RESEARCH ARTICLE

Water age prediction and its potential impacts on water quality using a hydrodynamic model for Poyang Lake, China

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Abstract The water quality in Poyang Lake, the largest freshwater lake in China, has deteriorated steadily in recent years and local governments have made efforts to manage the potential eutrophication. In order to investigate the transport and retention processes of dissolved substances, the hydrodynamic model, Environmental Fluid Dynamics Code (EFDC) was applied by using the concept of water age. The simulated results showed agreement with the measured water level, discharge, and inundation area. The water age in Poyang Lake was significantly influenced by the variations of hydrological conditions. The annual analysis revealed that the largest averaged water age was observed during the wet year (2010) with 28.4 days at Hukou, the junction of the Yangtze River and Poyang Lake. In the normal season (April), the youngest age with 9.1 days was found. The spatial distribution of water quality derived from the remote sensing images suggested that a higher chlorophyll-a concentration, lower turbidity, and smaller water age in the eastern area of Poyang Lake might threaten the regional aquatic health. The particle tracking simulation reproduced the trajectories of the dissolved substances, indicating that the water mass with greater nutrient loading would further lead to potential environmental problems in the east lake. Moreover, the water transfer ability would be weakened due to dam (Poyang Project) construction resulting in the rising water levels in periods of regulation. Generally, this study quantified an indicative transport timescale, which could help to better understand the complex hydrodynamic processes and manage wetland ecosystems similar to Poyang Lake.

Keywords Numerical simulation · Water age · Water quality · Remote sensing · Particle tracking · Poyang Lake

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Introduction

Eutrophication has threatened many inland lakes in China, particularly those located in the middle and lower Yangtze River (Chen et al. 2003; Jin 2003). This eutrophication has accompanied the economic development and human activities in the watershed upstream of these lakes. Although there have been few eutrophication reports for Poyang Lake in recent years, the excessive resource exploitation in the Poyang Lake basin has caused considerable increase in the nitrogen and phosphorus discharge and the water quality has been steadily deteriorating (Deng et al. 2011; Wang et al. 2008a). Additionally, the drought periods in the last decade for Poyang Lake have lasted much longer than in the twentieth century due to several reasons such as sand mining, Three Gorges Dam establishment, and climate change (Feng et al. 2012; Lai et al. 2014). Therefore, the Jiangxi Provincial Government developed the Poyang Lake Water Conservancy Project (Poyang Project) in 2008. It was suggested to build a series of sluice gates

across the narrow channel at the northern end of lake to alleviate water level declines resulting from the frequent droughts (Fig. 1). The effects of the dam construction on the lake ecosystem is also of great concern to local residents. Some researchers believe that the project would bring negative effect on the entire ecosystem including the water quality, biodiversity of fish, and habitats for migrating birds (Barzen 2008; Harris and Zhuang 2010; Lai et al. 2014). Because of these multiple natural and anthropogenic factors influencing the ecological system of Poyang Lake, it is important to monitor and estimate how healthy the lake is from different perspectives.

Many studies have indicated that the inflow discharges will affect the variations of nutrients and phytoplankton growth

(Jordan et al. 2003; Shen and Haas 2004). The reason is that the time required for the pollutants or nutrients to be transported to a specific location greatly correlates with the discharges. Thus, an indicator related to the water parcel transport time will provide valuable information in evaluating the water ecological environment. Various timescales such as the flushing time, turnover time, residence time, and water age have been applied to many water bodies with the aim of assessing the transport process of nutrients (Li et al. 2010; Monsen et al. 2002; Shen et al. 2011). Water age is defined as "the time that has elapsed since the particle under consideration left the region in which its age is prescribed as being zero" (Delhez et al. 1999), which has been regarded as a useful index for analyzing the distributions of pollutants under

Fig. 1 The location of Poyang Lake, inflow tributaries, the proposed dam, and hydrological stations
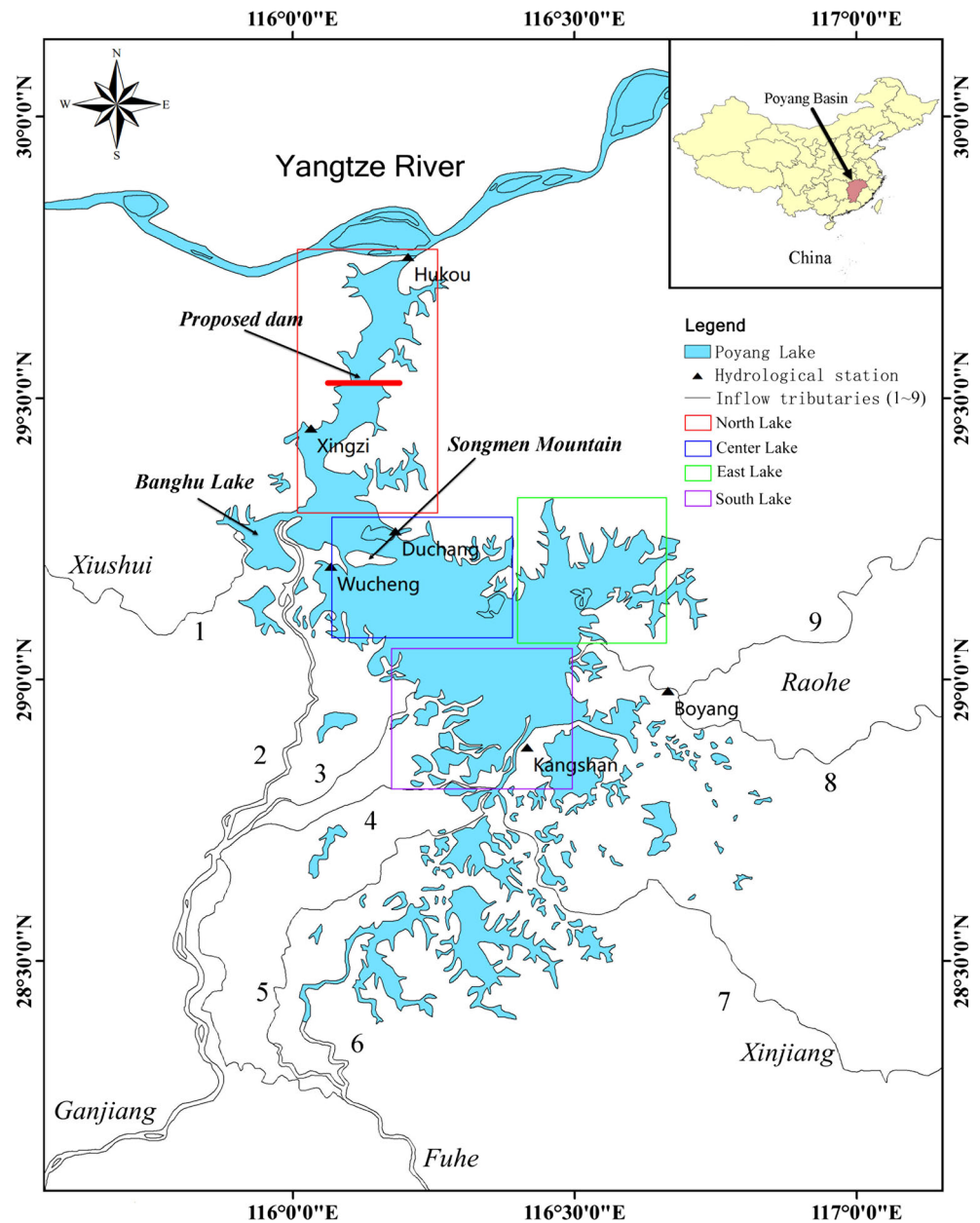
various conditions based on the spatio-temporal heterogeneity (de Brauwere et al. 2011; Li et al. 2011; Monsen et al. 2002; Liu et al. 2012). As a complementary definition of water age, the residence time describes the duration of time for the water parcel at any location will remain in the system. The flushing time and turnover time involve an overall dynamic condition of the water. However, both of them cannot be used to investigate the pollutant transport comprehensively because they do not take the spatial variations into account. The age of water can be calculated using different means including in situ experiments, theoretical analysis, and numerical simulation (Adkins and Boyle 1997; Gong et al. 2009; Kershaw et al. 2004), among which the numerical method is the most efficient and convenient. The constituent-oriented age and residence time theory (CART) method was developed by Deleersnijder et al. (2001) with the advantage of directly predicting the water age by simulating the change of tracer concentration. Also, it has been embedded in various hydrodynamic models and widely used in many water bodies (Gong et al. 2009; Liu et al. 2012; Shen and Haas 2004; Shen et al. 2011).

