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Comparison of the Hydrological Dynamics of Poyang Lake in the Wet and Dry Seasons

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Abstract: Poyang Lake is the largest freshwater lake connecting the Yangtze River in China. It undergoes dramatic dynamics from the wet to the dry seasons. A comparison of the hydrological changes between the wet and dry seasons may be useful for understanding the water flows between Poyang Lake and Yangtze River or the river system in the watershed. Gauged measurements and remote sensing datasets were combined to reveal lake area, level and volume changes during 2000–2020, and water exchanges between Poyang Lake and Yangtze River were presented based on the water balance equation. The results showed that in the wet seasons, the lake was usually around 1301.85–3840.24 km^2, with an average value of 2800.79 km^2. In the dry seasons, the area was around 618.82–2498.70 km^2, with an average value of 1242.03 km^2. The inundations in the wet seasons were approximately quadruple those in the dry seasons. In summer months, the lake surface tended to be flat, while in winter months, it was inclined, with the angles at around 10′′–16′′. The mean water levels of the wet and dry seasons were separately 13.51 m and 9.06 m, with respective deviations of around 0–2.38 m and 0.38–2.15 m. Monthly lake volume changes were about 7.5–22.64 km^3 and 1–5.80 km^3 in the wet and dry seasons, respectively. In the wet seasons, the overall contributions of ground runoff, precipitation on the lake surface and lake evaporation were less than the volume flowing into Yangtze River. In the dry seasons, the three contributions decreased by 50%, 50% and 65.75%, respectively. Therefore, lake storages presented a decrease (-7.42 km^3/yr) in the wet seasons and an increase (9.39 km^3/yr) in the dry seasons. The monthly exchanges between Poyang Lake and Yangtze River were at around -14.22–32.86 km^3. Water all flowed from the lake to the river in the wet seasons, and the chance of water flowing from Yangtze River in the dry seasons was only 5.26%.

Keywords: Poyang Lake; Yangtze River; hydrological changes; water balance

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1. Introduction

As the largest freshwater lake in China [1], Poyang Lake has drawn more and more attention [2–5], especially after the implementation of the Three Gorges Dam (TGD), which is located upstream of Yangtze River and began to impound water in 2003 [6–8]. The inundation extent of Poyang Lake showed a declining trend of around 30.2 km^2/yr during 2000–2010 [9]. Some research pointed out that the discharge flowed from Poyang Lake into Yangtze River increased by 7.86 km^3 after the implementation of TGD [10]. Nearly 1/3 of the Nanjishan Wetland National Nature Reserve has transformed from water into vegetation area even in the wet seasons during 2000–2010 [11]. With the water level decreased, the western part of the lake region was changed to emerged land, and many kinds of vegetation began to grow. In 2016, a dam was proposed, which would be built on the northern end of the lake to keep Poyang Lake in a sustainable state by managing the river–lake water flow, and this proposal was finally rejected from the view of ecology. The deteriorating hydrological conditions of Poyang Lake will finally lead to a negative impact on the diversity of the aquatic vegetation and marsh wildlife. Revealing the hydrologic changes of Poyang Lake is very important to understand the water flows between Poyang Lake and Yangtze River or the river system in the watershed. Though there are several hydrological stations around Poyang Lake, there are some restrictions in terms of hydrological data sharing, especially in recent observations. In addition, hydrological stations tend to be decentralized and punctate and thus may not reflect the comprehensive and objective dynamics of the whole lake.

Remote sensing can be used to monitor lake hydrologic conditions and their changes [12–14]. Altimeter data have been widely used to continuously monitor the water level changes of large rivers, lakes, and flood plains [15,16]. Since the 1990s, 25 years of altimeter data have been collected, which cover the globe with the highest frequency of 10 days, such as the Topex/Poseidon (T/P), Jason-1, and Jason-2 datasets. At present, there are four kinds of water level databases for large rivers, lakes, and reservoirs derived from altimeter data in the world: the Database for Hydrological Time Series of Inland Waters (DAHITI) [17], Global Reservoir and Lake Monitor (GRLM) [18], River Lake Hydrology product (RLH) [19], and Hydroweb [20]. T/P data during 1992–2002 were used in the six largest lakes in China, and the derived water level changes, with the precipitation and south oscillation, were analyzed [21]. Zheng et al. (2016) used T/P and ENVIromental Satellite (ENVISat) data during 1992–2010 to monitor the water level changes of Hulun Lake in Northeast China and found that the lake presented a decreasing trend, with the rate of -0.36 m/yr, and climate warming was the main cause [22]. Ice, Cloud, and Land Elevation Satellite (ICESat) data during 2003–2009 were applied to 56 lakes in China, which showed that the surface level of the lakes in Inner Mongolia and Xinjiang presented a decreasing appearance, while the lakes in the eastern plain fluctuated [23]. In addition, T/P data during 1992–1999 were applied to rivers with a width of more than 1 km in the Amazon watershed [16]. Chipman and Lillesand (2007) revealed the shrinkage of the Toshak lakes in Southern Egypt based on the ICESat data [24]. Additionally, remotely sensed images are able to capture lake area fluctuations occurring in a short period and to reveal long-term changes. Feng et al. (2012) used MODerate-resolution Imaging Spectro-radiometer (MODIS) images to monitor dynamic changes of Poyang Lake during 2000–2010 and found that the lake was 714.1 km^2 in the dry season and 3162.9 km^2 in the wet season [9]. Sun et al. (2014) used MODIS images to study the inundation changes of more than 600 large lakes in China during 2000–2010 [25]. Multisource remote sensing images were employed to delineate the monthly spatial distribution of global land surface water bodies during 1993–2004 [26,27].

In order to quantify the water storage of a water body, bottom topography is necessary. The traditional method for obtaining a bathymetry map was to survey the depth of water using sonar sensors. However, this method consumed a lot of time, labor, and money [28]. The Airborn Lidar was also used to detect underwater topography near the ocean up to a depth of 40 m; although this technique was sensitive to water turbidity, surface waves, and sun glint, its maximum detectable depth was only 2–3 times of the Secchi depth [14,29]. Some researchers have studied volume changes of large rivers and lakes based on altimeter data and remote sensing images. Water mass changes of the Negro River basin were revealed by Synthetic Aperture Radar (SAR), T/P, and in situ water level observations [30]. The ICESat data and Landsat images were used to construct area–level curves for 30 lakes on the Tibetan Plateau in order to study their volume changes, and the result showed an increase of 92.43 km^3 in volume for the 30 lakes from the 1970s to 2011 [31]. Cai et al. (2016) constructed area–volume models for 128 lakes and 108 reservoirs in the Yangtze River watershed, according to gauged measurements and MODIS images. The research found that 53.91% of lakes were shrinking at a rate of 14×10^6 m^3/m, while reservoirs were expanding at a rate of 177×10^6 m^3/m [10]. Crétaux et al. (2005) used bottom topography and water levels derived from T/P altimeter data to construct the water volume changes of the Aral Sea [32]. Medina et al. (2010) applied gauged water level measurements, ENVISat and Advanced Synthetic Aperture Radar (ASAR) images to estimate the storage changes of Lake Izabal [33].

Based on the above researches, it is practical to describe the detailed hydrological changes of Poyang Lake. The aim of this research was to obtain the variations of hydrological aspects of Poyang Lake during 2000–2020. An accurate and automatic method of extracting water-land boundaries was used to accomplish high frequency mapping of Poyang Lake. Water level records were obtained based on gauged observations and DAHITI. Then variations of lake storages were calculated by combining the surface area and water level data. The water flows between the lake and Yangtze River were derived from the view of water balance. Finally, driving forces were analyzed to illustrate the quantitative contributions of inflow (ground runoff, precipitation on the lake surface) and outflow (lake evaporation and exchanges with Yangtze River).

2. Study Area

Poyang Lake is located in the south of the Yangtze River and it is the largest lake directly connected to the Yangtze River. Poyang Lake absorbs water from five tributaries (Ganjiang river, Fu river, Xinjiang river, Rao river, and Xiu river) and flows into the Yangtze River at Hukou connection in most of time. The geographical range of Poyang Lake is 28°11′N–29°51′N and 115°49′E–116°46′E. The lake spans around 173.0 km from north to south, and the average west–east width is around 16.9 km. The width of northern part of the lake is only 5–8 km due to the restriction of the neighboring mountains, while the southern part of the lake tends to be an open surface, with a width of up to 60 km, as shown in Figure 1. The watershed of Poyang Lake has an area of about 162068.68 km^2, which is nearly 9% of Yangtze River basin and 97% of Jiangxi Province [1].

