Recent declines in China’s largest freshwater lake: trend or regime shift?

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Abstract

Poyang Lake is China’s largest freshwater lake with a high degree of spatio-temporal variation. The lake has shrunk in size in recent years, resulting in significant hydrological, ecological and economic consequences. It remains unknown whether the shrinkage is a trend or a regime shift, which is of high importance for policymakers as it may lead to different decisions. This study constructed a four-decade record of the lake area using multi-temporal satellite images and hydrological data. The Mann–Kendall analysis revealed a decreasing trend of Poyang Lake but it was statistically insignificant. The Rodionov sequential approach disclosed an abrupt change of the lake in 2006, implying a regime shift. Basically, the lake change was a synthetic result of precipitation, evapotranspiration and outflow discharge. However, precipitation and outflow did not show any significant trend or abrupt change, and evapotranspiration had an increasing trend in addition to an abrupt change in 1998. The trigger for the recent lake declines was principally ascribed to a weakened blocking effect of the Yangtze River. The findings provide an example of hydrologic non-stationarity and are valuable for effective promotion of climate adaptation and water resource management.

Keywords: Poyang Lake, regime shift, precipitation, evapotranspiration, discharge, multi-temporal remote sensing

1. Introduction

Poyang Lake is China’s largest freshwater lake, located on the south bank of the middle Yangtze River. The lake has multifaceted functions and has received increased international attention (Shankman et al 2006, Jiao 2009, Finlayson et al 2010, Hervé et al 2011, Environment News Service 2012). First, the lake is the primary part of the well-known Poyang Lake wetland which is in the first batch of The Ramsar Convention List of Wetlands of International Importance (The Ramsar Convention 2012). Second, approximately 10 million people live at the marginal areas of the lake. As it is a rice-growing area, the surrounding region serves as an important national food base. Third, the lake is principally fed by five river systems of the Poyang Lake Basin (figure 1). The basin occupies an area of 9% the Yangtze River Basin, but supplies 17% of the annual discharge of the Yangtze River (Zhu and Zhang 1997). In recent decades, however, Poyang Lake has experienced drastic hydrological change, and the change has resulted in significant hydrological, biological, ecological and economic consequences in the region (Environment News Service 2012).

Poyang Lake has an average depth of 8 m with a high degree of seasonal variation. It varies remarkably from several thousand km$^2$ in summer to less than one thousand km$^2$ in winter. Before the era of satellite remote sensing, the lake area was usually estimated from a bathymetric map. The estimated area of Poyang Lake was 5160 km$^2$ in 1954, and reduced to 3860 km$^2$ in 1998 (Shankman and Liang 2003). Recent
Figure 1. The geophysical location of Poyang Lake, China. The lake is principally fed by five river systems of the Poyang Lake Basin. Lake water flows into the Yangtze River via a sole outlet at the Hukou. Jiujiang is located at 25 km upstream of the Hukou on the Yangtze River and the Three Gorges Dam (TGD) is upstream of the river.

Satellite observations show that the lake area further decreased significantly in the last decade (Hervé et al. 2011, Song and Liu 2011, Feng et al. 2012). Given that the lake is located in a humid subtropical region with millions of residents, the lake declines are attributable to climatic and anthropogenic forces. Land reclamation is primarily responsible for the lake declines in the 1950s, 1960s and 1970s (Shankman et al. 2006, Jiang et al. 2008). With regard to climatic forces, Zhao et al. (2010) demonstrated that annual precipitation increased but was statistically insignificant while potential evaporation decreased significantly for the Poyang Lake Basin, and annual streamflow to the lake increased, for the period from the 1950s to 2003. In addition to the inflows generated by basin precipitation, Poyang Lake is also influenced by the blocking effect of the Yangtze River (Hu et al. 2007). When the blocking effect weakens, more lake water flows into the Yangtze River, unavoidably leading to lake declines (Guo et al. 2012).

The recent declines of the lake have had substantial effects on the Poyang Lake wetlands and surrounding areas (Jiao 2009, Finlayson et al. 2010, Environment News Service 2012). Existing studies have addressed changes in precipitation (Zhang et al. 2011) and streamflow (Guo et al. 2012, Zhao et al. 2010) for the Poyang Lake Basin prior to 2005 and detailed the lake decrease in the last ten years (Zhao et al. 2010, Hervé et al. 2011, Song and Liu 2011, Feng et al. 2012). However, it remains unclear whether the recent decline is a trend of long-term change or an abrupt change of the lake, and to what extent climatic and anthropogenic forces or a combination of two account for the change. By definition, a trend is likely to continue in the future but does not necessarily change the stationarity of the system. In contrast, an abrupt change means a shift of the system from one regime to another, and the status is likely to persist until a new regime shift takes place (Villarini et al. 2011). Examples of regime shifts include post-dam rivers and lake ecosystems (Magilligan and Nislow 2005, Andersen et al. 2008), but few have covered lake size (Oyebande 2001). Clarification of the issue is of high importance for policymakers as it may lead to different decisions in water resource management, wetland protection and climatic adaptation.

