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Key Points:
- Poyang Lake (PYL) sedimentation undergoes a unique phase shift around the year of 2000
- PYL presents no deposition in flood season and more erosion in dry season
- Channel erosion is the main sediment source from PYL to Changjiang currently

Supporting Information:
- Supporting Information S1

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Decadal Sedimentation in China's Largest Freshwater Lake, Poyang Lake

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Abstract Lakes, as key recorders of sedimentation regime variations, have undergone dramatic erosion/deposition worldwide in response to global warming and increasing anthropogenic interference. Poyang Lake, China's largest freshwater lake, has not escaped these variations. Herein, we show that the sedimentation in Poyang Lake has likely undergone a unique phase shift from sediment sink (annually storing 421×10^4 t) during 1960–1999 to sediment source (yearly losing 782×10^4 t) during 2000–2012, with respect to the Changjiang (Yangtze) River. In comparison with sedimentation during 1960–1999, Poyang Lake sedimentation during the period 2000–2012 is characterized by no deposition during the flood season and enhanced erosion during the dry season. Furthermore, Poyang Lake's largest delta, the Ganjiang Delta, prograded at a rate of 32.7 m/a from 1983 to 1996, which increased to 52.8 m/a from 1996 to 2005 but dropped significantly to 1.7 m/a from 2005 to 2015. A sediment core collected in the shallow-water shoal of the central lake indicates a stable increase in sedimentation flux from 1960 to 2002, with a mean value of 0.27 g/(cm^2·a), followed by a decline in sedimentation flux after 2002. Our findings show that the tributary sediment input from the lake catchment dominated the sedimentation of Poyang Lake prior to 2000, when it was significantly larger than the sediment output to the Changjiang River. However, thereafter, the contribution of tributary sediment to the output dropped by 50%, and the rest has been provided by the lake itself. Namely, channels along Poyang Lake's waterway became the additional source of the lake's sediment output in the 2000s.z

1. Introduction

Lake basins are some of the most biologically productive systems and provide a vital habitat for a multitude of species, in particular a large amount of rare, threatened, and endangered species (Zedler & Kercher, 2005). However, lacustrine systems around the globe fluctuate strongly in response to rising temperature, changing precipitation and evaporation, and increasing anthropogenic pressure (Beeton, 2002). For instance, a majority of lakes on the Tibet Plateau, such as Lake Serling Co and Lake Nam Co, began to expand rapidly in the late 1990s due to snow or glacier melting and evaporation decreases (Ma et al., 2016; G. Zhang et al., 2015). The total Siberian lake area in the continuous permafrost region increased by 12% from 1973 to 1997–1998, primarily driven by enhanced regional climate warming (Smith et al., 2005). In the Lower Tuktoyaktuk Peninsula, northwestern Canada, lake area enlarged by 14% from 1979 to 1991, caused by a cumulative precipitation increase (Plug et al., 2008). Meanwhile, the total surface area of nine major lakes in arid regions of Central Asia decreased by almost 50% from 1975 to 2007, caused by agricultural water consumption, reservoir construction, and decreased precipitation (Bai et al., 2011). Water level reductions have been observed in 18 large lakes in China, located in the Yarlung Zangbu River basin, northern Inner-Mongolia and Xinjiang, and the Northeast Plain of China, due to intensified evaporation, reduced precipitation, increased water consumption, and exacerbated soil erosion (Wang, Gong, et al., 2013). The surface areas of the Böön Tsagan and Orog lakes shrunk by 14% and 51%, respectively, from 1974 to 2013 because of decreasing precipitation and increasing evaporation (Szumińska, 2016). These changes are likely to affect lake sedimentation in the anthropogenic era, which, however, are not well documented, especially with regard to China's largest freshwater lake, Poyang Lake.

Poyang Lake, located in the middle stream of the Changjiang River, provides a habitat for approximately 44 million people (D. W. Zhang et al., 2015) as well as over 200 species of migratory waterfowl, including the special Siberian white crane (*Grus leucogeranus*; Jiao, 2009). Despite its vital socioeconomic and ecological significance, the depositional system of Poyang Lake has become more fragile since the beginning of the

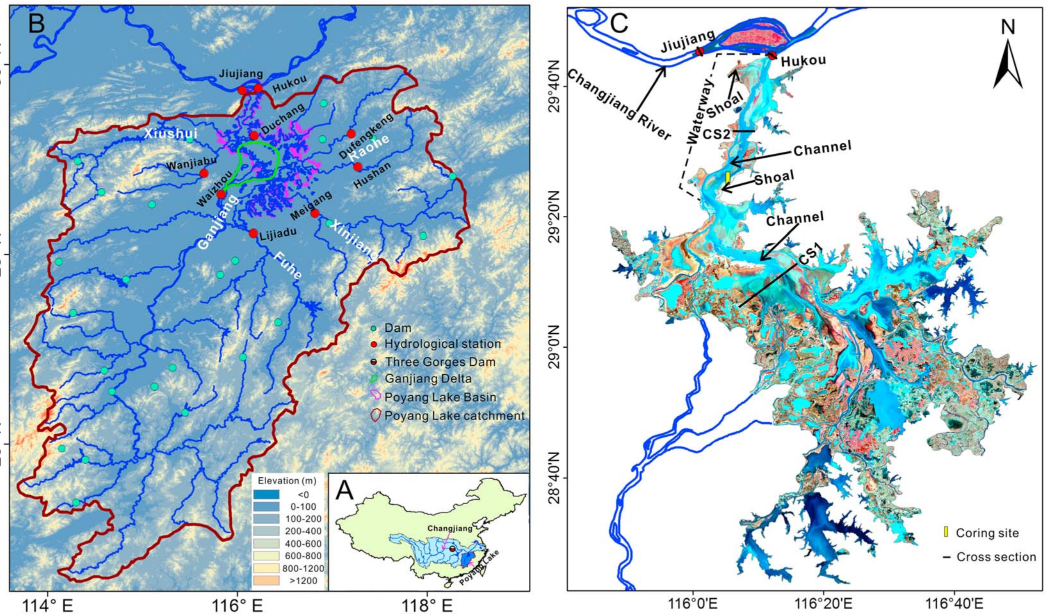

Figure 1. Study area of Poyang Lake, with (a) Poyang Lake's location relative to the Changjiang River, the Three Gorges Dam, and the East China Sea; (b) Poyang Lake Catchment; (c) Poyang Lake basin, where the cross sections CS1 and CS2 refer to the cross section shown in Figure 6 and the cross section Jiujiang and Hukou refer to the cross section shown in Figure 7.

