

Article

Investigation of Residence and Travel Times in a Large Floodplain Lake with Complex Lake–River Interactions: Poyang Lake (China)

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Abstract: Most biochemical processes and associated water quality in lakes depends on their flushing abilities. The main objective of this study was to investigate the transport time scale in a large floodplain lake, Poyang Lake (China). A 2D hydrodynamic model (MIKE 21) was combined with dye tracer simulations to determine residence and travel times of the lake for various water level variation periods. The results indicate that Poyang Lake exhibits strong but spatially heterogeneous residence times that vary with its highly seasonal water level dynamics. Generally, the average residence times are less than 10 days along the lake's main flow channels due to the prevailing northward flow pattern; whereas approximately 30 days were estimated during high water level conditions in the summer. The local topographically controlled flow patterns substantially increase the residence time in some bays with high spatial values of six months to one year during all water level variation periods. Depending on changes in the water level regime, the travel times from the pollution sources to the lake outlet during the high and falling water level periods (up to 32 days) are four times greater than those under the rising and low water level periods (approximately seven days).

Keywords: 2D hydrodynamic model; residence time; travel time; dye tracer; water level dynamics; Poyang Lake

1. Introduction

Lakes are vitally important components of the hydrosphere with indispensable ecological value and a large inventory of surface freshwater that is readily accessible for human consumption [1]. Many physical, chemical and biological processes that occur within particular environments, including the transport of pollutants, sediments and other materials, are influenced by lake hydrodynamics [2].

One important physical attribute of lakes is the transport time scale (e.g., residence time, water age, flushing time, and travel time) that describes the lake's ability to renew the water contained within it via water level regime dynamics [3,4]. Although the time scale concept was designed to characterize the transport processes of lakes, this scale does not have a universally accepted definition. The terms 'residence time' and 'travel time' are most commonly used to represent the time scale of the physical transport processes and to elucidate associated water quality problems in lakes and other hydrological systems [5]. In the literature, a widely used concept for quantifying the residence times for lakes is known as the *e*-folding time [2,4,5]. The *e*-folding time corresponds to the time when the average concentration of contaminants in the lake is reduced to $1/e$ or 37% of the initial concentration [6–8]. Travel time is defined as the time that elapses between the introduction of a conservative and passive tracer to the water column and the time required to reach its peak concentration at a given location [9–11]. When two or more peaks are observable, the representative value of the travel time is determined by using the peak that corresponds to the higher concentration [12,13]. Water circulation in a given lake is the end result of the complex interplay of various forces (e.g., inflows, outflows, winds, and tides), and therefore, knowledge of the transport time scale can substantially aid in the assessment of the environmental state of lakes and their sustainable management for engineers, scientists, managers and policy makers.

Poyang Lake, the largest freshwater lake in China, is one of the few lakes in China that remains naturally connected to surrounding rivers. The lake predominantly receives inflows from catchment rivers, which subsequently exchange flows with the Yangtze River [14]. Poyang Lake is an example of a highly valued water resource with particularly complex hydrological forcing and thereby exhibits a highly dynamic hydrological regime [15]. The water level in the lake is primarily controlled by seasonal variations in catchment river inflows during the water level rising period [14,16]. However, the flow regime changes in the Yangtze River largely influence the lake's behavior, mainly due to the 'blocking effect' of the Yangtze River during the high water level period [17,18] and to the 'empty effect' during the water level recession period [19]. Therefore, the lake exhibits varying interactions with the lake's catchment and the Yangtze River on a seasonal scale.

Poyang Lake serves multiple functions relating to industrial production, drinking water, irrigation, ecosystem maintenance, and the regulation of environmental functions as well as supporting cultural and recreational functions for approximately 12.4 million residents [20]. However, environmental degradation has begun due to increasingly intensive economic activities. Steadily deteriorating water

quality and the associated rapidly changing environmental conditions have intensified due to wastewater discharge from industrial and domestic sources as well as agricultural chemical inputs [20]. For example, the average total nitrogen (TN) and total phosphorus (TP) concentrations in the lake water were 1.1 mg/L and 0.07 mg/L, respectively, indicating severe eutrophication [21]. The water quality of Poyang Lake was very good prior to year 2000 (Grade I); however, it has deteriorated to Grades III and IV in the last 10 years (according to the Chinese Water Quality Classification System, Grade I is the best and Grade V is the worst) [22]. These urgent problems concerning Poyang Lake have recently gained considerable attention [23,24] because they have resulted in a serious threat to inhabitants that rely on this freshwater resource [25]. The lake water quality is known to exhibit significant temporal and spatial variations that are closely related to lake-dependent flushing [21,22,26]. Therefore, it is important to determine the residence and travel times within Poyang Lake, particularly with respect to its seasonal water level dynamics. However, no references or estimates that consider these specific water level regime changes are available in the literature.