This study took advantage of long-term hydrologic data and multi-temporal satellite images to investigate the recent shrinkage of Poyang Lake. A four-decade record of the water surface of the lake was constructed for the investigation. Section 2 describes the methods for the construction and for detecting trend and regime shift. Section 3 details the study materials and data processing. Section 4 reports intra- and inter-annual variations of Poyang Lake and discusses the trigger mechanism accounting for the recent lake declines. Section 5 gives our conclusions. Our findings will be helpful for understanding the role of natural and anthropogenic forces in lake change and be useful for local people and governments to protect and sustain China’s largest freshwater lake.

2. Methods

The lake stage-area approach is applied to construct historical records of Poyang Lake from hydrological data and multi-temporal satellite images. Non-parametric Mann–Kendall (M–K) analysis (Mann 1945, Kendall 1975) is utilized for detecting long-term trend. The sequential algorithm proposed by Rodionov (2004) is adopted for detecting regime shift.

2.1. Construction of historical lake change data with multi-temporal satellite images

The lake water surface can be estimated from a bathymetric map given a lake stage with an assumption of a horizontal plane (Hakanson 1978). However, Poyang Lake varies
spatially in lake stage; in particular, in the low water period the stage difference could be as large as 6 m from the south end to the north end. It is thus unsuitable to directly use the bathymetric map for the estimation. In contrast, satellite remote sensing can map real water surfaces routinely (Smith 1997). As the most discernible object in remote sensing, a water surface can be extracted with an accuracy of over 90% from a high-resolution image, for example, a Landsat Thematic Mapper (TM) image (Birkett 2000). In combination with lake stage, the extracted multi-temporal water surfaces can generate a stage–area relationship, which is more suitable for estimating the water surface in actual situations.

In remote sensing, visible and near-infrared (NIR) bands are often used for retrieval of a water surface (McFeeters 1996). Water absorbs much more light in the NIR band than in the visible band, which makes it different from other land covers. A water surface is easily extractable with an index such as the normalized difference water index (NDWI), the normalized difference vegetation index (NDVI) or the single NIR band (Richard and Mary 1988, Goward et al 1991, McFeeters 1996). NDWI is widely adopted in extracting water in the visible band, which makes it different from other land covers. A water surface is easily extractable with an index such as the normalized difference water index (NDWI), the normalized difference vegetation index (NDVI) or the single NIR band (Richard and Mary 1988, Goward et al 1991, McFeeters 1996). NDWI is widely adopted in extracting water from the Earth Resources Observation and Science Center (EROS), the United States Geological Survey (USGS) (http://glovis.usgs.gov/). The Landsat series offers probably the best source of cloud-free Landsat series images from the Earth Resources Observation and Science Center (EROS), the United States Geological Survey (USGS) (http://glovis.usgs.gov/). The Landsat series offers probably the best source of cloud-free Landsat series images.

2.2. M–K trend test

The M–K trend test is a rank-based non-parametric test (Mann 1945, Kendall 1975). It does not require time series data to be normal or linear, and has wide applications (Wang et al 2008, Zhao et al 2010, Zhang et al 2011). For a monotone trend in time series \( x_k, k = 1, 2, \ldots, n \), the univariate M–K statistic is defined as

\[
d_k = \sum_{i=1}^{k} r_i, \quad (2 \leq k \leq n),
\]

where

\[
r_i = \begin{cases} +1 & \text{if } x_i > x_j, \\ 0 & \text{otherwise} \end{cases} \quad (j = 1, 2, \ldots, i).
\]

The statistic index \( Z_k \) is defined as

\[
Z_k = \frac{d_k - E[d_k]}{\sqrt{\text{Var}[d_k]}},
\]

where \( E[d_k] = n(n-1)/4 \) and \( \text{Var}[d_k] = n(n-1)(2n+5)/72 \). A positive \( Z \) value denotes a positive trend while a negative value indicates a negative trend. For a two-sided test, the null hypothesis of no trend is rejected at a significance level of \( p \). \( p = 5\% \) is usually used to evaluate the significance of the tested trend.