21st century, with its surface area reduced by 226 km^2 between 1991 and 2010 (Q. Zhang, Li et al., 2014), while exposed wetland area in October increased by 1,078 km^2 from 1955 to 2012 (Mei et al., 2016). Meanwhile, sediment exchanges between Poyang Lake and the Changjiang has experienced dramatic variations. The Changjiang River no longer supplied sediment to Poyang Lake after 2003 but, instead, received significant amounts from the lake (Gao et al., 2014). Lai, Shankman, et al. (2014) indicated that extensive sand mining has deepened the Poyang Lake-Changjiang watercourse and increased the total sediment load outflow from Poyang Lake to the Changjiang. Mei et al. (2015) showed that riverbed erosion along the Changjiang River has increased the lake-river hydraulic gradient, causing the lake to discharge more sediment to the river. Furthermore, the sedimentation of Poyang Lake is also affected by the sediment input to the lake. Gao et al. (2015) showed that the sediment load entering Poyang Lake has undergone a dramatic decline since 1990 as the sediment interception by upstream dams has continued to increase. Wu et al. (2015) observed that because of afforestation and reservoir construction within the catchment, the bathymetry of the main body of Poyang Lake experienced much slower deposition during 1998–2010 in comparison with 1980–1998. Despite ongoing efforts to evaluate Poyang Lake's dramatic sediment variations as well as their possible causes, little study has been focused on Poyang Lake's sedimentation in response to its sediment budget variation. A quantitative understanding of Poyang Lake's sedimentation could greatly enrich lacustrine science research, which is an essential reference not only for the management of Poyang Lake itself but also for the management of other lake systems that are facing similar threats.

Therefore, the main goals of this study are (1) to explore Poyang Lake's sedimentation from 1960 to 2012 at seasonal and yearly scales, (2) to reveal the shoreline evolution of the lake delta and the sedimentation rate of the lake shoal, and (3) to detect the possible factors affecting the sedimentation of Poyang Lake.

2. Materials and Methods

2.1. Poyang Lake and Its Hydrological System

Poyang Lake (28°22′–29°45′N, 115°47′–116°45′E; Figure 1a), is China's largest freshwater lake, spanning 170 km from north to south and 74 km at its widest section from east to west (Lai, Huang, et al., 2014). The lake can be further divided into a northern and southern section. While the southern region is characterized by a relatively broad and shallow morphology, the northern area is narrow and long with a natural water

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Table 1
Remote Sensing Images and Corresponding Water Level at the Duchang Station

Type	Time	Resolution (m)	Band	Water level (m)
Landsat4-MSS	28 November 1983	80	4	12.78
Landsat5-TM	23 November 1996	30	7	12.88
Landsat5-TM	31 October 2005	30	7	12.39
Landsat7-ETM+	19 October 2015	30	8	12.58

channel connecting the lake to the Changjiang River (Figure 1b). The average bathymetry decreases from the south (>16 m) to the north (12 m; Wu & Liu, 2015). The hydrological regime of the lake catchment is dominated by the balance between the inflow from the upstream tributaries and the output to the Changjiang River.

The Poyang Lake catchment receives water and sediment from five major inland tributaries, namely, Xiushui, Ganjiang, Fuhe, Xinjiang, and Raohe (Figure 1b). These tributaries contribute 85.4% of the total water discharge and 87.2% of the sediment load entering the lake (Gao et al., 2014). The Ganjiang River, the largest contributing tributary, accounts for 62.8% and 67.9% of the total water and sediment discharge input, respectively (Q. Zhang, Sun et al., 2011). It also creates the largest lacustrine delta, the Ganjiang Delta, within the Poyang Lake basin (Ma & Wei, 2002).

Poyang Lake naturally connects to the Changjiang River at Hukou at the northernmost point of the lake and interacts with the river through a deep waterway (Figure 1c). Water discharge from the five tributaries reaches its maximum during April to June and declines rapidly from July to September. However, unlike the other tributaries, the flood season of Changjiang River ranges from July to September (Mei et al., 2018). As a consequence, Poyang Lake exhibits two distinct hydrologic processes at the outlet: discharging water/sediment into Changjiang River from April to June and occasionally receiving water/sediment from the river from July to September (Mei et al., 2015).

2.2. Data Sources and Contributions

Data used in this study mainly include the following: (1) monthly water discharge and suspended sediment discharges at Hukou, Wanjiabu, Waizhou, Lijiadu, Meigang, Hushan, and Dufengkeng from 1960 to 2012 were acquired from the Changjiang Water Resources Commission (CWRC, www.cjw.gov.cn). These data were used to estimate the net water and sediment budgets of Poyang Lake. (2) Geomorphic features of Hukou, Jiujiang, and Poyang Lake basin, specifically their cross-section morphologies from 1980 to 2011, which were used to evaluate the long-term bathymetric evolution of the Poyang Lake shoal-channel and intersection zone of Poyang Lake and the Changjiang River. The cross sections at Hukou and Jiujiang were measured with an echo sounder and GPS-RTK, where the specific number and location of sampling points were set according to the section width. The cross-section morphologies were acquired from the CWRC. The cross-section morphologies at two locations in Poyang Lake were extracted based on the bathymetric maps of 1980, 1998, and 2010 at the scale of 1:10,000 from CWRC and Wu et al. (2015), which were first digitized through ArcGIS and then gridded into 30 × 30 m resolution using the Kriging method (Wu et al., 2015). All the hydrological and geomorphological measurements strictly follow the national industry standards. (3) Remote sensing images of the Ganjiang Delta on 28 November 1983, 23 November 1996, 31 October 2005, and 19 October 2015, when the water level at the Duchang hydrometric station corresponded to a similar water level of 12.5 m (relative to Wusong datum), were obtained from the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center (https://eros.usgs.gov), with a spatial resolution ranging from 30 to 80 m (Table 1). In view of the small differences among the water levels in the four Landsat images, we assume that the one-dimensional shoreline variation magnitude can document erosion or accretion of Ganjiang Delta. In addition, a field survey was carried out over Poyang Lake on 2–8 January 2015, with a sediment core collected on 3 January 2015 at 29°25′59″N, 116°5′16″E (located at the lake shoal, a relatively shallow area along the waterway; Figure 1c). The sediment core sample was further analyzed in the laboratory to determine the lake shoal's long-term sedimentary features (supporting information). All the stations mentioned above are illustrated in Figure 1.

2.3. Methods

2.3.1. ^{210}Pb Activities and Sedimentation Fluxes

Radiometric chronologies for sediment cores can provide reliable estimates of the sediment accumulation rate and deposition process, which are of vital importance for inferring past environmental conditions. Examining the activity of ^{210}Pb in sediment deposits is the most common technique for dating old sediments. It was used in this study to trace the sedimentation of Poyang Lake.

