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Assessing Hydrological and Sedimentation Effects from Bottom Topography Change in a Complex River–Lake System of Poyang Lake, China

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Abstract: In recent years, a dramatic decline in Poyang Lake water levels and a shrinking water surface have raised concerns about water security and the wetland ecosystem. Changes in bottom topography due to sand mining activities in the lake was supposed to be one of the influencing factors of these changes. In response to this issue, the current study analyzed the change of lake bottom topography from observed digital elevation model (DEM) data, and quantitatively assessed the spatial and temporal responses of lake hydrology based on the framework of the neural network and the sediment effect was examined afterward. Results showed a total volume of 11.54×10^8 m^3/year (about 0.96×10^8 m^3/year or 1.58×10^8 t/year sediment) in net change of lake bottom topography in recent years, among which 97% was directly exported by commercial sand mining. During the study period, 2000–2011, intensive sand mining extended the central part of Poyang Lake and widened and deepened the outflow channel of the northern lake. This great change of lake bottom topography caused an average annual increase of 182.74 m^3/s of lake outflow and a decline of 0.23 m–0.61 m in water levels across the lake. However, lake water levels are not consistent and show remarkable spatial and seasonal differences. The effects of changes in lake bottom topography on lake hydrological processes continue to grow as sand mining activities in the lake continue. More research on the environmental impacts is required for sustainable management of the lake ecosystem.

Keywords: lake bottom topography; sand mining; hydrological effect; sedimentation; neural network model; Poyang Lake

1. Introduction

The properties of hydrology and water quality are of great importance for maintaining the stability of a river or lake ecosystem. For natural lakes, the bottom topography of the lake basin is the result of long-term natural evolution and human activities. Changes in lake bottom topography not only directly alter lake hydrological and hydrodynamic conditions such as lake water level, flow rate and lake volume [1,2], but also affect the lake water environment, wetland ecology, flood and drought events and even shipping security [3,4]. In response to the exacerbated global climate change and human activities, many lakes throughout the world have undergone great changes in their size, morphology and eco-environment during the past decades, and as a result processes of hydrology and sediment in the lakes have dramatically changed [5–8].

The Poyang Lake is the largest freshwater lake in China. It is one of only two lakes that still naturally connect to the Yangtze River. The lake wetlands are registered as internationally important habitats for a large number of rare and endangered wintering migrant birds, such as the white crane and Oriental white stork. Unfortunately, Poyang Lake has experienced seasonal, extreme low water levels that have persisted since 2000 and the lake surface has remarkably shrunk, which seriously threats the local water supply and aquatic habitats [9–12]. Many studies are concerned with the causes of this phenomenon, including seasonal hydrological droughts exacerbated by the Three Gorges Dam (TGD) operation (e.g., [13–16]) and the declining regional precipitation in the Yangtze River basin [17,18]. Recently, one of the most important influencing factors considered was the change of bottom topography due to sand mining activities in the lake [2]. It was reported that since the set-up of a regulation forbidding sand mining in the mainstream of the Yangtze River in 2000, numerous dredges have rushed into the Poyang Lake. Based on the statistical number of sand mining vessels from limited remote sensing images and the Ship Affairs Department of Jiujiang City, Jiang et al. [19] pointed out that the magnitude of sand mining in Poyang Lake was about 2154.3 Mt with a total mining area of 260.4 km^2 during the period 2000–2010. However, it should be noted that this calculation may have large errors since these vessels are changing at any time of the year and many of them are trying to escape from management of local government. Generally, accurate estimation of the magnitude of sand mining in Poyang Lake is quite a challenge. In addition, subsequent hydrological effects from sand mining may be inconsistent and show great spatial and temporal differences in this large lake.

Changes in lake morphology is widely prevalent all over the world, which will cause remarkable impacts on lake hydrological, sedimentation and eco-environmental processes. Also, sand mining activities in rivers, lakes and coastal areas are quite common. However, few studies have considered the combined effects of sand mining on local hydrology and sediment changes under different time scales [20]. Up to now, detailed changes of lake bottom topography and its response to sand mining activities was not revealed for Poyang Lake. How alterations in lake bottom topography effect hydrological and sedimentation processes and their spatiotemporal differences is still an open question. Furthermore, a potential developing trend of these effects, which are particularly important for the future scientific management of lake water resources and ecological protection, remains unknown in this lake region. In response to these scientific issues, the current study evaluates the effects of changes in bottom topography in Poyang Lake on hydrological and sediment processes from 2000–2011. Specifically, we aim to investigate: (1) the change of lake bottom topography and its response under extensive sand mining activities in recent years; (2) the effect of lake bottom topography changes on spatial and temporal variations of lake water levels and outflow; and (3) the effect of lake bottom topography changes on lake sedimentation processes and budget.

2. Material and Methods

2.1. Study Area

Poyang Lake (28°40′–29°46′ N, 115°49′–116°46′ E) is located on the south bank of the middle-to-lower reaches of Yangtze River (Figure 1a). The lake catchment covers an area of 162,225 km^2. Climatically, the lake catchment belongs to a subtropical monsoon climate zone with an average annual air temperature and precipitation of 17.5 °C and 1680 mm, respectively [21]. The lake receives water mainly from five tributaries in the catchment: Xiushui, Ganjiang, Fuhe, Xinjiang and Raohe, and discharges into the Yangtze River from a narrow outlet in the north (Figure 1b).

