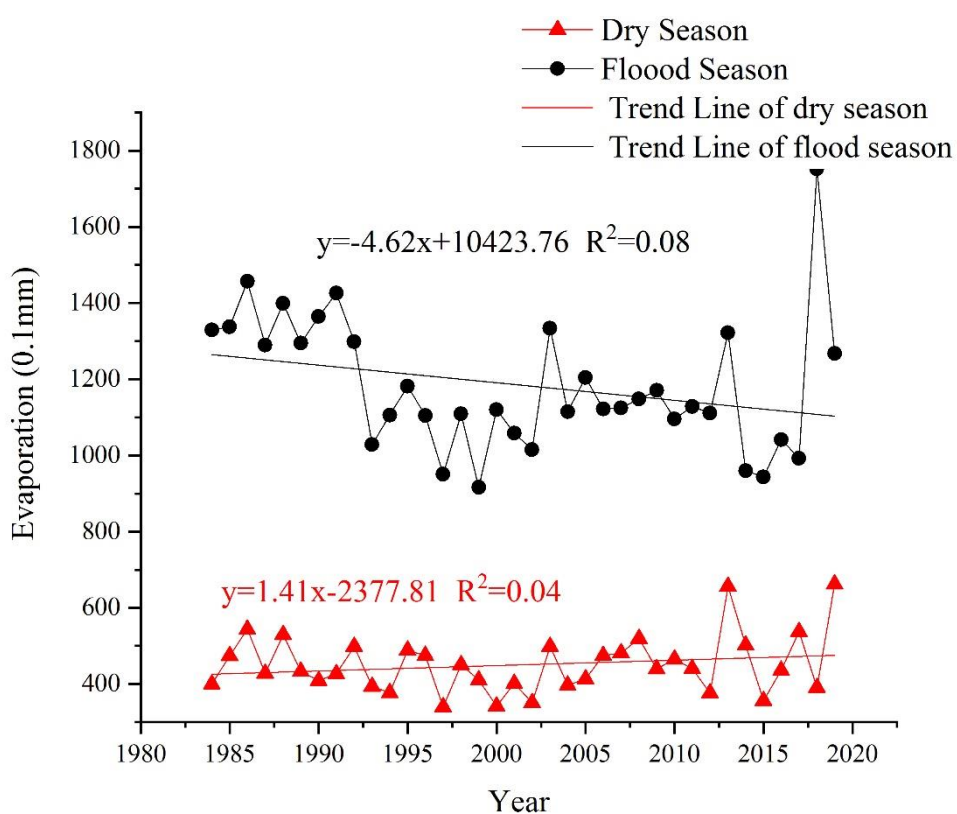


Figure8. Characteristics of evaporation in the Poyang Lake estuary during 1977-2020.

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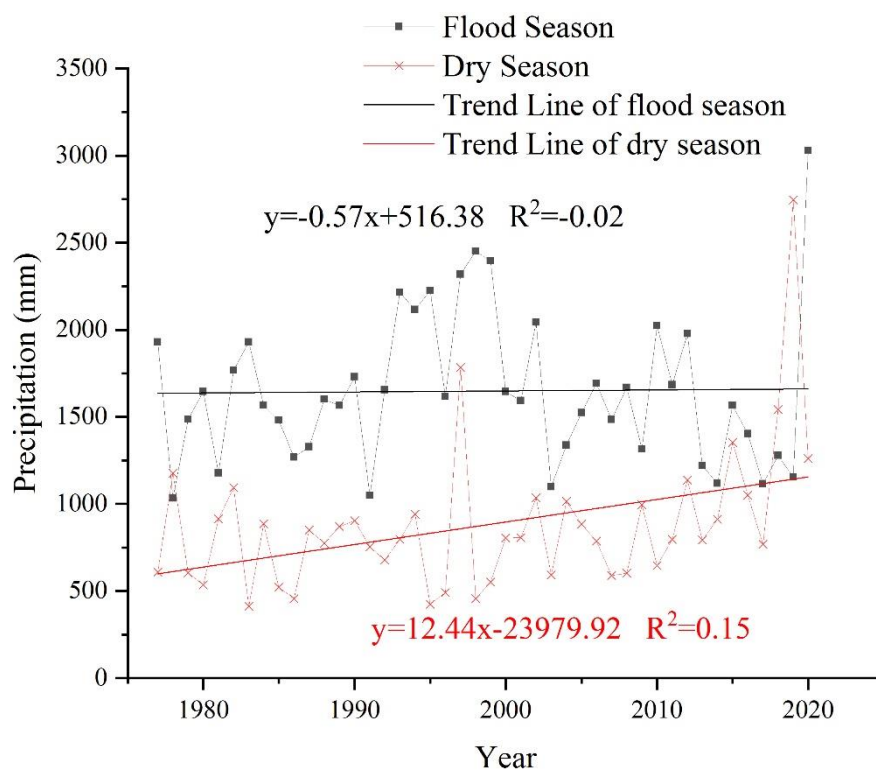