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The samples were oven-dried and sealed in a plastic box (70-mm diameter×35-mm height) for at least 20 days to ensure equilibrium between ^{226}Ra and its daughter nuclides. The ^{210}Pb activity analysis was conducted with an HPGe γ-ray detector (Canberra Be3830, 777 lead shield) with a 35% counting efficiency. The ^{210}Pb activity was determined from the γ-ray peak at 46.5 keV (4.25%), and the activity of ^{226}Ra was determined at 295.2 keV (19.3%). The activity of ^{214}Pb was determined at 351.9 keV (37.6%) and that of ^{214}Bi was determined at 609.3 keV (46.1%) and 1,120.3 keV (15%). Excess ^{210}Pb ($^{210}Pb_{ex}$) was calculated on the basis of the distribution of total ^{210}Pb by subtracting the supported ^{210}Pb (i.e., ^{226}Ra). An efficiency calibration of the detector systems was conducted by LabSOCS (Bronson, 2003). All data reported in the present work were corrected for radioactive decay to the times of sampling.

The sedimentation fluxes in core samples were calculated according to their $^{210}Pb_{ex}$ activities with the Constant Flux model, which assumes that the sedimentation rate is variable throughout the core while the $^{210}Pb_{ex}$ flux to the core surface is constant (Appleby & Oldfield, 1978, 1983; Goldberg, 1963; McCall et al., 1984).

2.3.2. Shoreline Extraction

The geomorphology of a delta can be delineated by its shoreline: the physical interface of land and water (Dolan et al., 1980). Estimating the temporal changes in the shape and position of a shoreline is an effective approach to detect the delta's dynamic geomorphological conditions (Davidson et al., 2010; Dellepiane et al., 2004; Maiti & Bhattacharya, 2009; Szmytkiewicz et al., 2000).

Shoreline data are generally extracted based on an adaptive threshold of a water detection index. In this study, the threshold was determined from single-band gray-scale using a histogram. Specifically, pixels with values higher than the threshold were coded as land pixels, while pixels with values lower than the threshold were coded as water pixels. The delta's shoreline can thus be generated by achieving a good separation between water and land regions. Boundary variations of the delta associated with accretion and erosion processes were calculated through the Digital Shoreline Analysis System (DSAS) in a geographic information system (GIS), which computes differences between shoreline positions based on the elapsed time and linear distance (Thieler et al., 2009).

All Landsat 7 scenes collected since 31 May 2003 have wedge-shaped scan-to-scan gaps, resulting in a data loss of approximately 22%. Filling in the gaps for these images in this study was carried out by the approach of Scaramuzza et al. (2004).

2.3.3. Sediment budget of Poyang Lake

Sediment storage within Poyang Lake is primarily determined by the total sediment input from upstream tributaries to the lake, the sediment release from the lake to the Changjiang River, and sediment loss through sand mining, which was computed by the following equation:

$$S = I_1 + I_2 + I_3 + I_4 + I_5 - O - M \tag{1}$$

where I_1, I_2, I_3, I_4, and I_5 represent the sediment input (t) from the five major tributaries of Poyang Lake (Xiushui, Ganjiang, Fuhe, Xinjiang, and Raohe Rivers, respectively); O indicates sediment output to the Changjiang River through Hukou (t); and M is sediment loss due to sand mining over the Poyang Lake basin (t). It needs to mention that there is also sediment input from the rest of the tributaries of Poyang Lake to the lake basin except the above five major tributaries. In view of their relatively small contribution rate to the total sediment entering the lake (12.8%; Gao et al., 2014) and shortage of long-term measurements, sediment input from these tributaries to the Poyang Lake are not considered in our study. The flow direction through Hukou is mainly from Poyang Lake to the Changjiang River, with approximately 14 days of inverse directed flows occurring approximately 2–3 times per year (Cai & Ji, 2009), which is around 7% of the sediment output and has a limited effect on the net sediment output.

2.3.4. Sediment Source Lifetime Estimation

When the tributary sediment input to Poyang Lake is less than the lake's sediment output to the Changjiang River, the lake itself provides sediment to the Changjiang River in order to maintain the sediment balance. Thus, a new sediment source in addition to the upstream tributaries appears.

The lifetime of a sediment source is defined by the length of time that it can contribute sediment. Channels along the waterway only provide sediment to the Changjiang River when the lakebed is higher than the riverbed under the force of a discharge gradient (the location of channels along the waterway is shown in

Figure 1c). The length of time over which the channels can provide sediment to the Changjiang River was calculated as follows:

$$T_c = H/E_r \tag{2}$$

where H is the elevation difference between the lakebed (channel) and the riverbed (Jiujiang; m) and E_r is the erosion rate (m/a). Note that the calculations in this study related to Poyang Lake's future sedimentation were based on the current high sediment loss rate, which is probably an extreme case since the sediment consumption rate in coming decades is likely to slow down gradually.

3. Results

3.1. Annual Variations in the Sediment Budget of Poyang Lake

Poyang Lake experienced only slight variations in annual water discharge input and output from 1960–2012, and as a result, there was no significant variation in the water budget (Figures 2a–2c). On the other hand, large changes were detected in the sediment budget of Poyang Lake. On the decadal scale, annual mean sediment input increased slightly, from 1,352 × 10^4 t/a during the 1960s to 1,532 × 10^4 t/a during the 1970s and 1,424 × 10^4 t/a during the 1980s; thereafter, it considerably dropped to 1,032 × 10^4 t/a during the 1990s and further to 603 × 10^4 t/a after 2000 (Figure 2f). Decadal average sediment output from the lake to the Changjiang River stabilized at approximately 1,000 × 10^4 t/a during the 1960s to the 1980s, but declined to 628 × 10^4 t/a during the 1990s, followed by a sudden increase to 1,200 × 10^4 t/a after 2000 (Figure 2f). Moreover, sand mining at a rate of 236 × 10^6 m^3/a during 2001–2008 (de Leeuw et al., 2010) further increased the lake's sediment loss and exacerbated the negative balance in the sediment budget of the lake (Figure 2d). Broader trends for the whole observation period show that annual sediment input to Poyang Lake exhibited a statistically significant decreasing trend ($p < 0.01$) over 1960–2012, while sediment output to the Changjiang River showed almost no change despite a significant rise occurring after 2000 (Figure 2d). This led to a statistically observable decrease ($p < 0.01$) in the sediment budget of Poyang Lake (Figure 2e). In summary, the total tributary sediment input was larger than the output to the Changjiang River during 1960–1999. In 2000, however, the sediment output surpassed the contemporaneous input for the first time, with the maximum yearly sediment loss of 1528 × 10^4 t/a occurring in 2003 (Figure 2e).

3.2. Seasonal Variations in the Sediment Budget of Poyang Lake

During the flood season, from May to October, both sediment input from the five tributaries and the sediment budget of Poyang Lake exhibited a statistically significant decrease ($p < 0.01$) from 1960 to 2012 (Figures 2g–2h). Specifically, average annual sediment input and output in flood season were 904 × 10^4 t and 123 × 10^4 t, respectively, during 1960–1999 (Figure 2i), indicating sediment deposition of over 781 × 10^4 t/a (Figure 2i). Since 2000, the sediment budget of Poyang Lake during the flood season was almost balanced with both sediment input and output equaling approximately 400 × 10^4 t (Figure 2i).