The Poyang Lake is a typical shallow water-carrying lake. The average depth of the lake is about 8 m and maximum depth can reach 29 m during flood seasons. As an open lake that connects to the Yangtze River, hydrological characteristics of Poyang Lake are affected by both the catchment inflows and the Yangtze water level or discharge [22]. Due to the blocking effect of the Yangtze River, the peak water level of the lake normally lags behind the maximum catchment inflow (Figure 1c,d). According to large seasonal water level fluctuations, the lake surface can expand to 3000 km^2 in the summer flood season but shrink to less than 1000 km^2 in the winter dry season, exposing extensive floodplains and wetland areas [17].

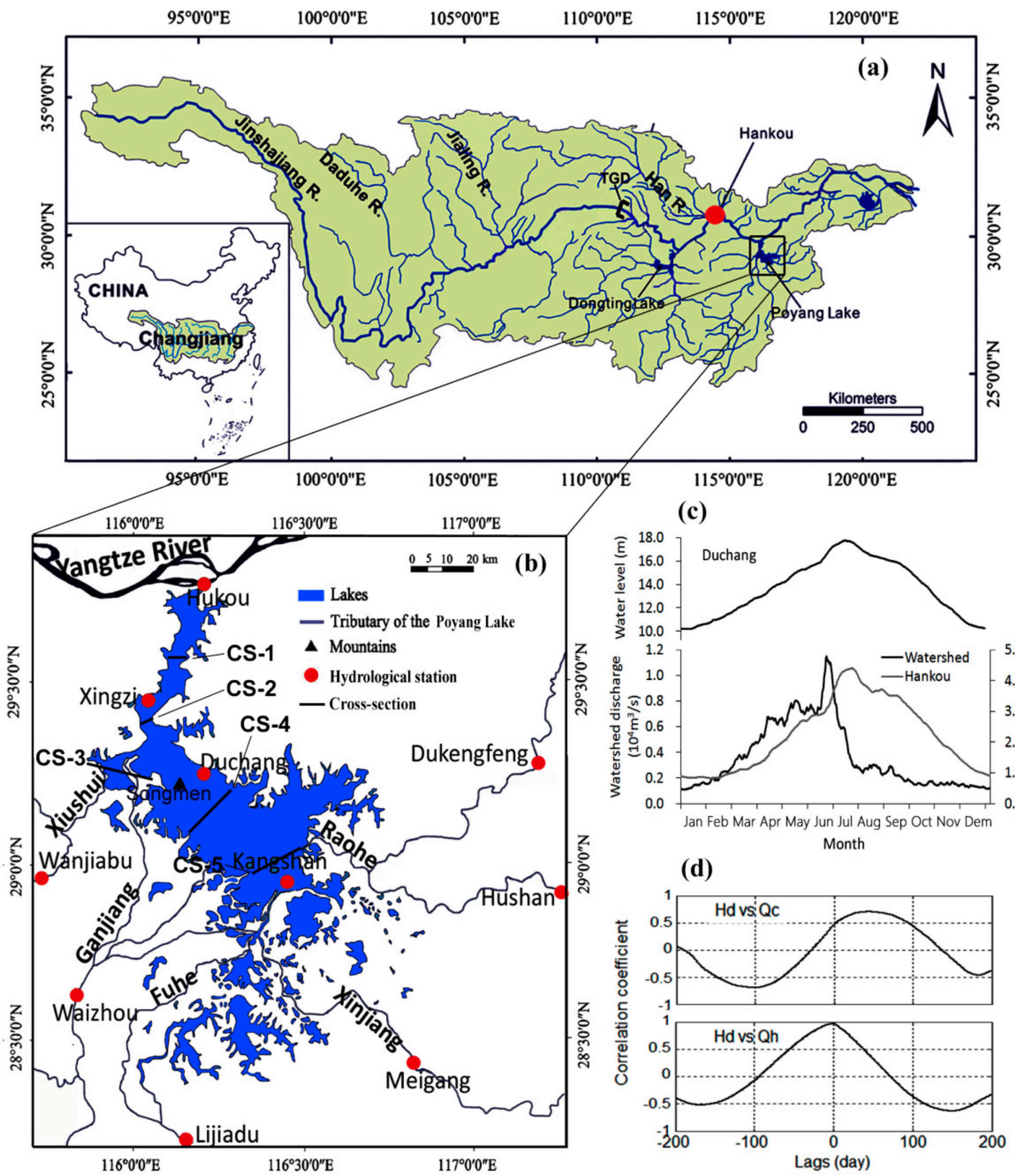

Figure 1. (**a**) Location of Poyang Lake; (**b**) Poyang Lake and its main inflow rivers with hydrological gauging marked; (**c**) intra-annual variation of catchment inflow, Yangtze flow (Hankou) and corresponding lake water level; (**d**) cross-correlation coefficients between lake water level (Hd—lake water level at Duchang station) and catchment inflow (Qc) as well as Yangtze flow (Qh—river discharge at Hankou station), respectively.