2.3. Regime shift detection

This study adopted Rodionov’s sequential approach. It can automatically detect multiple change points and is less sensitive to the presence of trends than the prevailing methods (Rodionov 2004). For a time series \( \{x_k, k = 1, 2, \ldots, n\} \), the mean of the first regime \( (R_1) \), \( \bar{x}_{R_1} \), is determined as

\[
\bar{x}_{R_1} = \frac{1}{l} \sum_{k=1}^{l} x_k \quad (1 \leq k \leq l),
\]

where \( l \) is the cut-off length of the regimes to be determined. The difference from the mean of the second regime \( (R_2) \) that would be statistically significant (Student’s \( t \)-test) is given by

\[
diff = t \sqrt{2\sigma^2/l},
\]

where \( t \) is the value of the \( t \)-distribution with \( 2l - 2 \) degrees of freedom at a probability level \( p. p = 5\% \) is often used in the evaluation. \( \sigma^2 \) is the average variance for \( l \)-year intervals in the time series.

Each \( x_k (k \geq l + 1) \) is evaluated in a sequential order. If \( x_k \) is within the range of \( [\bar{x}_{R_1} - \text{diff}, \bar{x}_{R_1} + \text{diff}] \), the \( \bar{x}_{R_1} \) is recalculated with the \( x_k \) value and \((l-1)\) previous \( x_k \) values. If \( x_k \) is out of \([\bar{x}_{R_1} - \text{diff}, \bar{x}_{R_1} + \text{diff}] \), it is considered as a possible start point \( (k = j) \) of the new (second) regime \( (R_2) \). In this case, the regime shift index (RSI) is determined to confirm or reject the null hypothesis of the regime shift starting at year \( j \) as

\[
\text{RSI}_{j} = \sum_{i=j}^{j+m} \frac{x_i - (\bar{x}_{R_1} + \text{diff})}{\sigma_{l}}
\]

\((m = 0, 1, \ldots, l-1)\).

If the RSI keeps the same sign as the one at year \( j \), it would increase the confidence that a shift did occur. Otherwise, the start point \( j \) is false. The search for the next start point continues.

Once the \( R_2 \) regime is established, it serves as the base regime. The search for the next regime shift proceeds until all the available data are evaluated.

3. Study materials and data processing

Poyang Lake is located in the northern part of the Poyang Lake Basin, which is a sub-basin of the Yangtze River Basin of China (figure 1). The lake water flows into the Yangtze River via a sole outlet at the Hukou, located at the north end of the Poyang Lake Basin. The basin has an area of 162225 km², belonging to a humid subtropical climate zone. The multi-year mean of surface air temperature was 17.5°C and the annual precipitation was 1635.9 mm for 1960–2010. The dominant land covers include forestlands, agricultural fields, grasslands, bare lands and water surfaces.

This study acquired cloud-free Landsat series images from the Earth Resources Observation and Science Center (EROS), the United States Geological Survey (USGS) (http://glovis.usgs.gov/). The Landsat series offers probably the longest time record of the Earth’s surface with a spatial
resolution of tens of meters (Williams et al. 2006). A Landsat Multispectral Scanner (MSS) image has a spatial resolution of 80 m. A Landsat TM or Enhanced Thematic Mapper Plus (ETM+) image has a resolution of 30 m. The acquired images include 18 MSS scenes for the period from 1973 to 1984, 37 TM scenes for the period from 1984 to 2010, and 9 ETM+ scenes for the period from 1999 to 2005. This yielded 59 images covering the whole of Poyang Lake for 1973–2010.

All the acquired Landsat data were projected onto the Universal Transverse Mercator (UTM) with a World Geodetic System datum (WGS-84). In practice, both surface reflectance and satellite digital number (DN) have been used for calculation of NDWI (e.g. Teillet et al. 1997, Carlson and Ripley 1997). In either case, equivalent results can be achieved (Liu et al. 2012). The DN-based NDWI is therefore utilized to reconstruct the time series of water surface using the green and NIR bands. MSS band 1 (0.5–0.6 µm), TM band 2 (0.52–0.60 µm) and ETM+ band 2 (0.52–0.60 µm) are green bands. MSS band 3 (0.7–0.8 µm), TM band 4 (0.76–0.90 µm) and ETM+ band 4 (0.77–0.90 µm) are NIR bands. An NDWI histogram was generated for each image. An optimal threshold value was determined to delineate the water surfaces from each histogram using typical objects (e.g. lake banks). The extracted water surfaces were also confirmed through visual inspection with ground-truth data. Accordingly, water surfaces were obtained for all the images used.