As for the dry season from November to April of the next year, the lake received 432 × 10^4 t of sediment and contributed 791 × 10^4 t to the Changjiang River during 1960–1999 annually (Figure 2l), which resulted in a yearly loss of 360 × 10^4 t (Figure 2l). During 2000–2012, the sediment loss became much more dramatic when the lake annually received 183 × 10^4 t but provided 820 × 10^4 t of sediment (Figure 2l), losing over 600 × 10^4 t yearly (Figure 2l). Accordingly, the seasonal sedimentation dynamics over Poyang Lake since 2000 are characterized by approximately no deposition during the flood season and strong erosion during the dry season.

3.3. Shoreline Variation of Poyang Lake's Delta

The sediment budget variability of Poyang Lake is partly reflected by the shoreline evolution of its delta. Located in the southwestern region of Poyang Lake, the Ganjiang Delta covers an area of 1,600 km^2, accounting for 70% of Poyang Lake's depositional area. The delta can be further divided into three zones, namely, upper delta plain, lower delta plain, and subaqueous delta (Figure 3).

The delta generally has a fan shape with a dendritic structure (Figure 4). Over time, it has become more protruded with crenulated margins. Specifically, from 1983 to 1996, the shoreline of the Ganjiang Delta prograded approximately 425 m lakeward on average, suggesting an annual mean shoreline migration rate of 32.7 m/a (Figure 4e, D-D′) and a total progradation area of 14.4 km^2. Progradation continued through 2005

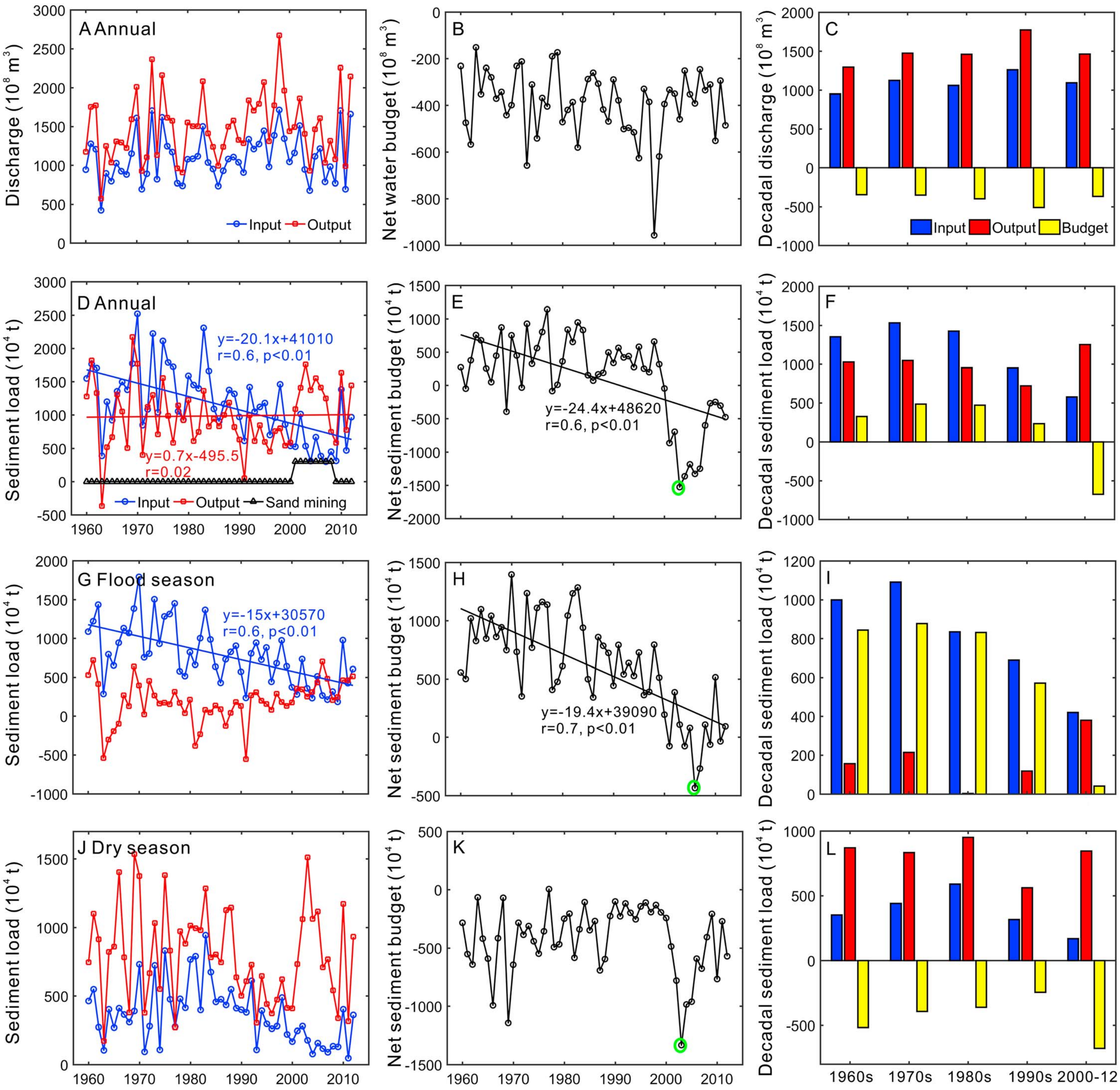

Figure 2. Temporal discharge and sediment budget for Poyang Lake from 1960 to 2012. (a) Annual discharge input and output of Poyang Lake. (b) Annual net water budget. (c) Decadal discharge input, output, and budget. (d) Annual sediment input, output, and sand loss due to sand mining in Poyang Lake, with the blue line showing a statistically significant trend and the red line showing an insignificant trend. (e) Annual net sediment budget, with the black line showing a statistically significant trend and the green circle indicating maximum sediment loss. (f) Decadal sediment input, output, and budget. (g) Sediment input and output of Poyang Lake during the flood season, with the blue line showing a statistically significant trend. (h) Net sediment budget during flood season, with the black line showing a statistically significant trend and the green circle indicating maximum sediment loss. (i) Decadal sediment input, output and budget during the flood season. (j) Sediment input and output of Poyang Lake during the dry season. (k) Net sediment budget during the dry season, with the green circle indicating maximum sediment loss. (l) Decadal sediment input, output, and budget during the dry season.