Previous efforts have focused on estimating the average residence times of Poyang Lake by using a single value based on the ratio of the lake volume to the outflow rate [26–29]. In its simplest form, this method may not be appropriate for systems that are similar to Poyang Lake, which have highly variable volumes (varying from 4.5×10^8 to $150 \times 10^8 \text{ m}^3$) and outflows (the lake discharges to the Yangtze River but with frequent backflow) due to complex water level dynamics [17]. In this case, it is unclear which variable values should be employed and which temporal averaging scales (e.g., annual, monthly, or bi-weekly) are reasonable [30]. In addition, a single ratio for a system is not valid for all periods, locations or constituents; thus, a single ratio cannot represent all transport processes [5]. More importantly, the single ratio provides no information regarding the connections between the transport and the spatial heterogeneity of water environmental factors within the lake, such as specific conductivity, temperature and chlorophyll *a* [31]. However, field experiments that infer the residence time are expensive; thus, the overall spatial and temporal data cannot be surveyed [32]. Due to large variations in the published values of the residence times (varied from 10 to 59 days) [26–29], approaches for more accurate and realistic expressions that identify and quantify the spatially heterogeneous phenomena of residence time are required for this highly dynamic lake. Therefore, this particular case can be considered to be a first study.

Most existing methodologies for investigating transport time scale are based on physically based hydrodynamic modeling. Hydrodynamic models combined with dye-tracer simulations are used to explore pollutant transport processes and associated residence time (or travel time) in different water bodies, such as the tidal-driven York River estuary (USA) [33], the Venice Lagoon (Italy) [8], Lake Tana (Ethiopia) [34], the Irish Sea (Irish) [3] and Mediterranean lagoons (Italy and Spain) [35]. These previous studies indicate that hydrodynamic models are efficient for investigating the transport time scale (e.g., residence time and travel time) because both advection and dispersion processes are considered using a combined dye tracer-based approach. An additional advantage of using a hydrodynamic model is that it can be used to test hypotheses and to simulate various scenarios that can affect the derived transport time scale, which strengthens confidence in the approach.

In this study, a 2D hydrodynamic model (MIKE 21) linked to a dye tracer approach was used in the first attempt to explore the detailed transport time scales of a large floodplain lake (Poyang Lake) using the concepts of residence and travel time. Although the ultimate purpose of this study was to provide

transport time scales for future assessments of the ecological and biochemical changes within Poyang Lake, this study was limited to three main objectives: (1) to characterize the spatial distribution of water residence times; (2) to investigate the seasonal behaviors of travel times for various water regime dynamics of the lake; and (3) to provide physical background information relating to Poyang Lake hydrodynamics and associated transport time scales. The spatial and temporal variability of the residence and travel times were investigated using a series of hydrodynamic model simulations.

2. Study Site

Poyang Lake ($28^{\circ}4'–29^{\circ}46' \text{ N}$, $115^{\circ}49'–116^{\circ}46' \text{ E}$) is located in the northern region of Jiangxi Province and on the south bank of the middle-lower reaches of the Yangtze River (Figure 1). Poyang Lake is internationally recognized as an important wetland system for its large numbers of wild water birds, including many endangered species [36]. Poyang Lake predominantly receives inflows from the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers within its $16.22 \times 10^4 \text{ km}^2$ catchment [14], which subsequently flows into the Yangtze River through a narrow channel at Hukou (the junction of the Yangtze River and Poyang Lake) and at its northern outlet (see Figure 1). The Ganjiang, Fuhe and Xinjiang Rivers contribute approximately 89% of the lake's inflow, and the remaining 11% of the lake's inflow is from the Raohe and Xiushui Rivers [37]. In addition, these five rivers are the greatest contributors of industrial wastewater and domestic sewage to the lake [24,25].

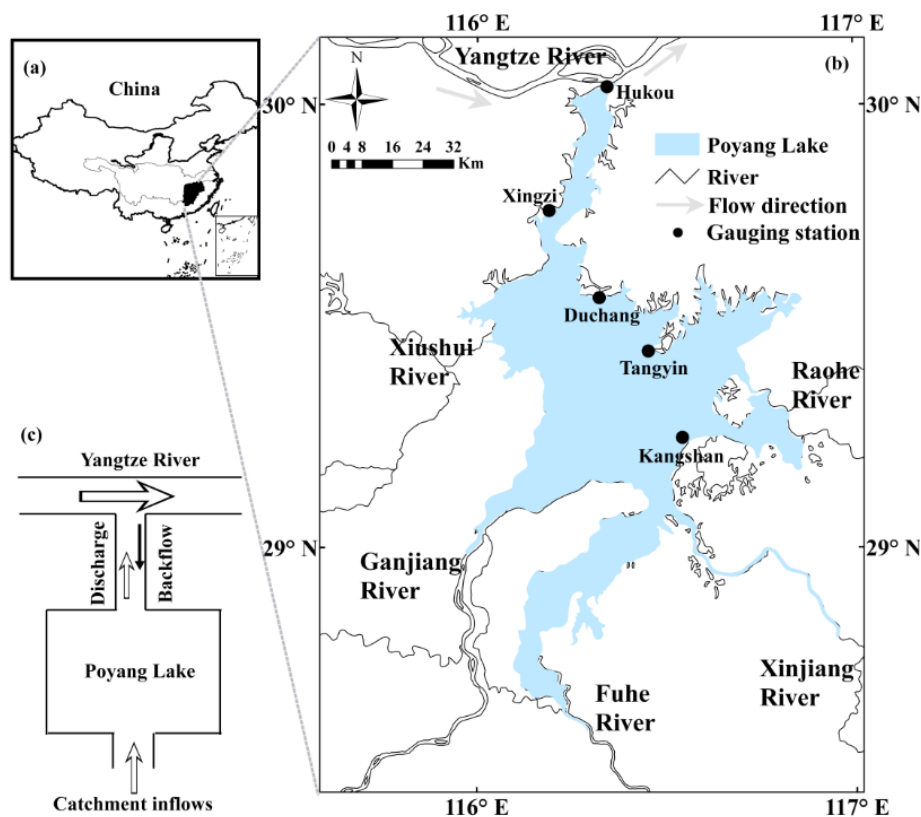


Figure 1. (a) Location of the Poyang Lake catchment in China; (b) the lake gauging stations and the major rivers surrounding the lake and (c) a schematic diagram of the river-dominated lake system.