The aforementioned timescales are helpful to estimate the water mass exchange ability and also can be treated as an effective factor to investigate the spatial pattern of water quality constituents. Delesalle and Sournia (1992) found a positive linear relation between phytoplankton biomass and the residence time in coral reef lagoons. Burford et al. (2012) proposed that chlorophyll-a (chl-a) concentration and phytoplankton productivity rates probably were correlated with the water residence time in a wet-dry tropical estuary. Zhang et al. (2010) also attempted to establish an empirical relation between water age and satellite measurements, which was sensitive to the colored dissolved organic matter (CDOM) and phytoplankton optical signatures. With regard to Poyang Lake, the grade of the eutrophication state is generally assessed by means of remote sensing techniques and field observations. Wang et al. (2015) and Wu et al. (2014a, 2014b) investigated the chl-a concentration from 2009 to 2012 in Poyang Lake by employing remotely sensed images and in situ observations, respectively. However, available satellite data are scarce and the cost of field sampling is relatively high. Moreover, unlike other freshwater lakes in China, retrieval algorithms for water quality constituents are commonly restricted by the atmospheric correction uncertainty in water with high turbidity like Poyang Lake. Therefore, the application of remotely sensed images in combination with numerical simulation provides a better prediction for water environment conditions (Zhang et al. 2015). Given the gradual deterioration of water quality in such a significant and valuable lake system, the water age concept is used here to investigate the hydrodynamic processes and transport timescales of dissolved substances by applying the three-dimensional Environmental Fluid Dynamics Code (EFDC) model (Hamrick 1992). The potential impacts of water age on water quality are then analyzed with the aid of satellite images and the particle tracking. Finally, the impact of the proposed Poyang Project on the water age is also discussed.

Materials and methods

Study area

Poyang Lake (115°50′ E~116°50′E, 28°00′ N~29°50′ N) is located in north central Jiangxi Province, and it constitutes a major hydrological subsystem of the middle and lower Yangtze River basin in central China (Fig. 1). It provides a habitat for many species including endangered ones. The lake is also well known as a unique freshwater wetland with high variability in water level and the land-water boundary. The inundation area shows an extreme disparity between dry and wet seasons, fluctuating from less than 1000 to over 3000 km^2 (Feng et al. 2012). When the water level at Hukou is 21.71 m in flood periods, the average water depth and lake capacity can reach 8.4 m and 27.6 billion m^3, respectively. In dry seasons, the lake separates into a number of small unconnected wetlands, floodplains, and even grasslands.

Five major tributaries flow into Poyang Lake (Fig. 1) including Xiushui (1), Ganjiang (2, 3, and 4 represent the north, middle, and south branches, respectively), Fuhe (5 and 6 represent east and west branches, respectively), Xinjiang (7), and Raohe (8 and 9 represent south and north branches, respectively) rivers. Discharges from these tributaries drain into the Yangtze River passing through a narrow channel in the north lake with Hukou as the only outlet. The Yangtze River can at times exert a great influence in regulating the flows from Poyang Lake. The water discharging from the lake will possibly be blocked and flow may reverse. This phenomenon usually occurs from July to September with a frequency of 708 days in 45 years (Gao et al. 2014).

The daily measured hydrological data including water level (the elevation system used in this study is the Wusong Datum, namely, above the sea level of the China East Sea) and runoff from 2004 to 2011 (after the construction of the Three Gorges Dam) are collected from the Yangtze River Water Resources Commission and Hydrological Bureau of Jiangxi Province. The annual and monthly average are calculated to present the variations in total inflow from all tributaries, water level, and outflow at the Hukou station (Fig. 2).

With the rapid economic growth of gross domestic product (GDP) in Jiangxi Province during the last 30 years, the eutrophication condition has increased in Poyang Lake (Deng et al. 2011). The excess of nutrients and pollutants discharged into the lake comes from the downstream portion of the tributaries, where large numbers of industrial facilities have been established. Through field sampling, many studies have
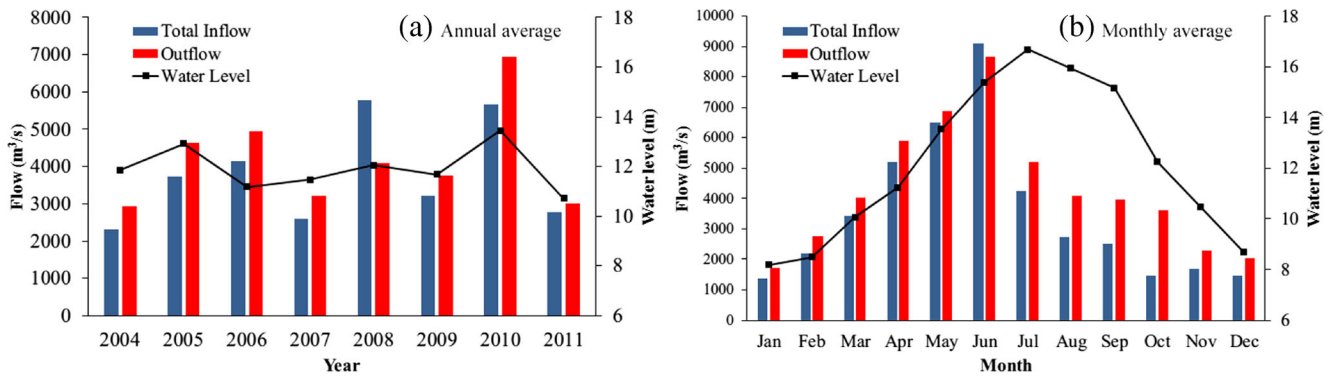
Fig. 2 Total inflow, outflow, and water level at the Hukou station from 2004 to 2011: **a** annual average data, **b** monthly average data

indicated that the total nitrogen (TN) and total phosphorus (TP) has exceeded the eutrophication level in some regions (Chen et al. 2013; Zhang et al. 2014). Also, a regional cyanobacteria bloom was observed by the wetland protection agency in 2012 (Feng et al. 2014), which has made the local government aware of the water quality problem.

Further, in response to the frequent severe droughts in recent years, a 2.8-km long structure proposed in the Poyang Project was planned to be built across the waterway near Xingzi (Fig. 1). It would be open during wet seasons allowing the flow to drain into the Yangtze River, while the dam would be controlled to restrict the discharge and keep a specified water level threshold in dry seasons. Table 1 lists the regulation scheme in detail over a hydrological year (provided by Hydrological Bureau of Jiangxi Province in May 2013), the main purpose being to raise the water level in dry periods.

Model description

The EFDC hydrodynamic model has been successfully used in simulating sediment transport, particle tracing, water quality, thermal stratification, and salinity intrusion in different types of aquatic systems (Li et al. 2011; Su et al. 2014). The model works with orthogonal curvilinear coordinates in the horizontal direction and sigma coordinates in the vertical direction. It solves the three-

dimensional momentum equations (1–3), continuity equations (4–5), and state equation (6) as follows:

$$\partial_t(mHu) + \partial_x(m_yHuu) + \partial_y(m_xHvu) + \partial_z(mwu)$$
$$-(mf + v\partial_x m_y - v\partial_y m_x)Hv = -m_yH\partial_x(g\xi + p) \qquad (1)$$
$$-m_y(\partial_x h - z\partial_x H)\partial_z p + \partial_z(mH^{-1}A_v\partial_z u) + Q_u$$

$$\partial_t(mHv) + \partial_x(m_yHuv) + \partial_y(m_xHvv) + \partial_z(mwv)$$
$$-(mf + v\partial_x m_y - v\partial_y m_x)Hu = -m_xH\partial_y(g\xi + p) \qquad (2)$$
$$-m_x(\partial_y h - z\partial_y H)\partial_z p + \partial_z(mH^{-1}A_v\partial_z u) + Q_v$$

$$\partial_z p = -gH(\rho - \rho_0)\rho_0^{-1} = -gHb \qquad (3)$$

$$\partial_t(m\xi) + \partial_x(m_yHu) + \partial_y(m_xHu) + \partial_z(mw) = 0 \qquad (4)$$

$$\partial_t(m\xi) + \partial_x\left(m_yH\int_0^1 udz\right) + \partial_y\left(m_xH\int_0^1 vdz\right) = 0 \qquad (5)$$

$$\rho = \rho(p, S, T) \qquad (6)$$

where g is the gravitational acceleration; u, v, and w are velocity components in orthogonal coordinates x, y, and z; m_x and m_y represent the square roots of the diagonal components of the matrix tensor; $m = m_x m_y$ is the square root of the metric tensor determinant. The total depth, $H = h + \xi$ is the sum of the water depth h and the free surface displacement ξ. p denotes the physical pressure in excess of the reference density hydrostatic pressure divided by the reference density ρ_0. The

Table 1 Regulation scheme of the Poyang Project over an entire year

Date	Regulation scheme
Mar 11~Aug 31	All sluices open, allowing free passage of water, energy, and organisms.
Sep 1~Sep 15	Water level is controlled at 15.7~16.7 m after the flood season.
Sep 16~Oct 10	Water level decreases to 13.7 m considering the demand of irrigation.
Oct 11~Oct 31	Water level decreases to 12.7 m.
Nov 1~Jan 10	Water level fluctuates around 12.7 m.
Jan 11~Mar 10	Water level decreases gradually to 11.7 m from Jan 11 to Feb 10, and then fluctuates between 11.7 m to 12.7 m from Feb 11 to Mar 10.

density, ρ, is a function of temperature, T, and salinity, S, while b is the buoyancy which is defined as the normalized deviation of density from the reference value. In the momentum equations, f and A_V represent the Coriolis parameter and the vertical eddy viscosity, respectively. Q_u and Q_v are momentum source–sink terms in the x and y direction, respectively. Moreover, the EFDC calculates vertical eddy diffusivity and vertical kinematic viscosity based on the Mellor–Yamada turbulence closure scheme (Mellor and Yamada 1982).