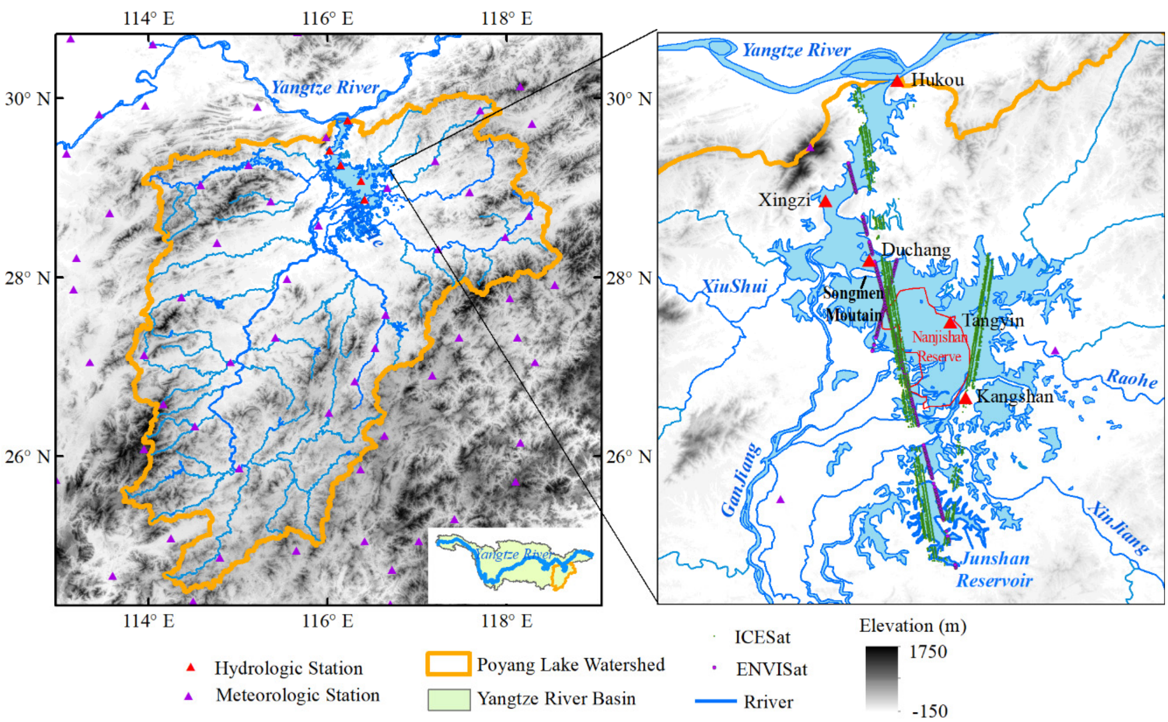

Figure 1. Spatial distribution of Poyang Lake and the feeding rivers in the watershed, and the paths of altimeter data on the lake.

The local climate is a subtropical monsoon climate. The local precipitation shows an obvious intra-annual variety and the annual average is around 1570 mm. Precipitation mainly occurs during April–June, accounting for about 45–50% of the annual rainfall. The annual average temperate is 16.5–17.8 °C. In summer, the temperature can reach 28.4–30.0 °C, while in winter, it is around 4.2–7.2 °C [1].

In the wet season (Jun–Sep), the lake surface usually presents a flat state, with the maximum inundation of more than 3000 km^2. Conversely, in the dry season (Nov–next Feb), with less rainfall and water flows from the south to Yangtze River, the corresponding water extent can shrink to less than 1000 km^2, showing a narrow and inclined state. The drop of the water level at Hukou Station can reach 3 m from summer to winter. The average water flow from Poyang Lake to Yangtze River is 1436.0 $\times$ 10^8 m^3 each year, accounting for about 15.5% of the annual Yangtze River discharge [11].

The seasonal changes of water level and inundation were favorable for Poyang Lake to create habitats for rich biodiversity/diversity of life. The famous Nanjishan Reserve is located in the main body of the lake. In hot summers, subtropical vegetation prospers and in cool and wet winters, temperate vegetation is productive [34]. In addition, over 98% of the population of the endangered Siberian crane, *Leucogeranus*, gathers in this reserve in winter [35].

3. Data and Methods

3.1. Data

3.1.1. Hydrological Data

Daily measurements of the flow rate of the five feeding rivers during 2001–2006 were obtained to calculate the total ground runoff flowing into Poyang Lake. The daily gauged water level at five hydrologic stations during 2001–2013 were used to present the fluctuation of the lake.

3.1.2. DAHITI

DAHITI is a database, presenting the time-series water level of 457 global lakes/reservoirs and rivers. DAHITI combines T/P, Jason-1, Jason-2, European Remote Sensing Satellites (ERS)-2, ENVISat, and Satellite with ARgos and ALtika (SARAL) altimetry data [17]. Compared with gauged measurements, the accuracies for lakes/reservoirs and rivers are 4–36 cm and 8–114 cm, respectively. DAHITI was used to analyze the fluctuation of Poyang Lake during 2000–2017.

3.1.3. MODIS Images

The 8-day level-3 composited product, MOD09A, with a 500 m resolution, available in the Earth Observing System (https://reverb.echo.nasa.gov/reverb/, accessed on 5 March 2021), was able to capture short-term and rapid fluctuations of inundations. MODIS images in the wet and dry seasons for each year from 2000–2020 were selected. Some images showed that Poyang Lake was covered by thick clouds, especially in the rainy seasons, and the lake could not be recognized correctly. In order to accurately depict the changes, these kinds of images were discarded, and 349 scenes were finally used in this research.

3.1.4. Meteorological Data

The daily gauged precipitation, evaporation, and temperature data of the stations from 2000–2010 were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/, accessed on 5 March 2021). The precipitations of the whole watershed were estimated by Kriging interpolation of the measured data, based on 66 meteorological stations, shown in Figure 1. The research assessed Kriging interpolated results of rainfall data in both wet and dry months in Lijiang River basin, and obtained that the average accuracy was 94.74% [36]. The land evaporation in the basin was calculated based on gauged observations, and the lake surface evaporation was estimated from the nearest in situ stations, according to the Penman–Monteith equation [37]. Penman–Monteith model was evaluated by gauged data in Taihu Lake and the accuracy was 93.50% [38].

3.2. Method

3.2.1. Inundation Extraction

An accurate water–land discrimination method was applied to delineate lake surface dynamics between 2000 and 2020. The method used the automatic selection of training data and Support Vector Machine (SVM) classifier. First, the classification system, including the water body, bare soil (including urban area), vegetation, ice, snow, and clouds was determined. Second, the training data of each image were collected based on six rules, considering the spectral characteristics of each class. Then, k-means and automated water extraction index (AWEI) were integrated and iterated to remove noise from the training samples. Finally, the filtered training data and SVM were combined to extract water bodies. The procedure can be implemented on long series of images automatically. The details of this method are illustrated in the literature [39]. This method has been used for the surface extraction of several major lakes on the Tibetan Plateau and Aral Sea, and the omission errors and commission errors were 0.9–1.5% and 2.94–4.23%, respectively [40,41].

Compared with several water indexes, such as the normalized differenced water index (NDWI), modified NDWI (MNDWI), and AWEI, this method has a high robustness. Water indexes need suitable thresholds, which depend on imaging environments, such as aerosol interference and viewing geometry. However, the proposed method was solely based on the spectrum presentations of the pixels of each image. The automatic selection of training data and the filtration of noise through iterated clustering can help obtain a high-accuracy water extraction, without manual intervention.

3.2.2. Water Level

The water level of Poyang Lake during 2000–2020 consisted of three kinds of data sources. The first part is gauged observations of five hydrological stations, which were taken daily from 2001 to 2013. The second part is DAHITI records from 2001 to 2017, and the third part is the left lake levels derived from the level–area relationship to match the length of the lake area data.

The five hydrological stations located around Poyang Lake were Hukou, Xingzi, Duchang, Tangyin, and Kangshan, from north to south. The available observed data from the five stations were for the following periods: 2001–2009, 2001–2013, 2001–2013, 2001–2007, and 2001–2007 respectively. As the inter- and intra-annual variabilities of Poyang Lake, the water level fluctuated greatly. In general, in the dry seasons, the 5 gauged water levels had large standard deviations, and the southern level was higher, suggesting that the lake surface was in an inclined state, supplying Yangtze River. In the wet seasons, the observations were high, and the corresponding deviations were small, indicating that there was little difference among them, and the surface tended to be flat.

To supplement data and create long-term records on the water level, DAHITI results were used in this research. DAHITI results start in 2002 and are missing for 2011–2012. To maintain consistency with the DAHITI data, the gauged heights of the lake surface relative to Wusong were converted to WGS-84. The DAHITI results showed a similar fluctuation with the average in-situ measurements, while they showed higher values. The DAHITI results were usually 3.39–5.02 m and 3.58–8.51 m higher than the gauged records in the wet and dry seasons, respectively. To assess the accuracy of DAHITI, comparisons of DAHITI results and the gauged records were executed separately for the wet and dry seasons, as shown in Figure 2.

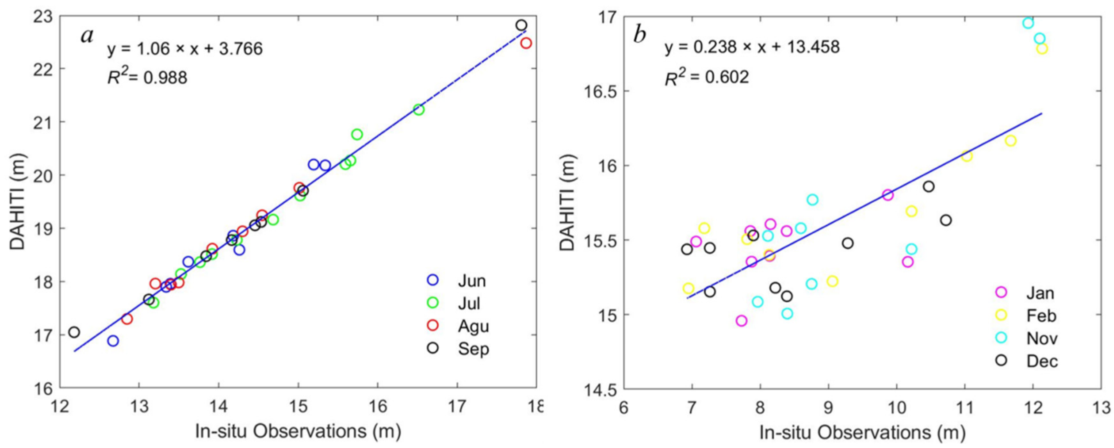

Figure 2. Comparisons of the gauged measurements and DAHITI records in the wet (**a**) and dry (**b**) seasons.

