Satellite observations make it possible to estimate Poyang Lake’s water budget

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Abstract
Using moderate resolution imaging spectroradiometer (MODIS) satellite imagery with hydrologic and meteorological data, we developed a box model to estimate the water exchange between Poyang Lake (the largest freshwater lake of China) and the Changjiang (Yangtze) River from 2000 to 2009. Significant intra- and inter-annual variability of the water budget was found, with an annual mean outflow of Poyang Lake of $120.2 \pm 31.2$ billion m$^3$ during 2000–2009 and a declining trend of $5.7$ billion m$^3$ yr$^{-1}$ ($p = 0.09$). The impoundment of the Three Gorges Dam (TGD) on the Changjiang River in June 2003 led to a rapid lake–river outflow of $760.6$ million m$^3$ day$^{-1}$, resulting in a loss of $7864.5$ million m$^3$ of water from the lake in a short period. Shortly thereafter, a statistically significant decrease in the drainage basin’s runoff coefficient was discovered. These findings provide large-scale evidence on how local precipitation and the TGD control the lake’s water budget, where continuous monitoring using the established approach and satellite data may provide critical information to help make water management decisions.

Keywords: water budget, Poyang Lake, MODIS, Three Gorges Dam

1. Introduction

In the drainage basin of the largest freshwater lake of China, Poyang Lake (28°22′–29°45′N and 115°47′–116°45′E, figure 1), frequent floods and droughts posed significant threats to local economic development, and the lives of animals and people (Min et al 2008, Qi et al 2009, Shankman et al 2006). The shrinking of the wetlands in recent years endangered the habitat for many winter birds (Cai 2010, Leeuw et al 2010, Li 2008). A severe drought in early 2011 caused various environmental problems and economic hardship (Yu 2011), which stoked the endless rumors of whether it was due to the impact from the Three Gorges Dam (TGD, figure 1 inset) on its upstream Changjiang (Yangtze) River (Wong 2011).

The main water supply of Poyang Lake is its five main tributaries (Ganjiang, Fuhe, Xiushui, Xinjiang and Raohe) and rainfall (Zhang 1988). Normally, Poyang Lake flows from the south and discharges into the Changjiang River at Hukou in the north (see arrows in figure 1), which is due to the higher elevation in the south (figure 1). However, during the summer months, the south–north water flow is impeded by the elevated
Figure 1. Location of Poyang Lake, where the bottom topography derived from MODIS imagery is shown (Feng et al 2011a). The elevation is higher in the south than in the north, leading to a south–north water flow (see arrows). The red and black triangles annotate the hydrologic stations in the lake and its main tributaries, respectively. A dam in the northern outlet is proposed by the local government. The inset figure shows the locations of the Poyang Lake drainage basin and the Three Gorges Dam (TGD).

water level of the Changjiang River, sometimes resulting in a reversal flow (Shankman et al 2006). Influenced by subtropical monsoons, the inundation area shows significant seasonality, which can change from >3000 km² during the wet season to <1000 km² during the dry season (Feng et al 2011b).

Understanding the water budget of Poyang Lake is important for flood control, water resource utilization, lake management, and understanding of water circulation and ecosystem connectivity (Birkett 2000, French et al 2005, Mercier et al 2002). The hydrologic budget of a lake is controlled by evaporation, rainfall, surface runoff, seepage and the water volume change of the lake (Neff and Killian 2003, Redmond 2007, Shih 1980). Traditionally, the runoff data can be obtained from hydrologic stations, and volume change is a function of the water level (Chebud and Melesse 2009, Kebede et al 2006, Troin et al 2010, Yin and Nicholson 1998). For Poyang Lake, however, two fundamental difficulties were faced when estimating the lake's water budget. First, there is no reliable measurement of the lake's outflow to the nearby Changjiang River (Shankman et al 2006). Second, due to its complex bottom topography (figure 1) and significant dynamic inundation range (the maximum/minimum ratio during any year can be 2–3 (Feng et al 2011b)), it has been impossible to estimate the lake's water volume change using any traditional means.