The age of water is calculated based on the hydrodynamic module. Assume that there is only one conservative tracer discharged to the water body and the sources and sinks are neglected, two advection–diffusion equations for calculating the concentration and the age concentration can be written as follows (Deleersnijder et al. 2001):

$$\frac{\partial c\left(t, \vec{x}\right)}{\partial t} + \nabla\left(uc\left(t, \vec{x}\right) - K\nabla c\left(t, \vec{x}\right)\right) = 0 \tag{7}$$

$$\frac{\partial \alpha\left(t, \vec{x}\right)}{\partial t} + \nabla\left(u\alpha\left(t, \vec{x}\right) - K\nabla \alpha\left(t, \vec{x}\right)\right) = c\left(t, \vec{x}\right) \tag{8}$$

where c and α are the tracer and age concentration, respectively, u represents the velocity field, K is the diffusivity tensor, t and $\vec{x}$ are time and distance. The water age a at any specific location and time is defined as:

$$a\left(t, \vec{x}\right) = \frac{\alpha\left(t, \vec{x}\right)}{c\left(t, \vec{x}\right)} \tag{9}$$

In addition, the flushing time of the lake was also taken into account to provide an overall evaluation for water renewal capacity. It describes the exchange characteristics of a water body without identifying underlying physical processes and spatial distribution (Monsen et al. 2002). The concept was defined by Geyer et al. (2000), meaning the "the ratio of the mass of a scalar to the rate of renewal of the scalar", which could be calculated as the volume of a water system, V, divided by the volumetric flow rate, Q_{out}. In the current model, it was written as follows:

$$T_f = \frac{V}{Q_{out}} = \frac{\sum_k N_k \cdot Dep_k}{Q_{out}} \tag{10}$$

where V is the total capacity of the lake, Q_{out} is the daily outflow from the lake, N_k and Dep_k are the area and the water depth of the k th grid point.

Model setup

Satellite images during the extraordinary flood period in 1998 were used to delineate the land–water boundary. The study site was divided into 19,481 rectangular grid cells horizontally with the resolution ranging from 300 to 500 m and five sigma layers in the vertical were applied to better adapt to the tremendous change in topography. The observed daily discharge of the five major incoming tributary rivers were set as the upstream boundary conditions and the downstream boundary condition was specified as the daily average water surface level at the Hukou station. The water level at each hydrological grid cell on the first day of simulation was interpolated over the lake as the initial condition using an inverse distance weighting scheme. Atmospheric data at the Boyang meteorological station (Fig. 1) was collected from the China Meteorological Data Sharing Service System (http://cdc. nmic.cn/) including daily precipitation, temperature, relative humidity, and atmospheric pressure. For wind data, a six hourly reanalysis product was acquired from the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/) at five locations around Poyang Lake as multiple inputs.

Considering the Courant–Friedrichs–Lewy (CFL) condition and computing costs, a dynamic time step solution was applied with a base increment of 1 s. The water age model was established based on the dye/age module in the EFDC. Passive tracers with a constant concentration of one unit were continuously released together with the discharges from all the inflows after a spin-up period of 2 months and the initial tracer concentration at each grid cell was set as zero.

Model application

From a management perspective, understanding the timescale for pollutants and nutrients discharged into a water body to be transported to another location or out of the system under different hydrological conditions is important, and thus, one can diagnose the contributions of underlying dynamic processes (Shen and Haas 2004; Shen and Wang 2007). In order to investigate the influence of the hydrological condition on the water age for Poyang Lake, a series of scenarios was set up based on the inflows, water levels, and meteorological data for different representative periods. A summary of these scenarios is listed in Table 2.

Scenarios 1 to 3 were used to present the inter-annual variations of the water transfer and exchange process. In 2010, serious floods occurred and the maximum inundation was found in 6 of 12 months during the last decade in Poyang Lake (Feng et al. 2012), while the most severe drought during the past 60 years happened in 2011. Therefore, the year of 2010 and 2011 were used to present the wet and the dry year, respectively. Additionally, with an annual mean water level

Table 2 A summary of different simulation scenarios

Simulation	Description	Inflow (m³/s)					Water level at Hukou (m)	Meteorological conditions
		Xiushui	Ganjiang	Fuhe	Xinjiang	Raohe		
Scenario 1	Wet year	2010 series					2010 series	2010 series
Scenario 2	Normal year	2009 series					2009 series	2009 series
Scenario 3	Dry year	2011 series					2011 series	2011 series
Scenario 4	Wet season	400	4686	928	1298	784	15.39	Not included
Scenario 5	Normal season	431	3119	623	935	509	11.24	Not included
Scenario 6	Dry season	309	860	141	229	115	8.18	Not included
Scenario 7	Poyang Project	2009 series					Regulated series	2009 series

with approximately 11.5 m in 2009 could be regarded as the normal year according to historical surveys. All the three scenarios were run for 365 days by applying the continuous time series data in the corresponding period. Similarly, the months of January, April, and June were selected as representing the dry, normal, and wet seasons, respectively (scenarios 4 to 6) by investigating the hydrological data from 2004 to 2011. Driven by the monthly averaged inflows and water level, each scenario was run for 50 days to reach a state of equilibrium. The wind and other atmospheric conditions were excluded for simplicity because the sensitivity analysis showed the meteorological effect played minor roles on water age features. The same condition was used in scenario 7 as in scenario 2, except the water level time series at the downstream boundary was regulated by the Poyang Project. The regional changes in water exchange in the normal year after the completion of the project could be obtained by comparing the water age in the two scenarios.

Although the transport capacity for dissolved substances could be estimated by the time series and spatial distribution of water age, monitoring how such substances moved and then exported or resided in the water body could not intuitively be determined. Therefore, in order to investigate the pathways of water mass imported from each inflow, a Lagrangian particle tracking method in the EFDC was applied (Hamrick 1994). At the exit of each tributary, 200 particles were released into Poyang Lake with a fixed water depth of 1 m considering a random walk process and the results were obtained for a state of equilibrium.

Satellite images

Moderate Resolution Imaging Spectroradiometer (MODIS) images have provided daily global measurements over the last decade. The temporal-spatial resolution of these data is suitable for hydrology and water quality monitoring in large-scale water bodies (Wu et al. 2013). The MODIS 8-day reflectance products, MOD09Q1 (http://ladsweb.nascom.nasa.gov) were

applied to extract the total inundation area for Poyang Lake from 2009 to 2011 to verify the model results. A simple normalized difference vegetation index (NDVI) threshold method proposed by Huete et al. (2002) combined with visual interpretation was applied for water area classification.

To investigate the relation between water age and water quality in spatial distribution, MODIS daily reflectance product (MOD09GA) was collected to derive the chl-a and sediment concentration using a semi-analytical method proposed by Wang et al. (2015) and Cui et al. (2013), respectively. It has been demonstrated that the chl-a concentration is higher in autumn and summer due to suitable water temperatures for phytoplankton growth (Wu et al. 2014a). Additionally, available data were limited by the sensor-induced noise and cloud cover. Consequently, two cloud free images with high quality were chosen for analysis, namely those from October 2009 and October 2010.

Results and discussion

Model verification

Three methods are often used in the parameter calibration process: manual trial-and-error, automatic optimal search, and man–computer interactive search (Chen et al. 2010). The manual trial-and-error method was applied in this study, namely, the simulated water level and discharges were compared with the measurements repeatedly by adjusting the primary physical and empirical parameters in a recommended range. The bottom roughness height was taken as uniform and set at a typical value of 0.02 m (Berntsen 2002). The horizontal momentum diffusivity was adjusted as 0.2 (Hamrick 1992) and the critical wet/dry depth of 0.5 m was specified in order to better simulate the extreme variation of inundation area during drought and flood periods.

The simulated water surface elevation shows close agreement with the observations at four gauging stations (Fig. 3a–d). The coefficient of determination (R^2) of the results at Xingzi, Duchang, Kangshan, and Wucheng was 0.996, 0.983, 0.895, and 0.939, respectively, and the root mean square error (RMSE) varied from 0.245 m (Xingzi) to 0.843 m (Wucheng), which indicates that the EFDC model has the capability to reproduce the high-dynamic changes in water level for different periods. These results also showed that the water levels were overestimated in dry periods, which could be attributed to the following: (1) the bathymetric data used in this study was measured in 2000 and the excess artificial sand dredging activities from 2001 to 2008 has changed the lake bed (Lai et al. 2014), or (2) the gradual recession of water changed the morphology of shorelines from a lake into a river channel. Consequently, a proportion of the dry grid cells in the model was not involved in the numerical computation and might cause an inaccurate prediction (about 70 % dry grids in the lowest water level period).