Poyang Lake is a geometrically complex lake with tortuous shorelines and an incised bottom morphology [15]. The bottom of the lake is shaped by a combination of lacustrine and riverine morphological processes. The lake bed elevation decreases from the south to the north, with a difference of approximately 6.5 m [37]. Flow throughout the lake follows a complex circulation pattern that is defined by topographical features, including deep channels, floodplains and islands. Poyang Lake is a river-dominated lake with dramatic seasonal water level fluctuations that vary from 8 to 18 m each year. During the late spring and early summer, the water level dramatically increases and the water surface area expands to $>3000 \text{ km}^2$ [38]. In contrast, during the winter, the water level decreases sharply, reaching a surface area of $<1000 \text{ km}^2$ [38]. The differences in the water surface elevation can reach up to 5 m in the lake during the low water level period (Figure 2), whereas the surface of the lake is nearly horizontal during the high water level period (Figure 2).

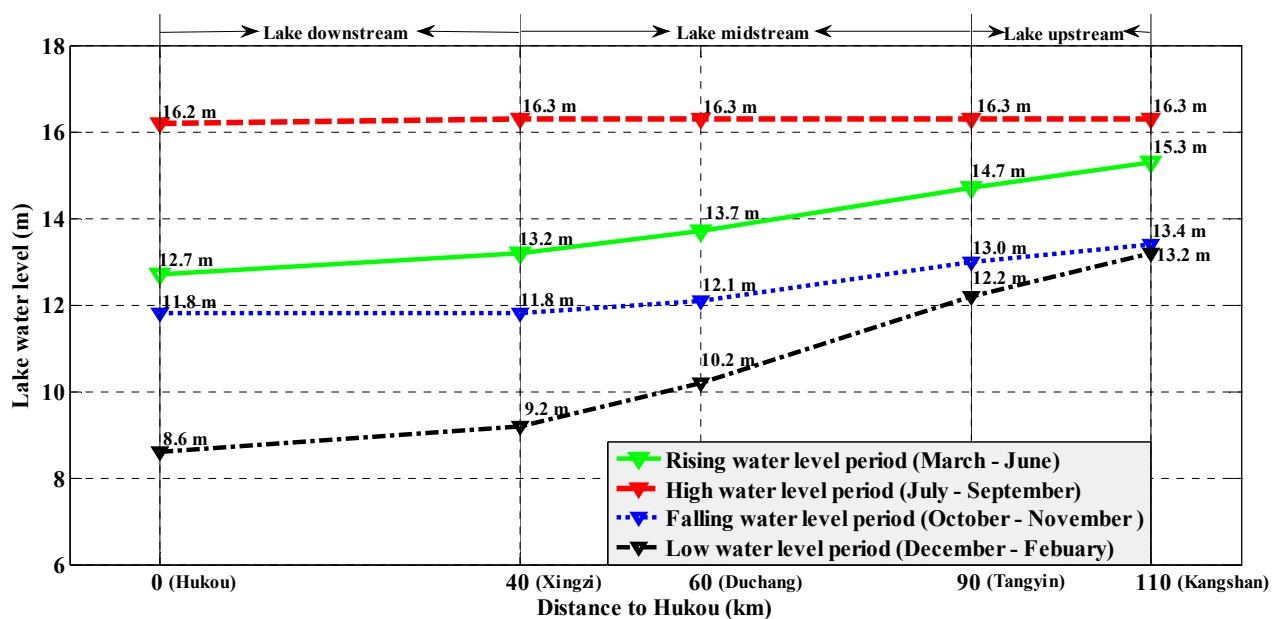


Figure 2. Observed lake water surface profiles for different water level periods based on the average water levels of the Hukou, Xingzi, Duchang, Tangyin and Kangshan gauging stations for the years 2000–2010.

3. Methodology

3.1. Hydrodynamic Model

As a river-dominated lake, Poyang Lake exhibits an extensive surface area ($>3000 \text{ km}^2$) [38], is shallow (the depth is 8.4 m averaged over the whole lake) and is vertically well mixed [28]. Therefore, the vertically averaged currents (or two-dimensional currents) may be suitable to represent the majority of the flow in the lake. In response to this, a 2D depth-averaged hydrodynamic model for the lake has been implemented [37] using the MIKE 21 code [39]. The MIKE 21 code has been extensively applied in studying various water bodies, including the Alberni Inlet (Canada) [40], the Emilia Romagna coastal area (Italy) [41], the Arabian Sea (India) [42] and Lake St Lucia (South Africa) [43]. Therefore, only a brief description of the code is given here.

