

Article

Temporal-Spatial Evolution Analysis of Lake Size-Distribution in the Middle and Lower Yangtze River Basin Using Landsat Imagery Data

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Abstract: Four natural lakes in the middle and lower reaches of the Yangtze River—Dongting Lake, Poyang Lake, Chaohu Lake and Taihu Lake—play a key role in the climate, environment, and ecology of this area. Upstream of these lakes, the Three Gorges Dam Project has been storing water for 12 years. Future monitoring and management of rivers and lakes can certainly benefit from research on the patterns of variation of natural lakes downstream of the Three Gorges Project. This research applies Landsat TM/ETM data to evaluate water area changes in the four lakes from 2002 to 2013. The water area is estimated using AWEI (Automated Water Extraction Index) from satellite images. The average areas decreased respectively 452, 11, and 5 km² (29.6%, 1.4% and 0.2%) from 2002 to 2013 for Dongting, Chaohu, and Taihu Lakes. Meanwhile, it increased 300 km² (11.0%) for Poyang Lake. Precipitation and changes in river inflow may account for the fluctuation in the surface area to a large degree, especially between 2009 and 2013. The present study was undertaken to characterize the evolution of lakes and to explore the potential driving force of variation in order to assist the management of dams upstream in the river basin.

Keywords: AWEI; Landsat; the Yangtze River Basin; lake evolution

1. Introduction

Lakes not only contain abundant freshwater, agricultural and aquatic products, minerals, and other resources but also play an important role in natural cycles, climate regulation, and ecological balance [1,2]. Under the influence of LUCC (Land-Use and Land-Cover Change) and other forms of environmental change, surface water, as one of the most important resources on Earth, has undergone constant temporal and spatial evolution. For many years, the impacts of surface water evolution on ecology, society, health and the economy have been topics of a large number of academic studies [3–10]. For example, the areas of 22 relatively large lakes in the southeast region of Qiangtang Plateau have been expanding during 30 years of increasing ice melt, snowmelt, and rainfall, and decreasing evaporation [11].

Remote sensing technology provides a more convenient platform for real-time monitoring and management of surface water resources, as it offers a broad scope of observation and rapid data collection [12–17]. For example, MODIS image data were used to monitor and analyze the changes in the inundated area of Poyang Lake over 11 years [18], and a near real-time water surface detection method based on MODIS data was developed and tested to be applied to other existing or scheduled sensors with similar bands [19]. Researchers analyzed different periods of volume change and built underwater terrain models of the Baiyangdian wetland using multiple Landsat and HJ-1A/B images, and CCD images combined with water levels from the hydrological station in Hebei province, China [20]. Time-series analysis of remote sensing data for mapping temporary surface water bodies was also applied in large scales [21]. NOAA AVHRR data, with their characteristic short cycles, have been used for statistics and analysis of flood areas in northeast India, providing advanced technological support to remote-sensing monitoring, evaluation, and decision-making for disaster prevention [22]. The four lakes in the middle and lower Yangtze River Basin are important freshwater reservoirs and serve both society and ecology so that monitoring them is a valuable feat. The lakes are downstream of the Three Gorge Dam and analysis of their temporal-spatial evolution can be important to water management in the region.

In this study, Landsat TM/ETM data are applied to monitor the water area changes of four lakes in the middle and lower reaches of the Yangtze River basin: the Dongting, Poyang, Chaohu, and Taihu Lakes. We applied a previously-validated lake extraction algorithm called AWEI (Automated Water Extraction Index) to Landsat satellite imagery to measure the area of the four lakes [23], then estimated variability and trends in lake area, and evaluated the correlation with precipitation data. The spatial changes such as displacement of lake centroids were also analyzed, because this can reflect the driving force of the lake evolution process [24,25]. Overall, the objectives of this study are to contribute to the goal of feasibly and conveniently mapping lake areas for long-term lake monitoring, as well as providing a way to analyze variation in lakes of the same river basin.

2. Study Area

The four lakes—Dongting, Poyang, Chaohu, and Taihu Lakes, respectively located in northern Hunan, Northern Jiangxi, Central Anhui and Southern Jiangsu—are known as China's four largest lakes in the Yangtze River basin. All of them are natural lakes and are downstream of the Three Gorges Dam (Figure 1). The dam was built for flood control, irrigation, and electricity. In the event of a flood, there are 22 cubic kilometers of space behind the dam to hold back the flood waters. The flood waters are stored behind the dam for future use. In the dry season, the water is released down the river, and the reservoir level drops to prepare for the next flood.

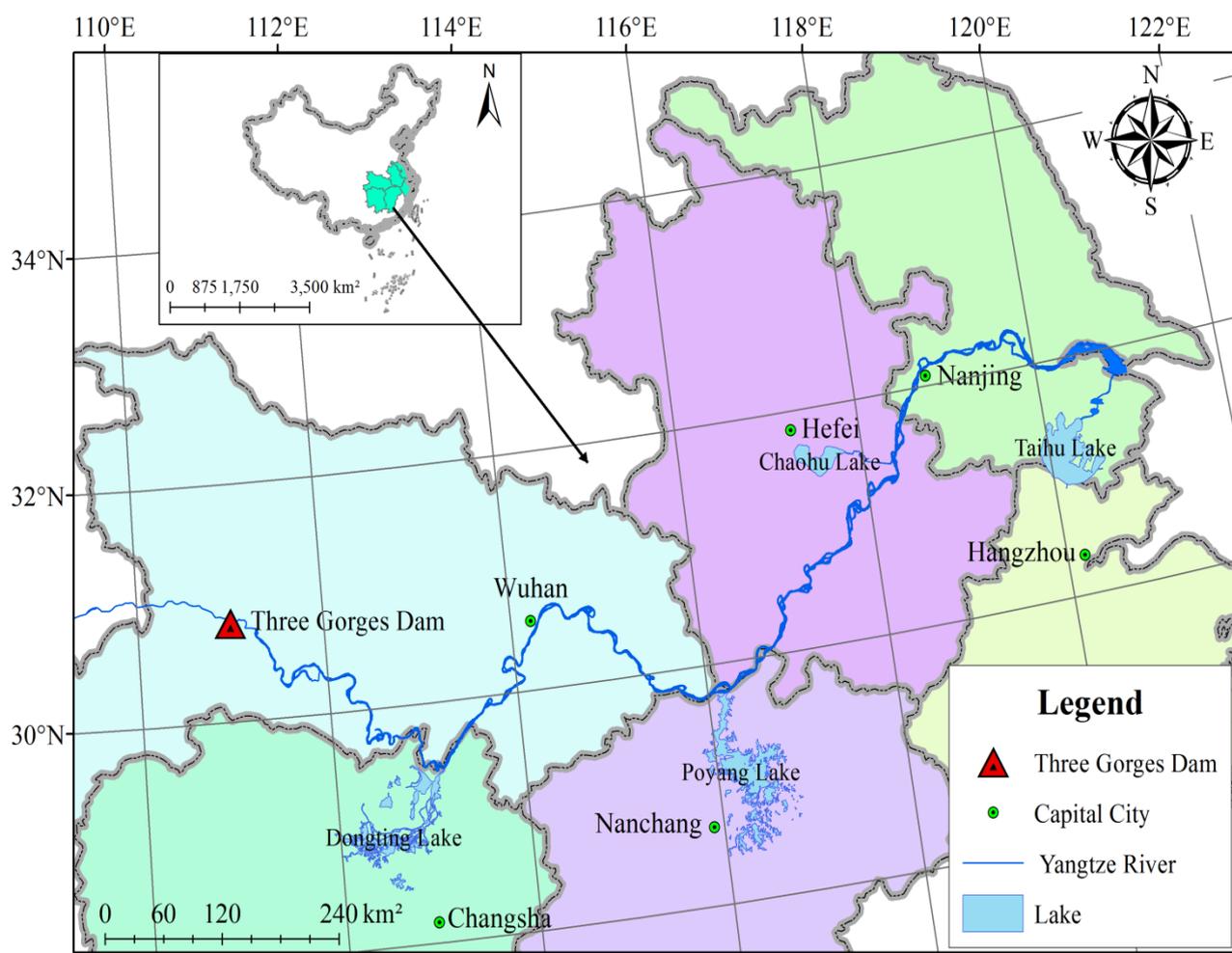


Figure 1. The study area and locations of the four lakes in China.