Figure9. Characteristics of precipitation in the Poyang Lake estuary during 1977-2020.

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4.2.4. Land Use Changes in the Poyang Lake

The Transfer matrix was used to calculate the transfer amount of different land features from 1980–2020, and showed clear changes in the different regions. Primarily, we determined that changes in land features in the Poyang Lake mainly occurred after 2000, while the amount of land surface conversion in the early stage was not noticeable. After 2000, the most significant land use changes included an increase in the area of croplands and water, a decrease in the area of forest and grasslands, and a 1.53% expansion in the settlement area (Table 1).

Figure 10 shows a comparison of the images, indicating that the urban area expanded significantly after 2000. In addition, the Transfer Matrix Analysis verified an apparent conversion relationship between Settlement and Cropland, and a substantial conversion relationship between the “water” and “other” land use categories was also observed (Table 2). Moreover, compared with the 1980s image, the “other” land use category in the Ganjiang River Estuary was replaced by “cropland,” and “settlement” was replaced with “cropland” in the year 2020. The significant increase in the “settlement” and “cropland” categories indicates an increase in water utilization in the basin.

Table 1. Land use change information of 1980-2020 (%) .

		Gain	Loss	Total change	Swap	Absolute value of net change
1980-2000	Cropland	0.40	0.49	0.89	0.81	0.08
	Forest	0.43	0.51	0.94	1.02	-0.08
	Grassland	0.29	0.24	0.53	0.58	-0.04
	Other	0.13	0.10	0.23	0.26	-0.03
	Settlement	0.14	0.00	0.14	0.00	0.14
	Water	0.27	0.32	0.60	0.65	-0.05
2000-2020	Cropland	12.04	12.77	24.81	24.09	0.73
	Forest	11.82	52.94	64.76	65.58	-0.81
	Grassland	3.00	3.47	6.47	6.49	-0.02
	Other	0.14	0.54	0.67	0.42	0.25
	Settlement	2.78	0.76	3.55	2.02	1.53
	Water	2.08	3.06	5.14	4.89	0.25

Table 2. Land Transfer Matrix of 1980-2020 (%) .

Relative Difference		2020					
(Increase)		Cropland	Forest	Grassland	Other	Settlement	Water
1980	Cropland	0.00	0.07	0.04	-0.43	1.26	0.08
	Forest	-0.10	0.00	0.01	-0.94	-0.55	-0.31
	Grassland	0.26	0.38	0.00	-0.60	-0.25	-0.45
	Other	-0.44	-0.93	-0.60	0.00	-0.52	10.79
	Settlement	2.36	-0.48	-0.13	0.38	0.00	-0.04
	Water	0.44	-0.58	-0.35	17.87	0.25	0.00
Relative difference		2020					
(reduced)		Cropland	Forest	Grassland	Other	Settlement	Water
1980	Cropland	0.00	-0.15	0.18	-0.50	2.24	0.28

Forest	0.06	0.00	0.39	-0.94	-0.22	-0.57
Grassland	0.10	-0.02	0.00	-0.69	-0.05	-0.16
Other	-0.53	-0.95	-0.61	0.00	-0.41	17.93
Settlement	1.54	-0.68	-0.24	-0.06	0.00	0.50
Water	0.87	-0.56	-0.02	21.12	1.39	0.00