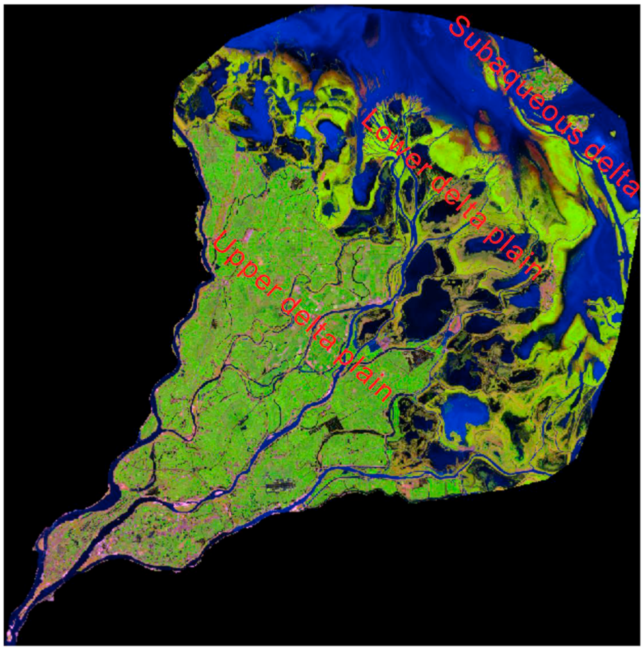

Figure 3. Components of the Ganjiang Delta.

and mainly occurred in the northern area, with a maximum distance of 1.5 km lakeward (Figure 4e, D-D′). On average, the progradation rate of the Ganjiang delta shoreline during 1996–2005 was 52.6 m/a with a total propagation area of 16.2 km^2. From 2005 to 2015, the shoreline change was no longer uniform along the delta front, since both progradation and retrogradation were detected in different regions. Specifically, the southern area exhibited observable progradation, with a maximum progradation of 951.7 m (Figure 4e, D-D′), while the northern area exhibited substantial shrinking, with a maximum retrogradation of 899.9 m (Figure 4e, A-A′). As a whole, the Ganjiang Delta's shoreline prograded at an average rate of 1.7 m/a from 2005 to 2015, showing a total propagation area of 1.6 km^2, which is much lower than the previous two periods. Furthermore, the once unified delta became fragmented in approximately 2005 and further deteriorated in 2015 when part of the delta became sediment starved (Figures 4c and 4d).

3.4. Sedimentation Rate of the Poyang Lake Shoal

The sedimentary dynamics of the Poyang Lake shoal can be evaluated via the core sample (the location of shoal is shown in Figure 1c). From top to bottom, the core column was divided into 13 layers (1 cm per layer), with median diameter, sorting coefficient, and skewness of sediment in the core ranging from 0.02–0.18 mm, 1.16–2.90, and −0.16–0.67, respectively (Figures 5a–5c). Specifically, the top six layers consist mainly of coarse sand, the middle layers from 7 to 12 are characterized by fine silt, while the bottom layer is dominated by sand again (Figures 5d–5f). According to the $^{210}Pb_{ex}$ activities, the core records a sedimentation history of approximately 50 years. From 1960 to 2013, the sedimentation flux was classified into two groups, with the highest flux occurring in approximately 2003. The sedimentation flux increased stably from 0.11 g/(cm^2·a) in 1960 to 0.35 g/(cm^2·a) in 2003, in good agreement with the net sediment storage as well as with the findings of Xiang et al. (2002). Thereafter, however, the sedimentation flux gradually declined to 0.32 g/(cm^2·a) in 2013 (Figure 5h).

3.5. Cross-Sectional Variation of Poyang Lake

The cross-sectional profiles in Poyang Lake during 1980–2010 suggest that the lake exhibited distinct bathymetric variations in different areas. In the middle of the lake, deposition between 1980 and 1998 caused the cross-sectional elevation to increase by 1.31 m annually (Figure 6a). This high deposition was followed by slight erosion during 1998–2010.The most observable erosion occurred in the channel zone located between 5.00 to 13.00 km from the west bank. The channel along the waterway that connects the lake basin and lake outlet experienced relatively slight deposition during 1980–1998, when the mean cross-sectional elevation increased by 0.52 m (Figure 6b). Thereafter, however, dramatic down cutting caused the bed elevation to decrease by 6.1 m yearly from 1998 to 2010. A point that is 3.40 km away from the west bank shows up to 12.64 m of erosion.

4. Discussion

Lake basins are sensitive to terrestrial recharge, lake discharge, and their own sedimentary environment (Downing et al., 2006; Yang & Lu, 2014). The Poyang Lake basin exhibited long-term deposition during 1960–1999, but in the past decade, it has experienced continuous erosion. Here the factors that could potentially influence such a phase shift are analyzed further.

4.1. Factors Impacting the Sediment Budget in Poyang Lake

Since the 1970s, sediment input to Poyang Lake showed a dramatic decrease that can be explained by extensive dam construction in the lake catchment. By 2001, approximately 9,600 reservoirs had been constructed within the Poyang Lake catchment, with a total storage capacity of 2.79 × 10^{10} m^3 (Liu et al., 2009). A great majority of the large dams were built in the 1960s for flood control, hydroelectric power, and irrigation