Dongting Lake, located in the area from 28°30'N to 30°20'N and from 112°25'E to 113°15'E, has a water storage capacity of approximately 17.8 billion m³ and plays an important role in flood storage. Its climate is mild and humid, and its MAAT (mean annual air temperature) is approximately 17 °Celsius. Dongting Lake district has an agriculture-based economy, and the population of its surrounding is approximately 11 million (3.46 people/ha). It is a major source of drinking and irrigation water for surrounding areas.

Poyang Lake, located between 28°22'N and 29°45'N and between 115°47'E and 116°45'E, has a water storage volume of approximately 25 billion m³. The annual inflow into Poyang Lake is about 16% of

the annual runoff of the Yangtze River. Its climate and MAAT are very similar to Dongting Lake. There are nearly 20 million people (3.81 people/ha) living around Poyang Lake and as a large bird sanctuary, Poyang Lake provides winter habitat to thousands of migratory birds from Siberia, Mongolia, Japan, North Korea, northeast China, and northwest China from late fall through early winter.

Chaohu Lake, 15 km southeast of the city of Hefei, is located between 31°25'N and 31°43'N and between 117°16'E and 117°51'E. The region is characterized by a northern subtropical monsoon moist climate with MAAT of approximately 15°–16°Celsius. The permanent population of its surrounding is about 11 million (4.56 people/ha), and the area of land under irrigation is nearly 3200 km².

Taihu Lake is geographically located between 30°55'N and 31°32'N and between 119°52'E and 120°36'E, with hilly mountains to the west. Its climate is mild and humid with MAAT is approximately 16°–18°Celsius. The permanent population of its surrounding is approximately 23 million (10.63 people/ha), and the area of land under irrigation is nearly 3240 km².

The time of wet and dry season alternation is variable in years for the four lakes. Dongting and Poyang Lake are leaf-shaped lakes with a lot of shallow areas, and their outlets are close to the Yangtze River, allowing water from the lake and the river to complement each other during the dry and the wet season, in time. In contrast, Chaohu Lake and Taihu Lake are block-shaped lakes with less shallow areas, and their outlets are far from the Yangtze River.

3. Data Use and Methodology

3.1. Landsat Data

The Yangtze River was blocked off in 2002 after the completion of key parts of the Three Gorges Dam. The goal of this research is to estimate changes in lake size and centroid, downstream of the dam, and identify the probable cause of changes to lake morphology. In total, 287 Landsat images covering the four large lakes from 2002 to 2013 were obtained from the USGS Global Visualization Viewer [26] and were used to extract the water area of the target lakes (Table 1). To cover the data range of 2002 to 2013, both Landsat TM and ETM were used. All spatial resolutions are 30 m. Bands 1, 2, 4, 5, and 7 of TM and ETM were included.

Table 1. Data selection in the study area.

Lakes	Number and Years of Landsat TM/ETM Data Used for Each of the Four Lakes												Total
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
Dongting Lake	4	8	6	8	5	4	4	2	3	5	0	9	58
Poyang Lake	5	6	10	2	6	5	5	6	7	4	5	1	61
Chaohu Lake	8	9	11	6	9	8	5	8	13	7	5	5	94
Taihu Lake	10	6	10	8	2	4	5	6	8	5	5	5	74
	TM						ETM						
Total	74						213						287

3.2. Methodology

3.2.1. Image Processing

Data obtained from the USGS Global Visualization Viewer are all from Level 1, meaning that the data have gone through the radiometric and geometric correction, but not terrain correction [26]. Since this study does not include a comparative analysis of water area with other topographic data, the terrain correction is not needed. Usually, satellite digital images provide a pixel's DN-values, with which only relative comparisons can be made within the same image. To quantitatively compare data obtained from different places and times with different types of sensors, the DN-values must be transformed into corresponding radiance pixel values via a conversion process called radiometric calibration [27,28].

Radiometric calibration methods for the TM and ETM sensor data are different. In this research, the ENVITM (version 5.0 SP2) desktop software Landsat calibration tool was used to conduct radiometric calibration [29], and FLAASH (Fast Line-of-sight Atmospheric Analysis of Hypercubes) atmospheric correction tool was used to correct for atmospheric contamination [30].

3.2.2. Water Extraction Method

Compared with types of land cover such as vegetation or bare land, water shows special characteristics in the near-infrared band, which can be used to distinguish water from other object types. There are numerous methods for recognizing water with a single band or multi-band, including the Open Water Likelihood (OWL) water extraction index method [31,32], among others. One of the most commonly-used methods is the Normalized Difference Water Index (NDWI) proposed by McFeeters, using band 2 and band 4 of the Landsat images for water extraction [33]. However, NDWI cannot effectively distinguish between buildings and water, leading to misclassification of the two cover types. The NDWI method was improved by replacing band 4 with band 5, which effectively distinguishes water from buildings. The new water index is named the Modified Normalized Difference Water Index (MNDWI) [34]. However, neither of the above methods can distinguish water from shadows.

In this study, a water index method, the Automated Water Extraction Index (AWEI) [23] was applied that distinguished water from shadows, buildings, asphalt, and other sources of spectral confusion. AWEI was defined as:

$$AWEI_{nsh} = 4 \times (\rho_{band2} - \rho_{band5}) - (0.25 \times \rho_{band2} + 2.75 \times \rho_{band5}) \quad (1)$$

$$AWEI_{sh} = \rho_{band1} + 2.5 \times \rho_{band2} - 1.5 \times (\rho_{band4} + \rho_{band5}) - 0.25 \times \rho_{band7} \quad (2)$$

where ρ represents spectral reflectance values of the band, and its subscript describes the specific band. The subscript “*nsh*” represents the formula applied to situations where non-shadow surface features (such as building surfaces and asphalt roads) constitute the main problem for water extraction. In contrast, the subscript “*sh*” indicates that this formula should be applied to remove shadows from water. Water usually absorbs almost all of the radiation of bands 4, 5, and 7, and it has the highest albedo in bands 1 and 2. Therefore, water can be effectively distinguished from other surface features by Equations (1) and (2). However, in some time series, lakes or parts of them are very turbid, and contain floating vegetation or intensive algal blooms. These are often inseparable from adjacent land. Visual interpretation was used to eliminate the error classified extraction results caused by algal blooms. Figure 2 is an example of the

lake area extracted by AWEI from Landsat TM/ETM images, where (a) is the water area of Dongting Lake extracted on 19 March 2002; (b) is the surface area of Poyang Lake extracted on 8 January 2002; (c) is the lake body of Chaohu Lake extracted from Landsat data on 8 January 2002; and (d) is the water area of Taihu Lake extracted on 2 January 2002.

The omission error and commission error of the AWEI method of water detection are only half of those of the MNDWI, and a fourth of the errors associated with the Maximum Likelihood method [23].