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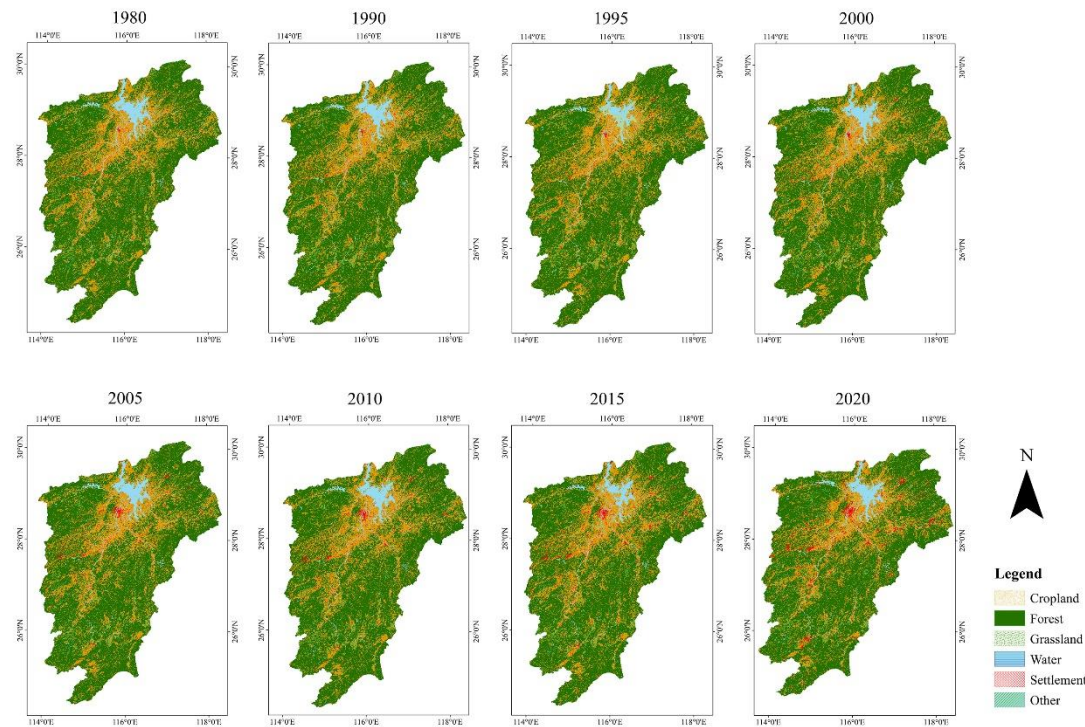


Figure10. Characteristics of land use in the Poyang Lake estuary during 1980-2020.

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5. Discussion

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The Poyang Lake is a classical river-connected drain lake characterized by complex hydrological relationships. Due to its connection with the Yangtze River, changes in the Yangtze River runoff impacts the water exchange in the lake estuary, leading to different influence mechanisms of lake area change in the Poyang Lake [20].

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5.1. Influence Mechanism of Lake Water Area Change in Flood Season

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The prophase analysis revealed a significant correlation between lake area and flow in the wet season. Numerous studies have also confirmed that during the wet season, the Poyang Lake water area is affected by runoff from the five major rivers in the Poyang basin as well as the Yangtze River. This runoff is exchanged and interplayed at the lake estuary [21,22]. The interaction between the Yangtze River and Poyang Lake can be divided into three stages:

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1. The Poyang Lake basin's dominant inflow period from December–March, whereby runoff into the Poyang Lake basin increases and the lake water level rises.

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2. The river–lake interaction period from April–August, when the mainstream of the Yangtze River begins to rise during and the water level in the Poyang Lake is also high. The high water level of the Yangtze River causes a blocking effect on the outflows from the Poyang basin. Runoff from the Poyang Basin cannot flow out, resulting in flood stagnation in the lake and water area expansion.

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3. The Yangtze River runoff dominant period from September–November, wherein, influenced by the upstream Yangtze River, runoff from the Yangtze River increases and

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the water level rises. The runoff from the Yangtze River flows into the Poyang Lake through the estuary.

The Poyang Lake maintains a high-water area, even at the end of the flood season in the years 1983, 2020, and 2021 (Fig. 11a). Combined with hydrological records, it was determined that the mainstream of the Yangtze River experienced flood events in September. In 2020, record floods occurred in the Yangtze River Basin, and this resulted in record-breaking water levels in the Poyang Lake. Figure 11b shows that the average water area in September in 2011 and 2019 was $\sim 1255.40 \text{ km}^2$; however, the hydrological records show that the lowest net outflow was recorded in 2018. Of note, serious drought events occurred simultaneously in the Poyang Lake Basin and Yangtze River Basin. Drought events in the Poyang Lake Basin result in a decrease in the flow of the five major rivers. Moreover, droughts lead to a lowered water level in the Yangtze River, eliminating the block or reverse flow from the Yangtze River into the Poyang Lake, thus reducing the water area. It should be noted that during the wet season, changes in the water area are closely related to changes in the river–lake interaction.