Discharges at the Hukou station in 2010 and 2011 were also calculated to investigate the water exchange process between the Yangtze River and Poyang Lake. The simulated discharge was in reasonable agreement with the gauged outflow with RMSE and R^2 of 1463.7 m^3 and 0.891 (Fig. 3e). Particularly, the blocking effect of the Yangtze River water levels could be observed during the period when reverse flow occurred in October and September 2011. Figure 3f also shows a good agreement between model prediction and MODIS extraction of the inundation area with RMSE and R^2 of 326.5 m^2 and 0.925, suggesting that the calibrated model could be further applied in water age estimation.
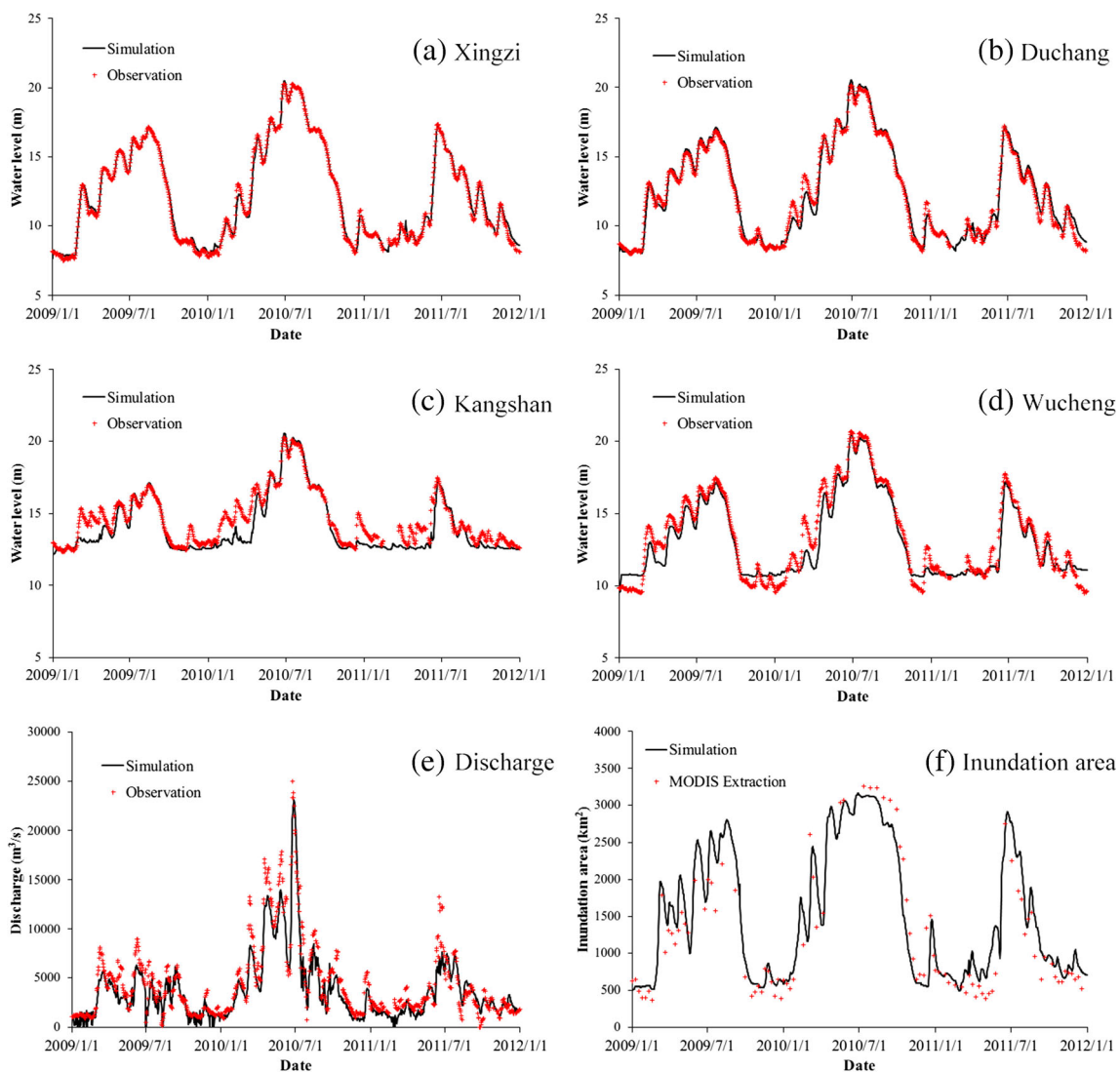

Fig. 3 Comparison between model results and observations: **a–d** water level at different hydrological stations, **e** daily discharge at the Hukou station, **f** inundation area extracted by MODIS images

Water age in Poyang Lake

Inter-annual variations of water age

The depth averaged water age at five hydrological stations for three representative years (scenarios 1~3) is shown in Fig. 4. In general, the water age exhibited a fundamental trend of Duchang > Hukou > Xingzi > Kangshan > Wucheng. The reason for this great disparity was attributed to the distance between the five tributaries and the stations. Duchang is north of Songmen Mountain, which is separated from all the inflows, while Kangshan and Wucheng are located near the outflows of the Xinjiang and Ganjiang rivers (Fig. 1). As a result, the minimum averaged water age for all three years was found at Wucheng and was less than 27.0 days, while the maximum was located at Duchang, ranging from 8.5 to 166.1 days. A longer water age was usually observed in the water recession periods (September and October), while the shorter ages mostly occurred during an overflow period in each year.

The water surface elevation of Poyang Lake varied significantly in different seasons. This variation led to a large number of dry grid cells in drought periods and consequently made it difficult to evaluate the water age over the entire lake. Besides, the model was driven by time-dependent inflows and could not reach a state of equilibrium. Therefore, flushing time and the water age at the sole outlet became the focus of this study. The latter concept also is known as the transit time (Bolin and Rodhe 1973), which was considered as a special case of the water age. Table 3 lists the water age at Hukou and the flushing time for the three years to express the discrepancy resulting from different characteristics of the years. The basic tendency of water age and flushing time is that wet year > normal year > dry year and the relation at other stations was almost the same (Fig. 4), suggesting the water mass is more "active" in dry years than either of the other two years. A standard deviation was also calculated and plotted, showing

Table 3 Annual averaged hydrological data, flushing time and water age at Hukou for scenarios 1 to 3

	Dry year	Normal year	Wet year
Period	2011	2009	2010
Measured inflows (m³/s)	2777	3212	5669
Measured water level (m)	10.73	11.71	13.47
Water age (day)	19.0	25.1	28.4
Flushing time (day)	21.2	25.0	26.0

that the largest variation range of the water age at five stations throughout an entire year was in the normal year scenario (21~60 % higher than other years). Overall, the features of water age highly depend on the hydrodynamic process variations caused by different hydrological conditions such as inflow and water level.

Seasonal variations of water age

Seasonal variations affect the water transport process substantially in many water bodies, especially those with high dynamics. The balance and regulation of biochemical characteristics might be further influenced by these variations. Figure 5 shows that the water age pattern is similar in different seasons although the spatial coverage of water varied extremely. The channel in the north lake showed a shorter water age with an average of about 15 days compared to other regions. The east lake and some branches of the south lake presented the largest water age with more than 40 days in all seasons. Notice that as the total simulation time increased (for example, 365 days), the water age in these areas went up steadily and could reach more than 300 days on Julian day 365, whereas other parts of the lake hold a constant level ranging from 10 to 30 days. This suggests that there is less water mass brought in by each inflow to such regions. Particularly, the Banghu Lake section

Fig. 4 Mean and standard deviation of simulated water age at five hydrological stations for scenarios 1 to 3. The standard deviation (S.D.) was derived from the daily water age for each year
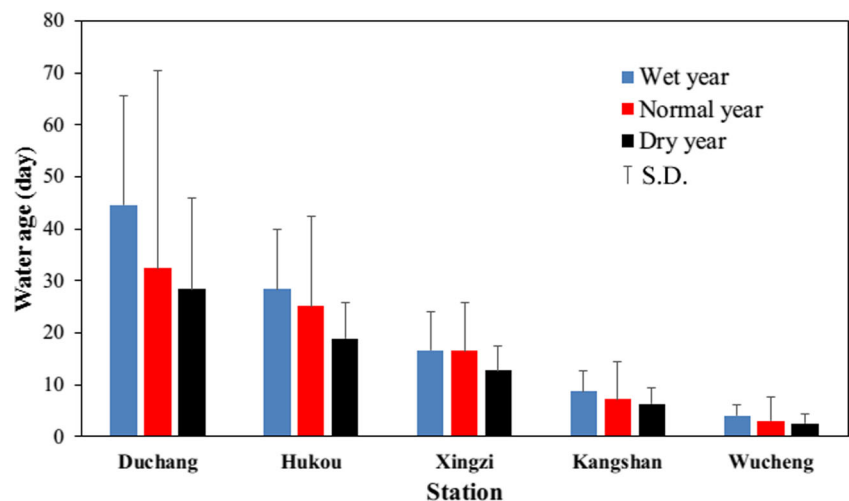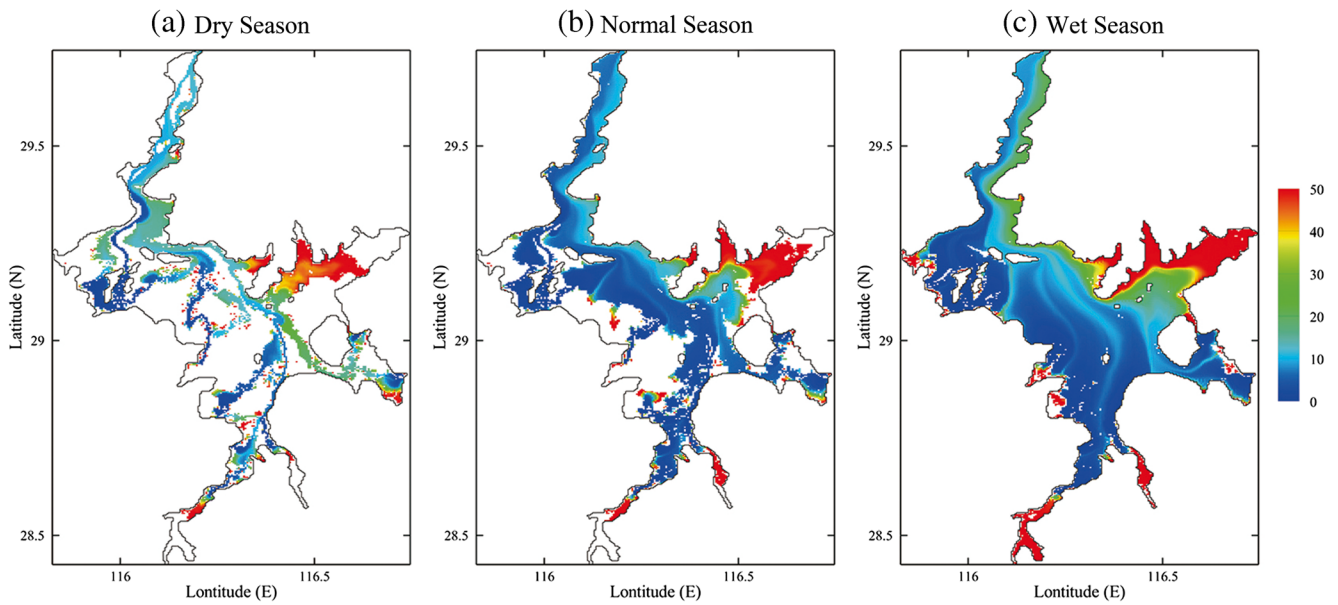
Fig. 5 Spatial pattern of water age (in days) for the 50th day of the simulation for scenarios 4 to 6