2.2. Available Data

Observed daily water level data at the four gauging stations of Hukou, Xingzi, Duchang and Kangshan were collected to represent spatial differences of Poyang Lake's water level (Figure 1b). Observed daily water level at Hankou station, which is situated 284 km upstream of Poyang Lake was used to reflect the Yangtze River effect (Figure 1a). In this study, lake inflow data are collected from the six gauging stations that are located at the lower reaches of the major tributaries (Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui) (Figure 1b). Discharge at Hukou measures the outflow series of the lake. The total drainage area of these six gauging stations is 127,229 km^2, which is about 78.4% of the whole catchment area of the Poyang Lake basin. All the above daily hydrological data were obtained from the Changjiang Water Resources Commission, and the data quality was well controlled before delivery. Time series of these data are available for the period 1980–2011.

Mean yearly-suspended sediment content (SSC) data of the lake inflow and outflow between 2000 and 2011 were collected from the Chinese river sediment bulletin. Other data for the period 1980–1999 were obtained from published literature [19,23].

Two scenarios of the digital elevation model (DEM) of the lake bed during 1998 and 2010, with a resolution of 1:10,000, were collected from Jiangxi Hydrological Bureau.

2.3. Model Simulation and Strategy

Accurate simulation of lake water level is paramount for quantifying the effect of morphology changes on lake hydrology. Previously, in order to analyze the effects of catchment inflow and Yangtze River discharge on lake water level variations, Li et al. [24,25] constructed two models: a physically-based mathematical model using the MIKE 21 and a back-propagation neural network (BPNN) model. By comparing the model performance, they concluded that both modeling approaches obtain very high accuracies for lake water level simulation. Although the 2D hydrodynamic model is physically based, it is very cumbersome due to extensive data and computational requirements. By contrast, the BPNN model has the advantages of a simple structure, high computing efficiency and great accuracy, making it suitable for long-term hydrological simulations.

In consideration of the successful application of the BPNN approach on lake and river stage investigations, and its potential ability and advantage for long-term prediction, we also applied the BPNN approach in this study. As shown in Figure 2, a standard three-layer feed-forward BPNN with a hyperbolic tangent sigmoid transfer function in the hidden layer, and a linear transfer function in the output layer was employed. For this arrangement, the input layer receives incoming information, which is processed by hidden layers. The target or output layer contains the simulation results. For the input variables, we not only considered the time lags of daily discharge rates for inflow rivers and Yangtze River to the lake as pointed out by Li et al. [25], but also incorporated the hydrological conditions of 20 days earlier that would have an impact on lake water level and outflow variations. On this basis, we constructed only one BPNN model for water level simulation of the four hydrological stations, not four models separately. Since our study focused on the effects from the lake bottom topography change, the influence of other factors needed to be excluded or minimized. In order to exclude the impacts of Yangtze riverbed downcutting due to Three Gorges Dam regulation, we used the observed water level at Hankou station but not river discharge as the input variable. Finally, we got 147 input variables (21 daily water level series at Hankou and 126 daily discharge series from the six gauging stations of inflow rivers) and four output variables (daily water level series of the four gauging stations in the lake) to construct the architecture of the three-layer BPNN model for lake water level simulation. Meanwhile, due to different mechanisms of lake–river interactions from the lake water level, we constructed another BPNN model for lake outflow, but used the same input variables as the lake water level BPNN model.

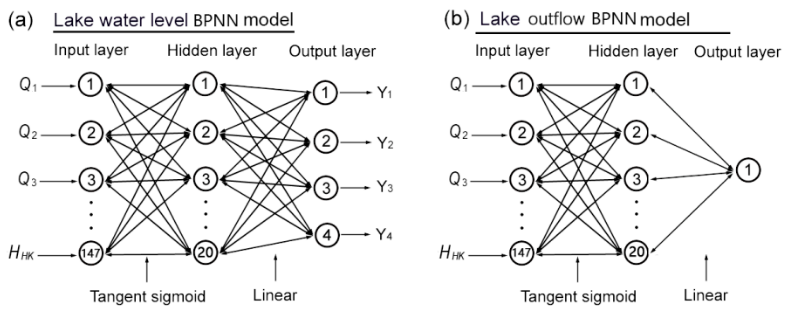

Figure 2. Structure of the two back-propagation neural network (BPNN) models. In the figure, Q means the daily discharge series from the six gauging stations of inflow rivers; H means the daily water level at Hankou station and Y means simulated lake water level at the four hydro-stations.

During the past decades, the artificial neural network technique has been widely used for forecasting river flow and stage with great accuracy (e.g., [25–29]). Details about model principles, structures and characteristics can be found in the aforementioned published papers. Due to the difficulty of hydrological data acquisition and the inconsistency of time series of different data, the study period was limited to 2000–2011. In the constructed two models, the gradient descent method was used as the training algorithm, and the early stopping method was applied to avoid over-fitting problems. By using the trial and error method, 20 hidden layers, a learning rate of 0.05 and a momentum coefficient of 0.98 were finally optimized. However, most of the parameters in the BPNN models are not sensitive to the modeling results of lake water level and outflow, except for the number of hidden layers.

In order to maximize the effect of bottom topography changes on lake water level and outflow, we selected the data series during 1987–1999 as the model training period according to relatively small changes of lake volume and land reclamation of Poyang Lake [5], and 1980–1986 as the model validation period. Table 1 summarizes the performance of the two BPNN models during the training and validation periods, from which the determination coefficient (R^2) and mean relative error (MRE) were used as the evaluation criteria. Results from Table 1 suggest a satisfactory accuracy of model performance for both lake water level and outflow simulations.

Table 1. Performance of BPNN models during the training and validation periods.