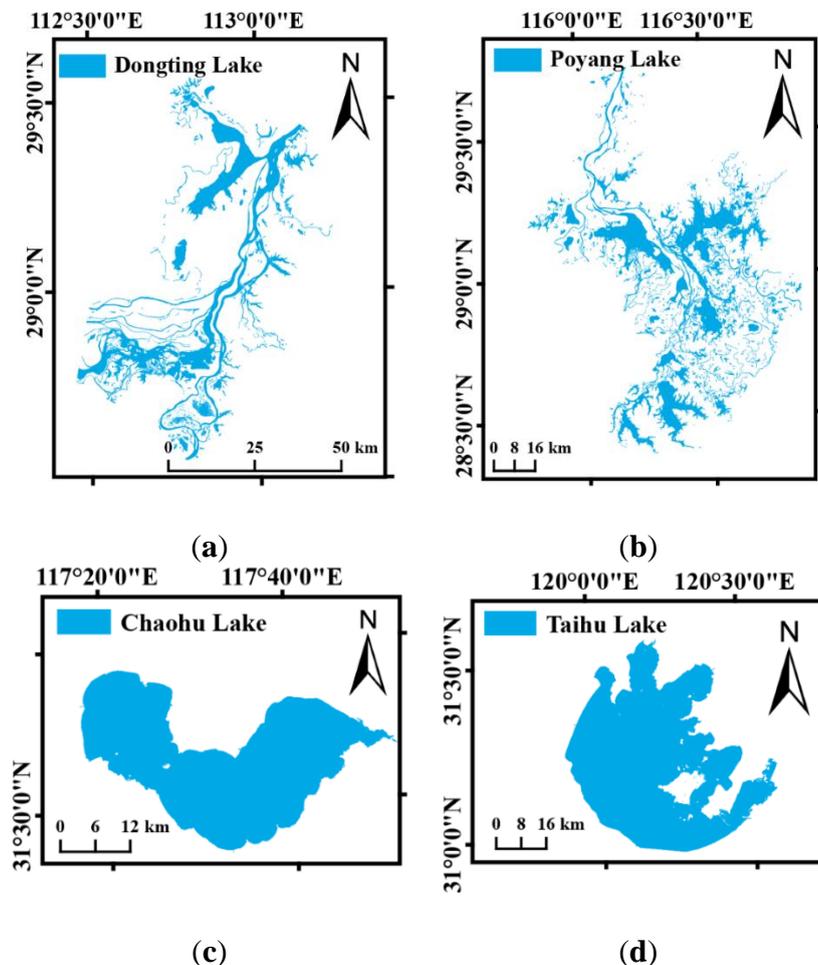


Figure 2. Extraction examples of (a) Dongting Lake; (b) Poyang Lake; (c) Chaohu Lake, and (d) Taihu Lake.

3.2.3. Lake Expansion Index (LEI)

To provide a quantitative analysis of the temporal and spatial changes in lake areas downstream of the Three Gorges Project, the annual rate of change in area relative to the previous period was estimated [11,35]. And an extended annual rate of change in area relative to the lake average size of the entire period was developed. The formulas for calculating the annual change and the extension in lake water area are defined as:

$$\eta = \frac{S_b - S_a}{S_a} \times \frac{1}{T} \times 100\% \tag{3}$$

$$\eta_{ext} = \frac{S_b}{S_{average}} \times 100\% \quad (4)$$

where η is the annual percent change in lake area. The subscript “*ext*” represents “extended”. S_a represents the lake area during the current period. S_b represents the lake area of the next period. $S_{average}$ represents the lake average area of the entire period. T indicates the length of the analysis period, in years. If η is positive, the lake area increases. If η is negative, the area decreases. If η_{ext} is larger than 1, the lake area is larger than average. If η_{ext} less than 1, the area is smaller than average.

The possible number of Landsat acquisitions that could be used for lake extraction in the time-series is limited by factors such as temporal resolution of the Landsat sensor, thick cloud covering the surface features, large area of eutrophication, turbid water, *etc.* Seasonal variations in lake sizes could not be estimated reliably with the available Landsat data. However, the annual average for the four lakes can be calculated more reliably with selecting an equal number of lake sizes evenly distributed throughout the wet and dry seasons. The annual average is the mean value of the selected wet and dry season lake sizes.

3.2.4. Precipitation Analysis

To estimate the impact of rainfall on the lake areas, the monthly rainfall data of the four lakes from 2002 to 2013 were obtained from the China Meteorological Data Sharing System [36]. This data set consists of monthly surface precipitation gridded data with a $0.5^\circ \times 0.5^\circ$ horizontal resolution since 1961. The latest precipitation data from approximately 2400 stations compiled by the National Meteorological Information Center were interpolated spatially by thin plate spline (TPS) using the ANUSPLIN software. The data were cross-validated, and error analysis was performed. We summed the monthly precipitation values to determine the annual surface precipitation. The average annual area and the annual surface precipitation were normalized [18,37] to improve visualization and comparison.

3.2.5. Centroid Determination Analysis

To examine the spatial-temporal characteristics, the lake centroid is extracted from each lake as a frame of reference, and the geographical space is divided into eight quadrants with intervals of 45 degrees. In this way, the offset can be estimated in every direction. The shifting distances and the shifting angles from the lake’s previous centroid to the next are calculated by identifying the quadrant in which the deflection occurs [38,39]. All of the distance values in each quadrant in each time period are accumulated, and values in the opposite direction (such as north and south) cancel out.

4. Results

4.1. Estimated Area and Surface Changes

To monitor the temporal and spatial changes in water area of the four downstream lakes, images of the lakes from 2002 to 2013 were used for data analysis. The statistical description of the water area extraction results by using AWEI was given in Table 2.

Dongting Lake, with the shortest distance from the Three Gorges Project, had an average area of 1225 km² from 2002 to 2013. Its largest area was estimated on 3 September 2002, and the smallest area was estimated on 12 March 2011. In contrast, the average area of Poyang Lake was 2586 km² from 2002 to 2013. The largest area was estimated on 16 August 2010, and the smallest area was estimated on 11 December 2011. The extraction results of Dongting and Poyang Lakes were more discrete. The coefficients of variation, which were 0.46 and 0.28 separately, indicated that the values are much different from the mean value. Data sets with positive kurtosis tend to have a distinct peak near the mean, decline rather rapidly, and have heavy tails. However, the kurtoses of the two lakes were -1.23 and -1.45, respectively, which showed that the area values are more evenly distributed (Figure 3).

Table 2. Statistical description of four lake extraction areas in southeastern China.

	Dongting Lake	Poyang Lake	Chaohu Lake	Taihu Lake
Number	52	61	73	67
Summation (km ²)	63,697	157,725	57,345	157,075
Minimum (km ²)	521	1390	769	2283
Maximum (km ²)	2232	3808	806	2423
Mean (km ²)	1225	2586	786	2344
Range (km ²)	1711	2418	38	140
SD	567.50	721.66	9.09	30.11
CV	0.46	0.28	0.01	0.01
Kurtosis	-1.45	-1.23	-0.50	-0.04

SD = standard deviation, CV = coefficient of variation.

Chaohu and Taihu Lakes are far away from the Three Gorges Project and have similar morphologies and temporal-spatial changes in water area (Figure 3). Overall, we can see that the CV of Chaohu and Taihu Lakes are both 0.01, which implies that the water areas of Chaohu and Taihu Lakes have not changed substantially. It could also be inferred from the kurtoses of Chaohu and Taihu Lakes (0.50 and 0.04, respectively) that the area results exhibited an approximate normal distribution. The average areas of Chaohu and Taihu Lakes were 786 km² and 2345 km², respectively, from 2002 to 2013. The seasonal water area changes of Chaohu and Taihu Lakes were within 3.7% and 5.1%, respectively, of the total lake areas.