(Fig. 1) in the west zone showed a higher age in the dry season than the other two seasons because the separation from the main lake made it unconnected with the inflows, leading to little freshwater exchange with the main water body. In addition, the water age difference in normal and wet seasons between the west and east bank in the north lake could be ascribed to the different arrival times of each source of water, the bathymetry, and the Coriolis force. The two sections were partitioned by a deep channel along the north lake, resulting in a stronger capacity for the west bank to export water to the Yangtze River.

The maximum flushing time and water age at the Hukou station are observed in wet seasons, while the minimum values are obtained in normal seasons (Table 4). The results indicate that once contaminants are brought into the lake from inflows, they tend to be transported out of the lake more rapidly during the normal season. Commonly, the water age at the mouth of an estuary is regulated by the discharge of rivers, and higher flows always correspond to a shorter water age and residence time (Liu et al. 2011). However, no obvious relation was found between water age and inflows for Poyang Lake. The reason is that the seasonal runoff and precipitation control the fluctuations of water level and hydraulic slope across the lake. The topography differences between south and north lake cause a greater water level difference in dry seasons. During the transition period from dry to wet, the water surface gradient gradually decreases and the water level at all the stations becomes nearly identical over the entire lake in the wet season due to the blocking impact of the Yangtze River (Fig. 3a–d). As a result, even though the discharge is relatively larger in wet seasons, the water exchange rate is usually restricted, which is evidenced by the hydrodynamics. Here, the whole lake was divided into four sections including north,

center, south, and east according to the flow characteristics (Fig. 1, Fig. 6). Clearly, the depth averaged velocity is the highest during the normal season in different regions except for the center lake, where the dry season and normal season have similar values. In terms of the four sections, the largest velocity can be observed in the north lake with values of 0.20, 0.27, and 0.21 m/s for dry, normal, and wet season, respectively. The velocity was almost equal in the center and south lake with values around 0.1 m/s. Finally, a circulation pattern with a minimum velocity was found in the east lake. A turbulent current was more conducive to stimulate material transport in the water and accordingly the spatial heterogeneity of the velocity field could be the main reason explaining the water age distribution.

Water age impact on chlorophyll-a distribution

It has been proven that the planktonic biomass and contaminant distributions are related to the water renewing timescales in many water bodies (Lucas et al. 2009; Monsen et al. 2002; Muylaert et al. 2000). As a consequence, the prediction of water age is helpful to evaluate the phytoplankton growth

Table 4 Monthly averaged hydrological data, flushing time, and water age at Hukou for scenarios 4 to 6

	Dry season	Normal season	Wet season
Period	January	April	June
Measured inflow (m³/s)	1642	5611	8106
Measured water level (m)	8.18	11.24	15.39
Water age (day)	~12.7	~9.1	~15.9
Flushing time (day)	~14.1	~9.9	~16.3

Fig. 6 Depth averaged velocity (m/s) in different sections of the lake for scenarios 4~6. The standard deviation (S.D.) was derived from the water ages for all the grid cells in the corresponding section
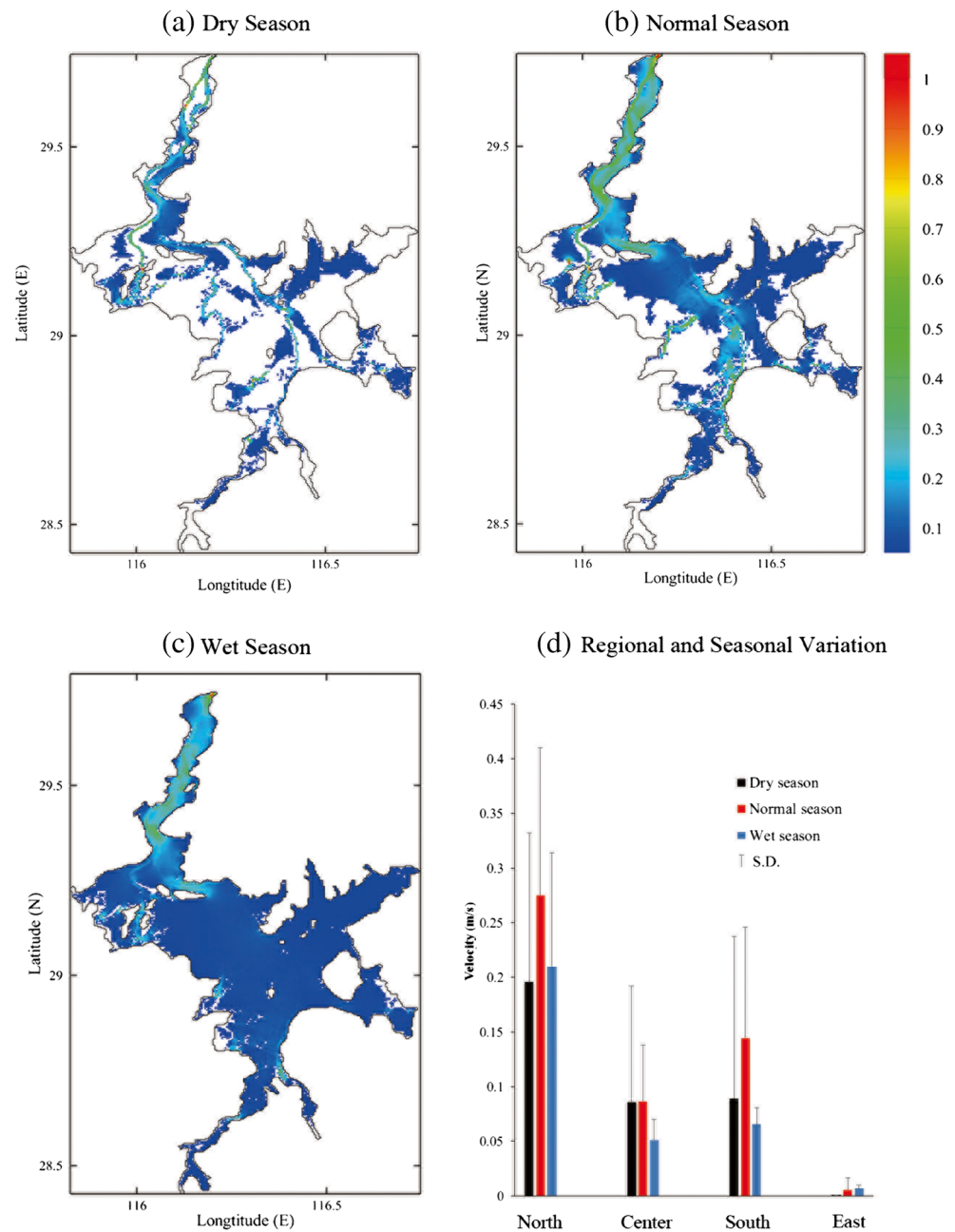
intensity in different areas. Figure 7a, b, d, and e displays the similarities in patterns of remote sensing retrieved chl-a concentration and water age. A larger age and higher chl-a concentration in the east lake was notable, whereas the north lake maintained a relatively lower chl-a concentration in accordance with the younger water age. Moreover, the water age distribution was also highly consistent with the spatial interpolation of chl-a based on the 4-year field observation (Fig. 2 in Wu et al. 2014b). Such spatial agreement suggests that the underlying cause of water quality heterogeneity could be the retention of substances induced by hydrodynamic conditions. A water body with a smaller residence time would export

nutrients more rapidly to downstream and inhibit the formation of algal blooms (Ji 2008), resulting in lower chl-a concentrations.