The same dates during 2001–2007 for the two datasets were selected. There were 36 pairs of data in the wet seasons and the R^2 value of their relation reached 0.99 (Figure 2a), indicating that DAHITI results were able to capture level changes in the wet seasons. There were also 36 pairs of data in the dry seasons, while the R^2 value was only 0.60 (Figure 2b), indicating that DAHITI results had large errors. In winters, the gauged data had standard deviations of around 0.96–2.17 m, while the deviations of DAHITI were around 0.33 m. The winter results of DAHITI were not able to present surface fluctuations, as in dry seasons, when Poyang Lake shrunk to a small lake of less than 1000 km^2, altimeter footprints may fall on the lakeside and the returned signals involved the wetland or vegetation, showing a low accuracy. The footprints of two kinds of altimeter data ICESat and ENVISat were shown in Figure 1. In the wet seasons, the lake was large, and the footprints could fully fall on the water surface. Thus, DAHITI could correctly delineate the lake level changes. Based on the linear relation shown in Figure 2a, 29 DAHITI results in the wet seasons during 2002–2017 were transformed into the gauged measurement standard.

Based on gauged observations and converted DAHITI results, there were 169 water level results, including 140 observed records, and each record was the mean value of the five observations. However, there were 349 records in the lake area data. To match the length between the level and area, the 180 missing water level data were derived according to the level–area relation, shown in Figure 3, which was constructed from the available level and area datasets.

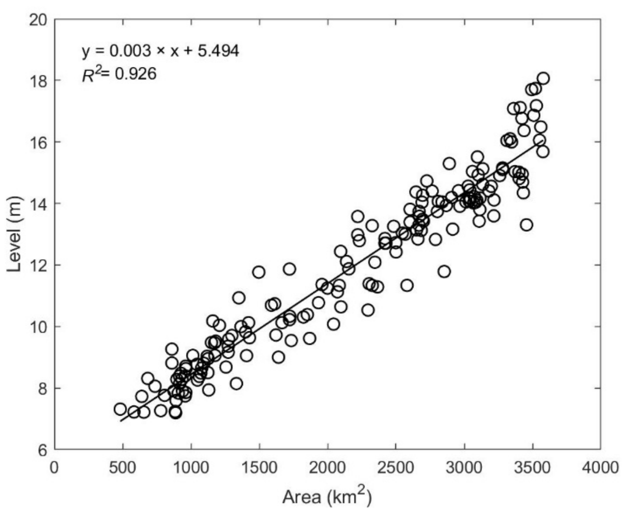

Figure 3. The relationship between the area and water level of Poyang Lake during 2000–2020.

Finally, the 349 water levels of Poyang Lake in the wet and dry seasons between 2000 and 2020 were integrated based on 29 DAHITI results, 140 in-situ measurements, and 180 area–level relation-derived data.

3.2.3. Lake Storage Changes

In this research, we assumed the lake to be a conical frustum [42,43], and the variation of the lake volume from one state to another was deduced by the following Formula (1). Volume changes of Poyang Lake were computed with the aid of the 349 pairs of level and area data acquired on the most proximate dates.

$$\Delta V = \frac{1}{3}(H_2 - H_1) \times \left(A_1 + A_2 + \sqrt{A_1 \times A_2}\right) \quad (1)$$

where ΔV means the changed lake storage from one state with level H_1 and area A_1 to another state with level H_2 and area A_2.

3.2.4. Water Balance of the Watershed

The water balance equation of Poyang Lake, considering precipitation, ground runoff, evaporation, and water exchange with the Yangtze River, was established based on climate data and gauged measurements. The main replenishments of Poyang Lake were rainfall and the five feeding rivers in the basin. The outflows were lake surface evaporation and water flowing to Yangtze River. The equation is as follows:

$$A_t \times P + R - E - W + V_t = V_{t+1} \quad (2)$$

where A_t is the area of Poyang Lake at time t, and P is the corresponding precipitation on the lake surface. R is the accumulated runoff, which is the total discharge from the five feeding rivers, and E is the evaporation of the lake. W indicates the water flowing from Poyang Lake to Yangtze River. When W is less than 0, this indicates that the water flows from Yangtze River to Poyang Lake. V_t and V_{t+1} are the water storages of Poyang Lake at two consecutive moments. In addition, according to the research [44,45], the infiltration of the lake was very stable and accounted for only 1.30% of the whole water resources in this region. Therefore, the infiltration was neglected in this research.

As the lake volume change data were on a monthly scale, daily observation data on precipitation and evaporation were accumulated on a monthly basis, so the monthly measurements were interpolated in the study area to calculate the land precipitation and land evaporation of the watershed. The evaporation of Poyang Lake was estimated from three nearest in-situ stations, according to the Penman-Monteith equation.

The gauged flowing data of the five feeding rivers from 2001–2006 on a monthly scale were obtained from Jiangxi Hydrologic station. Figure 4 shows that the total discharge of the five tributaries was highly related to net basin precipitation, which was the effect of precipitation on the land of the watershed. The net basin precipitation was the result of land precipitation minus land evaporation. Therefore, the total discharge from the five rivers of the rest years from 2000–2020 was deduced based on this linear relationship and the net basin precipitation.

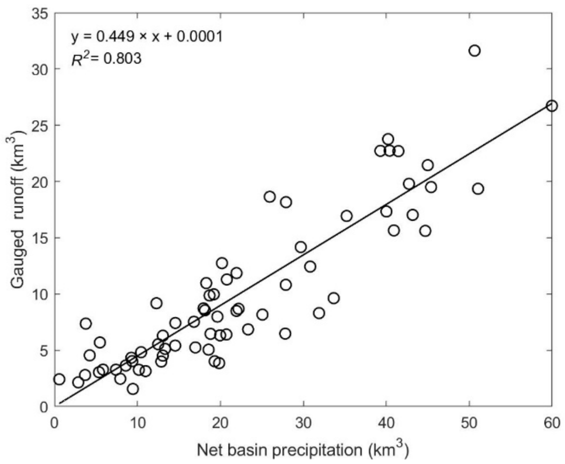

Figure 4. The relationship between the total discharge of the five rivers and net basin precipitation during 2001–2006.

Based on the above variables and lake volume changes, the water exchange W between Poyang Lake and Yangtze River was derived from the water balance equation.

4. Results

4.1. Comparison of the Water Surface in the Wet and Dry Seasons

The inundation areas in the wet and dry seasons during 2000–2020 were calculated, and the fluctuations of the surface extents are shown in Figure 5.

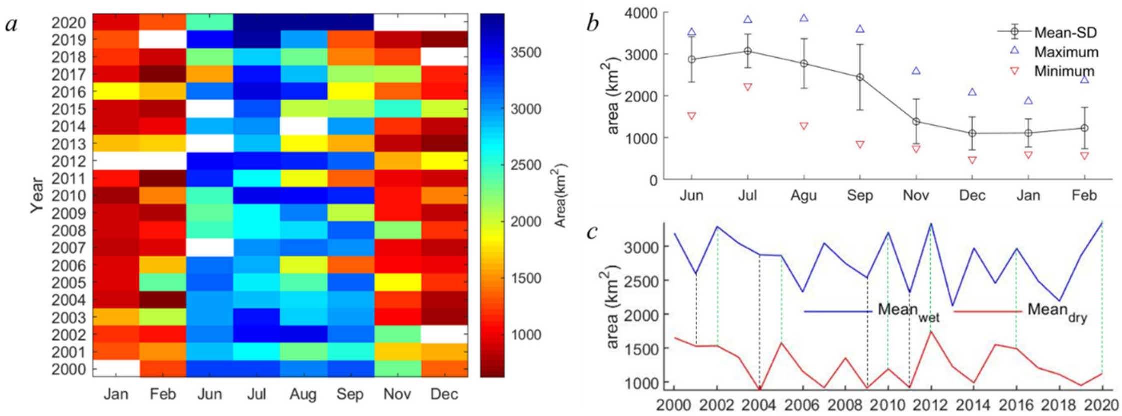

Figure 5. Inundation dynamics of Poyang Lake in the wet and dry seasons from 2000–2020 (**a**), and its seasonal (**b**) and yearly (**c**) variations. A white rectangle in (**a**) indicates that the data is not available for this month. The green and black dotted lines in (**c**) separately indicate wet and dry years, as the values in the wet and dry seasons were both local maximums (wet years) or local minimums (dry years).

In the wet seasons, the lake was usually around 1301.85–3840.24 km^2, with an average value of 2800.79 km^2. The maximum extent occurred in August 2020. In the dry seasons, the area was around 618.82–2498.70 km^2, with an average value of 1242.03 km^2, and Poyang Lake shrank and separated into several small water bodies. The smallest surface area occurred in February 2004. The lake underwent dramatic fluctuations, and the area in the wet seasons was usually 4 times of that in the dry seasons.

Poyang Lake usually begins to increase from May and then shrink in September. In the wet seasons, the lake usually had the highest extents in July, at around 3071.56 ± 399.00 km^2, and tended to be in a small state in each September, with an area of 2445.02 ± 778.41 km^2, as shown in Figure 5b. In the dry seasons, the lake presented a medium state, at around

1385.67 ± 530.56 km^2, and reached its minimum in December, with an area of 1104.39 ± 395.26 km^2.