For the large floodplain of Poyang Lake, the irregular shorelines for the lake model based on historical flood inundation records was determined using GIS (Geographic Information System) technique [37]. The wet-dry point treatment method of MIKE 21 [39] was suitable for simulating the wetting and drying processes associated with the considerable variations in the lake area. A 2D grid system with variable mesh resolutions (unstructured triangular grid) was adopted to capture the complex lake bathymetry (in year 2000; Figure 3a) and to provide a reliable simulation of lake hydrodynamics by using grid sensitivity test [37]. This approach provided computational efficiency and allowed sharper gradients to be maintained with coarse mesh resolution. A higher mesh resolution was applied to the relatively deep and narrow flow channels across the lake, whereas a coarse mesh covered the relatively flat plain area of the adjacent lake floodplains (Figure 3b). Thus, the grid has 11,251 nodes and 20,450 triangular elements with approximate minimum and maximum element sizes of 70 and 1500 m [37]. Daily catchment inflows from the five main rivers were specified as upstream boundary conditions in the hydrodynamic model. The connection of the lake to the Yangtze River was simulated by specifying the downstream boundary water levels as those observed at Hukou gauging station. Spatially uniform but time-varying precipitation and evaporation rates were averaged from five lake gauging stations (locations shown in Figure 1b) and used for the Poyang Lake surface in the hydrodynamic model [37]. The minimum time step of the numerical integration was set to 5 s to maintain the Courant–Friedrich–Levy (CFL) condition for a stable solution [37].

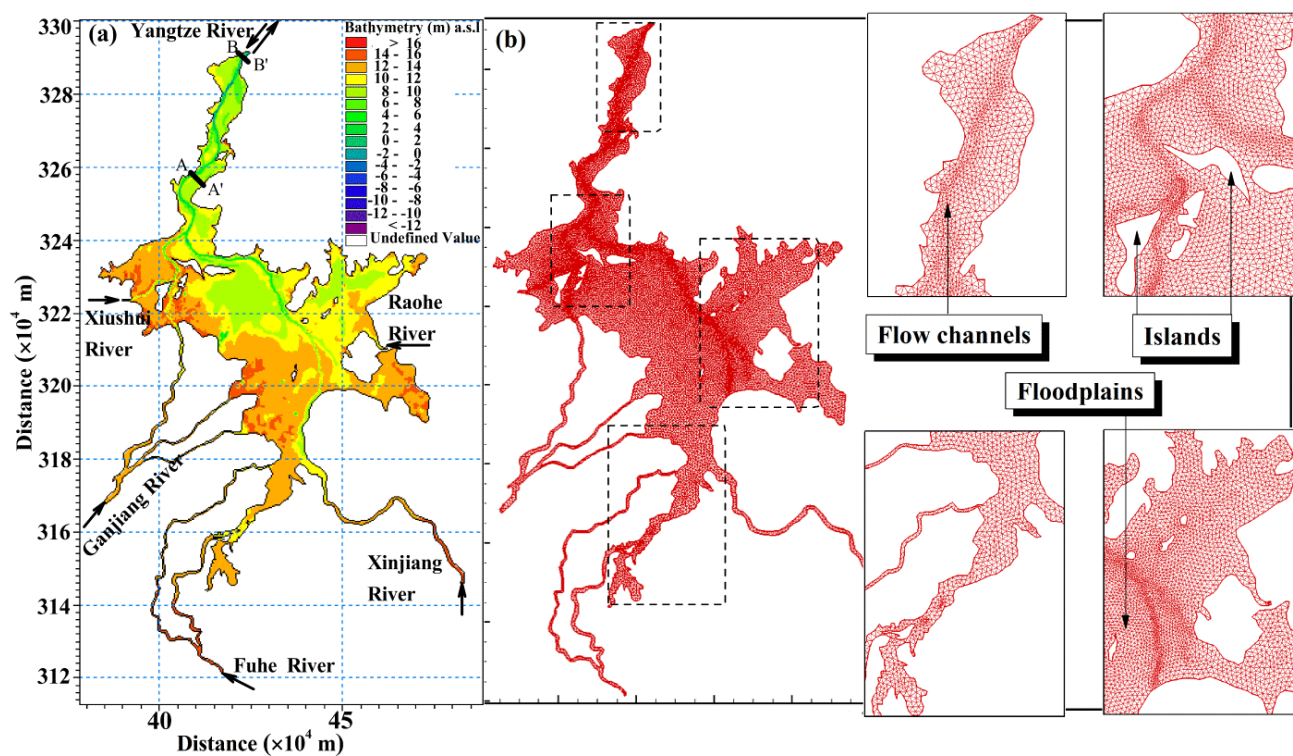


Figure 3. (a) Poyang Lake bathymetry, cross-sections of velocity observations (A-A' and B-B') and inflow/outflow sources of the lake (black arrows); (b) the unstructured grid for the MIKE 21 model and a close-up of the variable mesh resolution.