In addition, the excessive dredging activity in the lake and the construction of the Three Gorges Dam has caused a dramatic change in water transparency, the lake storage capacity, and the river–lake sediment exchange (Wu et al. 2007; Gao et al. 2014; Lai et al. 2014). Although sand mining disturbs the bed load and brings abundant nitrogen and phosphorous up to the water column, the weak transmission of light would limit the phytoplankton growth by insufficient photosynthesis. Zhang et al. (2014) indicated that the chl-a concentration in
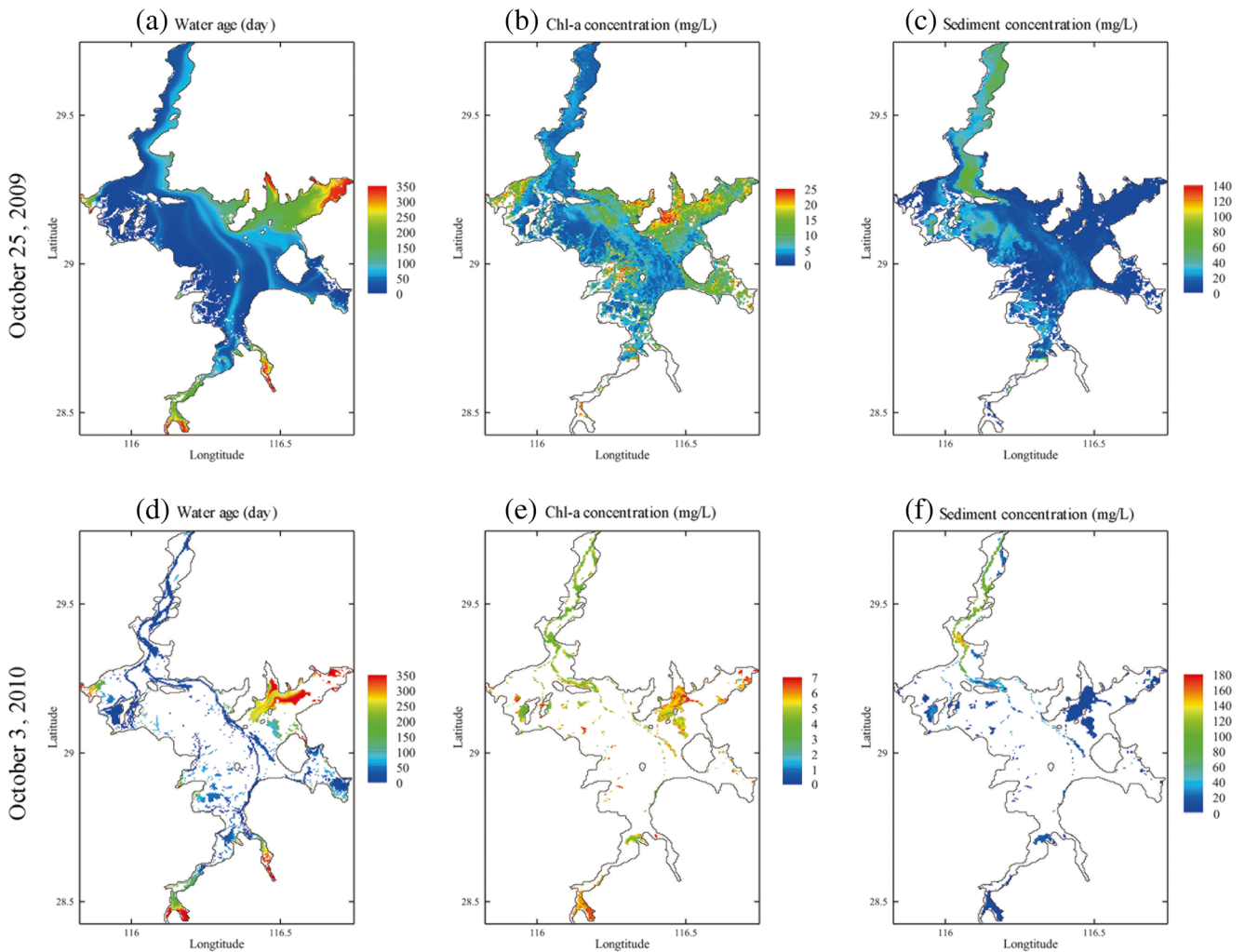
Fig. 7 Spatial distribution of water age, chl-a concentration (mg/L), and sediment concentration (mg/L): **a** water age on Oct 25, 2009, **b** chl-a concentration on Oct 25, 2009, **c** sediment concentration on Oct 25, 2009, **d** water age on Oct 3, 2010, **e** chl-a concentration on Oct 3, 2010, **f** sediment concentration on Oct 3, 2010

the east lake was higher than other regions with a lower sediment concentration and Wu et al. (2014a) also pointed out that the chl-a concentration was related to the shade index (the ratio of water depth to water transparency) in such regions. Fig. 7c, f shows that a lower sediment concentration (<20 mg/L) in the east lake was evident compared with other sections. Note that dredging vessels excavated mainly around the Songmen Mountain (Fig. 1) and the sediment concentration was mostly affected by the human activities at these locations. Basically, an area with higher chl-a concentration has lower sediment concentration in Poyang Lake, as well as a larger water age.

In principle, more rigorous analyses are required to determine whether the water age is the most important driving factor for chl-a concentration because several natural conditions and anthropogenic influences can affect the growth of aquatic plants, such as the solar radiation and sewage discharge. Nevertheless, the spatial distribution of water age reflects the water retention timescale in different zones, which provides a valuable indicator for diagnosing biological and chemical processes and monitoring the regional aquatic environment.

Trajectories of water parcel from tributaries

It is well known that most of the dissolved substances enter a water body from the upstream watershed of each tributary via the river flow. If the biological processes are not taken into consideration, the Lagrangian particles simulation can be used for tracking the trajectories of pollutants and nutrients. Given that larger discharges from the upper stream usually carry more substances into the lake, the particle tracking simulation was achieved based on the wet season scenario (scenario 4). Figure 8 shows that the majority of the particle transport routes were heading to the outlet (Hukou) rather than a non-directional flow pattern. There were few particles retained in
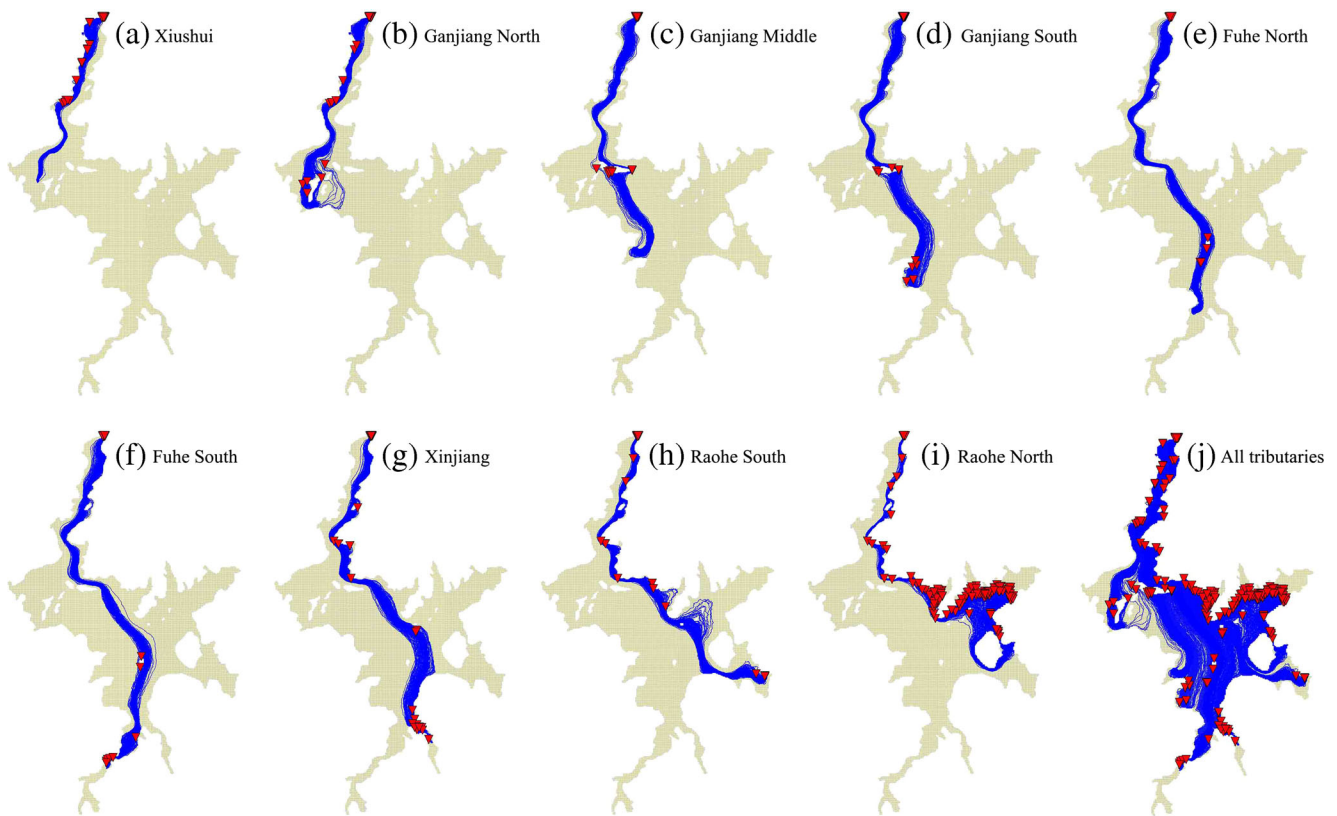
Fig. 8 Trajectories (*blue lines*) and end positions of water mass from each tributary (*red inverted triangles*)

the lake for most tributaries except for the Raohe River, where a portion of particles from the north branch resided in the east lake (Fig. 8i). The particles did not reach certain regions of the lake, like the narrow enclosed channel of the south and east section, in which higher water age could be observed (Figs. 8 and 5).