In the years 2006, 2011, 2013 and 2018, the lake had small areas in the wet seasons, at around 2118.13–2326.42 km^2, and it even shrank to 1900 km^2 in August in the years 2006, 2011 and 2013. In the years 2000, 2002, 2010, 2012 and 2020, the lake presented large extents in the wet seasons with an area of around 3000–3349.82 km^2.

In the years 2004, 2007, 2009, 2011, 2014 and 2019, the lake was frequently in a small state in the dry seasons, with an average value of less than 1000 km^2. In the years 2000, 2005, 2012, 2015, and 2002, the surface in the dry seasons showed relatively ample states, with an area of around 1527.01–1744.58 km^2.

From Figure 5c, the average areas in the wet and dry seasons were both local maximums in the years 2002, 2005, 2010, 2012, 2016 and 2020, indicating these years were wet years and Poyang Lake was in an ample state. However, the values were both minimums in the wet and dry seasons in the years 2001, 2004, 2009 and 2011, implying these years were very dry. This result coincided with the drought and flood events in researches and news reports [46–49]. In the years 2003, 2006, 2013, 2017 and 2018, though the areas in the wet and dry seasons were not all local minimums, the lake tended to be in droughts. In a word, for Poyang Lake, the number of wet years were less than dry years during the studied period. Some researches indicated that the drought frequency and intensity in the Poyang Lake region increased after TGD began to impound water in 2003 [5,7,33,48].

In each extracted result of lake surface, water pixels were with the value "1" and no water pixels were with the value "0". To obtain a clear picture of the spatial fluctuations of Poyang surface extents, 179 results in the wet seasons and 170 results in the dry seasons were separately overlaid and added to reflect the inundation frequency of each part. For each pixel on the summed images of the wet and dry seasons, the value ranged from 1 to 180, and this value indicated the inundated times, as shown in Figure 6.

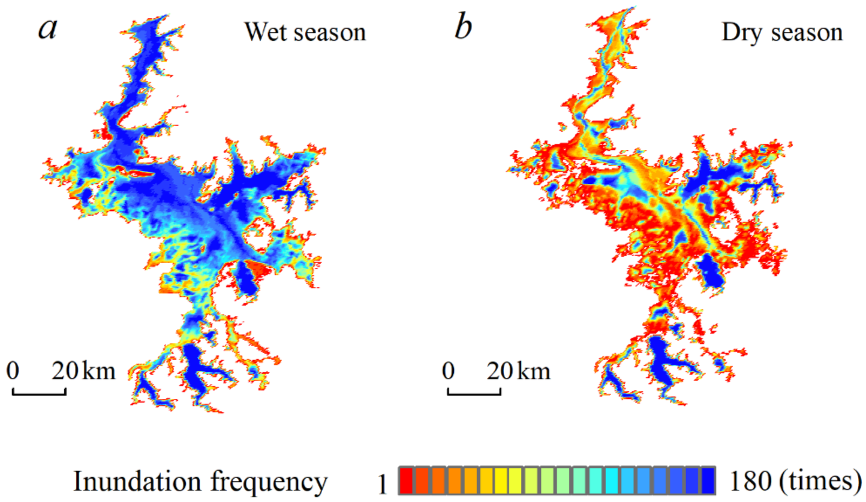

Figure 6. The inundation frequency of Poyang Lake in the wet (**a**) and dry (**b**) seasons during 2000–2020.

In the wet seasons, most regions were frequently inundated. In the dry seasons, the most frequently inundated regions were the central channel and several low-lying lakes, including Junshan Lake. In the south of Poyang Lake, Junshan Lake maintained a stable coverage in both the wet and dry seasons. In fact, Junshan Lake has been a reservoir since the 1950s, when the floodgates were constructed to separate it from the main lake. Thus, it was lightly influenced by the water flow between Poyang Lake and Yangtze River. In the dry seasons, the edge region of the lake had large dynamics, with the water and wetland replacing each other and the wetland vegetation period appearing longer year-by-year. In the central part of Poyang Lake, near Songmen mountain, the wetland vegetation area was becoming more abundant and prospering. Some research showed that in this area, the mudflats of the Nanjishan Wetland National Nature Reserve presented a shrinking trend, with a rate of $-12.1km^2/yr$, during the last three decades [11].

In addition, in the wet seasons, the lake, with an inundated frequency greater than 150, 120, 90, 60, and 30 during the studied period, had areas of 1687.65 km^2, 2470.51 km^2, 2926.66 km^2, 3311.97 km^2, and 3640.61 km^2, respectively. In the dry seasons, these results changed to 504.66 km^2, 741.00 km^2, 1007.18 km^2, 1378.11 km^2, and 2055.79 km^2, respectively. The differences between these several states revealed the drastic dynamics of Poyang Lake.

4.2. The Inclination of the Lake Surface

Figure 7 presents the daily fluctuations of gauged water level of the five hydrologic stations. As two stations had data during 2001–2007, one station had data during 2001–2009 and the rest two stations in the south had data during 2001–2013, curves in Figure 7 shows low variability after 2007. The gauged measurements were comparatively high in the wet seasons, with little difference (0–0.07 m), implying that the surface was flat. However, the water levels varied a lot in the dry seasons, with a standard deviation of 2–3 m. The minimum standard deviation of the five observations was 0.0027 m in June, 2011. The maximum standard deviation was 2.57 m in February 2002. The difference of the water level between the upper south and lower north could reach 7 m, which occurred in January–March, and only reached around 0.15 m during summer. When the mean water level was greater than 15.18 m, which usually occurred in summer, the standard deviation of the five measurements was less than 0.17 m. When the mean water level was less than 13.72 m, which generally occurred in winter, the standard deviation was usually greater than 1.05 m, showing fluctuations of the lake.

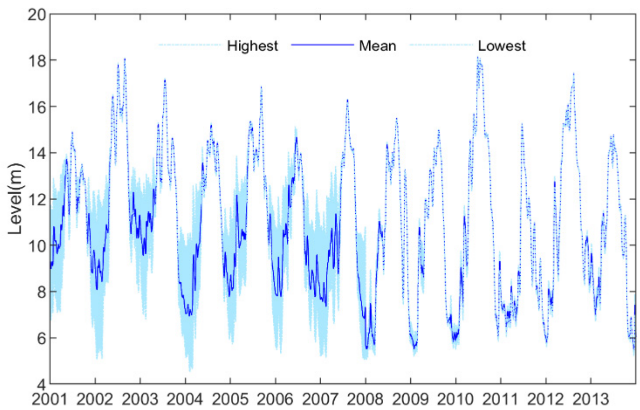

Figure 7. Daily in situ water level observations from the five stations during 2001–2013. The highest, mean and lowest lines indicate the maximum, mean and minimum of the five observations. Because only two observations were available after 2009, the three lines overlap with each other.

In the dry seasons, the lake levels had their lowest values from Dec–next Feb, and the five observations were all lower than 13.00 m. The gauged levels increased from north to south, with great deviations, by around 1.52–2.59 m. The northernmost station Hukou had large fluctuations during 2001–2009 of around 4.71–8.75 m, with a mean level of 6.35 m. The lake levels in the southernmost station of Kangshan were around 10.09–12.67 m, with the minimum occurring in April 2004. In the wet seasons, the gauged levels had high values greater than 15.2 m, with small deviations of around 0.01–1.36 m. Hukou station varied from 8.32 m to 16.51 m, and the mean value was 13.69 m, while Kangshan station fluctuated from 11.60 m to 16.53m, with a mean value of 14.20 m.

The research indicated that there was an obvious linear relationship between the latitudes and observed water levels of the stations in winter [9]. The correlations between the latitudes and daily water levels of the five stations were evaluated in this research. Nearly 50% of the relationships had R^2 values of more than 0.90, especially in the dry seasons from November to February, as shown in Figure 8. In the dry seasons, R^2 had high values and little variance. If the lake surface was supposed to be a plane, then the corresponding inclined angles could be derived by the gradient of the linear relation. Based on this supposition, the inclined angles were calculated and they were usually greater than 10″ in the winter months. Conversely, in the summer months, the R^2 values showed fluctuations, and sometimes they were less than 0.3, indicating that there were no strong relationships between the latitudes and water levels. In these cases, the corresponding derived angels were nearly 0″, especially in July. In addition, the negative values for the angles meant that the surfaces declined from south to north.

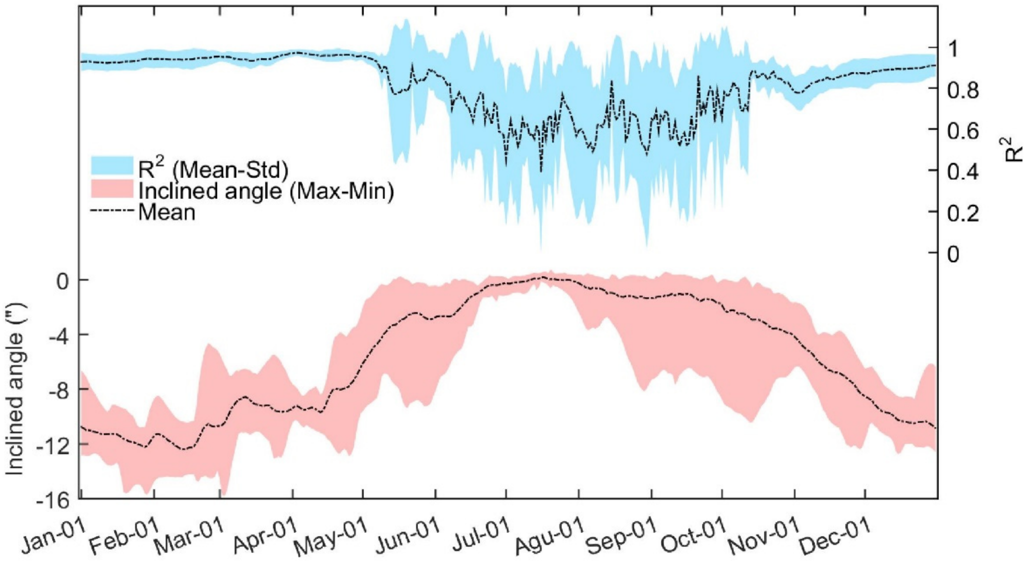

Figure 8. Daily changes of R^2 and inclined angles based on in situ measurements. The black dashed lines are the daily mean values of R^2 and inclined angles. The area in shallow blue shows the ranges of standard deviation, relative to the means. The area in pink shows the daily max and min ranges of the inclined angles, which were determined based on the linear relationship of the latitudes and daily measurements of the gauged stations.