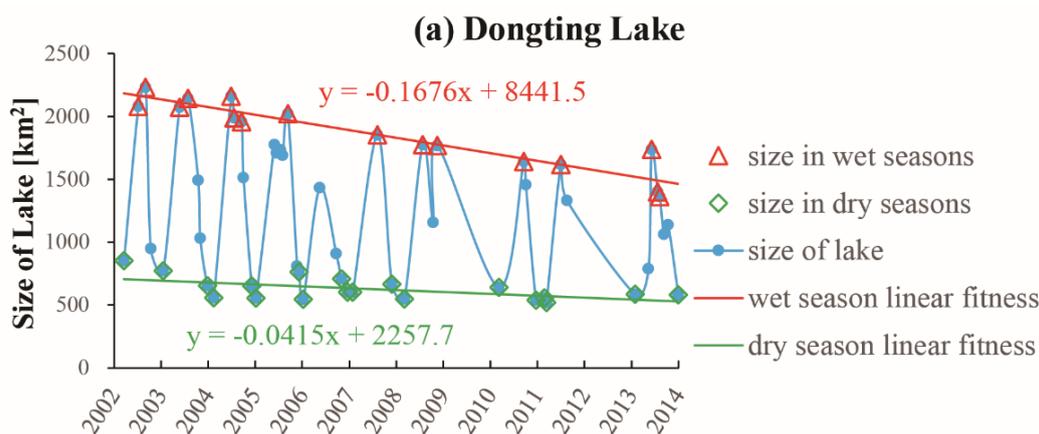


Figure 3. Cont.

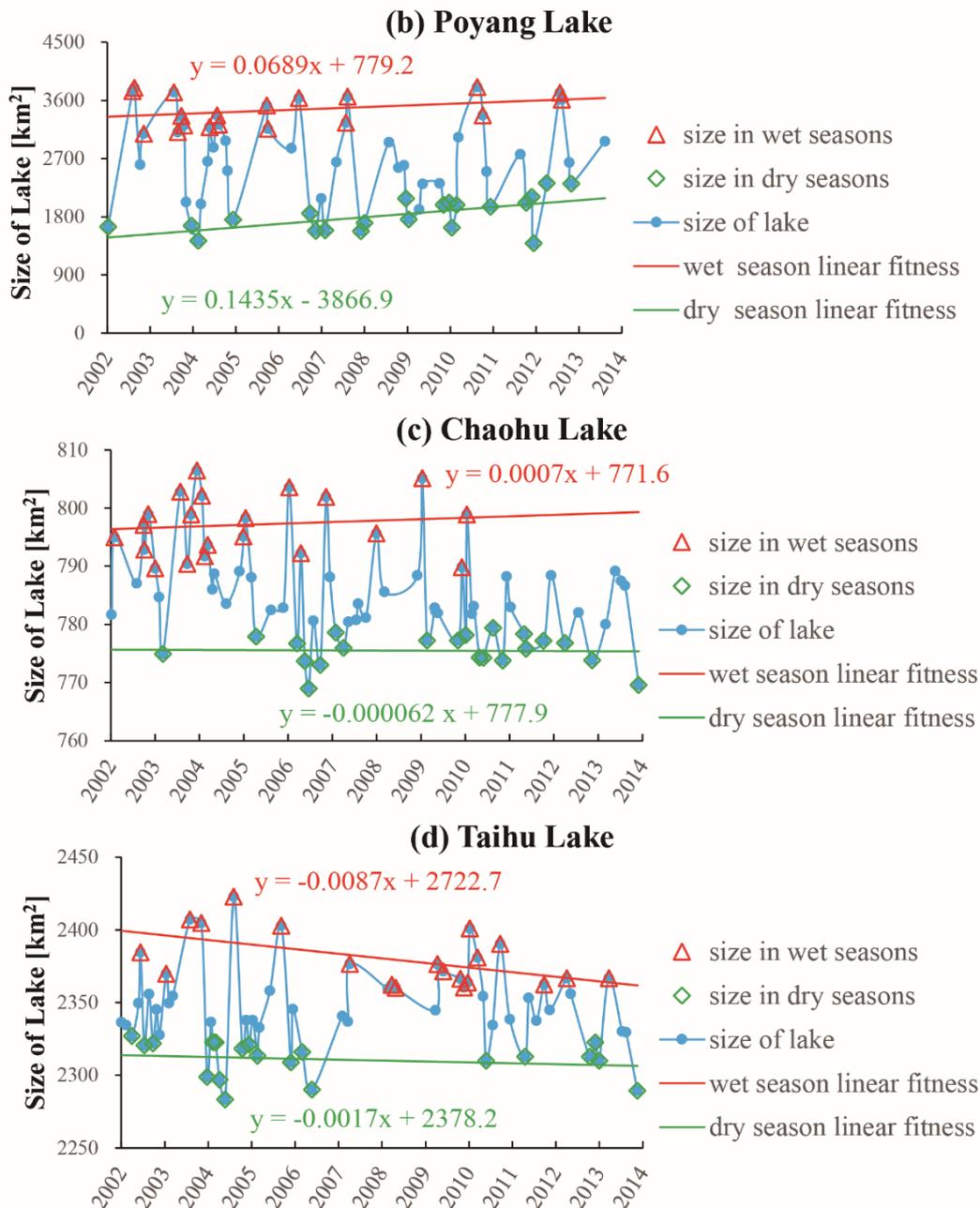


Figure 3. Seasonal sizes of four Yangtze River lakes from 2002 to 2013 for (a) Dongting Lake; (b) Poyang Lake; (c) Chaohu Lake, and (d) Taihu Lake.

Four images of the lakes were chosen for accuracy assessment. The method in assessment of the positional accuracy of AWEI method is a human visual inspection towards Landsat images. Water and non-water areas were distinguished by visual inspection in each pixel of the lake edges and the extraction result was used as the ground truth comparing to the result extracted at the same time period by AWEI method. The results of accuracy assessment were summarized in a confusion matrix and the specific information of classification accuracy for AWEI method of four lakes is shown in Table 3.

Table 3. Summary of classification accuracy of the four lakes.

	Dongting Lake		Poyang Lake		Chaohu Lake		Taihu Lake	
Date	13 October 2002		20 August 2002		8 January 2002		9 October 2002	
Class	Non-Water	Water	Non-Water	Water	Non-Water	Water	Non-Water	Water
Commission (%)	1.09	1.26	0.8	0.79	0.06	0.6	2.08	1.76
Omission (%)	0.15	8.68	0.24	2.62	0.19	0.19	1.69	2.16
Prod. Acc. (%)	99.85	91.32	99.76	97.38	99.81	99.81	98.31	97.84
User Acc. (%)	98.91	98.74	99.2	99.21	99.94	99.4	97.92	98.24
Overall Accuracy (%)	98.89		99.2		99.81		98.08	
Kappa Coefficient	0.94		0.98		0.99		0.96	

The LEI and extended LEI for the four lakes from 2002 to 2013 were reported in Figures 4 and 5. The largest percent change of water area increase for Dongting Lake was 0.4% from 2011 to 2013, when the water area increased by 3.8 km² per year. The largest annual decrease of the Dongting water area was 8.0% from 2005 to 2006, corresponding to a decrease of 101.2 km² per year. The largest percent change of water area increase for Poyang Lake was 45.1% from 2009 to 2010, an increase of 947.8 km² per year. The largest annual decrease in the water area was 24.7% during 2010 to 2011, which corresponded to a decrease of 752.8 km² per year. Area changes of Poyang Lake substantially fluctuated, which may be due to two factors. First, Poyang Lake is the largest of the four lakes. Under the condition of the same change rate, the change in area was much larger than the others. Second, severe drought occurred in 2009 and 2011, which also contributed to a large area change in the corresponding time period in Poyang Lake (Figure 4). The subsequent chapters will explain this in detail.