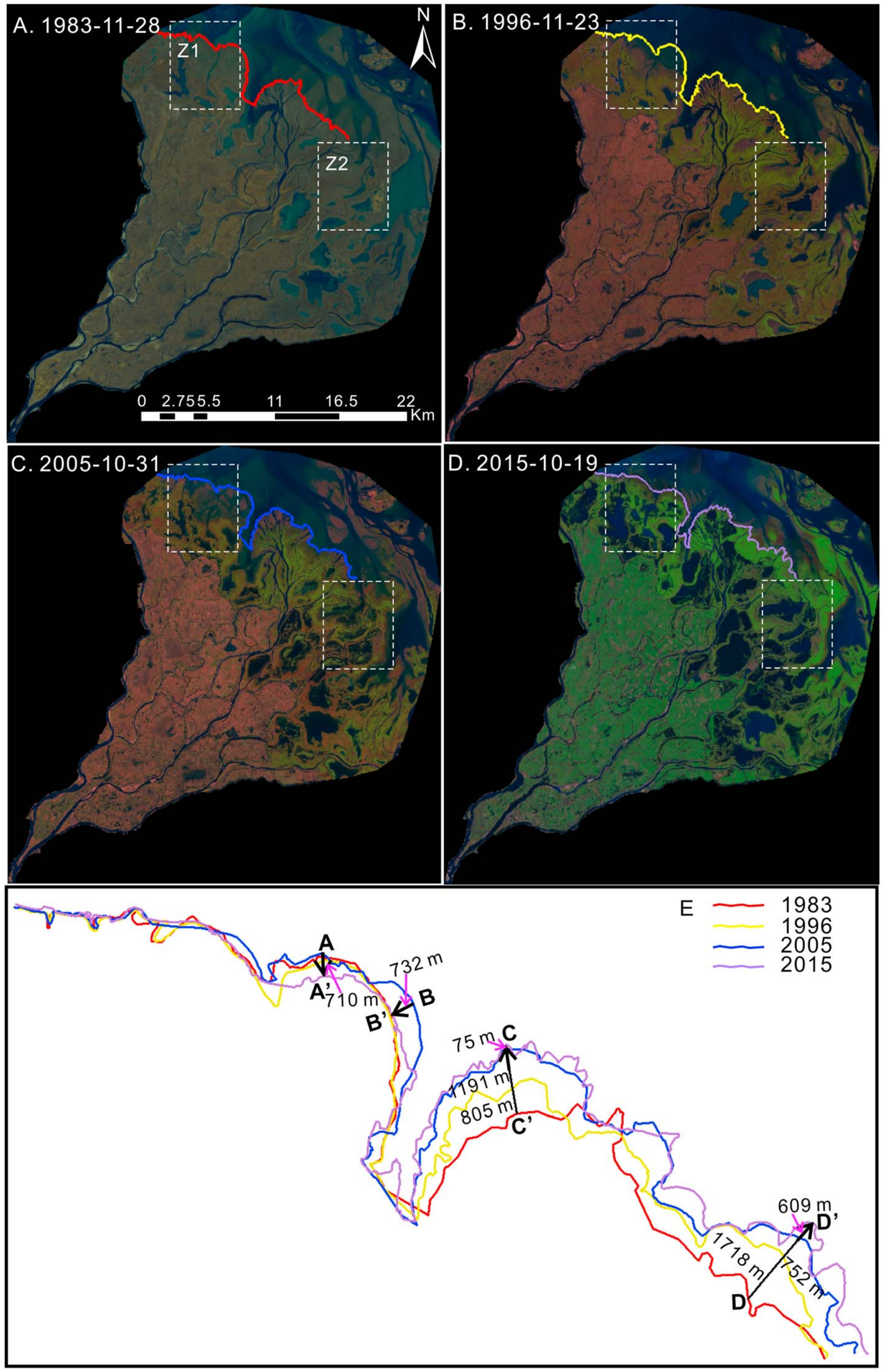

Figure 4. Shoreline evolution of the Ganjiang Delta: (a) 28 November 1983, (b) 23 November 1996, (c) 31 October 2005, (d) 19 October 2015, and (e) temporal shoreline series during 1983–2015. The dotted boxes indicate areas with obvious fragmentation.

(Table 2), which trapped a large amount of sediment in their reservoirs and reduced the sediment input to Poyang Lake (Q. Zhang, Sun et al., 2011). For instance, following the construction of the Wan'an Reservoir upstream, with a storage capacity of 2.22×10^9 m^3, the sediment load delivered by Ganjiang River to Poyang Lake decreased by around 85×10^6 t/a during 2000–2005 compared with the non-Wan'an case during 1980–1989 (Q. Zhang, Li et al., 2011).

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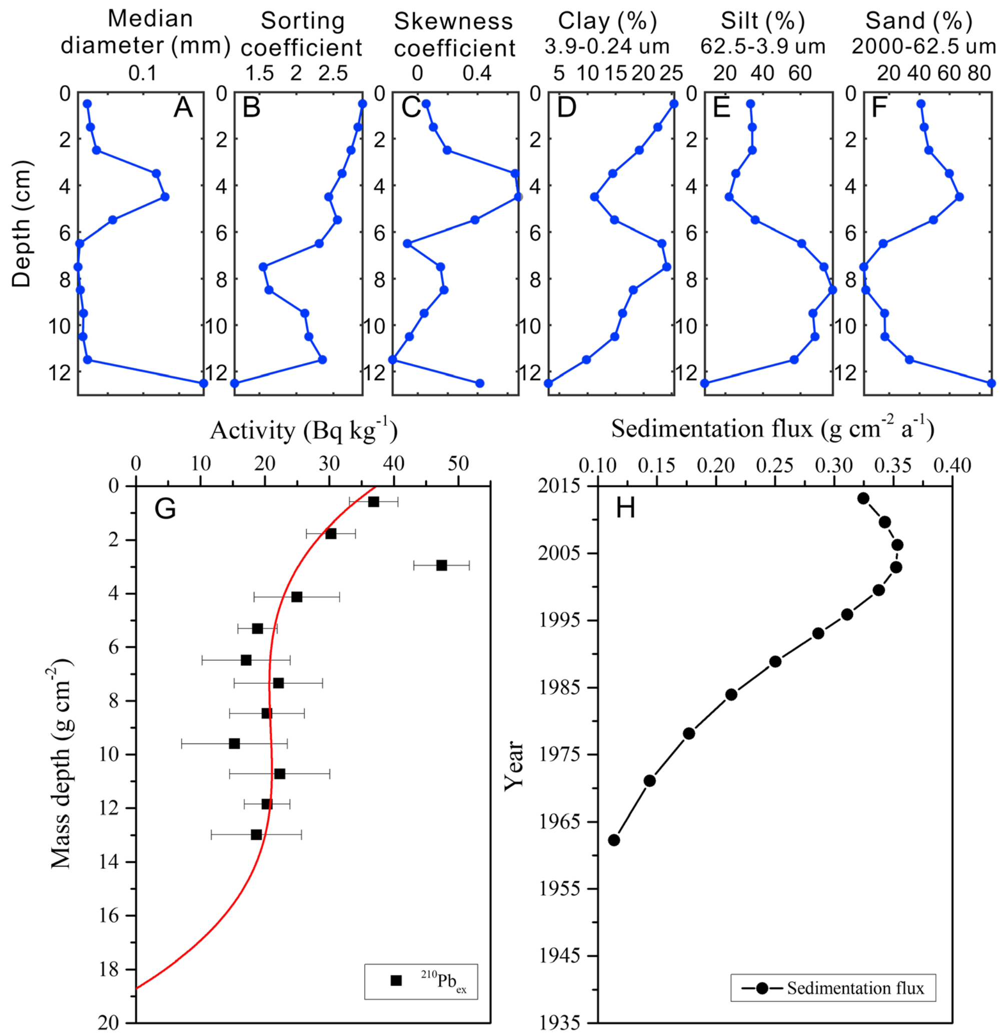

Figure 5. Vertical distributions of (a) median diameter, (b) sorting coefficient, (c) skewness coefficient, (d) clay content, (e) silt content, (f) sand content, (g) excessive ^{210}Pb activity, and (h) yearly sedimentation flux.

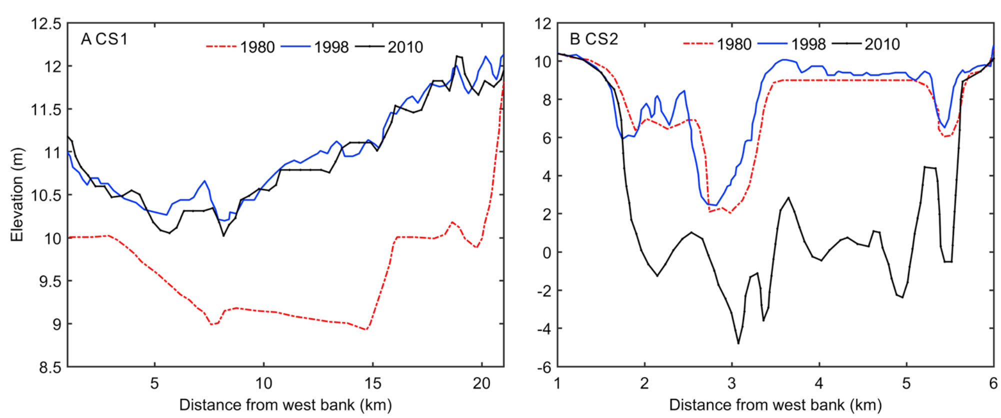

Figure 6. Cross-section evolution of Poyang Lake (source: Wu et al., 2015); the location of the cross section is shown in Figure 1c.