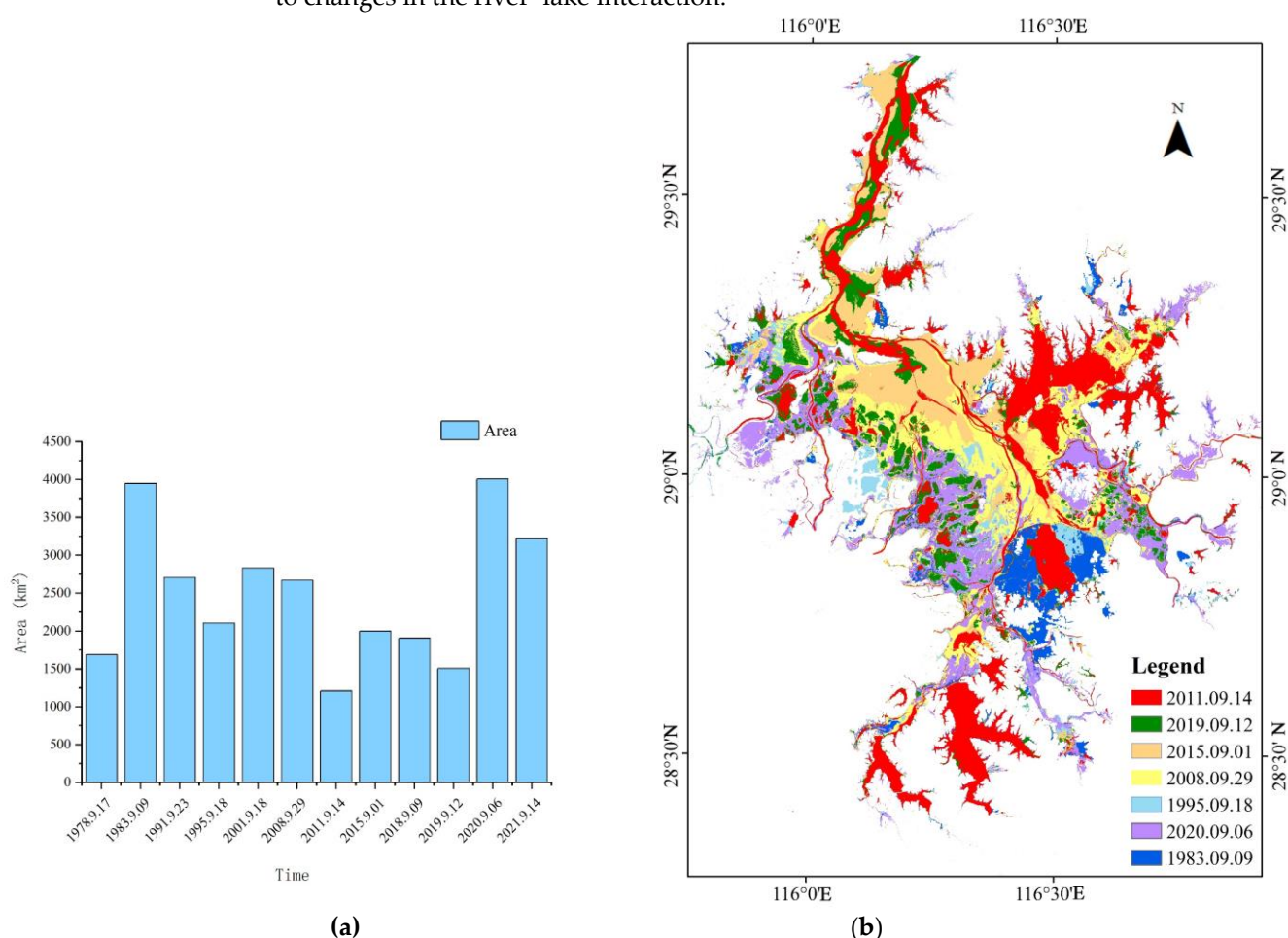


Figure 11. Comparison of lake water area at the end of flood season: (a) Description of lake water area at the end of the flood season; (b) Comparison of lake water area extraction results at the end of flood season.