MODe rate resolution Imaging Spectroradiometer (MODIS) data (Masuoka et al. 1998) were also acquired for water surface delineation but the results were less good due to the poor spatial resolution. Thus, the Landsat-based water surfaces were utilized to construct the lake stage–area relationship with hydrological data. It should be mentioned that the lake volume reduced significantly with land reclamation before the 1970s. Therefore, the constructed relationship is only suitable for the period after then. The monthly and annual means of Poyang Lake area were subsequently obtained from the relationship using observed stage data for 1973–2011.

Daily precipitation data from 13 national weather stations within the Poyang Lake Basin are available from the China Meteorological Data Sharing Service System at http://cdc.cma.gov.cn/ for 1960–2010. Mean data from the 13 stations were used for the basin-scale analysis (Hu et al. 2007, Zhao et al. 2010). Daily discharge and water level data for Hukou were obtained from the Hydrological Bureau of the Yangtze River Water Resources Commission for 1960–2011. The regional evapotranspiration of the Poyang Lake Basin was extracted from MOD16 products of satellite MODIS, available at www.ntsg.umt.edu/project/mod16 (Mu et al. 2011). They have a spatial resolution of 1 km at eight-day, monthly and annual intervals for 2000–2010. The MOD16 datasets were validated with the principle of sub-basin water balance using precipitation and discharge data and proved to have an overall accuracy of 90.4% for the Poyang Lake Basin (Wu et al. 2013). Because long-term regional evapotranspiration data prior to 2000 were unavailable, the multi-year mean of monthly evapotranspiration was estimated to be the difference between monthly precipitation and discharge with a one-month lag, which accounted for peak rainfall and peak discharge for the Poyang Lake Basin (Senay et al. 2011).

Monthly and annual statistics of precipitation, evapotranspiration and discharge were calculated with statistical analysis. The M–K trend test was applied to the time series of monthly or annual means for trend detection. The Rodionov sequential approach was applied to detect regime shift. The cut-off length l was determined to be 10. All the data sets were used to investigate the mechanism of recent lake declines.

4. Results and discussion

4.1. Intra- and inter-annual changes of Poyang Lake in the last four decades

Poyang Lake had a range from 907.7 to 3752.7 km², with a mean of 2388.0 km² and one standard deviation (SD) of 735.0 km², as extracted from the available Landsat images. The extracted lake area (y) had a positive relationship with lake stage (x) ranging from 7.33 to 20.34 m at Hukou. The relationship was described with a second order polynomial

\[ y = -7.25x^2 + 417.16x - 1772.9 \quad (R^2 = 0.8653, n = 59, p < 0.005, \text{S.D.} = 292.4 \text{ km}^2) \]

(figure 2). The close correlation allowed it to be used reliably for reconstructing historical variation of the lake. Given that the systematic errors in lake area estimates were minimized with the polynomial regression and the data followed a normal distribution (p < 0.01), the mathematical expectation of the random errors (n = 365) in the annual mean of lake area would generally approach zero.

Figure 3 shows variations of annual mean and annual S.D. of Poyang Lake area for the period from 1973 to 2011. Annual mean represents the average state of the lake for a whole year, and annual SD signifies the intra-annual variation within the year. The multi-year mean of the lake was 2385.8 ± 230.7 km². The top three largest values of annual mean

\[
\begin{align*}
\text{S.D.} &= \sqrt{\frac{\sum (x - \bar{x})^2}{n-1}} \\
\text{R}^2 &= \frac{\sum (y - \bar{y})^2 - \sum (x - \bar{x})(y - \bar{y})}{\sum (x - \bar{x})^2}
\end{align*}
\]

where \(\bar{x}\) and \(\bar{y}\) are the mean of x and y, respectively.
were $2886.8 \pm 826.7$ km$^2$ in 1998, $2829.2 \pm 828.7$ km$^2$ in 1983 and $2706.8 \pm 871.3$ km$^2$ in 1973. These coincided with flooding events that occurred in the Poyang Lake region for all three years. In contrast, the top three smallest values of annual mean were $1828.0 \pm 687.9$ km$^2$ in 2011, $1985.7 \pm 687.9$ km$^2$ in 2006 and $1997.8 \pm 762.5$ km$^2$ in 1978. Severe drought events occurred in these three years. Furthermore, Mann–Kendall analysis revealed a slight decreasing trend in annual mean described by $y = -6.15x + 2508.8$ ($R^2 = 0.0923$, $p = 0.1346$), where $x$ is the calendar year. In addition, the Rodionov sequential approach disclosed an abrupt change in 2006 ($p = 0.0218$) (figure 3). The multi-year mean of the lake area was $2433.7$ km$^2$ for the first regime (regime-1) and $2122.1$ km$^2$ for the second regime (regime-2). This indicates that the lake state shifted from one regime to a new one. With regard to intra-annual variations, the annual SD of Poyang Lake ranged from $608.5$ km$^2$ to $1116.8$ km$^2$ (figure 3). It had a mean of $830.5 \pm 117.3$ km$^2$. The intra-annual variation ($830.5$ km$^2$) was approximately 3.9 times the inter-annual change ($210.3$ km$^2$) for 1973–2011. Although the annual SD had a slightly decreasing trend described by $y = -2.10x + 877.4$ ($R^2 = 0.0429$), it was statistically insignificant ($p = 0.1629$). No abrupt change was detected in the annual SD, indicating that the intra-annual variation of Poyang Lake remained relatively stable in the past four decades.