The performance of MIKE 21 was successfully validated against a wide variety of field observations conducted over 9 consecutive years (2000–2008) [37], including (1) lake water-level records at the Xingzi,

Duchang, Tangyin and Kangshan gauging stations (locations shown in Figure 1b); (2) flow rates at the Hukou gauging station (location shown in Figure 1b); and (3) lake water-surface areas and 2D inundation maps obtained from 14 MODIS (Moderate Resolution Imaging Spectroradiometer) images from year 2004. In an effort to further validate the model's ability to predict the lake hydrodynamics, a particular focus is placed on the predicted velocity variations at two typical cross-sections (see A-A' and B-B' in Figure 3a). In the present study, a comparison between depth-averaged velocity magnitudes from the ADCP (Acoustic Doppler Current Profile) velocity profile observations and model simulations at the cross-sections of Hukou and Xingzi were conducted over the wet (May 2008) and dry (December 2008) seasons (Figure 4). Although the model appears to be in agreement with the observed flow velocities for different water level periods (Figure 4), some model components proved somewhat difficult to accurately reproduce, such as the under- or over-estimated flow velocities in magnitude and phase (Figure 4), because the complex bathymetry exerted more influence on the velocity than the water level [37]. However, as the model is able to capture most of the important hydrodynamic characteristics and has an acceptable accuracy (the determination coefficient R^2 varies from 0.79 to 0.84; see Figure 4), it meets the requirements for using the 2D depth-averaged hydrodynamic model (see the insert chart in Figure 4) for transport time scale investigations.

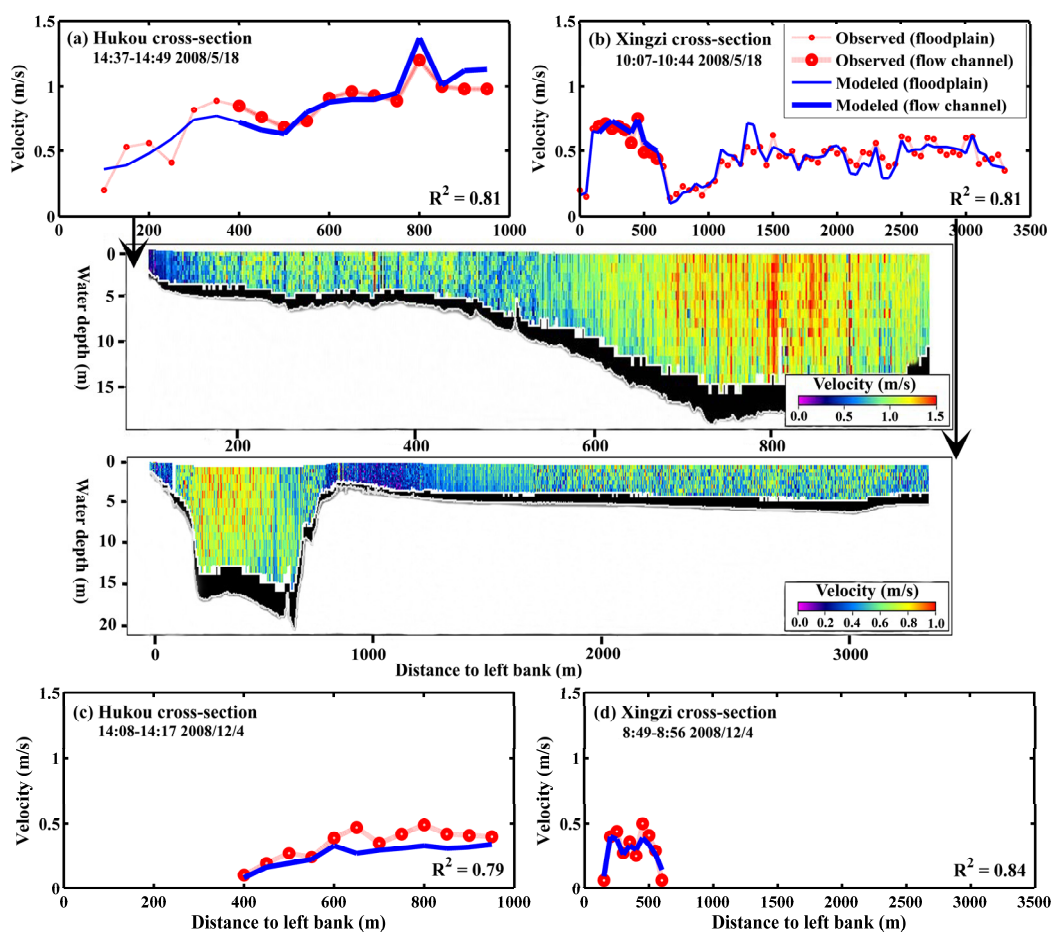


Figure 4. Comparison between depth-averaged velocity magnitudes from ADCP observations and simulations at two cross-sections of Hukou and Xingzi for periods of rising (a,b) and low water levels (c,d). Note that the insert chart represents the ADCP velocity profile observations sampling every 1 s.

3.2. Physical Setting of the Simulation Scenarios

To investigate the residence and travel times in Poyang Lake, the hydrodynamic model MIKE 21 [37] was used to generate the relevant hydrodynamic fields that drive the dye tracer simulations (2D advection-dispersion) [39].

Residence time (*e*-folding time in the present study) was measured to track the spatial and temporal distributions of a conservative tracer following its uniform distribution throughout the lake at an initial concentration (instantaneous release) corresponding to 100% (arbitrary unit; kg/m³ used in this study) and a concentration of zero at the boundaries. Consequently, the *e*-folding times for each computational cell of the hydrodynamic model MIKE 21 were obtained to show the spatial distributions of the residence times. Seasonal variability in water circulation implies a need to perform separate simulations for various water level regimes of Poyang Lake. Hence, the releases were assumed to take place in the spring (on the 1st of April; water level rising period), summer (on the 1st of July; high water level period), autumn (on the 1st of October; water level recession period) and winter (on the 1st of January; low water level period). Subsequently, the travel times were calculated for these four seasons by assuming continuous injection of a conservative tracer at three different locations (see Section 4.3 for more detail). Three locations were chosen because they best represented the pollution sources frequently occurring at the mouths of the rivers entering Poyang Lake [23,24]. In these locations, the tracer was released continuously (1.0 kg/m³ used in this study) over a period of 24 h (*i.e.*, the first day of the simulations), and a concentration of zero was imposed for the boundaries and for any other areas in the lake domain. Finally, travel times were determined based on the simulated peak concentrations at the lake outlet (Hukou).