Item	Station	Model Training (1987–1999)		Model Validation (1980–1986)	
		R^2	MRE (%)	R^2	MRE (%)
Water level	Hukou	0.998	−0.02	0.983	0.10
	Xingzi	0.997	0.10	0.982	0.21
	Duchang	0.997	0.11	0.977	0.31
	Kangshan	0.964	0.08	0.956	0.60
Outflow	Hukou	0.965	0.89	0.890	1.31

Since the established BPNN models were based on the average lake bottom topography during 1980–1999, by application of these models, we can reconstruct the lake water level and outflow series during 2000–2011 according to observed catchment inflow and the Yangtze water level under the same lake basin condition. With this result, the hydrological effect of lake bottom topography changes can be further explored according to the differences between the predicted and observed lake water level and outflow series during 2000–2011.

2.4. Sediment Balance of Poyang Lake

Sediment balance of Poyang Lake was calculated according to the following equation:

$$S_{f\text{-}in} - S_{f\text{-}out} - S_{export} = \Delta S \quad (1)$$

where $S_{f\text{-}in}$ is the total sediment inflow from the catchment and can be calculated by catchment inflow ($Q_{f\text{-}in}$) multiplying the average inflow suspended sediment load ($SSC_{f\text{-}in}$); $S_{f\text{-}out}$ is the total sediment outflow and can be calculated by lake outflow ($Q_{f\text{-}out}$) multiplying the average suspended sediment load at Hukou ($SSC_{f\text{-}out}$):

$$S_{f\text{-}in} = Q_{f\text{-}in} \times SSC_{f\text{-}in} \quad (2)$$

$$S_{f\text{-}out} = Q_{f\text{-}out} \times SSC_{f\text{-}out} \quad (3)$$

In addition, S_{export} in Equation (1) is the sand mining export from the lake and ΔS is the total change of sediment in the lake.

In the above sediment balance equation, bedload was not considered due to the very small proportion of bedload that was involved in the sedimentation processes of Poyang Lake [30]. As the only outlet of the lake, the $S_{f\text{-}out}$ components in the equation actually reflect the total sand flux that include the sand flux from the lake to the Yangtze River and the sand flux from the Yangtze River to the lake.

In Equation (1), ΔS can be further calculated as:

$$\Delta S = \Delta V \times \rho_{sand} \quad (4)$$

ΔV is the change volume of lake bottom topography according to two scenarios of DEM data in 1998 and 2010; ρ_{sand} is sand bulk density and was set to 1.65 t/m^3 [19].

Based on the above equations, the total amount of sediment export (sand mining) from the lake can be calculated as:

$$S_{export} = Q_{f\text{-}in} \times SSC_{f\text{-}in} - Q_{f\text{-}out} \times SSC_{f\text{-}out} - \Delta V \times \rho_{sand} \quad (5)$$

3. Results

3.1. Changes of Lake Basin Topography

By overlying the two scenarios of the DEM of Poyang Lake, the change of bottom topography can be calculated during the period 1998–2010 (Figure 3). Spatial analysis shows that there was a total volume of 11.54 × 10^8 m^3 lake bottom topography change in the past decade. Generally, it can be seen from Figure 3 that natural sand deposition mainly occurred at the front zone of the Gangjiang delta. In most parts of the center and northeastern lake, the sediment can reach the balance on scouring and siltation. Sand mining activities have extended from the northern channel into the central lake near Duchang station and even into some channels of major tributary rivers (such as the Gangjiang River) where a remarkable decrease in lake bottom elevation was observed. Especially, in the north part of the lake, there is a significant scouring zone along the main waterway from Duchang to Hukou (Figure 3c). An average of >6 m scouring of the lake bottom topography can be observed at those areas.

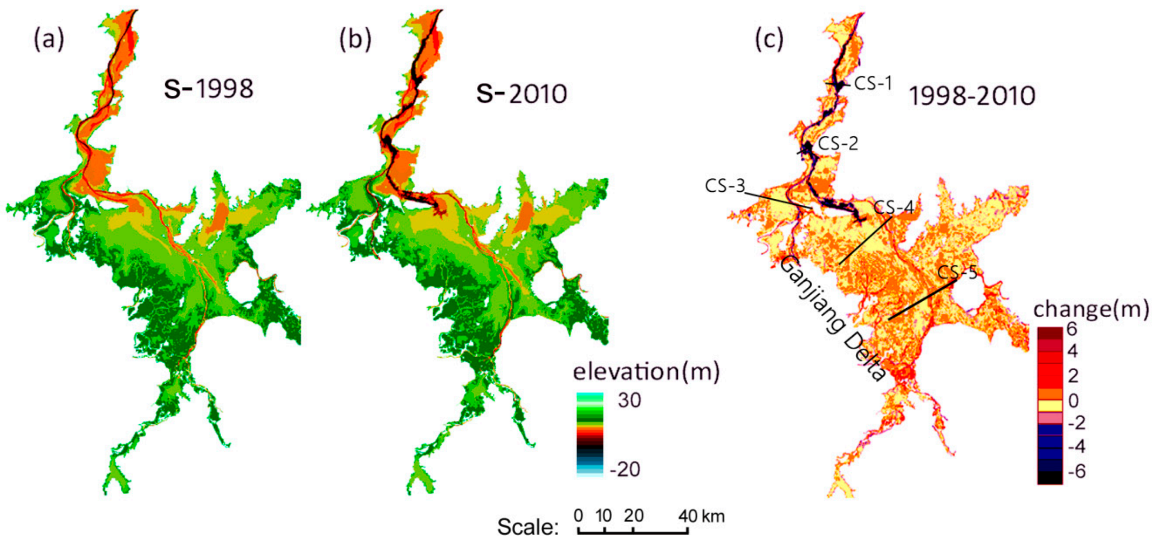

Figure 3. Two scenarios of bottom topography digital elevation models (DEMs) of Poyang Lake in (**a**) 1998 and (**b**) 2010; and (**c**) relative changes between 1998 and 2010.