Why did Poyang Lake display an abrupt change in the annual mean but the annual SD remain stable? What happened at a seasonal scale? On a monthly basis, the M–K statistics increased for January, February, March and August for 1973–2011. The M–K statistics decreased for the remaining months, especially for October ($p = 0.0012$) and November ($p = 0.0278$) (figure 4(a)). In regime-1, the largest water area appeared in July, followed by August and September. In regime-2, the largest area occurred in the same month, followed by August and June, indicating a seasonal shift. By comparison of the two regimes, the lake area decreased for almost all months except March (figure 4(b)). In March, Poyang Lake increased by $64.3$ km$^2$. On the other hand, the largest drops occurred in October, by $-688.3$ km$^2$, followed by $-513.4$ km$^2$ in November. The decreases contributed to overall declines in the annual mean of the lake. With regard to monthly SD, it increased significantly for September by $242.8$ km$^2$, October by $196.9$ km$^2$ and November by $163.7$ km$^2$. The increases of the monthly SD were attributed to the large ranges of the lake declines in these months. In general, the lake decreased from regime-1 to regime-2, dominantly in September, October and November.

4.2. The trigger mechanism for regime shift of Poyang Lake

Regime shift can be triggered by external perturbation or the system’s internal dynamics. Since the 1950s, two factors responsible for the volume change of Poyang Lake are land reclamation and lake sedimentation (Min 2000). However, lake sedimentation had negligible effects on lake volume (Min 2000, Min et al 2011). Land reclamation was substantially reduced in the 1970s and has been banned since the 1980s (Jiang et al 2008). The lake volume has remained relatively stable since the 1970s. Therefore, the regime shift in 2006 was likely driven by external forces rather than the system’s internal dynamics. The change of Poyang Lake is a synthetic result of input and output water. Lake water is input from precipitation and inflows of five sub-basins, and water is output through evaporation and outflow to the Yangtze River. It is straightforward to use a lake water balance approach to investigate the mechanism of regime shift of the lake. However, at least two difficulties make detailed analysis impractical. First, there are seven hydrological control stations distributed in five sub-basins to measure the discharges of five major rivers into Poyang Lake. The long-term discharge data of all seven stations are incomplete or unavailable for
the present analysis, especially for recent years. Second, the lake region is 23,189 km$^2$ downstream from the seven control stations, approximately six times the lake area. It remains largely unknown how much precipitated water evaporates or flows into the lake for the region. Therefore, we made an analysis of the hydrologic components of the whole basin instead. The major components for the analysis include precipitation, evapotranspiration and discharge.

4.2.1. Hydrologic change of Poyang Lake Basin. On an annual basis, the annual mean of lake surface had a positive correlation with annual precipitation ($R^2 = 0.7300, p < 0.005$) and annual outflow discharge ($R^2 = 0.7790, p < 0.005$) of the Poyang Lake Basin. Both annual precipitation and discharge decreased slightly but were statistically insignificant. The decreasing trends were described by $y = -0.316x + 2294.4$ ($R^2 = 0.0002, p = 0.4308$) for the precipitation and $y = -0.573x + 2086.5$ ($R^2 = 0.0006, p = 0.2873$) for the discharge, where $x$ is the calendar year. In contrast, the residuals between precipitation and discharge displayed an increasing trend $y = 0.257x + 713.8$ ($R^2 = 0.0008$). Neither annual precipitation nor annual discharge nor their difference exhibited abrupt change. In regard to evapotranspiration, because the long-term time series data were unavailable and the multi-year mean values could hide abrupt change if it existed, surface air temperature was used as a proxy for the examination. The annual mean of surface air temperature had a significant increasing trend described by $y = 0.0334x - 48.4$ ($R^2 = 0.5791, p < 0.005$). Moreover, it displayed an abrupt change in 1998 ($p < 0.005$). The average temperature was 17.8 °C for the previous regime and 18.6 °C for the present regime. The temperature change implies that evapotranspiration had an increasing trend with an abrupt change in 1998, coinciding with Liu et al. (2010). Obviously, the inter-annual change of major hydrologic components did not offer an explanation for the regime shift of Poyang Lake.