Before running the model, the length of the residence and travel times were unknown; therefore, a reasonable simulation period had to be selected. In each case, starting from the date of release, the simulation covered a period of 365 days. The initial condition for each case was specified according to the previous lake water surface of the release date. To define a representative condition for hydrological regimes, the major forcings such as the observed five river inflows and Hukou water levels were averaged over a period of 10 years (2001–2010) and were used as model inputs rather than using an arbitrary year. Additionally, uniform precipitation and evaporation to/from the Poyang Lake surface and a constant wind field (wind direction = 45° NE, wind speed = 3.03 m/s) were considered. It should be noted that these meteorological conditions across the lake, though variable, were proven to have a relatively minor effect on the hydrodynamics of this unique lake system [28]. Furthermore, the values of the validation coefficients and other settings of the MIKE 21 model are the same as previous work [37]. The simulations differed in the tracer release dates and forcing functions applied.

4. Results and Discussion

4.1. Spatial Distribution of the Residence Time and Physical Interpretation

Figure 5 shows the spatial distribution of the residence times for the tracer release in the spring (1st of April) during the water level rising period. The results indicated that the water residence times at magnitudes of 5–10 days were observed in the main flow channels of the lake, which is mainly governed by along-channel advection during this wet season [27]. This result is consistent with previous study [44]. The study concluded that the monthly mean residence time varies from 5 to approximately 15 days for

the water level rising period of Poyang Lake. In addition, the downstream values of the residence times appeared to increase upstream (e.g., 8 days for Hukou gauging station and 5 days for Duchang gauging station; see Figure 5b), which was partly attributed to hydraulic gradient differences for the Hukou–Xingzi and Duchang–Kangshan sections during this water level rising period (Figure 2). The residence times were shorter than 2 days for most upstream areas with high bed elevations (Figure 5a), depending on the frequent wetting and drying processes of the lake as a result of the changing catchment inflows [16]. The residence times in the eastern bay of the lake reached approximately 150 days (Figure 5c) due to the regional clock-wise water recirculation (Figure 6) caused by the combined effects of the islands and the relatively sharp bathymetric features in this region (Figure 3a). This type of water recirculation has been confirmed by the previous field observations [27] and is most likely responsible for the slower tracer removal in this area. Overall, the residence times in the main flow channels are significantly shorter than the values in other areas due to the velocity differences and associated water flows (Figure 6).