Recently, Feng et al (2011a) developed a novel method to derive the bottom topography of Poyang Lake by combining remote sensing and water level data. To our knowledge, this is the first time that the lake’s complex bottom topography along with its inter-annual variability has been quantified, without which it is impossible to estimate the lake’s water volume, not to mention its water budget. Based on this most recent work, we further developed a box model by accounting for all inputs and outputs of the lake using remote sensing, hydrologic and meteorological data, with the ultimate objective to quantify and understand the lake’s water budget (inflow and outflow) and its inter-annual variability. In particular, we seek to determine whether and how the construction of the TGD upstream affected the water budget of this downstream lake.

2. Data and method

Daily runoff data collected from seven hydrologic stations in the five main tributaries of Poyang Lake (figure 1) were summed to represent the total runoff of Poyang Lake. Water level data from the hydrologic stations in the lake were obtained to be combined with the lake’s topography and inundation area to estimate the lake’s water volume.

Daily meteorological data (air temperature, humidity, sunshine hours, wind speed and pressure) from the eight nearest stations (obtained from the China Meteorological
Data Sharing Service System [http://cdc.cma.gov.cn], were averaged to represent the condition of the lake and then used to estimate the evaporation. Monthly precipitation data between 2000 and 2009 were obtained from NASA’s Tropical Rainfall Measuring Mission monthly product (TRMM 3B43), validated using data collected from ten local rain gauges. Excellent agreement was found between the two independent measurements between 2000 and 2010 (see supplementary figure S1 available at stacks.iop.org/ERL/6/044023/mmedia), with high correlation ($R^2$ between 0.73 and 0.92) and similar histogram distributions for their mean, standard deviation, and range (both mean and standard deviation difference <15%).

The slight difference between the two datasets may be a result of their different spatial resolutions (rain gauge is a point measurement while each TRMM data point represents 0.25° × 0.25°), and therefore does not indicate errors. Thus, we believe that TRMM data integrated over the Poyang Lake’s drainage basin can be used to represent local precipitation.

Moderate resolution imaging spectroradiometer (MODIS) satellite data (daily coverage from both Terra and Aqua) from February 2000 to December 2009 (~500 cloud-free images near the satellite scan center) were obtained from the US NASA Goddard Space Flight Center (GSFC), and used to estimate the lake’s inundation area and bottom topography using methods detailed in Feng et al. (2011a, 2011b), respectively. Briefly, the 250 m resolution near-infrared band at 859 nm was atmospherically corrected by removing Rayleigh scattering and gaseous absorption effects and most of the aerosol scattering effects, resulting in a relatively stable index (floating alga index or FAI to differentiate water from floating vegetation, Hu 2009) against variable atmospheric and observational conditions. The 250 m resolution FAI images were co-registered to a cylindrical equidistance (rectangular) projection, with geo-reference errors <0.5 pixel (Wolfe et al. 2002). Because of the large difference in the FAI values (i.e. atmospherically corrected 859 nm reflectance) for water and land pixels, a gradient method was used to delineate the water–land boundary (Feng et al. 2011b), from which the lake’s inundation area was derived.

The inundation area showed substantial variability at both seasonal and inter-annual scales, with maximum/minimum ratios exceeding 2.3 for any given year. These characteristics, when combined with water level data at several hydrological stations, made it possible to derive the lake’s bottom topography. Such a task has been extremely difficult in the past because field-based mapping suffers from slow speed while LIDAR and passive optical remote sensing suffer from high water turbidity (light cannot reach the bottom). At any given time, the MODIS-based water–land boundary was treated as a bathymetric isobath, calibrated by concurrent water level data after correction for the water level’s spatial gradient. Spatial interpolation from many of the isobaths during a calendar year resulted in a continuous bottom topography of the lake, whose uncertainty was estimated to be about 0.5 m for most of the lake’s bottom (Feng et al. 2011a). Note that this technique is inapplicable for lakes with a stable water level or inundation area, but efficient and cost effective for Poyang Lake, and can be extended to any other lakes with dynamic inundation areas.