4.3. Variations of the Lake Level and Volume

In the wet seasons, the water level had relatively low values of around 11.94–12.87 m in the years 2001, 2006, 2011, 2013, 2015, and 2017, while it had high values of around 15–16.34 m in the years 2002, 2007, 2010, 2012, 2016, and 2020, as shown in Figure 9. The deviation of the water level in the wet seasons was around 0–2.38 m. In the dry seasons, the lake had low mean levels of around 8.02–8.32 m in 2004, 2007, 2009, 2011, 2014, and 2019 and high values between 10.00 m and 10.70 m in the years of 2000, 2012, 2015, and 2016. The deviation of the water level in the dry seasons was around 0.38–2.15 m. High levels were usually accompanied by large deviations of around 1.50–2.15 m in 2000, 2008, 2015, and 2017. Low levels with small deviations of less than 0.50 m occurred in 2006, 2009, 2011, and 2014. As for monthly fluctuations, the largest variation reached 2.30 m, which occurred in September, followed by 1.85 m in August. Several months in the dry seasons had low variations of around 1.00 m.

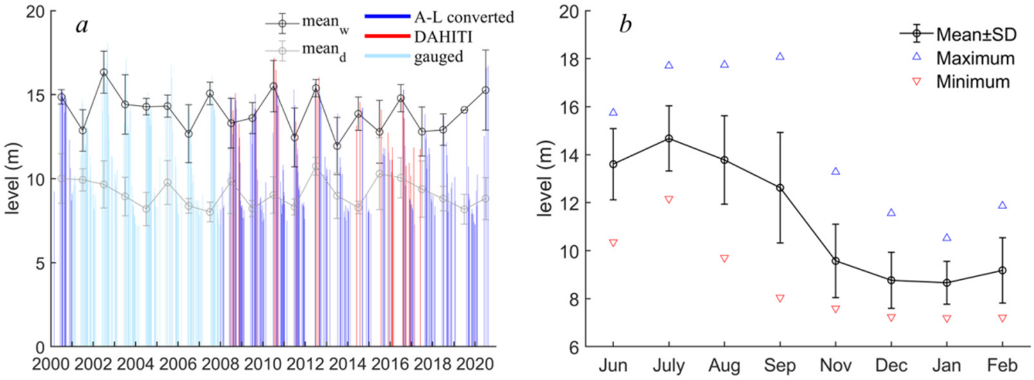

Figure 9. The fluctuations of the lake level from the gauged observations, results converted from DAHITI records, and results converted from the area–level relationship (**a**) and its seasonal variations (**b**).

From Figure 10, in the wet seasons, the monthly volume changes were usually greater than 20 km^3 in 2002, 2010, and 2020, mainly from Jul–Aug. The maximum was 22.64 km^3, which occurred in August 2002. The volume changes were low in the wet seasons of 2006, 2011, and 2013, with a monthly mean value of around 7.5 km^3. In the dry seasons, the volume changes had low values of less than 1 km^3 in the years 2003, 2007, 2013, and 2014, while high values of between 4.36–5.80 km^3 were found in the years 2002, 2012, and 2015. The lake volumes from November to December were usually 1.61 km^3 higher than those from January to February. Considering monthly variations, the largest monthly variation reached 5.28 km^3, which occurred in September, followed by 4.72 km^3 in August. Several months in the dry seasons had low variations of around 1.19–2.54 km^3.

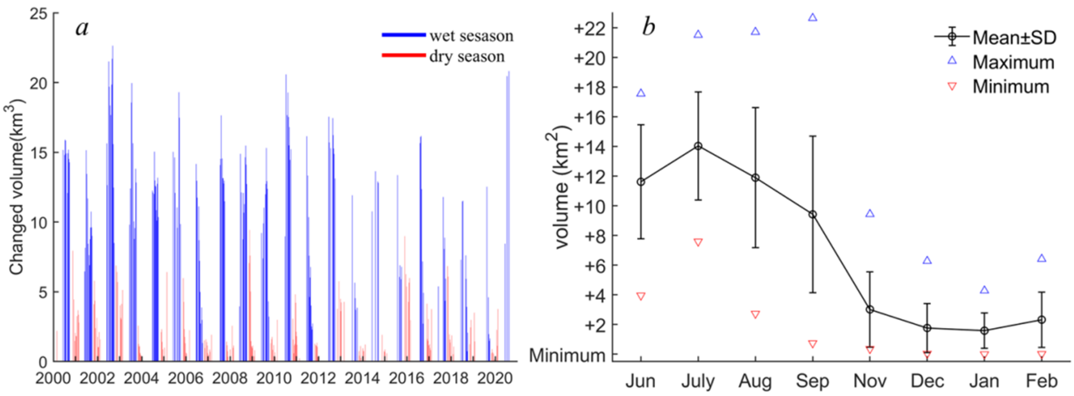

Figure 10. Lake storage changes in wet and dry seasons on a monthly scale (**a**) and their seasonal variations (**b**). The red bars in (**a**) indicate the changed volumes in the dry seasons, and the blue bars indicate those in the wet seasons. Because the volume under the smallest inundated area during 2000–2020 was unknown, the unknown volume was considered as the minimum in (**b**).

4.4. Water Flowing into Yangtze River

As the data were only available on a monthly scale, the water exchange between Poyang Lake and Yangtze River can only be derived according to the volume changes between two adjacent months. The wet and dry seasons both consist of four consecutive months; therefore, the water exchanges over six months (Jun, Jul, Aug, Nov, Dec, and Jan) for each year were calculated. In total, there were 110 values indicating the monthly water exchanges, as shown in Figure 11. They ranged from -14.22 km^3 to 32.86 km^3, with 53 values in the wet seasons and 57 values in the dry seasons. Positive values imply that Poyang Lake supplied Yangtze River, while negative values mean that water flowed from the river to the lake, which occurred occasionally.

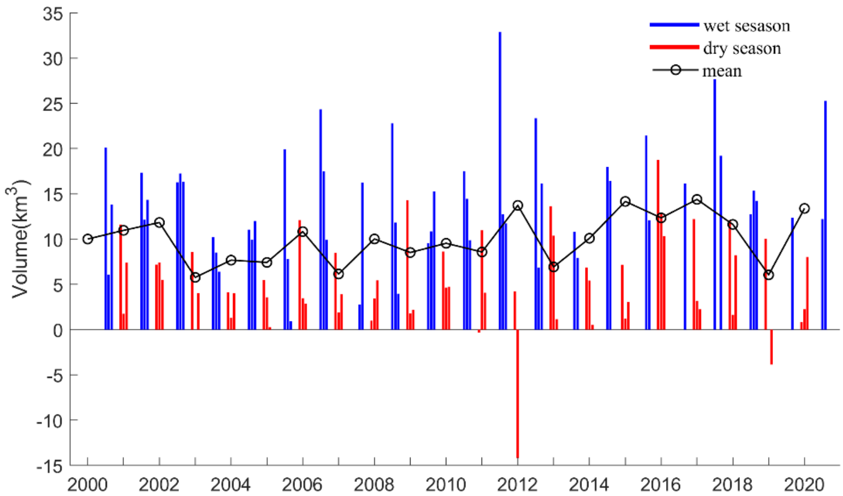

Figure 11. Water exchange between Poyang Lake and Yangtze River on a monthly scale during 2000–2020. The red bars indicate the water flows in the dry seasons, the blue bars indicate those in the wet seasons, and the circle-line symbol indicates mean value of the wet and dry seasons.

Water all flowed from the lake to the river in the wet seasons, with a value of around 0.94–32.86 km^3/m. The values in June were usually higher than those in July and August. In the last two decades, the average volume that flowed to the Yangtze River in June was 18.49 km^3, followed by 12.66 km^3 in July and 12.04 km^3 in August. Some studies have pointed out that the summer monsoon was in the south of Yangtze River during May–Jun, causing increased precipitation in the watershed of Poyang Lake. Therefore, the discharge from the five tributaries increased in June, and more water flowed to Yangtze River. However, the summer monsoon moved to the north of Yangtze River during Jul–Aug, resulting in more rainfall in the upstream of the river. Thus, the increased discharge of Yangtze River flowed backward to the supply from Poyang Lake. The annual mean flow discharge from Poyang Lake to the river in the whole wet seasons was 14.36 km^3 from 2000–2020, with a maximum of 23.44 km^3 occurring in 2017. The exchange was low in the years 2003 and 2013, with values of 8.38 km^3 and 9.36 km^3, respectively.