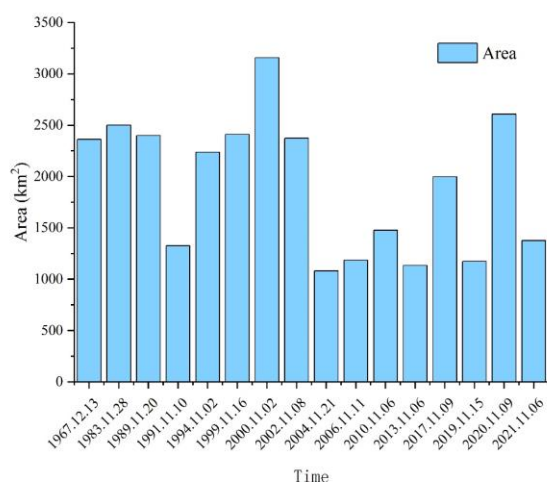
5.2. Influence Mechanism of Lake Water Area Change in Dry Season

In the dry season, temperature and sediment significance correlated with the lake area. Comparing annual images of the region in the dry season indicates that changes in the water area are concentrated in the Ganjiang River Estuary and Poyang Lake Estuary (Fig. 12). In 1991, 2004, 2006, 2010, 2013, 2017, 2019, and 2021, the water area at the estuary of the Ganjiang River decreased. In 1991, 2006, 2004, 2006, 2010, 2013, 2019, and 2021, the

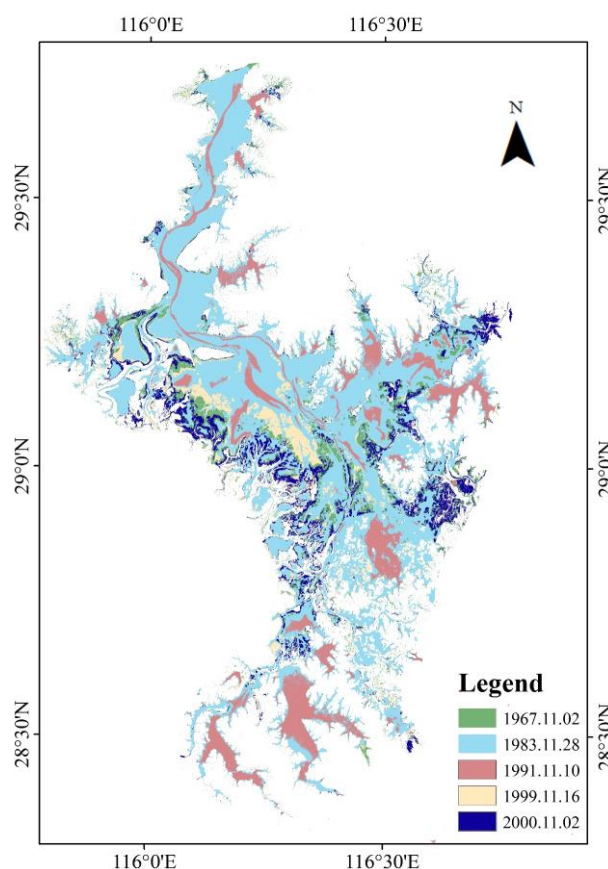
water area at the Poyang Lake Estuary decreased and, consequently, the lakebed was visible. Overall, the dry season resulted in a significant decreasing trend in the sediment of the five major areas during these years. From 1980–1990, the high sediment load of these rivers caused higher sedimentation in the river estuary, and this siltation phenomenon was primarily evident for the Ganjiang River Estuary. However, several studies have indicated that the elevation of the lake estuary decreased significantly during this period and this decrease was related to the factors such as continuous sand mining and current scouring [23–27].

The MK mutation test confirmed that the change-point year was 2003. The average water area was 2300 km² in the early dry season of the 1990s; however, after 2003, the average water area decreased to 1500 km². Further, sediment load and temperature did not alter drastically during these periods. Therefore, combined with various characteristics of the water body area in the flood season, it is evident that the water body decreases in extent ahead of the wet season. Several researchers have suggested that the Three Gorges Dam (TGD) water impoundment in 2003 significantly exacerbated the water level and runoff decline from late September to November, weakening the Yangtze River's blocking effect on outflows of the Poyang Lake through the estuary [28–30]. Changes in the Yangtze River runoff impact the interrelationship between the Yangtze River and Poyang Lake, disturbing the hydrological processes in the lake.