On a monthly basis, precipitation, discharge, evapotranspiration and water budget displayed considerable differences for the two regimes (figure 5). The monthly precipitation ranged from 46.0 mm (December) to 283.8 mm (June) with 139.7 ± 78.6 mm, more distributed in March–June for regime-1 (1973–2005) (figure 5(a)). For regime-2 (2006–2010), the seasonal pattern of precipitation remained as in regime-1 but it decreased for the nine months other than July, November and December. The largest decrease occurred in October, by −36.2 mm, followed by −35.2 mm in May. The annual precipitation was 1676.8 mm for regime-1 and 1583.1 mm for regime-2, suggesting a 93.7 mm drop on average for the regime shift.

With regard to discharge, its monthly value ranged from 33.9 mm (January) to 133.3 mm (June) with 79.8 ± 36.4 mm for regime-1. It had seasonal pattern similar to precipitation, but roughly half in magnitude (figure 5(b)). In comparison with regime-1, the monthly discharge generally decreased for most months with the largest drops in November (22.3 mm) and May (22.1 mm). It increased by 11.4 mm in June and 0.2 mm in December. The annual discharge changed from 958.0 mm to 860.0 mm, yielding a 98.0 mm drop for the regime shift.

In contrast, the monthly evapotranspiration had a seasonal pattern different from discharge and precipitation. It ranged from 13.8 mm (December) to 119.9 mm (July) with 60.7 ± 39.6 mm for regime-1. It was generally lower than the monthly discharge and more evapotranspiration appeared in June–September (figure 5(c)). Notably, the monthly evapotranspiration increased in every month for...
The largest increase appeared in August (10.6 mm). The annual evapotranspiration was 727.8 mm for regime-1 and 784.2 mm for regime-2, equivalent to 56.4 mm increase for the regime shift.

It is speculated that lake water is a residual of regional precipitation, evapotranspiration and outflow discharge. Figure 5(d) shows that the water budget was positive for December–June and negative for July–October in the Poyang Lake Basin. The water budget ranged from −75.0 mm (July) to 65.4 mm (March) with 0.0 ± 54.3 mm for regime-1. In regime-2, the water budget generally decreased for most months except for April, July, November and December. The largest decrease (−28.4 mm) appeared in October and the largest increase (27.2 mm) in November. Compared to regime-1, the annual water budget decreased by 61.1 mm, a synthetic result of decreased precipitation and discharge and increased evapotranspiration. Overall, precipitation decrease (−93.7 mm) and evapotranspiration increase (65.4 mm) contributed to water budget reduction, and the reduction was compensated by the decreased outflow discharge (−98.0 mm). It seems that the drop in precipitation and the increase in evapotranspiration could account for the regime difference, yet this is not the complete mechanism for the regime shift.

4.2.2. Interactions between Poyang Lake and the Yangtze River. Poyang Lake varies with precipitation, evapotranspiration and outflow discharge. More importantly, the outflow is basically controlled by interactions between the lake and the Yangtze River (Guo et al 2012) and the lake stage is primarily determined by the Yangtze River (Shankman and Liang 2003). For example, the lake area reached a minimum in 2006 (table 1). However, the basin-scale precipitation and outflow discharge were slightly higher, and the evapotranspiration was 53.1 mm higher than that of regime-1. In contrast, the precipitation and outflow discharge were approximately 200 mm lower, and the evapotranspiration was 55.6 mm higher in 2008, but the lake area was 12% larger than in 2006. In addition, the lake area (γ) had a weak correlation with the water budget (x) (γ = 0.3484x − 820.9, R² = 0.4581, p = 0.2131), indicating that the lake area did not purely rely on water incomes from regional precipitation, evapotranspiration and discharge. Because the same water input does not necessarily mean the same increase of lake area for different stages, the lake area also relies on the water stage at the outlet (Hukou), representing the interactions between the lake and the Yangtze River.

As stated in section 4.1, the lake area had a close relationship with water stage at the Hukou. A one-meter decrease of the water stage could result in lake shrinkage by approximately 300 km². Change of the water stage from 13.1 ± 0.9 m (1973–2005) to 11.8 ± 0.9 m (2006–2011) led to lake shrinkage by 306 km². The lake stage had a high correlation (γ = 1.03x − 1.05, R² = 0.9998) with the river stage at Jiujiang, located 25 km upstream of the Hukou on the Yangtze River (figure 1). The decreased river stage weakened the blocking effect of the Yangtze River on Poyang Lake (Guo et al 2012). It becomes clear that the decreased stage of the Yangtze River triggered the regime shift of Poyang Lake. The stage decrease of the river is attributable, though this is widely argued, to both climate change and water impoundment at the Three Gorges Dam (TGD) established upstream of the Yangtze River in 2003 (Yang et al 2006, Dai et al 2008, Yuan et al 2011, Guo et al 2012). Whether the present lake regime will persist relies greatly on the stage change of the Yangtze River in the coming years. Further investigations include to what extent climate change and TGD water impoundment contributed to the stage decrease of the Yangtze River and whether the decrease will continue.