The exchanges in the dry seasons were around -14.22–18.75 km^3/m. In total, there were three negative values, indicating that the chance of water flowing from Yangtze River in the dry seasons was only 5.26%. The maximum value of the water flow from the river was -14.22 km^3 in December 2011. The mean exchanges in January, November, and December were 3.90 km^3, 8.35 km^3, and 3.50 km^3, respectively. During 2000–2020, the mean water flowing from the lake to the river in the dry seasons was 4.96 km^3/yr, with a maximum of 13.06 km^3 in 2015 and minimum of -2.50 km^3 in 2011.

In 2002, 2012, 2015, 2017, and 2020, the exchanges were higher than those in the adjacent years, with values of between 10.56 km^3/m and 11.32 km^3/m. The exchanges in 2003, 2007, 2013, and 2019 were low, at around 5.77–6.91 km^3/m.

5. Discussion

5.1. Driving Forces

Based on the water balance equation, including ground runoff (R), lake surface precipitation (P), lake surface evaporation (E), and water exchange (W), the driving forces of lake storage changes (ΔV) were analyzed. The monthly contributions of these factors are listed in Table 1.

Table 1. Contributions of the factors to lake storage changes.

Month	R (km^3)	P (km^3)	E (km^3)	W (km^3)	ΔV (km^3)
June	21.03	1.40	1.25	18.49	2.69
July	11.21	0.91	1.70	12.66	−2.25
August	10.60	0.72	1.59	12.04	−2.30
September	5.98	0.39	1.29	10.63	−5.56
Wet season	48.82	3.43	5.84	53.83	−7.42
November	6.94	0.44	0.65	8.35	−1.61
December	4.12	0.26	0.47	3.50	0.42
January	5.19	0.38	0.41	3.90	1.26
February	6.68	0.49	0.47	−2.63	9.33
Dry season	22.93	1.57	2.00	13.11	9.39

In the wet seasons, the monthly ground runoff was around 5.98–21.03 km^3/m, with a mean value of 12.21 km^3/m. The maximum value was 21.03 km^3/m in June. In the dry seasons, the monthly ground runoff was between 4.12 km^3/m and 6.94 km^3/m, with a mean value of 5.73 km^3/m. The average total ground runoff had values of 48.82 km^3 and 22.93 km^3 in the wet and dry seasons, respectively.

The total lake surface evaporation in the wet seasons was 5.84 km^3/yr, which is about 2.92 times that in the dry seasons. The evaporation reached a maximum of 1.70 km^3/m in July. The monthly mean value of evaporation in the wet seasons was 1.46 km^3/m, and that in the dry seasons was 0.50 km^3/m.

The monthly precipitation on the lake surface was 0.86 km^3/m, with a maximum of 1.40 km^3/m in June. The monthly mean values of lake surface precipitation in the wet and dry seasons were 0.86 km^3/m and 0.39 km^3/m, respectively

The lake evaporations were higher than the precipitations on the lake surface in both the wet and dry seasons, and they occupied 11.96% and 8.72% of the supply from the ground runoff in the wet and dry seasons, respectively.

The ground runoff and precipitation on the lake surface gradually decreased as the rainfall usually reduced from around 500 mm in June to less than 100 mm in September in the watershed. As the lake evaporation remained stable in the wet seasons, the water flowing to Yangtze River decreased from 18.49 km^3 in June to 10.63 km^3 in September. In the wet seasons, the overall contributions of runoff, precipitation, and evaporation were less than the volume supplying Yangtze River. Therefore, the lake storages presented a decrease, at a rate of -7.42 km^3/yr.

It is worth mentioning that as the rainfall decreased to around 10–15 mm in September in the years 2001 and 2019, the ground runoff had relatively low values of 1.69 km^3 and 1.85 km^3, respectively. Therefore, the monthly ground runoff in September was lower than that in February and November.

In the dry seasons, the three factors, ground runoff, precipitation on the lake surface, and lake evaporation, occupied 50%, 50%, and 34.25% of those in the wet seasons, respectively. The average volume of water supplying Yangtze River was 13.11 km^3, occupying 58.27% of the whole input of the lake. Therefore, Poyang lake showed an increase, at a rate of 9.39 km^3/yr.

The monthly basin precipitation and lake storage changes showed a similar pattern on annual and seasonal scales as shown in Figure 12a. On average, the monthly basin precipitation and lake volume were correlated in the research period, although several discrepancies existed in some detailed changes. In 2002, 2010, 2012, and 2020, the rainfall was higher than in the other years, and the corresponding lake storages also increased. However, during 2006–2007, the precipitation and lake volume in Poyang showed opposite performances. Poyang Lake was at the local minimum in 2006, whereas the precipitation appeared to be normal. The lake storage had a low value in 2006 and got better in 2007, while the precipitation in 2006 was higher than that in 2007. The precipitation in the basin increased in 2019, while the corresponding storage had no obvious changes. These discrepancies may be because the precipitation needs to convert to ground runoff in order to feed the lake, and there may be a delay of the effect from rainfall. Moreover, besides the basin precipitation, the constant discharge flowing into Yangtze River also had an effect on the lake storage changes. The temperatures of the three nearby stations presented stable states and had no relation with the lake storage changes (Figure 12b), indicating that the lake evaporation induced by temperature was not the main driving factor. On the whole, basin precipitation was the most important driving force.

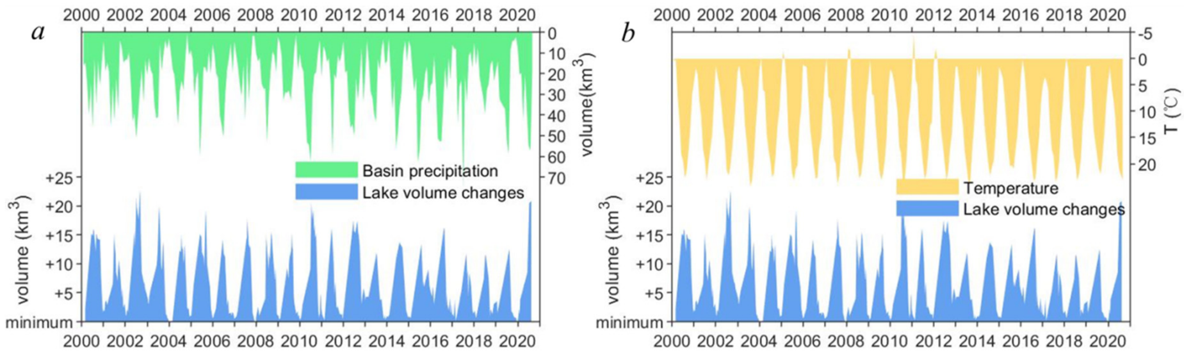

Figure 12. Comparisons of the lake storage changes and the equivalent precipitation (**a**) and temperatures (**b**) in the basin on a monthly scale. Because the volume of the smallest inundated area during 2000–2020 was unknown, the unknown volume was considered as the minimum.

5.2. Accuracy Assessment

Two 30 m interpretation results based on Landsat images in the years of 2009 and 2016 were collected to check the accuracy of the inundation results of this research. The interpretation results showed a higher accuracy (96%) [39].

To ensure that the lake states were consistent, the MODIS results on the nearest dates to the 30 m Landsat results were selected. The two pairs of water boundaries were presented in Figure 13. Evaluations were carried out spatially, and the outcome showed that the omission errors were 11.56% and 2.56%, and the commission errors were 10.94% and 5.47% for the MODIS results in the years 2009 and 2016, respectively. The inundation area of the lakes was higher in the 30 m results. The area differences were 9.31% and 12.76% for the selected inundation results in the wet and dry seasons, respectively. The boundaries of some small tributaries were not correctly depicted in the MODIS images due to its coarse resolution. Nevertheless, the overall accuracy of the MODIS results was greater than 85%, and they indicated that the results were convincible to study lake inundation changes.

Hukou station is located at the intersection of Poyang Lake and Yangtze River. The gauged monthly average flow velocities at Hukou station were available during 2000–2008 and 2013–2014. The fluctuations of the exchanged water coincided with the dynamics of the flow velocity at Hukou station, as shown in Figure 14. The observed velocities were all greater than zero, and the simultaneous water exchanges were all positive values, indicating the water flowing into Yangtze River. The high velocities usually matched large exchanges, and the low velocities corresponded to a small water flow at Hukou station. The flow velocities tended to be high in the wet seasons and had low values in the dry seasons. The maximum was 12,600 m^3/s, occurring in June 2006, when the exchange also reached the peak of the adjacent years. The minimum velocity was 895 m^3/s in February 2004. In addition, June and July usually had higher velocities than August and September, and this phenomenon was consistent with the results of this study, which found that the water exchange in June was higher than in other months. The 25 pairs of velocity and volume data occurred in the same months had the R^2 value of 0.72. Therefore, a similar pattern between the fluctuations of the flow rate and water exchange changes showed the credibility of this research.