Figure 4 presents the profile changes at five cross-sections from 1998 to 2010 in Poyang Lake. CS-1 and CS-2 are the profiles along the waterway to Hukou in the north part of the lake, which show a dramatic decline of channel bed elevation and enlargement of the cross-sectional area. The decrease of channel bed elevation at CS-1 and CS-2 was approximately 10 m and 6 m, and the increase of channel width was approximately 2.4 km and 1 km, respectively. It is obvious that according to the process of intensive sand mining activities in the lake, the profiles of some channels were very reshaped with most of the places having been eroded and some points deposited. CS-3 also indicates a riverbed decline of >2 m in the north branch of the Ganjiang River. All these indicate a strong response of lake bottom topography change to the intensive sand mining activities in the lake. However, the change of profiles at CS-4 and CS-5 located in the center and south parts of the lake was not obvious, and in even some places where lake bottom topography increased due to natural deposition.

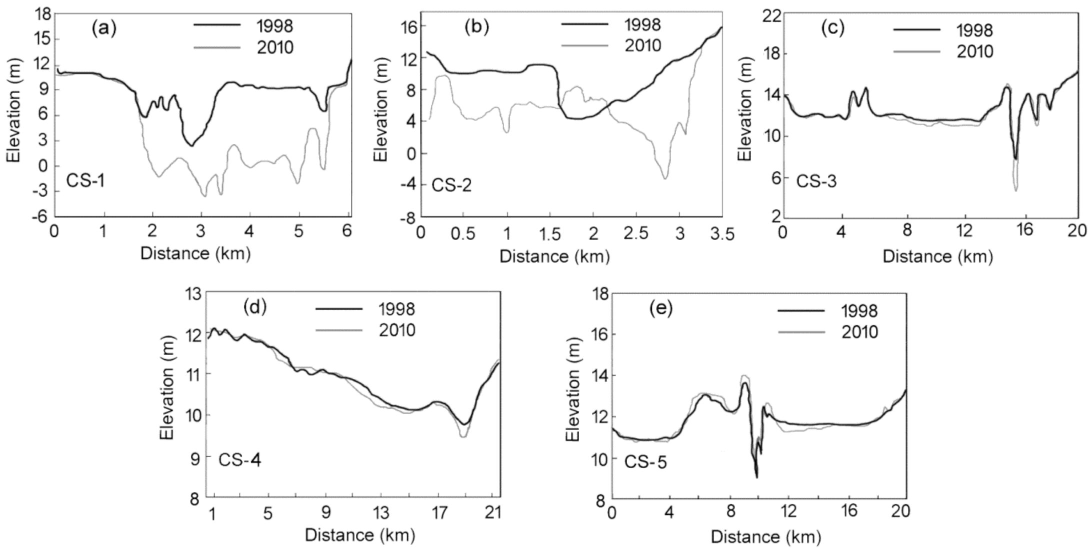

Figure 4. Profile changes at the five cross-sections in Poyang Lake.

3.2. *Effect on Lake Water Level*

Simulated results of lake water level were compared with observations at the four hydro-stations (Figure 5). In the figure, the simulated water level indicates the reconstructed lake water level during 2000–2011 according to observed catchment inflow and Yangtze water level under the average lake basin condition during 1980–1999. Results demonstrate a common decrease in water level across the lake due to the change of lake bottom topography, which was especially significant at Xingzi and Duchang stations, but slight at Hukou and Kangshan stations. The general decline of lake water level also shows notable seasonal differences, with a maximum in winter, followed by spring, autumn and summer. Statistical results show that the average decline of lake water level was about 0.87 m, 0.70 m and 0.37 m for Duchang, Xingzi and Hukou stations, respectively, in the winter season (Table 2). Yet for Kangshan station, the decline during the winter season was smaller than during the summer and autumn seasons. During the summer season when the lake water level was relatively high, spatial differences of the decline of the four hydro-stations were relatively small, with an average decline between 0.36 m to 0.42 m. On an annual basis, Duchang showed the biggest average decline of 0.61 m of lake water level, followed by 0.50 m for Xingzi, 0.34 m for Hukou and 0.23 for Kangshan.

Table 2. Average changes of seasonal and annual lake level and outflow.

Item	Spring	Summer	Autumn	Winter	Annual
Hukou (m)	−0.33	−0.36	−0.30	−0.37	−0.34
Xingzi (m)	−0.55	−0.39	−0.38	−0.70	−0.50
Duchang (m)	−0.59	−0.42	−0.55	−0.87	−0.61
Kangshan (m)	−0.11	−0.36	−0.29	−0.15	−0.23
Outflow (m^3/s)	+134.95 (2.4%)*	+250.65 (4.3%)	+156.34 (4.4%)	+190.89 (7.9%)	+182.74 (4.2%)

Note: "−" denotes decline of lake level; "+" denotes increase of lake outflow; "*" denotes the percentage to the observed outflow during 2000–2011.