From a perspective of management, more attention should be paid to the regions near these particle trails when industrial waste or domestic sewage from river inflows contains a higher nutrient or pollutant load. Studies indicated that developing industries and agriculture in the upstream watershed produced a large quantity of polluted water entering Poyang Lake, especially from the Xinjiang and Raohe rivers that suffer severe pollution from the large numbers of copper mines (He et al. 2001, 2013). Furthermore, as the largest tributary of Poyang Lake, the Ganjiang River passes through the major agriculture land in Jiangxi Province. The river carries non-point source pollution into the lake, which results in higher nutrient concentrations than for other rivers (Wang et al. 2008b). This high nutrient loading could also be one possible reason for a higher chl-a concentration around outlets of Xinjiang, Raohe, and Ganjiang, even though the water age at these locations are smaller (Fig. 8d). It was demonstrated by field sampling that not only were the nutrients sufficient for eutrophication (Chen et al. 2013), but the concentration of TN/TP also peaked in the east area (Wu et al. 2014a). Based on the synthetic effect of the

retained substances from the Raohe River, non-turbid water column, higher water age, and sufficient nutrients for phytoplankton growth in the east lake, there might be a potential threat for water quality deterioration, even for eutrophication.

The effect of Poyang Project on water age

After the Poyang Project is completed, the regional hydrodynamic processes will be altered. The raising water level in the north lake will cause a decrease in the south–north water surface gradient and affect the flow rate and the water self-purification ability. Hu et al. (2012) also indicated that the TN/TP concentration in the entire lake will increase by more than 12 % after the establishment of the dam. In the view of the water age, the increase will enhance the water exchange ability and dilute the nutrient loading, while the decline suggests weaker water movement and more appropriate conditions may be reached for phytoplankton growth. The difference in the water age time series between scenario 2 and scenario 7 at the Hukou station indicates that such timescale was significantly influenced by the water conservancy project (Fig. 9a). In the flood season, namely, from April to October, the water ages in the two cases were similar because of the open sluices (free discharge). The backflow from the Yangtze River gave rise to the sudden reduction of water age on 10 August, which meant that the Yangtze River became an additional inflow. In contrast, the water age in the regulation
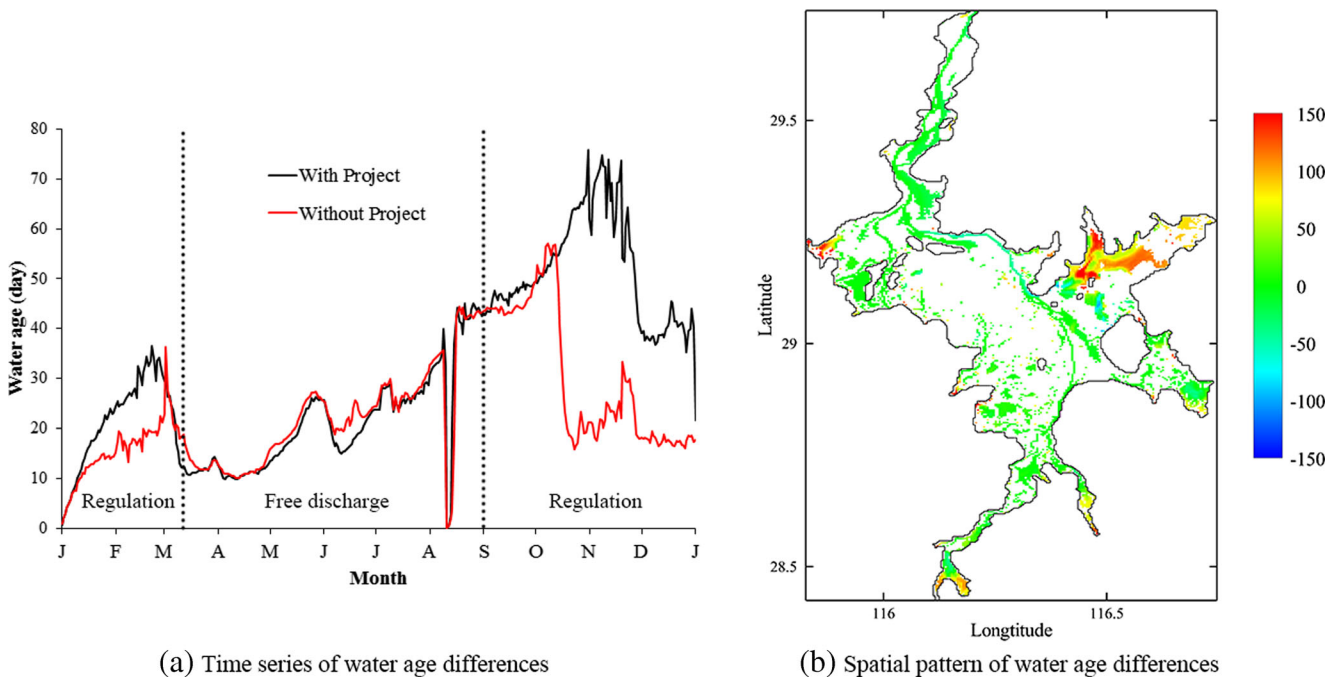
(a) Time series of water age differences   (b) Spatial pattern of water age differences

Fig. 9 Time series of water age differences at the Hukou station and spatial pattern of water age differences on Dec 2, 2009 between the project case and the non-project case

period altered dramatically because of the controlled water level. The mean water age in the regulation period at Hukou was 40.8 days with Poyang Project, which was about 13.6 days more than the non-project case. The spatial difference of water age between the two circumstances also was investigated under an extreme drought condition with a water level of 8 m at the Hukou station (Fig. 9b). In general, the water age increased at all sections on average. The inundation area with increasing ages occupied 15.3 % more than that with decreasing ages. Especially for parts of the east lake, the establishment of the dam would raise the water age most remarkably by more than 50 days. Due to the weaker water exchange ability in these specific regions, there might be higher risks for water quality deterioration.

Conclusions

The main purpose of this study was to reveal the water mass transport ability in Poyang Lake, the largest freshwater lake with high risks of eutrophication in China. The water age was computed based on the three-dimensional hydrodynamic model EFDC under several representative hydrological conditions. At an annual scale, the water age at the sole outlet of Poyang Lake peaked in wet years (28.4 days) indicating that the water mass was more likely to reside longer in the lake for wet years than for normal (25.1 days) and dry years (19.0 days). The water exchange ability in Poyang Lake was dominantly controlled by both inflows and water level, which provided evidence that the water age in a normal season (9.1 days) is younger than that in wet (15.9 days) and dry seasons (12.7 days).

The spatial heterogeneity of water age was pronounced in spite of the dynamic inundation changes. In most areas of the lake, the age ranged from 10 to 30 days, while it reached more than 300 days in the east lake and some enclosed channels of the south lake. The spatial distribution of water age was highly correlated with the pattern of chl-a and sediment concentrations derived from satellite images, which illustrates that the water quality variations at different sites could be predicted by the water age. With the aid of Lagrangian particle tracking, it was found that the water with higher nutrient concentrations from the Raohe River could be trapped within the east lake. Coupled with the higher water age and lower turbidity, the potential risks of eutrophication might exist in such region. Additionally, the proposed Poyang Project would decrease the mobility of dissolved substances during dry periods in most areas even though the droughts could be alleviated. On the whole, a valuable timescale indicator has been provided for environment monitoring and it could also help policy makers to better understand the physical and hydrodynamic processes in Poyang Lake.