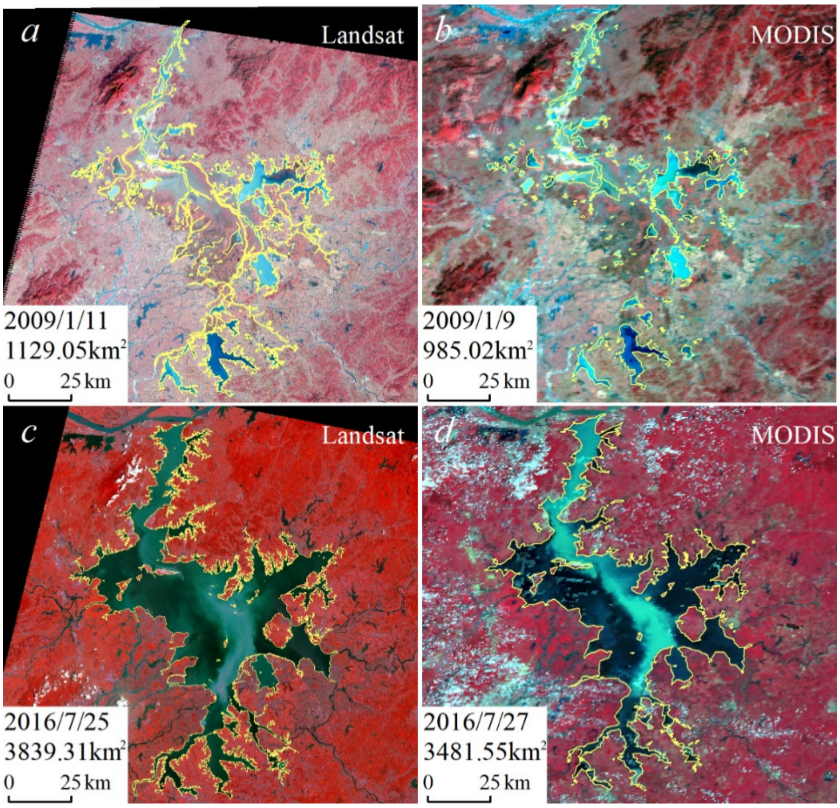

Figure 13. Comparison of 30 m interpretation products and the extracted extents based on MODIS images. (**a**,**b**) indicate water boundaries extracted from Landsat and MODIS images in 2009. (**c**,**d**) separately indicate Landsat and MODIS results in 2016.

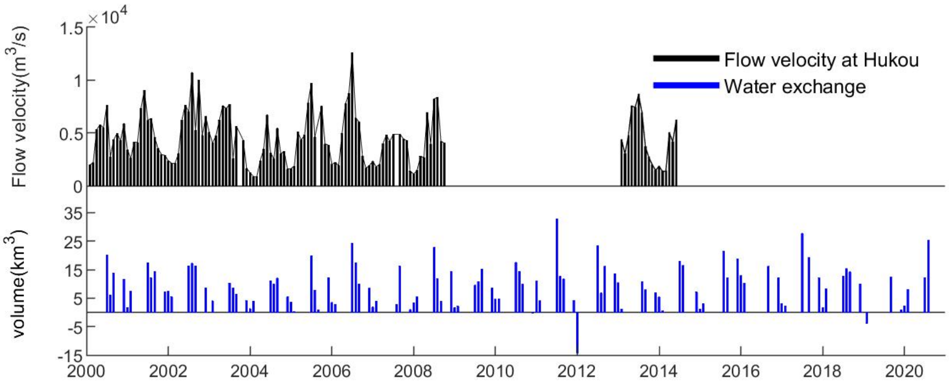

Figure 14. Gauged observations of the flow velocities (2000–2008, 2013–2014) at Hukou station and water exchanges between Poyang Lake and Yangtze River (2000–2020).

6. Conclusions

In this research, gauged observations, altimeter database, and MODIS images were combined to depict the changes of several hydrologic variables. The water extents were delineated with a high accuracy when evaluated using the 30 m interpretation results. The surface extents of Poyang Lake expressed great dynamics and seasonality. The five hydrologic stations around Poyang Lake showed disagreement in most of the years, suggesting that the lake was not flat, and the water was flowing. The lake surface inclined from south to north, with an angle of around $0''$–$16''$, and it was usually greater than $10''$ in the winter seasons. According to the appearance of the water flowing into Yangtze River, it can be concluded that, in the wet seasons, water all flowed from south to north, and there was a chance of only 5.26% in the dry seasons that it flowed backward. Precipitation was the main source of the ground runoff flowing into the lake. Thus, rainfall can be regarded as the primary influencing factor of Poyang Lake. However, there were some discrepancies between precipitation and water storage changes, as the state of Poyang Lake was also affected by the water quantity of Yangtze River.

There were several uncertainties in this research. The bathymetry of Poyang Lake during 2000–2020 was assumed to be unchanged when calculating the storage changes. Though several dredging activities have been reported in the past, they mainly occurred in the tributaries of Poyang Lake. Therefore, the changes in the lake bottom topography can be ignored, considering its large span. The ground runoff of the five tributaries flowing into Poyang Lake was estimated according to the relation between the basin precipitations and gauged discharges. It was inevitable that there were some errors in this estimation. However, the similar pattern and high correlation between the observed Hukou flow velocities and water exchanges proved the practicability of this method. In the respective of lake volume changes, the Formula (1) which treated the lake as a conical frustum definitely caused uncertainties. Though the real bathymetry of Poyang Lake has been surveyed by sonar devices, the bathymetry map was not available due to restrictions on data sharing. Considering the formula has been widely applied in some researches [22,41–43] and the accuracy assessment on water exchanges, the studied results can reveal the volume changes of Poyang Lake to a certain extent.

This paper analyzed the driving factors in the water balance equation. The effect of human activities was not determined. As for human actions, 9603 dams have been built on the five feeding rivers, compounding around 27.9 billion m^3 water until 2001 [50], and this may affect the natural flowability of water in the basin. The TGD resulted in a decrease of the water inflow to the downstream Yangtze River and caused more water to flow from Poyang Lake to the Yangtze River, especially during late autumn and winter [5]. Some researchers have pointed out that lake precipitation decreased and the evaporation increased during the post-TGD periods, compared with those during the pre-TGD periods [51]. In addition, the construction of dikes for fish ponds may affect the variation of the local flow [52].

On the whole, this research compared variations of Poyang Lake between the wet and dry seasons, quantified contribution factors of volume changes, and derived exchanges between the lake and Yangtze River. The results can serve as important information to better understand the water cycle of the watershed, and the studied datasets may also be used in hydrologic modeling and wetland studies.

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Data Availability Statement: Publicly available datasets were analyzed in this study. These include MODIS images from https://reverb.echo.nasa.gov/reverb/, meteorological Data from http://cdc.cma.gov.cn/, and DAHITI database from https://dahiti.dgfi.tum.de/en/ (accessed on 5 March 2021).

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Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Wang, S.; Dou, H. *China Lake Catalogue*; Science Press: Beijing, China, 1998.
2. Gao, J.H.; Jia, J.; Kettner, A.J.; Xing, F.; Wang, Y.P.; Xu, X.N.; Yang, Y.; Zou, X.Q.; Gao, S.; Qi, S.; et al. Changes in water and sediment exchange between the Changjiang River and Poyang Lake under natural and anthropogenic conditions. *China Sci. Total Environ.* **2014**, *481*, 542–553. [CrossRef]
3. Ye, X.; Li, Y.; Li, X.; Zhang, Q. Factors influencing water level changes in China's largest freshwater lake, Poyang Lake, in the past 50 years. *Water Int.* **2014**, *39*, 983–999. [CrossRef]
4. Zhang, D.; Liao, Q.; Zhang, L.; Wang, D.; Luo, L.; Chen, Y.; Zhong, J.; Liu, J. Occurrence and spatial distributions of microcystins in Poyang Lake, the largest freshwater lake in China. *Ecotoxicology* **2014**, *24*, 19–28. [CrossRef]
5. Guo, H.; Hu, Q.; Zhang, Q.; Feng, S. Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008. *J. Hydrol.* **2012**, *416–417*, 19–27. [CrossRef]
6. Dai, Z.; Liu, J.T. Impacts of large dams on downstream fluvial sedimentation: An example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). *J. Hydrol.* **2013**, *480*, 10–18. [CrossRef]
7. Feng, L.; Hu, C.; Chen, X.; Zhao, X. Dramatic Inundation Changes of China's Two Largest Freshwater Lakes Linked to the Three Gorges Dam. *Env. Sci. Technol.* **2013**, *47*, 9628–9634. [CrossRef]
8. Dai, Z.; Liu, J.T.; Chen, J. Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. *Sci. Rep.* **2014**, *4*, 6600. [CrossRef] [PubMed]
9. Feng, L.; Hu, C.; Chen, X.; Cai, X.; Tian, L.; Gan, W. Assessment of inundation changes of Poyang Lake using MODIS observations between 2000 and 2010. *Remote Sens. Environ.* **2012**, *121*, 80–92. [CrossRef]
10. Cai, X.; Feng, L.; Hou, X.; Chen, X. Remote Sensing of the Water Storage Dynamics of Large Lakes and Reservoirs in the Yangtze River Basin from 2000 to 2014. *Sci. Rep.* **2016**, *6*, 36405. [CrossRef] [PubMed]
11. Han, X.; Chen, X.; Feng, L. Four decades of winter wetland changes in Poyang Lake based on Landsat observations between 1973 and 2013. *Remote Sens. Environ.* **2015**, *156*, 426–437. [CrossRef]
12. Smith, L.C. Satellite remote sensing of river inundation area, stage and processes: A review. *Hydrol. Process.* **1997**, *11*, 1427–1439. [CrossRef]
13. Cazenave, A.; Milly, P.C.D.; Douville, H.; Benveniste, J.; Kosuth, P.; Lettenmaier, D.P. Space techniques used to measure change in terrestrial waters. *Eos Trans. Am. Geophys. Union* **2004**, *85*, 59–60.
14. Alsdorf, D.E.; Rodríguez, E.; Lettenmaier, D.P. Measuring surface water from space. *Rev. Geophys.* **2007**, *45*, RG2002. [CrossRef]
15. Birkett, C.M. The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. *J. Geophys. Res. Ocean.* **1995**, *100*, 25179–25204. [CrossRef]
16. Birkett, C.M.; Mertes, L.A.K.; Dunne, T.; Costa, M.H.; Jasinski, M.J. Surface water dynamics in the Amazon Basin: Application of satellite radar altimetry. *J. Geophys. Res.* **2002**, *107*, D20. [CrossRef]
17. Schwatke, C.; Dettmering, D.; Bosch, W.; Seitz, F. DAHITI-an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry. *Hydrol. Earth Syst. Sci.* **2015**, *19*, 4345–4364. [CrossRef]
18. Birkett, C.M.; Reynolds, C.; Beckley, B.; Doorn, B. From research to operations: The USDA global reservoir and lake monitor. In *Coastal Altimetry*; Vignudelli, S., Kostianoy, A., Cipollini, P., Benveniste, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 19–50.
19. Berry, P.A.M.; Wheeler, J.L. JASON2-ENVISAT Exploitation—Development of Algorithms for the Exploitation of JASON2-ENVISAT Altimetry for the Generation of a River and Lake Product. In *Product Handbook v3.5*; De Montfort University: Leicester, UK, 2009.
20. Crétaux, J.F.; Jelinski, W.; Calmant, S.; Kouraev, A.; Vuglinski, V.; Berge-Nguyen, M.; Gennero, M.-C.; Nino, F.; Abarca Del Rio, R.; Cazenave, A.; et al. A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data. *Adv. Space Res.* **2011**, *4*, 1497–1507.
21. Hwang, C.; Peng, M.; Ning, J.; Luo, J.; Sui, C. Lake level variations in China from TOPEX/Poseidon altimetry: Data quality assessment and links to precipitation and ENSO. *Geophys. J. Int.* **2005**, *161*, 1–11. [CrossRef]
22. Zheng, J.; Ke, C.; Shao, Z.; Li, F. Monitoring changes in the water volume of Hulun Lake by integrating satellite altimetry data and Landsat images between 1992 and 2010. *J. Appl. Remote Sens.* **2016**, *10*, 16029. [CrossRef]
23. Wang, X.; Gong, P.; Zhao, Y.; Xu, Y.; Cheng, X.; Niu, Z.; Luo, Z.; Huang, H.; Sun, F.; Li, X. Water-level changes in China's large lakes determined from ICESat/GLAS data. *Remote Sens. Environ.* **2013**, *132*, 131–144. [CrossRef]
24. Chipman, J.W.; Lillesand, T.M. Satellite-based assessment of the dynamics of new lakes in southern Egypt. *Int. J. Remote Sens.* **2007**, *28*, 4365–4379. [CrossRef]
25. Sun, F.D.; Zhao, Y.Y.; Gong, P.; Ma, R.H.; Dai, Y.J. Monitoring dynamic changes of global land cover types: Fluctuations of major lakes in China every 8 days 2000–2010. *Chin. Sci. Bull.* **2014**, *59*, 171–189. [CrossRef]