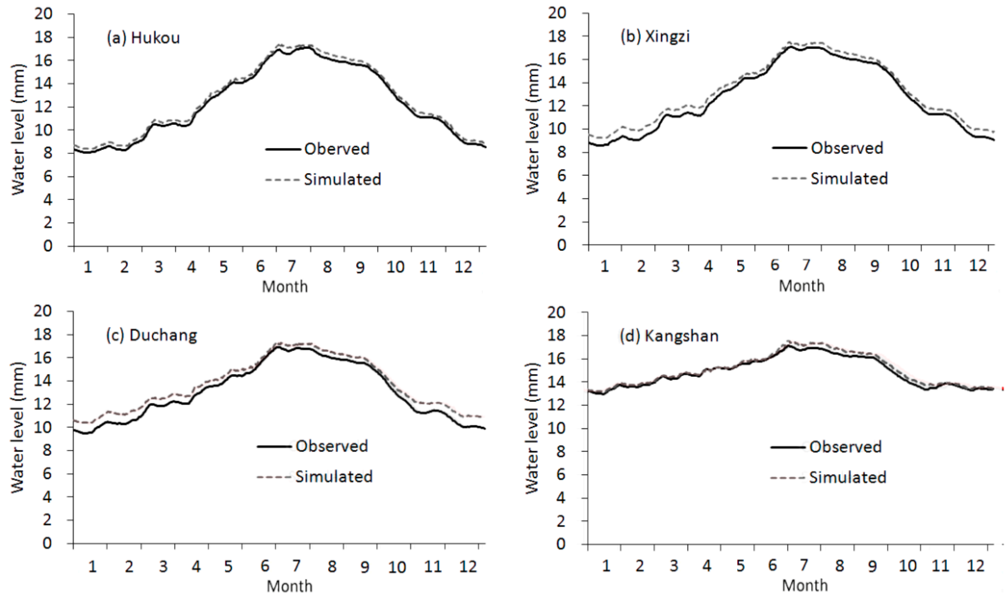

Figure 5. Comparison of observed and simulated lake water level during 2000–2011.

Figure 6 further shows the variation and linear trends of lake water level changes during 2000–2011 according to the changes of lake bottom topography. From the figure, a significant increasing trend ($p < 0.05$) of lake water level decline can be observed for Duchang station. The fitted linear regression function ($y = -0.1x + 0.08$) indicates a ~1.0 m/10 years decline of lake water level at this place. During the study period, the maximum decrease of lake water level occurred in 2011, and the value was about 1.31 m. Although a significant increasing trend ($p < 0.05$) of lake water level decline can also be observed at Xingzi station (the fitted linear regression function is $y = -0.04x - 0.21$), the variation features show two different stages. Before 2006, the decline of lake water level showed an obvious increasing trend, while small difference was observed after that. However, the decline of lake water level at Duchange station was still increasing after 2006. This feature of annual lake water level variation is highly related to the movement of sand mining area in the lake and will be discussed later in Section 4 (Discussion). The decline of lake water level shows a slight increasing trend at Kangshan station. However, almost no trend can be observed for Hukou station.

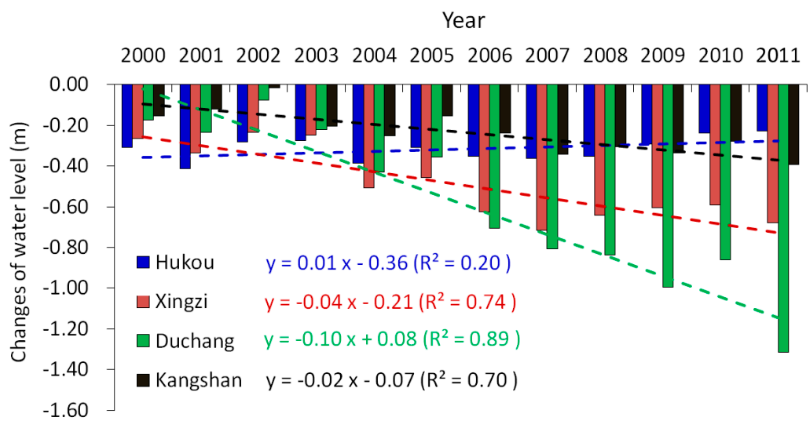

Figure 6. Variation and linear trends of annual water level changes during 2000–2011.

3.3. *Effect on Lake Outflow*

Figure 7 shows the changes of averaged lake outflow due to the change of lake bottom topography during the period 2000–2011. Same as the example in Figure 5, the simulated outflow indicates the reconstructed lake outflow during 2000–2011 according to observed catchment inflow and Yangtze water level under the average lake basin condition during 1980–1999. The change in the figure means the difference between the simulated lake outflow and observed lake outflow, which reflects the effect from lake bottom topography change. From the figure, a most obvious change is the increase of lake outflow at flood peaks during the summer season, with a maximum value of 1332 m^3/s. In addition, during the dry season (October–March), lake outflow commonly increased. Seasonally, statistical results indicate that the increase of lake outflow was most prominent in the summer. The increased lake outflow was about 250.65 m^3/s, approximating 4.3% of the total observed lake outflow in the summer. The average increase of lake outflow in winter was 190.89 m^3/s, which was about 7.9% of the observed lake outflow in winter, followed by 156.34 m^3/s (4.4%) in autumn and 134.95 m^3/s (2.4%) in spring. On an annual basis, the average increase of lake outflow was about 182.74 m^3/s during the period 2000–2011, which approximates 4.2% of the observed annual lake outflow.