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Table 2
Description of the Major Dams in the Poyang Lake Catchment

No.	Reservoir	River	Lat.	Long.	Purpose	Finish year	Capacity (10^8 m^3)
1	Feijiantan	Ganjiang	114.12	27.92	FC,I,H	1960	1.01
2	Daduan	Xiushui	114.57	28.65	FC,I,N	1990	1.15
3	Shangyoujiang	Ganjiang	115.10	28.52	FC,I,H	1960	1.35
4	Ziyunshan	Lakeside	115.82	27.78	FC,I,H	1960	1.2
5	Panqiao	Lakeside	115.98	27.93	FC,I,H	1960	0.74
6	Jiangkou	Ganjiang	114.83	27.73	FC,I,WS	1964	3.46
7	Communism	Raohe	117.43	29.22	FC,I,H	1960	0.83
8	Dongjin	Xiushui	114.32	28.98	FC,I,H	1995	5.61
9	Zhelin	Xiushui	115.50	29.21	FC,I,H,N	1975	50.17
10	Jiepai	Xinjiang	116.97	28.32	N,FC,H	1998	0.51
11	Da'ao	Xinjiang	117.96	28.19	FC,H,I	2000	2.76
12	Qiyi	Xinjiang	118.27	28.82	I,FC,H	1960	2.49
13	Junmin	Lakeside	116.91	29.59	I,FC,H	1972	1.89
14	Bintian	Raohe	116.90	29.21	I,FC,WS	1960	1.15
15	Hongmen	Fuhe	116.43	27.28	H,FC,I	1969	5.42
16	Shangyoujiang	Ganjiang	114.40	25.83	H,FC,N	1957	7.21
17	Youluomen	Ganjiang	114.30	25.38	H,FC,WS	1981	0.86
18	Longtan	Ganjiang	114.15	25.95	H,FC	1996	1.06
19	Tuanjie	Ganjiang	116.06	26.91	H,FC,I	1971	1.02
20	Changgang	Ganjiang	115.45	26.33	H,FC,I	1970	2.51
21	Wan'an	Ganjiang	114.68	26.55	FC,I,H	1990	11.16
22	Laoyingpan	Ganjiang	115.13	26.60	FC,I,H	1983	0.77
23	Sheshang	Ganjiang	114.27	27.38	FC,I,H	1973	1.43
24	Baiyunshan	Ganjiang	115.32	26.80	FC,I,H	1969	0.9
25	Nanche	Ganjiang	114.60	26.77	FC,I,H	1999	1.23

Note. FC is flood control structure, WS is water supply, H is hydroelectric, I is irrigation, and N is navigation.

Meanwhile, serious riverbed incision along the Changjiang River (Dai & Liu, 2013; Wang, Sheng, et al., 2013; Lai, Jiang, et al., 2014) combined with the relatively stable lakebed elevation at Poyang Lake outlet increased the lake-river elevation difference from 5.06 m in 2007 to 6.09 m in 2011 (Figures 7a and 7b). Thus, the hydraulic gradient between Poyang Lake and the Changjiang River (the ratio of elevation difference to distance) increased by over 20% (Mei et al., 2015). Because of the enlarged hydraulic gradient between Poyang Lake and the Changjiang River, the mean flow velocity at Hukou increased by over 30%, which forced the lake to discharge more sediment to the Changjiang River. Moreover, the enlarged river-lake hydraulic gradient significantly weakened the so-called *blocking effect* that constrains the drainage of the lake to the Changjiang River in flood season and as a consequence, further increased the sediment discharge ability (Q. Zhang, Li et al., 2012). Specifically, Poyang Lake discharged 255×10^4 t more sediment yearly into the Changjiang River during the flood season in the 2000s (Figure 2e). Decreased sediment input from upstream tributaries, combined with increased sediment discharge into the Changjiang River, shifted the lake's depositional system from sediment sink to sediment source (Figures 2d–2f).

In addition, large scale sand mining was carried out along the waterway of Poyang Lake during 2001–2008 at a rate of 236×10^6 m^3/a (de Leeuw et al., 2010), approximately 625×10^4 t per year. Such a sediment loss is approximately 50% of the contemporary sediment output at Hukou, which further increased the sediment budget imbalance of the lake. Furthermore, sand mining can generate transient high suspended sediment concentrations by mobilizing sediments into the lake discharge, which is likely to increase the lake's sediment output to the Changjiang River even further.

4.2. Sediment Source Detection for the Poyang Lake Basin Since 2000

Prior to 2000, sediment input from the upstream tributaries was significantly larger than the sediment output through Hukou, and as a consequence, considerable amounts of sediment were deposited in Poyang Lake (Figure 8a). Since 2000, Poyang Lake's discharge rate sharply increased, which combined with a noticeable decrease in tributary sediment input, forced the lake to provide a great amount of that sediment itself.

10.1029/2018GC007439

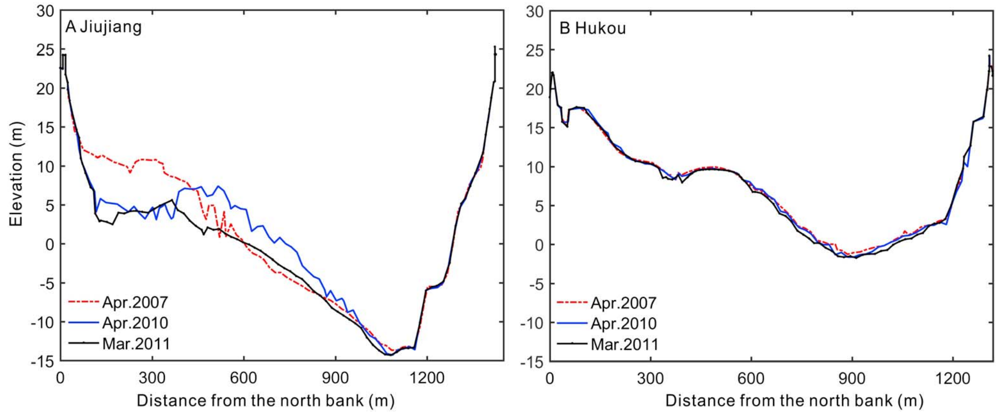

Figure 7. Cross-section evolution of (a) Jiujiang in the Changjiang River and (b) Hukou at the Poyang Lake outlet; the location of the cross section is shown in Figure 1c.