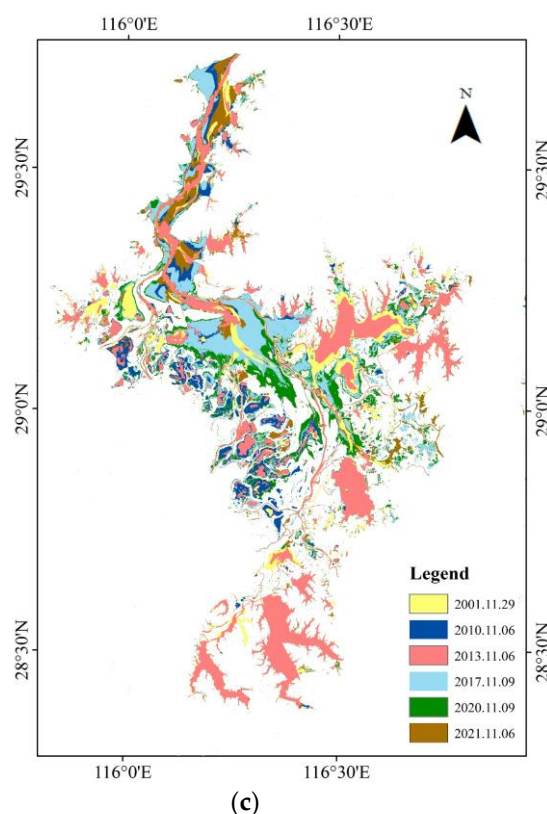
Given the above discussion, an apparent linkage between the sediment of the five major rivers and the change in the water area during the dry season is evident. In addition, it is likely that the TGD water impoundment affected the river–lake interaction, eventually leading the premature flow of water from the Poyang Lake into the Yangtze River. This would have resulted in decreases in the lake area at the end of the wet season, with changes in the lakebed topography also causing the water to flow more rapidly into the Yangtze River.



(a)



(b)



(c)

Figure 12. Comparison of lake water area during the early dry season: (a) Description of lake water area at the end of the dry season; (b) Comparison of lake water area extraction results at the end of dry season.

6. Conclusions

Based on a comparative analysis of the water area of the Poyang Lake in the past 42 years, the following conclusions can be drawn:

1. During the wet seasons of the study period, the lake water area showed a significant decreasing trend, with an average annual size decrease of -9.14 km^2 . In the dry season, the lake water area showed a significant downward trend, measuring a decrease rate of $-17.52 \text{ km}^2/\text{a}$. In addition, it was determined that the change point years of the wet season and dry season water areas were 2005 and 2003, respectively.

2. Lake runoff, sediment, and precipitation significantly correlate with the wet season water area. In the dry season, the sediment significantly correlates with the water area.

3. The analysis of satellite imagery confirmed a direct correlation between the change in the water area and the change in the net outflow of the lake in the wet season, and the net outflow is affected by the river–lake interactions. The Poyang Lake is a classical river-connected drain lake. Flood or drought events in the mainstream of the Yangtze River will affect the blocking or reversing of the Yangtze River on the Poyang Lake Estuary, impacting the net outflow of the lake and altering the water area.

4. In the dry season, based on the analysis of image and land use, the sediment deposition at the elevation of the estuarine entrance lakebed was raised, especially at the Ganjiang river estuary, affecting the water body shape. However, after 2000, the TGD water impoundment operation on the upper Yangtze River affected the runoff of the lower reaches of the Yangtze River at the end of the wet season. This impacted the river–lake interaction and decreased the area of the Poyang Lake.

Overall, the results indicate that the variation in the Poyang Lake water area is affected by the runoff of the Poyang Lake Basin as well as the runoff from the Yangtze River

and the sediment in the Poyang Lake basin. Although our findings contributed significantly to our knowledge on the hydrological dynamics of the Poyang Basin, the effects of groundwater were not considered here, which can be accounted as a limitation of this study. Therefore, water resource utilization in the Poyang Lake Basin needs to consider the changes in the lake basin and the runoff outside the basin in future studies.

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Data Availability Statement: The data that support the findings of this study are available in United States Geological Survey at [<https://earthexplorer.usgs.gov/>], [reference number \[reference number\]](#).

Conflicts of Interest: It should be understood that none of the authors have any financial or scientific conflicts of interest with regard to the research described in this manuscript.

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