Based on the derived bottom topography and water level data, the lake’s water volume at the MODIS measurement time ($t$) was determined as follows. First, water depth at location ($x$, $y$) was estimated as

$$\text{Depth}(t, x, y) = H(t, x, y) - Z(x, y)$$  \hspace{1cm} (1)

where $H$ is the water level and $Z$ is the bottom topography. The lake’s water volume $V$, as defined above the lake’s minimum inundation, was estimated through the integration of water depths over the entire inundation area of the lake (see supplementary figure S2 available at stacks.iop.org/ERL/6/044023/mmedia). Then, the changing rate of the lake’s water volume during two consecutive MODIS observations was estimated as

$$\frac{\Delta V}{\Delta t} = (V_{t1} - V_{t2})/(t_2 - t_1),$$  \hspace{1cm} (2)

where positive $\Delta V$ means decreased volume with time.

Thus, the lake’s water budget was estimated as (Chebud and Melesse 2009, Shih 1980):

$$\text{Outflow} = \Delta V + G_{\text{net}} + \text{Runoff} + P^\ast A - ET^\ast A$$  \hspace{1cm} (3)

where Outflow is the water outflow from the lake to the Changjiang River (output); Runoff is the total runoff of the five main tributaries to the lake (input); $P$ is the mean precipitation over the lake (input), estimated using TRMM measurements; $ET$ is mean evaporation (output), estimated using the Penman equation with local meteorological data (Allen et al. 1998); $A$ is the daily inundation area of the lake, estimated through interpolation of two consecutive MODIS measurements; and $G_{\text{net}}$ is the net groundwater flux, assumed to be zero since it only represents 1.3% of total water resource in this region (Wan and Xu 2010).

Because several MODIS measurements were available during each calendar month, the image with its inundation equal to the median inundation was selected to estimate the water volume to represent that month (supplementary figure S2 available at stacks.iop.org/ERL/6/044023/mmedia).

In equation (3), all terms on the right-hand side were derived using data and methods described above, with the left-hand side Outflow estimated. Indeed, similar to the negligible groundwater contributions, evaporation and precipitation over the lake only accounted for ~2% of the runoff. For simplicity, the last three terms of equation (3) (i.e. Runoff$+P^\ast A - ET^\ast A$) are defined as inflow in the following text.

3. Results

3.1. The water budget of Poyang Lake

Figure 2(a) shows the monthly outflow rate, inflow rate, and rate of change of the lake’s volume from 2000 to 2009, where significant seasonality is revealed. Generally, both inflow and outflow increased from late spring to summer months and then decreased. While the lake’s volume peaked in July–September (supplementary figure S2 available at stacks.iop.org/ERL/6/044023/mmedia), inflow and outflow reached a maximum between April and June, as shown in the monthly climatology in figures 2(b) and (c). From January to July, the outflow rate...
was lower than the inflow rate, corresponding to an increase in the lake’s volume, after which the pattern reversed.  
2003 and 2007 were identified as two anomalous years (figures 2(b) and (c)). Between July and August 2003, a swift outflow (760.6 million m$^3$ day$^{-1}$) and a small inflow resulted in the fastest volume change in the past 10 years (631.4 million m$^3$ day$^{-1}$). Between July and August 2007, the opposite occurred, with the maximum negative outflow anomaly (−125.5%). Combined with the positive inflow, this negative outflow corresponded to a rapid increase of the lake’s volume during this period (185.7 million m$^3$ day$^{-1}$).

The monthly time series revealed two distinctive periods, separated at about June 2003. Most (>70%) of the months in the first period showed positive outflow rates, especially during 2002. In contrast, most (>70%) of the months in the second period showed negative outflow rates. This leads to the question of what may have caused these contrasting patterns.

The annual outflow of Poyang Lake was estimated using the monthly mean outflow rate during each year from which the mean annual outflow and inter-annual variability were derived (figure 3(a)). Between 2000 and 2009, mean annual outflow was 120.2±31.2 billion m$^3$. Maximum and minimum annual outflow occurred in 2002 and 2004, respectively, with a factor of 2.3. There appeared a decreasing trend in the 10 year period (5.7 billion m$^3$ yr$^{-1}$, $p = 0.09$; dashed line in figure 3(a)). In terms of a balanced budget, during most years the annual outflow matched the annual inflow, with a determination coefficient ($R^2$) of 0.96 and mean difference < 5% (except for 2003) (figure 3(b)). During 2003, annual outflow was ~15% higher than inflow (red dot in figure 3(b)), indicating an unusual mechanism.