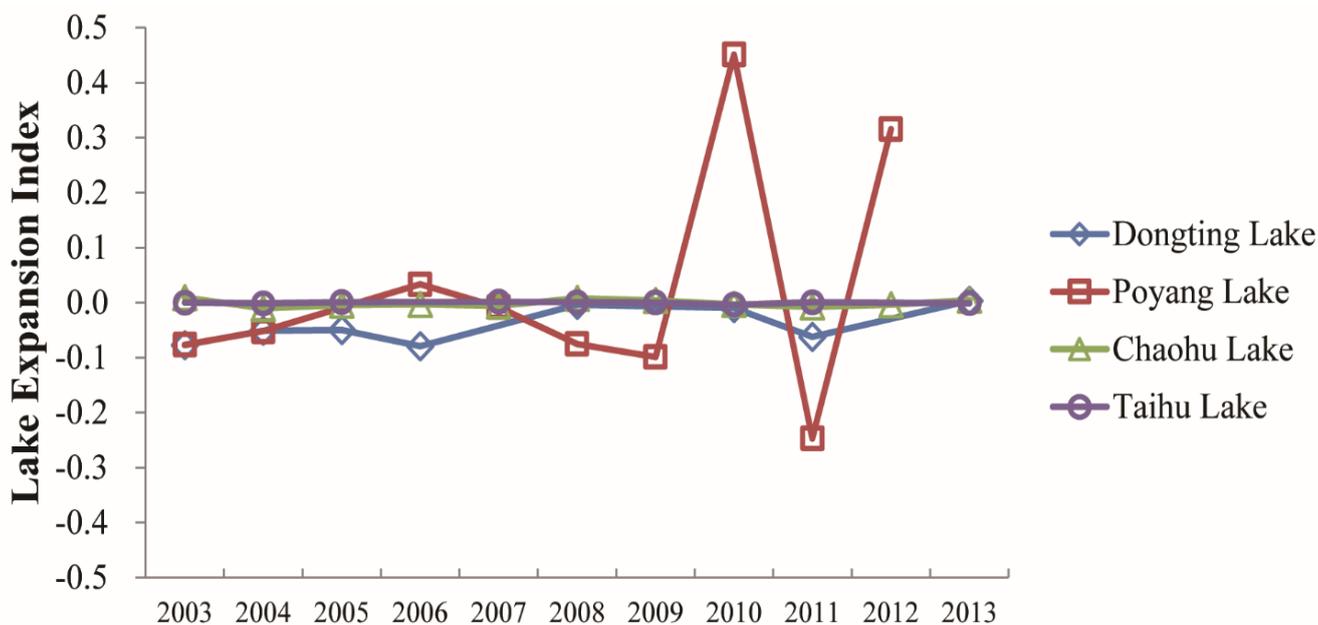


Figure 4. The LEI of the four lakes from 2002 to 2013.

The annual rates of area change for Chaohu Lake were most variable in 2002–2004. During 2002–2003, the water area of Chaohu Lake increased by 7.4 km² but then decreased by 8.2 km² in 2003–2004. The annual percentage changes of water area for the two years were 0.9% and –1.0%, respectively. Throughout

the study period, the annual rate of water area change of Chaohu Lake was $\pm 1.1\%$. This shows that the water area of Chaohu Lake was stable during the study period. Overall, the patterns of change for Taihu and Chaohu Lakes are similar. The annual percent change for Taihu Lake was $\pm 0.4\%$. The minimum and maximum values were -0.4% and 0.1% , respectively.

During the 12 years, the difference between the maximum and the minimum areas of Dongting Lake was 460 km^2 , and the difference for Poyang Lake was 948 km^2 . However, the differences between the maximum and the minimum areas of Taihu Lake and Chaohu Lake were only 22 km^2 and 13 km^2 , respectively. Comparing the annual average areas of the four lakes, the annual average for Chaohu and Taihu Lakes are very regular, whereas the seasonal differences for Poyang Lakes is great and Dongting Lake shows a steady decline (Figure 5).

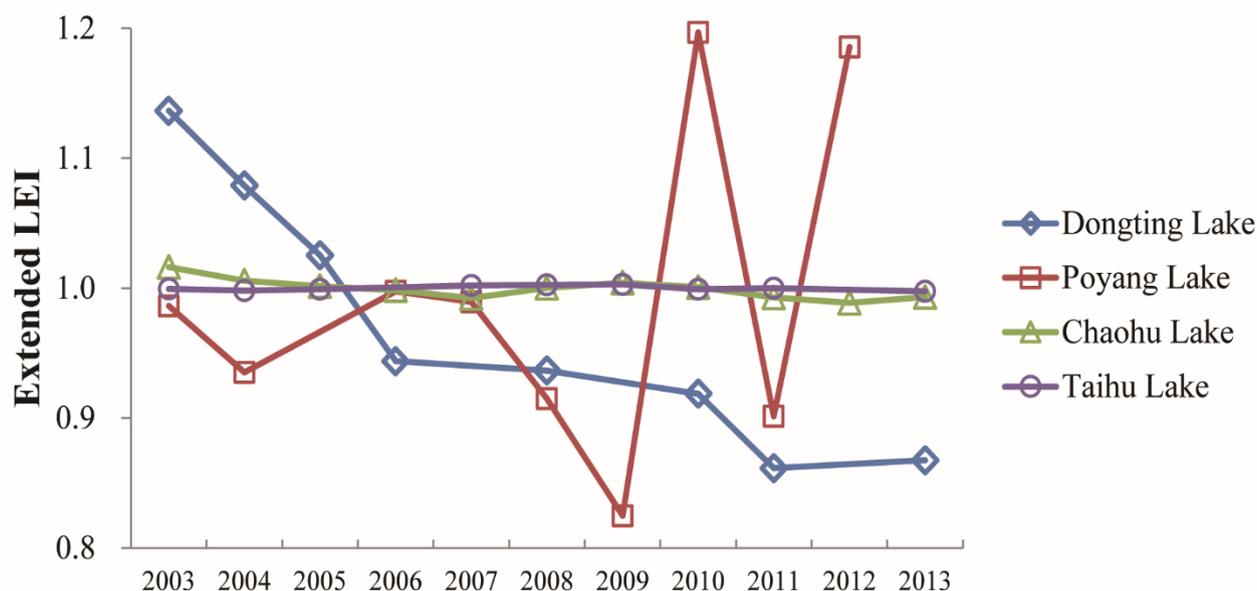


Figure 5. The extended LEI of the four lakes from 2002 to 2013.

Anomaly is the difference between estimated lake size values and statistical averages of the four lakes. And it is mainly used for volatility observation of sample data relative to the average. By calculating the anomalies of water areas from 2002 to 2013 [40], this study shows that the anomaly in Dongting Lake area declined from 2002 to 2013, even as the anomaly fluctuated considerably over that time. During the period from 2002 to 2006, the water area was generally larger than average, whereas from 2006 to 2013, the water area was statistically significantly smaller than average. Poyang Lake showed a similar trend in water area anomaly, but with a different timing (2007 vs. 2006) of the switch from larger to smaller than average anomalies (Figure 6).

The anomaly of Chaohu Lake changed little from 2002 to 2013. The water area fluctuated within 25 km^2 of the annual average area. Before April 2007, the water area tended to be larger than the 2002–2013 average area, and it was smaller than average after August 2007. The trend-line of the anomaly histogram of Taihu Lake shows that the water area changed so little that the trend-line almost overlaps the horizontal axis (Figure 6).