5. Conclusions

This study used hydrological data and multi-temporal satellite images to construct a historic record of Poyang Lake for past four decades. The results demonstrate that the recent lake shrinkage was not a long-term trend but a regime shift that occurred in 2006. The lake change was a synthetic result of precipitation, evapotranspiration and outflow discharge. Precipitation and outflow did not show any significant trend or abrupt change, and evapotranspiration had an increasing trend in addition to an abrupt change in 1998. None of the major hydrologic components nor their combinations fully accounted for the regime shift of the lake. The lake change was found to coincide with a stage decrease of the Yangtze River, the trigger mechanism for the regime shift. The findings provide an example of hydrologic non-stationarity and will be valuable for effective promotion of climate adaptation and water resource management. Further study should investigate to what extent climate change and TGD impoundment contributed to the stage decrease and whether the change will continue.
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References

Andersen T, Carstensen J, Hernández-García and Duarte C M 2008 Ecological thresholds and regime shifts: approaches to identification Trends Ecol. Evol. 24 49–57

Birkett C M 2000 Synergetic remote sensing of Lake Chad: variability of basin inundation Remote Sens. Environ. 72 218–36

Carlson T N and Ripley D A 1997 On the relation between NDVI, fractional vegetation cover, and leaf area index Remote Sens. Environ. 62 241–52

Dai Z, Du J, Li J, Li W and Chen J 2008 Runoff characteristics of the Changjiang River during 2006: effect of extreme drought and the impounding of the Three Gorges Dam Geophys. Res. Lett. 35 L07406

Davranche A, Lefebvre G and Poulin B 2010 Wetland monitoring an early draft of the manuscript.

Environment News Service 2012 China’s Largest Freshwater Lake Shrinks in Record Drought (available from: www.ens-newswire.com/ens/jan2012/2012-01-05-01.html, accessed 8 August 2012)

Feng L, Hu C, Chen X, Cai X, Tain L and Gan W 2012 Assessment of inundation changes of Poyang Lake using MODIS observations between 2000 and 2010 Remote Sens. Environ. 121 80–92

Finlayson M, Harris J, McCartney M, Lev Y and Zhang C 2010 Report on Ramsar Visit to Poyang Lake Ramsar Site, PR China (available from: www.ramsar.org/pdf/PoyangLake_report_v8.pdf, accessed 16 January 2013)

Goward S N, Markham B, Dye D G, Dulaney W and Yang J 1991 Normalized difference vegetation index measurements from the advanced very high resolution radiometer Remote Sens. Environ. 35 257–77

Guo H, Hu Q, Zhang Q and Feng S 2012 Impacts of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008 J. Hydrol. 416/417 19–27

Hakanson L 1978 Optimization of lake hydrographic surveys Water Resources Res. 14 545–60

Hervé Y et al 2011 Nine years of water resources monitoring over the middle reaches of the Yangtze River, with ENVISAT, MODIS, Beijing-1 time series, altimetric data and field measurements Lake Reservoir Manag. 16 231–47

Hu Q, Feng S, Guo H, Chen G and Jiang T 2007 Interactions of the Yangtze River flow and hydrologic processes of the Poyang Lake, China J. Hydrology 347 90–100

Jiang L, Bergen K M, Brown D G, Zhao T, Tian Q and Qi S 2008 Land-cover change and vulnerability to flooding near Poyang Lake, Jiangxi Province, China Photogramm. Eng. Remote Sens. 74 775–86

Jiao J 2009 Scientists line up against dam that would alter protected wetlands Science 326 508–9

Kendall M G 1975 Rank Correlation Methods (London: Charles Griffin)

Liu Y, Song P, Peng J and Ye C 2012 A physical explanation of the variation in threshold for delineating terrestrial water surface from multi-temporal images: effects of radiometric correction Int. J. Remote Sens. 33 5862–75

Liu J, Zhang Q, Xu C, Zhai J and Xin X 2010 Change of actual evapotranspiration of Poyang Lake watershed and associated influencing factors in the past 50 years Resources Manag. Yangtze Basin 19 139–45 (in Chinese with English abstract)