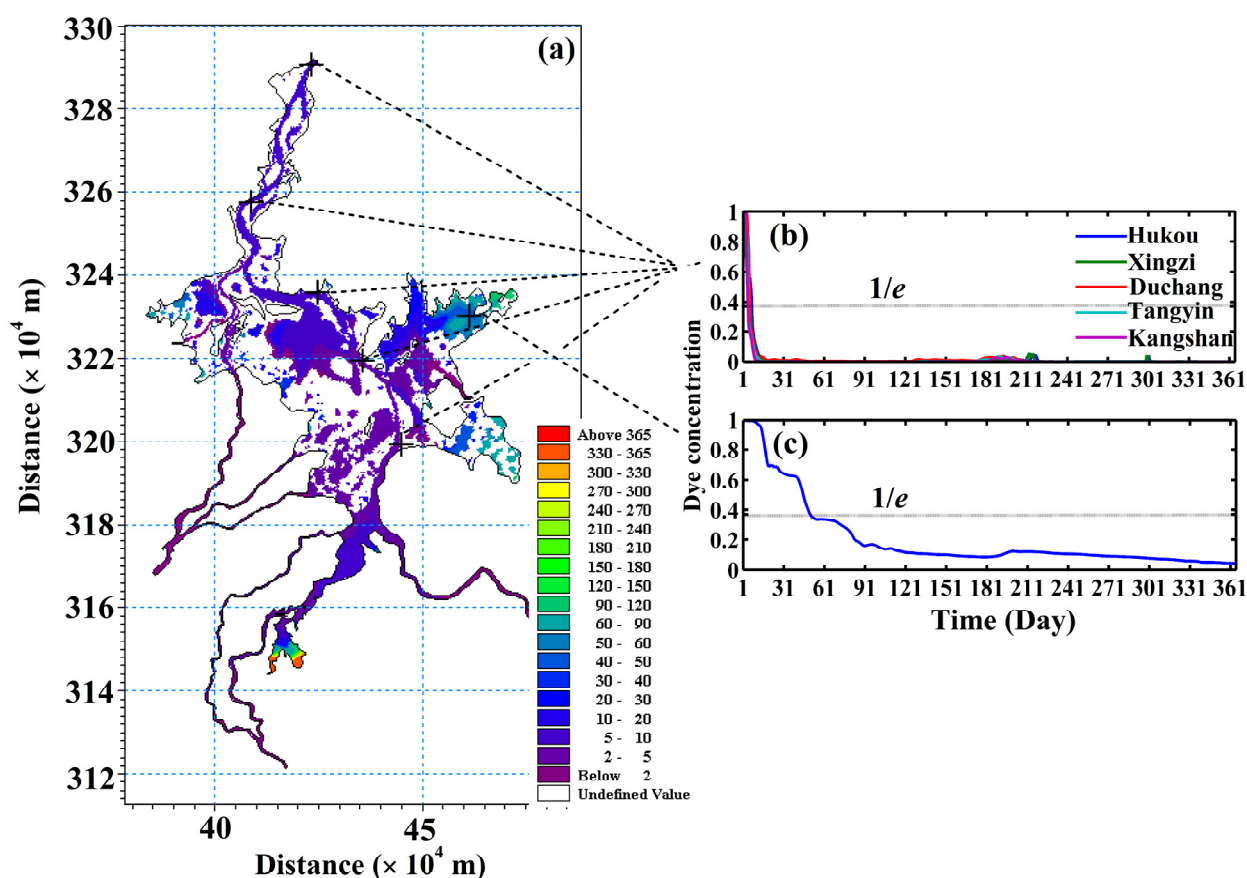


Figure 5. (a) Spatial distribution of the depth-averaged residence times (in days) for the water level rising period; (b,c) the computed dye concentrations (in kg/m³) with time for the areas of interest. Releases were performed on the 1st of April during the spring. Note that the “Undefined Value” represents dry land.

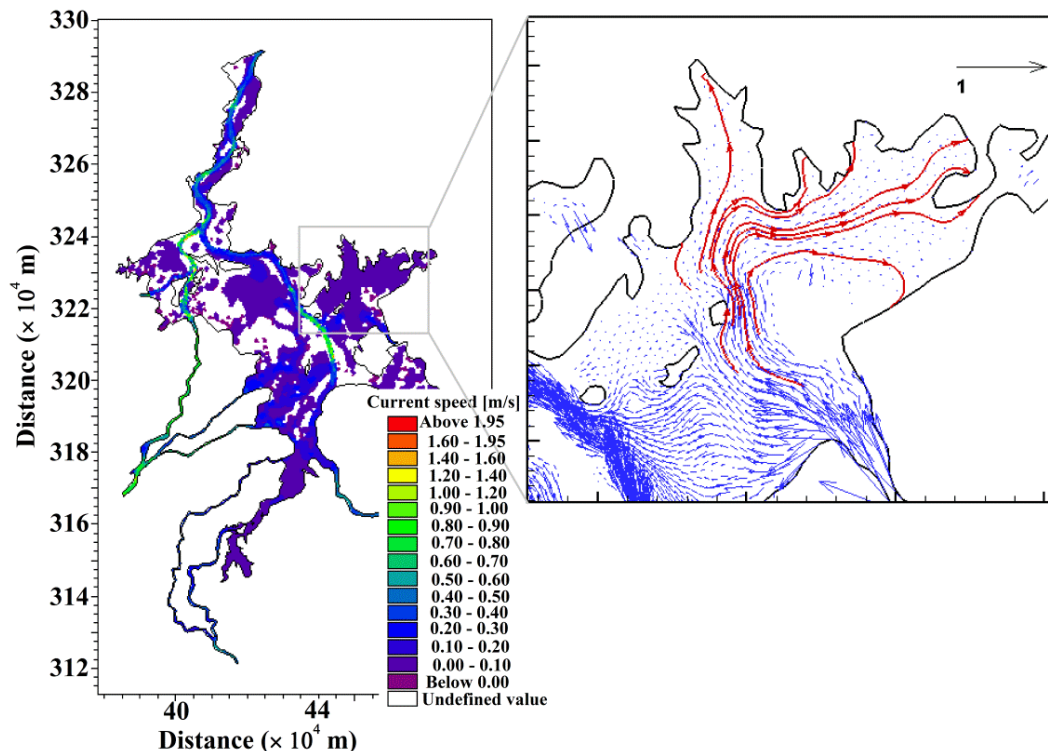


Figure 6. Map of the depth-averaged velocity (m/s) averaged over the water level rising period of MIKE 21 runs and a close-up of the velocity field for the region of interest. Red arrows represent the streamlines and associated flow directions. Note that the “Undefined Value” represents dry land.

The summer release (1st of July) with high lake water levels is illustrated in Figure 7. It is evident that the residence times of this “lake behavior” are significantly higher than the residence times of the “river behavior” in the spring during the water level rising period. This expected result coincides with evidence that suggests a negligible hydraulic gradient in the water surface (Figure 2) with significantly lower velocities (<0.1 m/s; Figure 8) across the entire lake domain, and a higher lake volume during the summer seasons. The waters adjacent to the lake’s catchment river mouths are renewed considerably more quickly, with residence times of shorter than 2 days (Figure 7a,d), due to the stronger flushing of the catchment river inflows (Figure 8). From the upstream gauging station of Kangshan to the lake outlet of Hukou, the tracer concentrations along this main flow channel and its floodplain drop below the e -folding time after approximately 20–30 days following its introduction (Figure 7b), which is consistent with the average value of 26 days (in July and August) found by previous study [26]. However, areas characterized by slightly higher residence times are located in the downstream flow channels of the lake (Figure 7a), which is mainly attributed to the strong effects of backflow from the Yangtze River on northern Poyang lake (Figure 8) [17,27]. In addition, this complex water exchange process causes some perturbation in the dye concentrations from the downstream extremity to the most upstream ends of the lake (Figure 7b). The effect of this type of lake-river interactions on the hydrodynamics can reach the upstream ends of the lake [19]. The strong gradient in residence times from the catchment river mouths to the main flow channels in the lake were clearly reproduced (Figure 7a). This finding indicates that the influences of the river catchments (on residence times) gradually decrease in the center of the lake from the surrounding river mouths. Furthermore, the significantly lower velocities resulted in the highest