Poyang Lake's shoal is currently in an accumulation state with a positive sedimentation rate (Figure 8b), while the Ganjiang Delta exhibited slight overall deposition from 2005 to 2015 (Figure 8b), which exclude the shoal and delta as potential main sediment contributors to the Changjiang River. The lake channel, then, is the only possible dominant sediment source. Indeed, channels along the waterway experienced severe erosion in the 2000s under lake current forcing (Figure 8b). Because Poyang Lake lost most of its sediment during the dry season (Figures 2i and 2l), we can infer that the waterway's channel mainly provided additional sediment in the dry season, when the lake shoal emerged from the water.

However, channel erosion cannot go on forever. The lowest elevation of the channel along the waterway in 2010 was −4.8 m, indicating a decrease of 9.23 m in comparison with 1998 (Figure 6b) and an erosion rate of 0.71 m/a. The elevation difference between the lowest points of the lakebed (CS2; Figure 6b) and the riverbed (Jiujiang; Figure 7a) was 10.18 m in 2010. Assuming that the waterway channels in the lake will continue to erode at the current rate, their deepest area will be at the same elevation as the Changjiang riverbed in approximately 13 years. In that case, the lake channel would likely cease offering sediment to the Changjiang River. Thereafter, new sediment sources will be needed to support the high sediment output. As Figure 8c indicates, the northern Ganjiang Delta, the lake shoal, and the channel in the southern lake would be the potential contributors of sediment to the Changjiang River in the future.

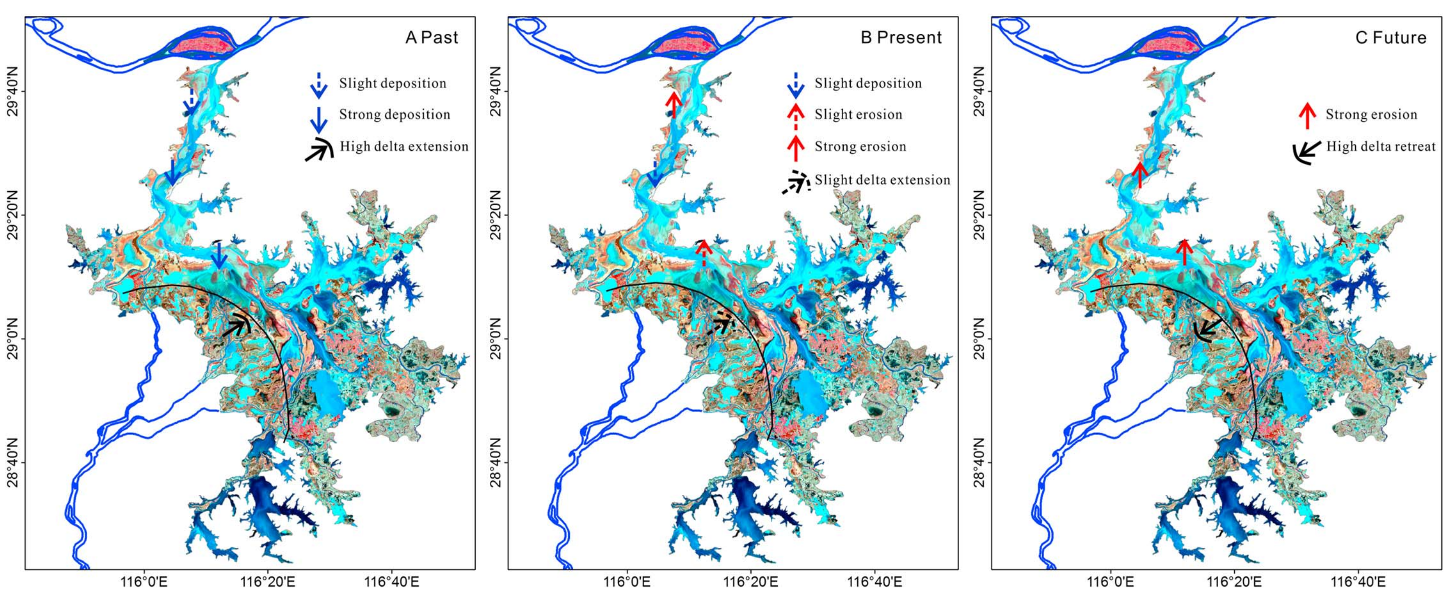

Figure 8. Dynamic sedimentation of Poyang Lake: (a) past, (b) present, and (c) future.

4.3. The Potential Relationship Between the Three Gorges Dam and Poyang Lake's Sedimentation

As indicated above, Poyang Lake underwent the maximum sediment loss in 2003 (Figure 2d), when the operation of the Three Gorges Dam (TGD) began along the Changjiang River. However, there is still a need for further research on the relationship between the TGD impacts and Poyang Lake's sedimentation. Yang et al. (2007) attributed the riverbed erosion along the entire reach from the TGD to the estuarine delta front, a distance of approximately 1,600 km, to the TGD-induced sediment load decrease. Dai et al. (2014) indicated that the TGD construction generated channel down-cutting throughout the river course, approximately 1,000 km below the dam site. Recently, Lai et al. (2017) suggested that the effect of the TGD on riverbed incision would probably stop at Chenglingji, approximately 400 km from the dam site. In view of the great diversity in the reports of river channel erosion extent below the TGD, whether the TGD-induced fluvial sediment load reduction is responsible for the riverbed erosion around Hukou remains an open question, and the TGD's relationship to Poyang Lake's sedimentation still needs further monitoring and analysis.

5. Conclusions

Poyang Lake, as the largest freshwater lake in China, is of vital ecological and economic significance. In this study, decadal sedimentation of Poyang Lake was thoroughly assessed. The main conclusions obtained are as follows:

1. Once storing 421×10^4 t of sediment annually (1960–1999), Poyang Lake itself currently (2000–2012) provides 596×10^4 t sediment yearly to the Changjiang River. Furthermore, the lake exhibited a distinct seasonal sedimentation pattern of no deposition during the flood season and more erosion during the dry season during the 2000s.
2. The Ganjiang Delta entered a period of slower expansion during 2005–2015, with its shoreline progradation rate decreased from the 52.6 m/a during 1996–2005 to the current 1.7 m/a. The sedimentation flux in the shallow-water shoal area indicated a stable declining trend from 0.35 g/(cm^2·a) in 2003 to 0.32 g/(cm^2·a) in 2013.
3. The current erosion of Poyang Lake was caused by the coupled effects of decreasing tributary sediment input from the lake catchment and increasing sediment output from the lake to the Changjiang River. If the current high sediment loss rate of 596×10^4 t/a continues, the lake delta and lake shoal would expect to serve as new sediment sources in approximately 13 years. This would likely cause severe erosion and could gradually destroy the entire lacustrine depositional system.

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