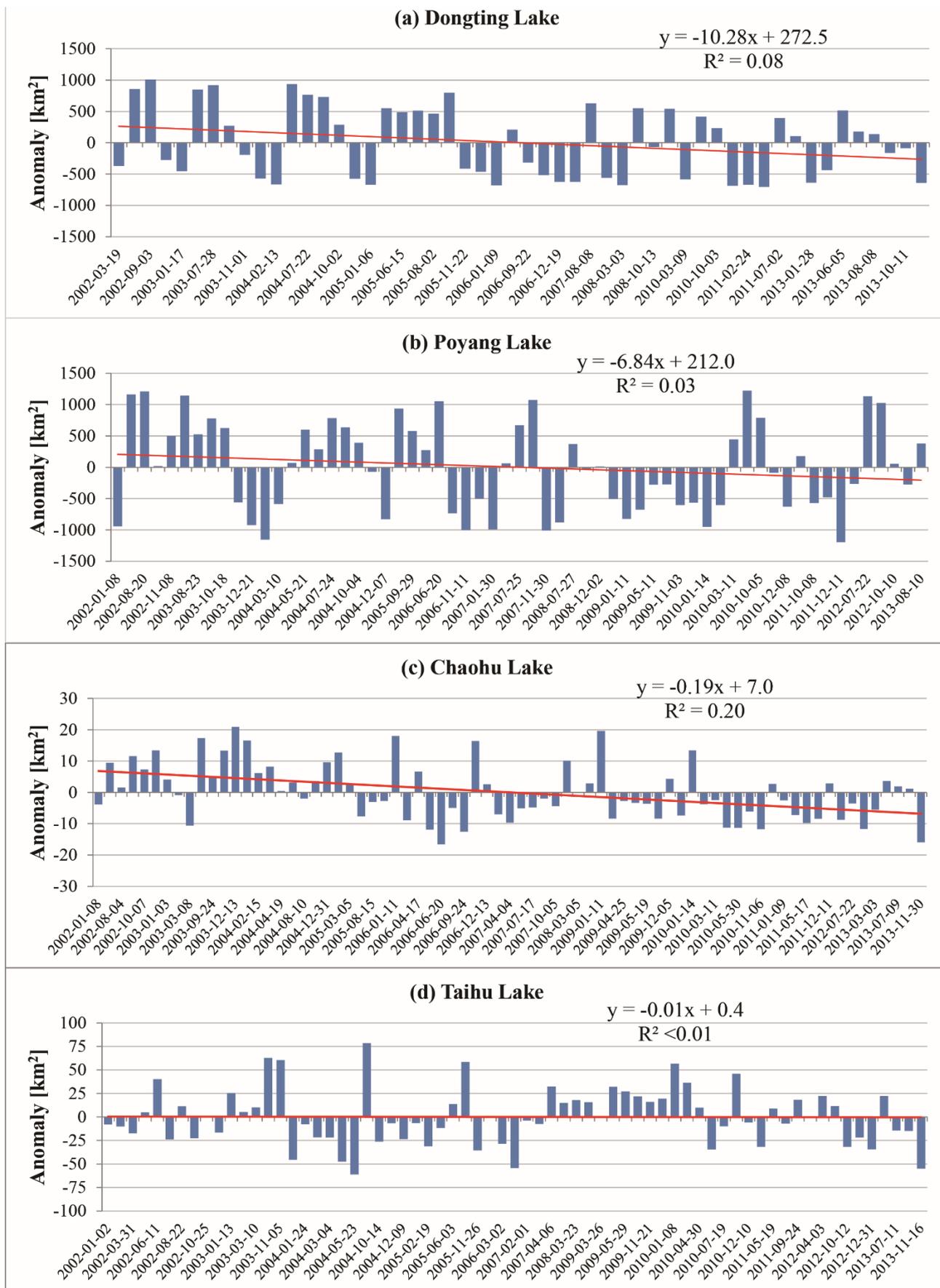


Figure 6. Anomaly of lower Yangtze River lakes from 2002 to 2013 for (a) Dongting Lake; (b) Poyang Lake; (c) Chaohu Lake, and (d) Taihu Lake.

4.2. Relationship between Rainfall and Lake Area

Annual precipitation and annual average area of the four lakes are significantly correlated. The *p*-values for Dongting and Poyang Lakes are all less than 0.05, indicating a significant correlation between rainfall and lake area. The *p*-values of Chaohu and Taihu Lakes are both less than 0.01, indicating highly-significant correlations. The Pearson correlation coefficient *r*-values of the four lakes are between 0.4 and 0.8, indicating that lake area is positively correlated with precipitation (Figure 7).

It is evident from Figure 7b that Poyang Lake suffered droughts in 2009 and 2011. Rainfall at Poyang Lake decreased, and the Yangtze River water level decreased at the same time, which led to the water of Poyang Lake pouring into the Yangtze River. Thus, in 2009 and 2011, the annual area reached a minimum, resulting in more fluctuation in the area change of Poyang Lake during the period from 2009 to 2013.

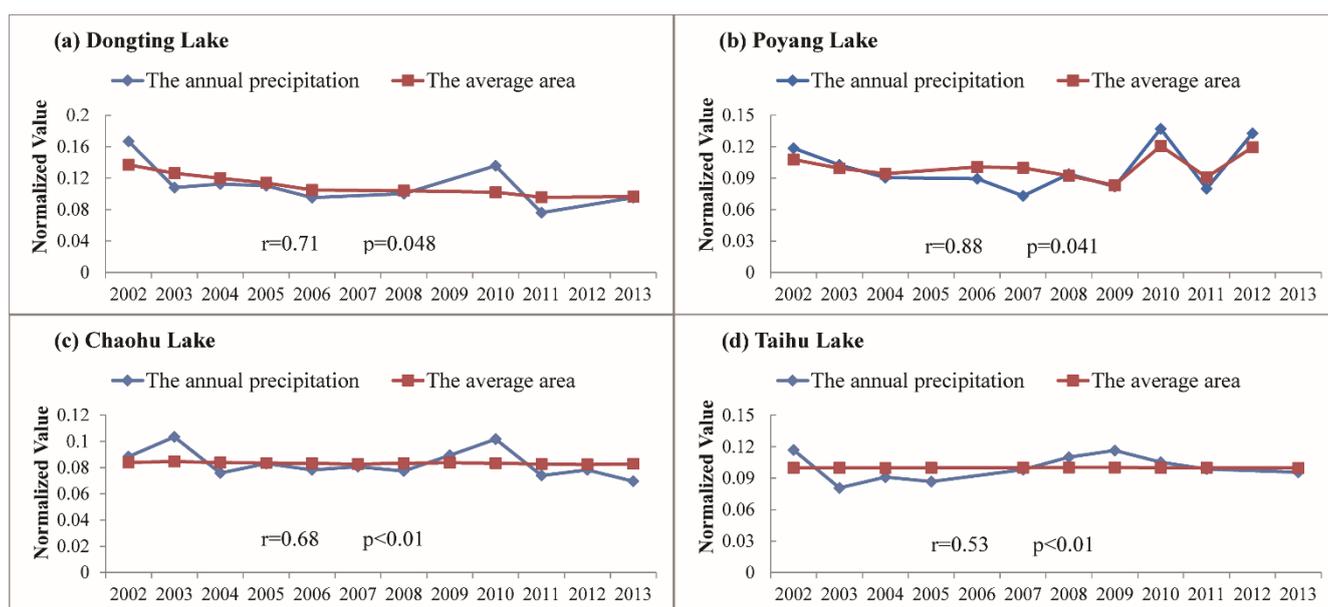


Figure 7. Normalized annual precipitation and average lake area correlation analysis for 2002–2013. (a) Dongting Lake; (b) Poyang Lake; (c) Chaohu Lake; (d) Taihu Lake.