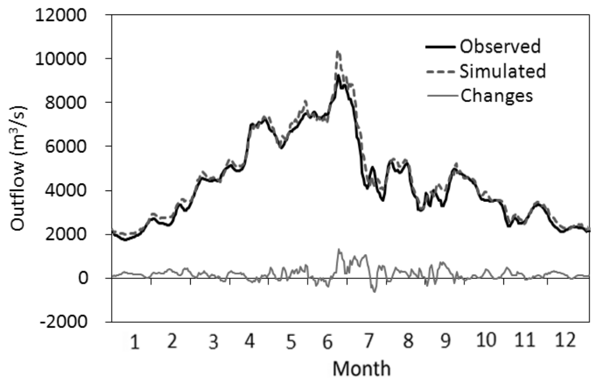

Figure 7. Comparison of observed and simulated lake outflow during 2000–2011.

3.4. Effect on Sedimentation

Figure 8 shows the variation of annual average suspended sediment content (SSC) of catchment inflow to Poyang Lake and outflow to the Yangtze River from Hukou station in the past decades. It is clear from the figure that before the year 2000, the fluctuations of inflow SSC and outflow SSC were relatively consistent. Both curves show an obvious decreasing trend, and inflow SSC is commonly bigger than that of outflow. However, variation characteristics of outflow SSC has changed since the last decade. In contrary to the continued decreasing trend of inflow SSC of the catchment, outflow SSC of the lake has shown a significant increase process during 2000–2007. The average outflow SSC (0.089 kg/m^3) is much bigger than that of inflow SSC (0.055 kg/m^3). Since 2008, outflow SSC from Hukou station decreased significantly.

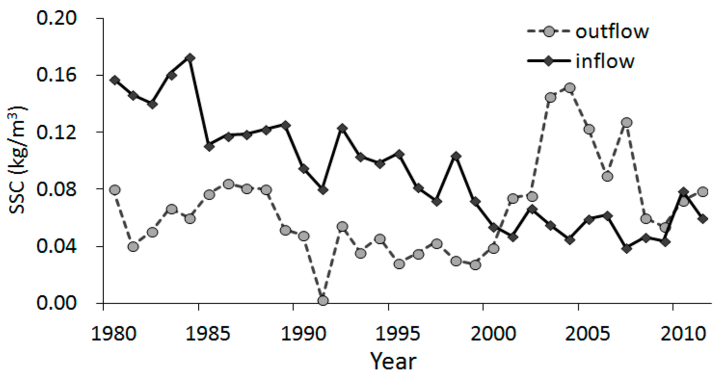

Figure 8. Variation of annual average suspended sediment content (SSC) of lake inflow and outflow during 1980–2011.

The lake sediment balance has largely changed in recent years. Before the year 2000, siltation was prevalent in Poyang Lake and the average annual sand deposition was about 0.1×10^8 t during 1980–1999. During the following years of 2000–2011, it was revealed that there was a total of 18.98×10^8 t (about 1.58×10^8 t/year) net sediment export according to the change of lake bottom topography (Figure 9). Also, during this period, the outflow sediment from the lake exceeded the inflow sediment from the catchment and contributed a 0.49×10^8 t sediment deficit to the total change of lake bottom topography. On this basis, the net direct sand mining export of 18.49×10^8 t (about 1.54×10^8 t/year) can be expected from the lake during 2000–2011 (Figure 9). The amount of direct sand mining export from the lake within only one year exceeded 15 years of natural sand deposition before 2000.

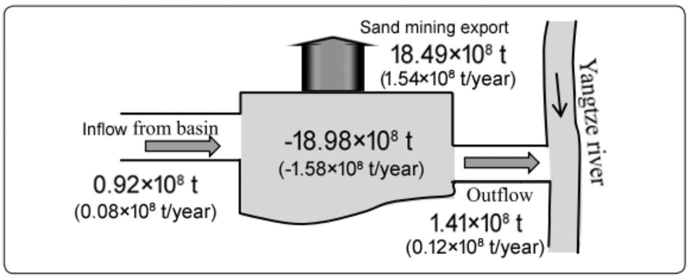

Figure 9. Sediment budget of Poyang Lake during the period 2000–2011.

4. Discussion

Our observation indicates a total volume of 11.54×10^8 m^3 net change of lake bottom topography during the study period, among which, 97% (equal to 18.49×10^8 t or 1.54×10^8 t/year) was directly exported by commercial sand mining. This result is basically similar to the report in Jiang et al. [19] which pointed out a total volume of 12.9×10^8 m^3 sand mining in the lake during 2001–2010. Whereas, the calculated amount of sand mining in our study was much smaller than the results from some other studies. For example, Chen [31] revealed that the average amount of sand mining during 2005 to 2007 was about 2.30–2.90×10^8 t/year according to the statistical data from the Ship Affairs Department of Jiujiang City; de Leeuw et al. [20] reported an average amount of sand mining export of 236×10^6 m^3/year (equal to 3.89×10^8 t/year) based on the estimation of the number of vessels leaving the lake from four Aster images during November 2005 to June 2006. In this study, we introduced a new calculation of using lake DEM data for the estimation of sand mining and its contribution to the change of lake bottom topography in recent years. Although, uncertainties still exist, the result in our study is an important extension and improvement from previous studies.