26. Prigent, C.; Papa, F.; Aires, F.; Rossow, W.B.; Matthews, E. Global inundation dynamics inferred from multiple satellite observations, 1993–2000. *J. Geophys. Res.* **2007**, *112*, D12107. [CrossRef]
27. Papa, F.; Prigent, C.; Aires, F.; Jimenez, C.; Rossow, W.B.; Matthews, E. Interannual variability of surface water extent at the global scale, 1993–2004. *J. Geophys. Res.* **2010**, *115*. [CrossRef]
28. Peng, D.Z.; Guo, S.L.; Liu, P.; Liu, T. Reservoir storage curve estimation based on remote sensing data. *J. Hydrol. Eng.* **2006**, *11*, 165–172. [CrossRef]
29. Davis, P.A. *Review of Results and Recommendations from the GCMRC 2000–2003 Remote-Sensing Initiative for Monitoring Environmental Resources Within the Colorado River Ecosystem*; U.S. Geological Survey: Reston, VA, USA, 2004; p. 1206.
30. Frappart, F.; Seylerb, F.; Martinezc, J.M.; Leónb, J.G.; Cazenavea, A. Floodplain water storage in the Negro River basin estimated from microwave remote sensing of inundation area and water levels. *Remote Sens. Environ.* **2005**, *99*, 387–399. [CrossRef]
31. Song, C.; Huang, B.; Ke, L. Modeling and analysis of lake water storage changes on the Tibetan Plateau using multi-mission satellite data. *Remote Sens. Environ.* **2013**, *135*, 25–35. [CrossRef]
32. Crétaux, J.F.; Kouraev, A.K.; Papa, F.; Bergé-Nguyen, M.; Cazenave, A.; Aladin, N.V.; Plotnikov, I.S. Water balance of the Big Aral Sea from satellite remote sensing and in situ observations. *Great Lakes Res.* **2005**, *31*, 520–534. [CrossRef]
33. Mei, X.; Dai, Z.; Du, J.; Chen, J. Linkage between Three Gorges Dam impacts and the dramatic recessions in China's largest freshwater lake, Poyang Lake. *Sci. Rep.* **2015**, *5*, 18197. [CrossRef]
34. Zheng, Y. Prediction of the Distribution of C3 and C4 Plant Species from a GIS-Based Model: A Case Study in Poyang Lake, China. Master's Thesis, ITC, Enschede, The Netherlands, 2009.
35. Harris, J.; Zhuang, H. *An Ecosystem Approach to Resolving Conflicts among Ecological and Economic Priorities for Poyang Lake Wetlands*; International Crane Foundation/IUCN: Gland, Switzerland, 2010.
36. Fan, Y.J.; Yu, X.X.; Zhang, H.X.; Song, M.H. Comparison between Kriging interpolation and Inverse Weighting Tension for precipitation data analysis: Taking Lijing river basin as a study case. *J. China Hydrol.* **2014**, *34*, 61–66. (In Chinese)
37. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper*; FAO: Rome, Italy, 1998.
38. Gao, Y.Q.; Wang, Y.W.; Hu, C.; Wang, W.; Liu, S. Variability of evaporation from Lake Taihu in 2012 and evaluation of a range of evaporation models. *Clim. Environ. Res.* **2016**, *21*, 393–404. (In Chinese)
39. Sun, F.D.; Ma, R. Hydrologic changes of Poyang Lake based on radar altimeter and optical sensor. *J. Geogr. Sci.* **2020**, *75*, 544–557.
40. Sun, F.D.; Ma, R. Hydrologic changes of Aral Sea: A reveal by the combination of radar altimeter data and optical images. *Ann. Gis* **2019**, *25*, 247–261. [CrossRef]
41. Sun, F.D.; Ma, R.; He, B.; Zhao, X.; Zeng, Y.; Zhang, S.; Tang, S. Changing Patterns of Lakes on The Southern Tibetan Plateau Based on Multi-Source Satellite Data. *Remote Sens.* **2020**, *12*, 3450. [CrossRef]
42. Liu, Y.; Yue, H. Estimating the fluctuation of Lake Hulun, China, during 1975–2015 from satellite altimetry data. *Environ. Monit. Assess.* **2017**, *189*, 630. [CrossRef] [PubMed]
43. Zhang, G.; Chen, W.; Xie, H. Tibetan Plateau's lake level and volume changes from NASA's ICESat/ICESat-2 and Landsat Missions. *Geophys. Res. Lett.* **2019**, *46*, 13107–13118. [CrossRef]
44. Wan, X.; Xu, X. Analysis of supply and demand balance o of water resources around Poyang Lake. *Yangtze River* **2010**, *41*, 43–47.
45. Feng, L.; Hu, C.; Chen, X.; Li, R. Satellite observations make it possible to estimate Poyang lake's water budget. *Environ. Res. Lett.* **2011**, *6*, 44023. [CrossRef]
46. Liu, Y.; Wu, G.; Zhao, X. Recent declines in China's largest freshwater lake: Trend or regime shift? *Env. Res. Lett.* **2013**, *8*, 14010. [CrossRef]
47. Lai, X.; Shankman, D.; Huber, C.; Yesou, H.; Huang, Q.; Jiang, J. Sand mining and increasing Poyang Lake's discharge ability: A reassessment of causes for lake decline in China. *J. Hydrol.* **2014**, *519*, 1698–1706. [CrossRef]
48. Zhang, Q.; Ye, X.-C.; Werner, A.D.; Li, Y.-L.; Yao, J.; Li, X.-H.; Xu, C.-Y. An investigation of enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts. *J. Hydrol.* **2014**, *517*, 425–434. [CrossRef]
49. Xinhua Net. China's Largest Freshwater Lake Sees Record Water Rise. 12 July 2020. Available online: http://www.xinhuanet.com/english/2020-07/12/c_139207311.htm (accessed on 16 July 2020).
50. Liu, J.; Zhang, Q.; Xu, C.; Zhang, Z. Characteristics of run off variation of Poyang Lake watershed in the past 50 years. *Trop Geogr.* **2009**, *29*, 213–218.
51. Zhang, Z.; Huang, Y.; Xu, C.Y.; Chen, X.; Moss, E.M.; Jin, Q.; Bailey, A.M. Analysis of Poyang Lake water balance and its indication of river–lake interaction. *SpringerPlus* **2016**, *5*, 1555. [CrossRef] [PubMed]
52. de Leeuw, J.; Shankman, D.; Wu, G.; de Boer, W.F.; Burnham, J.; He, Q.; Yesou, H.; Xiao, J. Strategic assessment of the magnitude and impacts of sand mining in Poyang Lake, China. *Reg. Environ. Chang.* **2010**, *10*, 95–102. [CrossRef]