4.3. Lake Centroid Displacement

The changes of a lake are evident not only in its area but also in its centroid. The spatial analysis shows some directionality in lake expansion and contraction during the study period, and the directionality depends on the centroid displacement of lakes. The results are shown in Figure 8. The initial positions of the centroid of each year are also extracted, connected as a time-sequence and attached with shifting directions. The four lakes are connected to the Yangtze River during all time periods considered in this study. The results show that the lake centroid of Dongting Lake mainly shifted towards the northeast and southwest from 2002 to 2013, whereas the lake centroid of Poyang Lake mainly shifted towards the northwest and southeast. However, the centroids of Chaohu and Taihu Lakes shifted less than 1 km over nearly 12 years, remaining relatively stable. The lake centroid of Chaohu Lake mainly shifted towards the west and the southeast, with distances of 305.7 m and 287.8 m, respectively. The centroid of Taihu Lake mainly shifted towards the west, the northeast, and the southeast, with distances of 989 m, 441.7 m, and 883.2 m, respectively (Figure 8). Although the movement of Poyang and Dongting Lakes seems

to be much bigger than Chaohu and Taihu Lakes, comparing to the size of themselves, the changes are not significant (for example, centroid of Poyang Lake shifted about 8 km during 12 years, but this is approximately 1/80 of the length between one side to the other side of Poyang Lake). The centroids of the two lakes shift in the direction of the lakes' outlets, suggesting that the main driver of lake centroid displacement in Dongting and Poyang Lakes is the water complementation between the lakes and the Yangtze River. Unlike Dongting and Poyang Lakes, there is no regularity in the shifts of the centroids of Chaohu and Taihu Lakes.

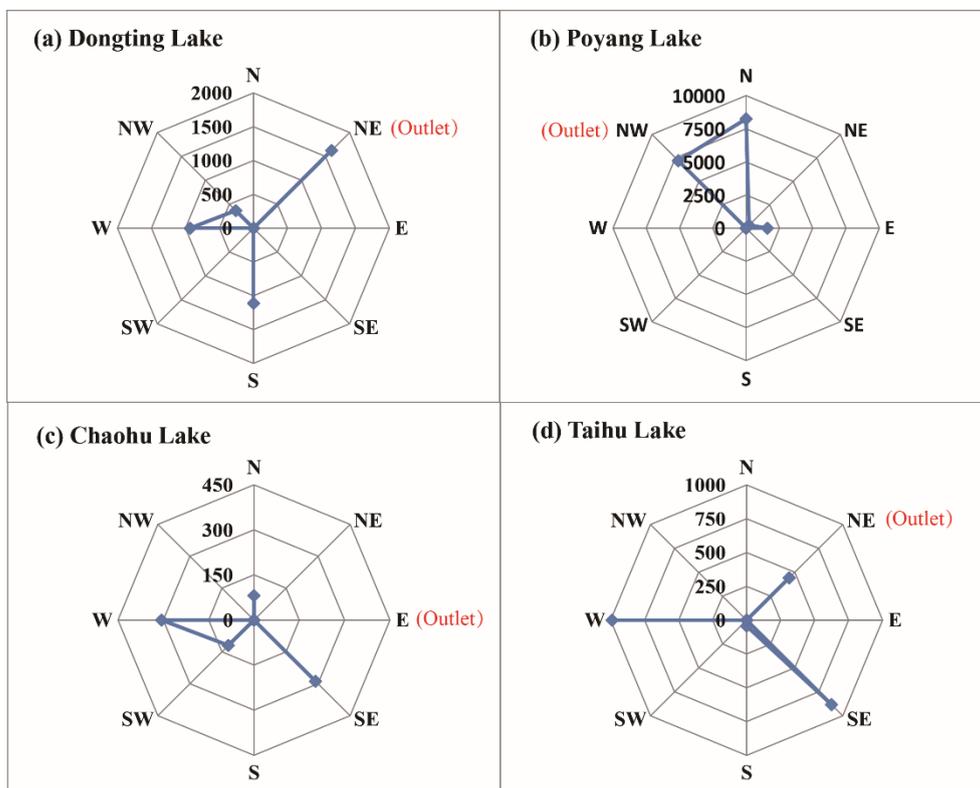


Figure 8. Rose diagrams of the movements of the centroids of the four lakes, (a) Dongting Lake; (b) Poyang Lake; (c) Chaohu Lake; (d) Taihu Lake. The units are in meters.

5. Discussion

5.1. Different Size-Distribution Variations for Four Lakes

Both the flood season and the dry season water areas of Dongting Lake have been decreasing during the 12 years since the Three Gorges Project started to store water. However, Poyang Lake, which has the second shortest distance from the Three Gorges Project and has a similar morphology to Dongting Lake, is very different from Dongting Lake in the temporal and spatial patterns of water area. The water area of Poyang Lake in the flood and dry seasons has been increasing from 2002 to 2013. Moreover, there are only slight fluctuations of the wet and dry seasons for Chaohu Lake and Taihu Lake which can be seen clearly from the slopes of the wet and dry season fitting lines in Figure 3c,d, which are all less than 0.01. Additionally, Chaohu and Taihu Lakes have low shifts comparing to Dongting and Poyang Lakes.

Figure 6 shows that there are many anomaly values larger than 1000 km² or less than -1000 km² in Poyang Lake, while values in Dongting Lake are all within ± 1000 km². This indicates that Poyang Lake might have different size change trends from Dongting Lake, although they are very similar in morphology. Related to the precipitation analysis, it could be argued that the different climate in these two lakes is a major cause for the different size change. Weather might be the main factor for the quite different variation of Poyang Lake from the other lakes. It also can be seen from the correlation analysis of precipitation and area that the area of Poyang Lake and rainfall are synchronous, especially during 2008 to 2013 (Figure 7). Furthermore, the annual inflows into Poyang Lake is about 16% of the annual runoff of the Yangtze River, which means the water inflows of Poyang Lake are the highest among the four lakes. In addition, Poyang Lake is an important protected area in China. From the end of the last century to the beginning of the 21st century, farmers returned to the fields in lakeside areas to Poyang Lake in large scales and a large number of embankments on the low-lying land were demolished. Overall, the unique character of size variation of Poyang Lake might be caused by precipitation, water inflows from the Yangtze River, and government policy.

The morphology and topography of the four lakes may also impact the centroid changes. Dongting Lake and Poyang Lake are leaf-shaped lakes with a lot of shallow areas, and their outlets are close to the Yangtze River, allowing water from the lake and the river to complement each other during the dry and the wet season in time. This results in the sizes of the two lakes being related to precipitation and the centroids of the two lakes moving back and forth towards or away from the outlets (Figure 9). In contrast, Chaohu Lake and Taihu Lake are block-shaped lakes, and their outlets are far from the Yangtze River. Therefore, they seem to show almost no response to precipitation, despite this relationship being significant and their lake centroids are not regularly displaced towards the outlet.

5.2. Dam Influence or Dissipate Influence on Lakes

Poyang Lake suffered large variations in rainfall during some periods of time, resulting in substantial lake area fluctuations, which can also cause substantial fluctuations in the surrounding ecological parameters, and cause losses of lake products. Therefore, lake area monitoring using multi-temporal remote sensing data can be used for assisting the management of upstream dams, such as increasing the drainage capacity of the dam in severe drought years but increasing the storage capacity of the dam in flood years. Implementation of such management of dams can preserve the surface area stability and sustainability of downstream lakes.

The impact of the Three Gorges Dam downstream has been a weakening in the Yangtze River forcing on the lakes downstream, allowing more lake flows to the river from July to March. This effect might also partially complete the dam's mission to mitigate flood risks in the lake basin, especially during the peak wet season of the Yangtze River basin from July to September. When the flood season faded away, the water would be kept from flowing downstream. When the dry season comes, the water storage, which was blocked before, could feed the lakes downstream for mitigating drought risks. These measures for dam management can make the downstream lake areas keep in a stable range.