The increased lake outflow ability (about 182.74 m^3/s during 2000–2011) originated from the widened and deepened water channel along the Hukou waterway. Since the lake bottom topography inclines to the Yangtze River with a certain gradient, the obviously widened and deepened water channel will accelerate the discharge of lake water to the Yangtze River and decrease the lake water level. The investigation from Lai et al. [2] also confirmed this point. In addition, the enlarged lake volume further promotes the decrease in lake water level. Spatially, the effect on the magnitude may come from the spatial differences of relative changes of lake bottom topography according to south movement of the dredges. The relative change of lake bottom topography is the most at Duchang station, and so the decrease of lake water level at Duchang station is the largest. Temporally, the effect of lake bottom topography change is much more prominent in winter and spring seasons due to relatively low water levels in a year.

The decline of annual lake water level due to the impact of lake bottom topography change showed an increasing trend during 2000–2011, which reflected the annual cumulative effects of sand mining in the lake. However, when sand mining activities continue moving south and beyond specific hydro-stations, hydrological effects from lake bottom topography change at these stations will be weakened and very limited. For example, there are no visible change trends of lake water level decrease at Hukou during 2000–2011 and Xingzi after 2006. This process of south movement of sand mining activities in the lake can also be reflected by the annual variation of lake outflow suspended sediment content (SSC), because sand mining activities will stir up the sediment in the riverbed, leading to an increase of water SSC and turbidity [32]. Figure 8 shows that before the year 2000, the fluctuations of inflow SSC and outflow SSC are relatively consistent, and both curves show an obvious decreasing trend. This characteristic of the decreasing trend of lake inflow SSC and outflow SSC was mainly affected by continuous afforestation and water conservancy construction in the lake basin [21]. However, in contrary to the continued decreasing trend of inflow SSC of the catchment, outflow SSC of the lake has shown a significant increase process during 2000–2007 when sand mining areas were mainly concentrated in the northern part of the lake. Due to increased suspended sediment from sand mining, the calculated outflow sediment from the lake exceeded the inflow sediment during the period 2000–2011 as shown in Figure 9. Since 2008, due to continuous movement of sand mining areas towards the south and relatively decreased number of dredges in the lake, the sediment deposition increased with the distance from the outlet, and so outflow SSC from Hukou station decreased accordingly [19,33]. It is anticipated that sand mining in the lake will continue. So far at least, the related hydrological and sedimentation effects from bottom topography change are still growing across the lake.

In this study, we employed a complicated neural network model to quantify the effect of lake bottom topography change on the hydrology of a complex river–lake system, which may serve as a reference for other regions with similar situations. The model considered both the effects from catchment inflow and Yangtze discharge on lake water level variations and showed high computing efficiency and great accuracy in long-term hydrological simulations. Since the BPNN model is a black box model with no physical basis, limitations exist in the description of hydrological processes. Although the simulation results in the current study are satisfactory, the comparison with a physically-based model, such as MIKE 21, is necessary and left for future research. In addition, uncertainties still came from the hypothesis of stable lake bottom topography during the baseline period (1980–1999). Human activities in the lake catchment, such as land use change and land reclamation around the lake, exert influences on lake morphology and lake bottom topography changes [5,23].

5. Conclusions

This study quantitatively assessed the hydrological and sediment effects from bottom topography change in China's largest freshwater lake, Poyang Lake. Results revealed a total change of 1.154×10^9 m^3 in the lake bed during the past decade, which was mainly caused by extensive sand mining activities in the lake. During the period 2000–2011, a remarkable change of sand mining induced lake bottom topography to extend into the central lake and even into some channels of major tributary rivers. Due to this great change of lake bottom topography, an average annual increase of 182.74 m^3/s of lake outflow and a decline of 0.23 m–0.61 m of water level across the lake were estimated during the period 2000–2011. In addition, sand mining activities in the lake also resulted in a big change in suspended sediment content (SSC) of lake outflow and disturbance of lake sediment balance. A total of 18.49×10^8 t (about 1.54×10^8 t/year) commercial sand mining export during the study period was revealed, which accounts for 97% of net sediment change in the lake.

It is worthy of noting that the responses of the lake water level are not consistent across the lake and show great spatiotemporal differences. Due to the changed lake bottom topography from sand mining activities, lake water level shows the largest decline at Duchang near the center of the lake. Temporally, the effect of increasing lake outflow and decreasing lake water level is much more prominent during the winter and spring seasons due to the large gradient of lake surface when lake water levels are relatively low. The annual variation and linear trend of lake water level reflects the cumulative effects of lake bottom topography change, and this effect on the north parts of the lake will be weakened and limited because of reduced or disappeared bottom gradient to the lake outlet after sand mining activities move south. As sand mining activities in the lake continue to move south in the near future, the effects on lake hydrological and sedimentation processes are still growing. It is very difficult for the lake to reestablish a normal or pre-mining sediment budget in a short time, and therefore the changing lake water level and outflow processes will exist for a long time. More research on the subsequent influences on the water environment and wetland ecosystem is required in order to provide a scientific basis to support the sustainable management of this lake ecosystem.

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