3.2. Driving forces: the role of the TGD

Correlation analysis showed that the coefficients of determination ($R^2$) between the monthly climatological precipitation of the lake’s drainage basin and the inflow and outflow rates were 0.79 and 0.75, respectively, suggesting a dominant force. High precipitation during the rainy months between April and June resulted in the highest inflow and outflow rates.
Between July and September, the water level of the upstream Changjiang River was elevated due to high rainfall and snow melt water (Shankman et al. 2006), leading to reduced and sometimes negative outflow rates.

The annual outflow was significantly correlated with the annual precipitation, with a coefficient of determination ($R^2$) of 0.47, i.e., 47% of the inter-annual outflow variability between 2000 and 2009 can be explained by local precipitation. Annual outflow peaked in 2002, concurrent with the highest precipitation (figure 3(a)). In contrast, both annual outflow and precipitation were small between 2007 and 2009. During the dry year of 2007, a low water level of the lake and high water level in the upstream Changjiang River led to a rapid reverse flow (i.e., negative outflow) from July to August (figure 2(c)). Clearly, both local precipitation and the upstream Changjiang River can modulate the lake’s water budget.

The estimation of the lake’s water volume change, a result of the recently developed bottom topography, made it possible to quantify the lake’s water budget. However, interpretation of the results requires caution. Because the outflow was not from an independent measurement but rather derived from the inflow and lake water’s volume change, the tight relationship between outflow and inflow (figures 2(a) and 3(b)) cannot be used as a measure of the model fidelity, but only indicates that the lake’s volume change is primarily driven by the inflow. In the extreme case when the lake’s volume is driven 100% by the inflow, the outflow should be identical to inflow (mass balance). After accounting for model uncertainties, the imperfect match between inflow and outflow suggests that, in addition to inflow primarily driven by precipitation, there are also other mechanisms affecting the lake’s water budget.

One such mechanism is the impoundment of world’s largest hydropower plant, the TGD (figure 1). When the TGD reservoir (upstream of Poyang Lake) began to store water in June 2003 (Zhao et al. 2010), a strong water level gradient was created, triggering a rapid lake–river outflow during July 2003 (figure 2(b)). Water level data collected at Hukou station (figure 1) showed a sharp decrease from 19.0 m to 15.1 m from 25 July to 16 August (figure 2(d), red crosses). The lake’s water volume also showed a rapid decrease during the same period (figure 2(d), green dots). The decreased volume from 25 July to 16 August was estimated to be $\sim 7865$ million m$^3$, corresponding to $\sim 78.6\%$ of the reported water volume of the TGD reservoir after its June 2003 impoundment (http://news.xinhuanet.com/newscenter/2003-06/10/content_913019.htm). The temporal lag between the impoundment (June) and volume change (July–August) appears to be a result of large distance ($\sim 800$ km) between the TGD and the lake, yet the impact on the lake’s water budget is apparent. Indeed, such an impact appears to have continued through the following years, resulting in negative outflow anomalies from August 2003 to December 2004. This effect can be clearly demonstrated through the runoff coefficient, defined as the ratio between runoff and precipitation (figure 3(a)).

The annual runoff coefficient of the lake’s drainage basin showed a minimum of 0.29 in 2004, about a 44% decrease from 2003 (figure 3(a)). This sharp decrease indicates that a significant amount of the precipitation during 2004 was used to compensate for the dramatic water loss of the tributaries in 2003 due to the TGD’s impoundment. From 2005 to 2009, the mean runoff coefficient ($0.39 \pm 0.04$) became statistically significantly (i.e., $>2$ standard deviations) smaller than that between 2000 and 2003 ($0.49 \pm 0.04$). In other words, the same amount of precipitation between 2005 and 2009 resulted in less surface runoff from the tributaries to the lake than between 2000 and 2003, suggesting the continued impact of the TGD’s impoundment.