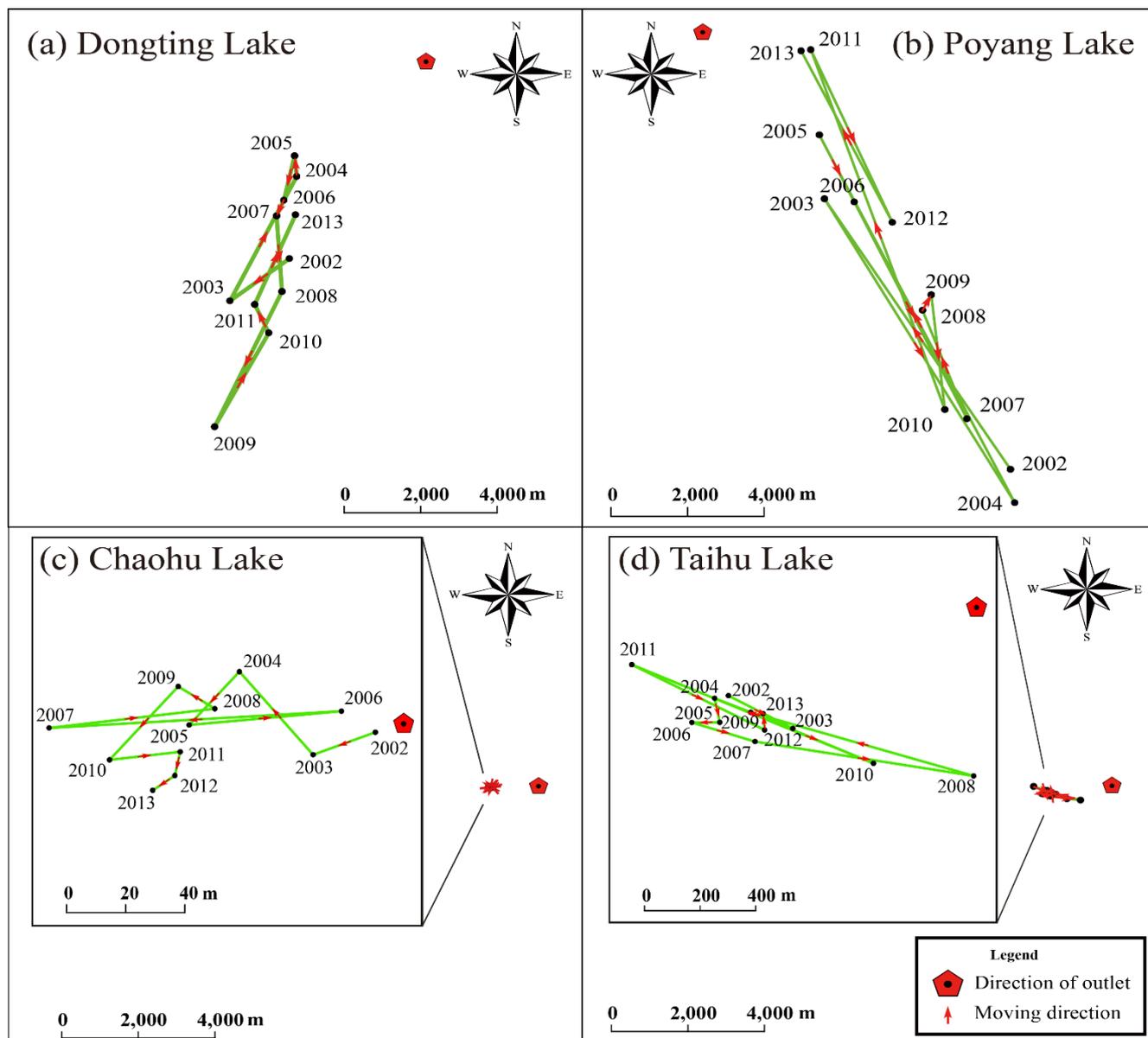


Figure 9. The movement of the centroids of the four lakes, (a) Dongting Lake; (b) Poyang Lake; (c) Chaohu Lake; (d) Taihu Lake.

5.3. Lake Monitoring and Other Applications

The Landsat TM and ETM sensors provided available measurements per 16 days, even though, as a result of high evaporation in the lake regions, there was sometimes only three or four cloud-free images available during a year. Although an insufficient number of images may lead to some uncertainties in the lake size statistics, the observation frequency of at least two images covering dry and wet seasons, after discarding cloudy scenes, could meet the requirements for this research. Higher frequency remote data can be applied to our research method for lake size monitoring, as well. For example, HJ-1A/1B CCD instruments provided one image with resolution of 30 m every two days [20], and MODIS instruments provided two daytime images per day [18,19]. These data could be better used in monitoring the long-term lake size and distribution changes in the future.

The results of the four lake size-distribution evolution presented here also have implications for water resource monitoring and management. This is very important because the lakes benefit the society and ecology in the surrounding regions [31,41], and lake water is the most important water supply in aquaculture, industry, and domestic water use around the four lakes regions [42,43]. The 12-year monitoring data record can serve as additional data to assess and quantify the seasonal water conditions around the lakes. For example, a comprehensive water pollution index (WPI) was used to describe water quality and identified the major pollutants in 28 Chinese large lakes and reservoirs [44]. Annual variations of water level in Dongting Lake during the period of 1961–2010 were analyzed to determine whether anthropogenic or climatic factor should be responsible for the variations [45].

6. Conclusions

China is rich in surface water, especially in the middle and lower Yangtze River Basin downstream of the Three Gorges Project. Dongting, Poyang, Chaohu, and Taihu Lakes are the largest natural lakes in this region. The temporal-spatial evolutions of these lakes largely represent the overall trends of other lakes in this basin [46,47]. Water extraction methods of remote sensing technology provide the scientific basis for long-term monitoring and analysis of variation for lakes in the middle and lower Yangtze River areas.

In this paper, the areas of the four lakes are extracted from 12 years of multi-temporal Landsat TM/ETM satellite image data with an overall accuracy of higher than 98%. The changes in the four natural lakes are analyzed from several approaches, including lake area statistics from 2002 to 2013, lake expansion index, correlation analysis between rainfall and lake area, and lake centroid displacement. Overall, this study provides the following conclusions:

The annual average areas of Dongting, Chaohu, and Taihu Lakes decreased respectively 452, 11, and 5 km² (29.6%, 1.4% and 0.2%) from 2002 to 2013, while Poyang Lake shows a increasing of 300 km² (11.0% of the total area in 2002), which is related to the different precipitation in great extent. If the decreasing trend continues, there is cause for concern for the environment of the three lakes in the future, especially the Dongting Lake. Therefore, timely and appropriate measures need to be taken by policy-makers to stop the drop in lake area and restore the original environment.

Furthermore, our study also revealed that regional climate and morphology of lake are two key factors for the spatio-temporal evolution of lake size-distribution in the middle and lower reaches of the Yangtze River. Size variation of leaf-shaped lakes with a lot of shallow areas, with outlets close to the river, is closely related to the precipitation (with correlation coefficient of 0.71 and 0.88, respectively, in Dongting and Poyang Lakes) and the inflow/outflow of the river. Meanwhile, size variation of block-shaped lakes with little shallow areas, with outlets far from the river, is much depended on the precipitation and the consumption of water.

However, in this study, size variation and centroid movement of the four lakes were monitored from the period after the dam's water storage. Variability in lake size and distribution showed certain trends over the time series, but climate change is a slow process that can be expected to occur over an extended time. Contextualizing lake behavior pre- and post-dam within long term trends in climate will require analysis over the total time span of the Landsat archive and is that we hope to investigate in follow-up studies.

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Author Contributions

This research was mainly conducted and the article prepared by Lin Li and Hui Xia. Lin Li supervised this research, and his comments were considered throughout the paper. Hui Xia and Zheng Li collected, analyzed and processed data, including the satellite imagery, and contributed to the data analysis. Zhijun Zhang contributed to the correlation analysis.

Conflicts of Interest

The authors declare no conflict of interest.

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