References

Adkins JF, Boyle EA (1997) Changing atmospheric Δ14C and the record of deep water paleoventilation ages. Paleoceanography 12(3):337–344

Berntsen J (2002) Internal pressure errors in sigma-coordinate ocean models. J Atmos Ocean Technol 19(9):1403–1414

Bolin B, Rodhe H (1973) A note on the concepts of age distribution and transit time in natural reservoirs. Tellus 25(1):58–62

Burford MA, Webster IT, Revill AT, Kenyon RA, Whittle M, Curwen G (2012) Controls on phytoplankton productivity in a wet–dry tropical estuary. Estuar Coast Shelf Sci 113:141–151

Chen Y, Fan C, Teubner K, Dokulil M (2003) Changes of nutrients and phytoplankton chlorophyll-a in a large shallow lake, Taihu, China: an 8-year investigation. Hydrobiologia 506(1–3):273–279

Chen X, Lu J, Cui T, Jiang W, Tian L, Chen L, Zhao W (2010) Coupling remote sensing retrieval with numerical simulation for SPM study—taking Bohai Sea in China as a case. Int J Appl Earth Obs Geoinf 12:S203–S211

Chen X, Zhang Y, Zhang L, Chen L, Lu J (2013) Distribution characteristic of nitrogen and phosphorus in Lake Poyang during high water period. J Lake Sci 25(5):643–648. doi:10.3969/j.issn.1003-5427.2013.05.004

Cui L, Qiu Y, Fei T, Liu Y, Wu G (2013) Using remotely sensed suspended sediment concentration variation to improve management of Poyang Lake, China. Lake Reservoir Manage 29(1):47–60

de Brauwere A, De Brye S, Blaise S, Deleersnijder E (2011) Residence time, exposure time and connectivity in the Scheldt Estuary. J Mar Syst 84(3):85–95

Deleersnijder E, Campin JM, Delhez EJ (2001) The concept of age in marine modelling: I. Theory and preliminary model results. J Mar Syst 28(3):229–267

Delesalle B, Sournia A (1992) Residence time of water and phytoplankton biomass in coral reef lagoons. Cont Shelf Res 12(7):939–949

Delhez EJ, Campin JM, Hirst AC, Deleersnijder E (1999) Toward a general theory of the age in ocean modelling. Ocean Model 1(1):17–27

Deng X, Zhao Y, Wu F, Lin Y, Lu Q, Dai J (2011) Analysis of the trade-off between economic growth and the reduction of nitrogen and phosphorus emissions in the Poyang Lake Watershed, China. Ecol Model 222(2):330–336

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

Feng L, Hu C, Han X (2014) Long-term distribution patterns of chlorophyll-a concentration in China's largest freshwater lake: MERIS full-resolution observations with a practical approach. Remote Sens 7(1):275–299

Gao J, Jia J, Albert JK, Xing F, Wang Y, Xu X, Yang Y, Zou X, Gao S, Qi S, Liao F (2014) Changes in water and sediment exchange between the Changjiang River and Poyang Lake under natural and anthropogenic conditions, China. Sci Total Environ 481:542–553

Geyer WR, Morris JT, Prahl FG, Jay DA (2000) Estuarine science: a synthetic approach to research and practice. In: Hobbie JE (ed) Interaction between physical processes and ecosystem structure: a comparative approach. Island Press, Washington D. C., pp 177–206

Gong W, Shen J, Hong B (2009) The influence of wind on the water age in the tidal Rappahannock River. Mar Environ Res 68(4):203–216

Hamrick JM (1992) A three-dimensional environmental fluid dynamics computer code: theoretical and computational aspects, vol 317. Virginia Institute of Marine Science, Gloucester Point

Hamrick JM (1994) Estuarine and coastal modeling: proceedings of the third international conference. In: Spaulding ML (ed) Linking hydrodynamic and biogeochemical transport model for estuarine and coastal waters. American Society of Civil Engineers, New York, pp 591–608

He M, Wang Z, Tang H (2001) Modeling the ecological impact of heavy metals on aquatic ecosystems: a framework for the development of an ecological model. Sci Total Environ 266(1):291–298

He C, Liu J, Li J, Liang X, Chen X, Lei Y, Zhu D (2013) Spatial distribution, source analysis, and ecological risk assessment of DDTs in typical wetland surface soils of Poyang Lake. Environ Earth Sci 68(4):1135–1141

Hu C, Shi W, Hu L, Zhou W (2012) Simulation study on the impact of Poyang Lake hydro-junction Projects on nitrogen and phosphorous nutrient in lake region. Resour Environ Yangtze Basin 21(6):749–755

Huete A, Didan K, Miura T, Rodriguez EP, Gao X, Ferreira LG (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens Environ 83(1):195–213

Ji Z (2008) Hydrodynamics and water quality: modeling rivers, lakes, and estuaries. Wiley, New York

Jin X (2003) Analysis of eutrophication state and trend for lakes in China. J Limnol 62(1s):60–66

Jordan TE, Weller DE, Correll DL (2003) Sources of nutrient inputs to the Patuxent River estuary. Estuaries 26(2):226–243

Kershaw PJ, Heldal HE, Mork KA, Rudjord AL (2004) Variability in the supply, distribution and transport of the transient tracer 99Tc in the NE Atlantic. J Mar Syst 44(1–2):55–81

Lai X, Shankman D, Huber C, Yesou H, Huang Q, Jiang J (2014) Sand mining and increasing Poyang Lake's discharge ability: a reassessment of causes for lake decline in China. J Hydrol 519:1698–1706

Li Y, Acharya K, Chen D, Stone M (2010) Modeling water ages and thermal structure of Lake Mead under changing water levels. Lake Reservoir Manage 26(4):258–272

Li Y, Acharya K, Yu Z (2011) Modeling impacts of Yangtze River water transfer on water ages in Lake Taihu, China. Ecol Eng 37(2):325–334

Liu W, Chen W, Hsu MH (2011) Using a three-dimensional particle-tracking model to estimate the residence time and age of water in a tidal estuary. Comput Geosci 37(8):1148–1161

Liu Z, Wang H, Guo X, Wang Q, & Gao H (2012) The age of Yellow River water in the Bohai Sea. Journal of Geophysical Research: Oceans (1978–2012), 117(C11).

Lucas LV, Thompson JK, Brown LR (2009) Why are diverse relationships observed between phytoplankton biomass and transport time. Limnol Oceanogr 54(1):381–390

Mellor GL, Yamada T (1982) Development of a turbulence closure model for geophysical fluid problems. Rev Geophys 20(4):851–875

Monsen NE, Cloern JE, Lucas LV, Monismith SG (2002) A comment on the use of flushing time, residence time, and age as transport time scales. Limnol Oceanogr 47(5):1545–1553

Muylaert K, Sabbe K, Vyverman W (2000) Spatial and temporal dynamics of phytoplankton communities in a freshwater tidal estuary (Schelde, Belgium). Estuar Coast Shelf Sci 50(5):673–687

Shen J, Haas L (2004) Calculating age and residence time in the tidal York River using three-dimensional model experiments. Estuar Coast Shelf Sci 61(3):449–461

Shen J, Wang H (2007) Determining the age of water and long-term transport timescale of the Chesapeake Bay. Estuar Coast Shelf Sci 74(4):585–598

Shen Y, Wang J, Zheng B, Zhen H, Feng Y, Wang Z, Yang X (2011) Modeling study of residence time and water age in Dahuofang Reservoir in China. Sci China Phys Mech Astron 54(1):127–142

Su Q, Qin H, Fu G (2014) Environmental and ecological impacts of water supplement schemes in a heavily polluted estuary. Sci Total Environ 472:704–711

Wang H, Liang X, Jiang P, Wang J, Wu S, Wang H (2008a) TN: TP ratio and planktivorous fish do not affect nutrient–chlorophyll relationships in shallow lakes. Freshw Biol 53:935–944

Wang M, Zhou W, Hu C (2008b) Status of nitrogen and phosphorus in waters of Lake Poyang Basin. J Lake Sci 20(3):334–338. doi:10.3321/j.issn:1003-5427.2008.03.011

Wang J, Zhang Y, Yang F, Cao X, Bai Z, Zhu J, Chen E, Li Y, Ran Y (2015) Spatial and temporal variations of chlorophyll-a concentration from 2009 to 2012 in Poyang Lake, China. Environ Earth Sci 73(8):4063–4075

Wu G, de Leeuw J, Skidmore AK, Prins HH, Liu Y (2007) Concurrent monitoring of vessels and water turbidity enhances the strength of evidence in remotely sensed dredging impact assessment. Water Res 41(15):3271–3280

Wu G, Cui L, He J, Duan H, Fei T, Liu Y (2013) Comparison of MODIS-based models for retrieving suspended particulate matter concentrations in Poyang Lake, China. Int J Appl Earth Obs Geoinf 24:63–72

Wu Z, He H, Cai Y, Zhang L, Chen Y (2014a) Spatial distribution of chlorophyll a and its relationship with the environment during summer in Lake Poyang: a Yangtze-connected lake. Hydrobiologia 732(1):61–70

Wu Z, Lai X, Zhang L, Cai Y, Chen Y (2014b) Phytoplankton chlorophyll a in Lake Poyang and its tributaries during dry, normal and wet seasons: a 4-year study. Knowl Manag Aquat Ecosyst 412:06

Zhang W, Wilkin JL, Schofield OM (2010) Simulation of water age and residence time in New York Bight. J Phys Oceanogr 40(5):965–982

Zhang L, Chen X, Zhang Y, Chen L, Zhang P (2014) Spatial distribution of water quality and its impacting factor in the wet season of Poyang Lake using the hydro-geomorphological partitions. China Environ Sci 34(10):2637–2645. doi:10.3969/j.issn.1000-6923.2014.10.028

Zhang P, Chen X, Lu J, Zhang W (2015) Assimilation of remote sensing observations into a sediment transport model of China's largest freshwater lake: spatial and temporal effects. Environ Sci Pollut Res 22(23):18779–18792

Unpublished Material:

Barzen J (2008) Phase 1 Report: How development projects may impact wintering waterbirds at Poyang Lake, Unpublished report submitted to Hydro-ecology Institute of the Yangtze Water Resources Commission, available from International Crane Foundation (ICF), https://www.savingcranes.org/wp-content/uploads/2008/05/Phase%201%20Report_English.pdf

Harris J, & Zhuang H (2010) An ecosystem approach to resolving conflicts among ecological and economic priorities for Poyang Lake wetlands, available from International Union for Conservation of Nature (IUCN), http://www.iucn.org/news_homepage/news_by_date/?6464/Poyang-Lake-Wetlands-Management-Report