4. Discussion: uncertainty estimates

Because both groundwater and evaporation are negligible as compared with the runoff to the lake, the accuracy of the estimated water outflow depends primarily on the accuracy of the lake’s water budget, which was estimated using MODIS-based inundation area and bottom topography. Comparison with higher resolution (30 m from HJ-CCD measurements) showed near-identical spatial distributions in the lake’s inundation area with <5% difference in the area estimates (Feng et al. 2011b). From simple algebra, the 150 m navigation uncertainty of MODIS (Wolfe et al. 2002) would lead to at most 1–2% error in the inundation estimates even when navigation errors over all pixels have the same sign (which is unlikely). Thus, such navigation-induced errors, assumed to be random in time, would result in only negligible effects on the inter-annual variability and long-term trend of the water budget estimates. On the other hand, the MODIS-based bottom topography was believed to have an uncertainty of $<0.5$ m (Feng et al. 2011a). A sensitivity test was performed to assess how this uncertainty might propagate to the water volume and budget estimates. Random values between $\sim 0.5$ and 0.5 m were added to the lake’s bottom topography at pixels whose 10 year standard deviations exceeded a pre-defined threshold. These locations represent where large errors may occur. The water volume and outflow rate derived from the noise-free topography and noise-added topography were compared. The mean ratios between the two results were $0.97 \pm 0.15$ for water volume and $0.99 \pm 0.04$ for outflow rate, suggesting that, although the uncertainty in the MODIS-derived bottom topography may lead to a small difference ($\sim 3\%$) in calculating the lake’s water volume, its impact on the rate calculation is indeed insignificant ($\sim 1\%$).

Ideally, the derived outflow rate should be validated against direct observations. Unfortunately, reliable outflow data never existed; this was actually the primary motivation of this work. However, other consistency checks were used to verify whether the results are reasonable. First, the nearly 1:1 relationship between the outflow and inflow during normal years suggests that, although modulated by Poyang Lake (manifested by its volume change), mass balance of the water was achieved in the Poyang Lake system. Second, some of the non-steady state dynamics of the water budget (both driven by natural and human forces) were clearly revealed in the time series. Specifically, the impoundment of the TGD in June 2003 resulted in a decreased water level of the downstream
Changjiang River, accelerating the lake–river water flow and leading to the observed outflow anomaly (figures 2(b) and 3(b)). In contrast, extensive rainfall occurred during April 2002 (TRMM data show 69% higher than the climatology), causing significant inflow anomaly. The disequilibrium of the inflow and outflow at that time (inflow > outflow) led to a rapid increase in the lake’s water volume, with its volume change rate 3.72 times higher than the monthly climatology. These results suggest the validity of the volume and budget estimates. Nevertheless, we expect to validate these MODIS-based estimates using independent assessment in the future (e.g., through analyzing satellite-based gravity data or other means).

5. Concluding remarks

Estimating the water volume of the dynamic Poyang Lake has been impossible in the past due to lack of bottom topographic data, which may have changed from year to year as a result of human activities (e.g., sand dredging). This information gap has been filled with MODIS observations and water level data using a novel approach (Feng et al 2011a, 2011b), which led to the water budget estimation in this study for Poyang Lake between 2000 and 2009. To our knowledge, this is the first time that a 10 year record of Poyang Lake’s water budget has been established. In addition to the documented seasonality and inter-annual variability of the water budget (primarily driven by local precipitation), the most significant finding is the apparent impact of the impoundment of the TGD on the lake’s water budget. The immediate effect is an unusually high lake–river outflow during summer 2003, followed by a statistically significant impact on the surface runoff to the lake in the following years.

Even though the initial justification for the TGD was largely for hydropower, the entire Changjiang River system downstream of the TGD, including many lakes and rivers that experience flood and drought as part of their annual ecological cycle, will have to be coordinated across many jurisdictions and managed collectively. Decision makers need to include integrated and larger scale information on the regional ecosystems and communities in subsequent development. For example, the local government of Jiangxi Province is planning to construct another dam in the north outlet of Poyang Lake (figure 1) in order to control the water outflow to the Changjiang River during the dry season (www.chinadaily.cn/usa/epaper/2011-08/04/content 201001054). We thank NASA/GSFC for providing MODIS and TRMM data and China Meteorological Data Sharing Service System for providing meteorological data. We are much indebted to the two anonymous reviewers who provided extensive and critical comments that helped improve this paper.

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