Magilligan F J and Nislow K H 2005 Changes in hydrologic regime by dams Geomorphology 71 61–78

Mann H B 1945 Non-parametric tests against trend Econometrica 13 245–59

Masuoka E, Fleig A, Wolfe R E and Patt F 1998 Key characteristics of MODIS data products IEEE Trans. Geosci. Remote Sens. 36 1313–23

McFeeters S K 1996 The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features Int. J. Remote Sens. 17 1425–32

Min Q 2000 Study on the relationship between shape, water regime and inundations of Poyang Lake Adv. Water Sci. 11 76–81 (in Chinese with English abstract)

Min Q, Shi J and Min D 2011 Characteristics of sediment into and out of Poyang Lake from 1956 to 2005 J. China Hydrol. 31 54–8

Mu Q, Zhao M and Running S W 2011 Improvements to a MODIS global terrestrial evapotranspiration algorithm Remote Sens. Environ. 115 1781–800

Oyebande L 2001 Streamflow regime change and ecological response in the Lake Chad basin in Nigeria Hydro-Ecology: Linking Hydrology and Aquatic Ecology (IAHS Publication no 266) (Wallingford: IAHS Press) pp 101–11

Richard P S and Mary A T 1988 Satellite detection of bloom and pigment distributions in estuaries Remote Sens. Environ. 24 385–405

Rodionov S N 2004 A sequential algorithm for testing climate regime shifts Geophys. Res. Lett. 31 L09204

Rogers A S and Kearney M S 2004 Reducing signature variability in unmixing coastal marsh thematic mapper scenes using spectral indices Int. J. Remote Sens. 25 2317–35

Senay G B, Leake S, Nagler P L, Artan G, Dickinson J, Rogers A S and Kearney M S 2004 Reducing signature variability of MODIS data products Remote Sens. Environ. 72 54–8

Shankman D, Keim B D and Song J 2006 Flood frequency in China’s Poyang Lake region: trends and teleconnections Int. J. Climatol. 26 1255–66

Shankman D and Liang Q 2003 Landscape changes and increasing flood frequency in China’s Poyang Lake region Prof. Geogr. 55 434–45

Smith L C 1997 Satellite remote sensing of river inundation area, stage, and discharge: a review HydroL. Process. 11 1427–39

Song P and Liu Y 2011 Satellite-based tracking of water surface variation of Poyang Lake during the last three decades Hydro–Climatology: Variability and Change (IAHS Publication no 344) (Wallingford: IAHS Press) pp 215–20

Teillet P M, Staenz K and Williams D J 1997 Effects of spectral, spatial, and radiometric characteristics on remote sensing vegetation indices of forested regions Remote Sens. Environ. 61 139–49

The Ramsar Convention 2012 The List of Wetlands of International Importance, 25 April 2012 (available from: www.ramsar.org/pdf/sitelist.pdf, accessed on 8 August 2012)

Villarini G, Smith J A, Serinaldi F and Nelekos A A 2011 Analyses of seasonal and annual streak discharge records for central Europe J. Hydrol. 399 299–312

Wang W, Chen X, Shi P and van Gelder P 2008 Detecting changes in extreme precipitation and extreme streamflow in the
Dongjiang River Basin in southern China *Hydrol. Earth Syst. Sci.* **12** 207–21

Williams D L, Goward S and Arvidson T 2006 Landsat: yesterday, today, and tomorrow *Photogramm. Eng. Remote Sens.* **72** 1171–8

Wu G, Liu Y and Zhao X 2013 Analysis of spatio-temporal variations of evapotranspiration in Poyang Lake Basin using MOD16 products *Geophys. Res. at press* (in Chinese with English abstract)

Yang Z, Wang H, Saito Y, Milliman J D, Xu K, Qiao S and Shi G 2006 Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: the past 55 years and after the Three Gorges Dam *Water Resources Res.* **42** W04407

Yuan W, Yin D, Finlayson B and Chen Z 2011 Assessing the potential for change in the middle Yangtze River channel following impoundment of the Three Gorges Dam *Geomorphology* **147–148** 27–34

Zhang Q, Liu Y, Yang G and Zhang Z 2011 Precipitation and hydrological variations and related associations with large-scale circulation in the Poyang Lake basin, China *Hydrol. Process.* **25** 740–51

Zhao G, Hormann G, Fohrer N, Zhang Z and Zhai J 2010 Streamflow trends and climate variability impacts in Poyang Lake Basin, China *Water Resources Manag.* **24** 689–706

Zhu H and Zhang B 1997 *Poyang Lake* (Hefei: University of Science and Technology of China Press) (in Chinese)