residence time (up to 365 days) in some bays relative to any other areas in the lake domain (Figure 7a). Previous study found that the residence times in the bays of the lake reached a peak of approximately 270 days during this high water level period (in year 2008) [44,45]. In general, this study delivers the estimates of the same order for this high water level period.

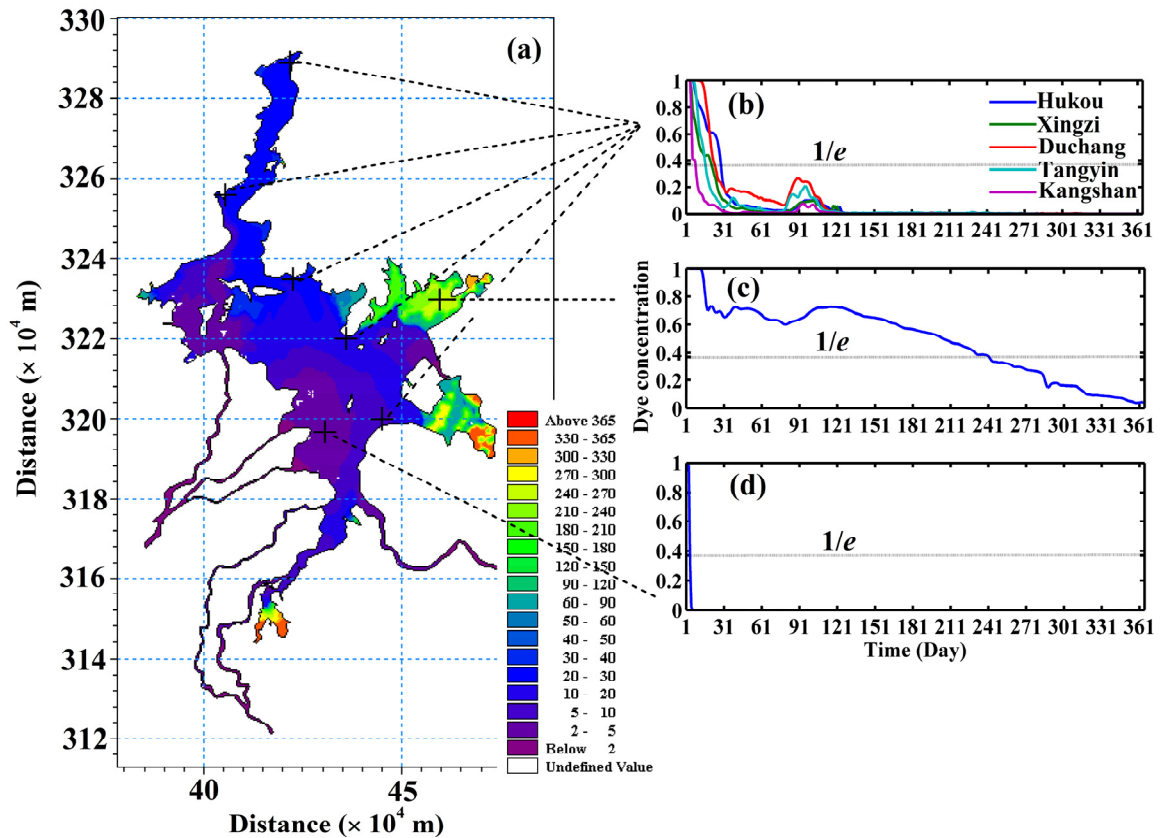


Figure 7. (a) Spatial distribution of the depth-averaged residence times (in days) for the high lake level period; (b–d) the computed dye concentrations (in kg/m^3) with time for the areas of interest. Releases were performed on the 1st of July during the summer. Note that the “Undefined Value” represents dry land.

Although no observation was made to confirm the spatial pattern of the residence times, the locations and magnitudes of the concentrations of water environmental factors can be explained, in part, by the “residence time distribution” phenomenon [5,26,32,46]. Figure 9 shows the spatial distribution of algae biomass averaged over 83 field samplings during the high water level period (in July 2012) of Poyang Lake. Notably, the maximum accumulation of algae biomass (e.g., the eastern and southern bays of the lake) appears to coincide with the maximum residence time shown in Figure 7. The low concentrations are in agreement with the short residence times along the main flow channels of the lake (Figure 9). Moreover, the spatial distributions of chlorophyll *a*, TN, TP and COD_{Mn} (chemical oxygen demand, measured by potassium permanganate) concentrations (averaged over July–September from year 2009 to 2012) are also consistent with the residence time distribution of the present study [46], indicating that the spatial pattern of the residence times has important environmental implications for Poyang Lake [26,45].

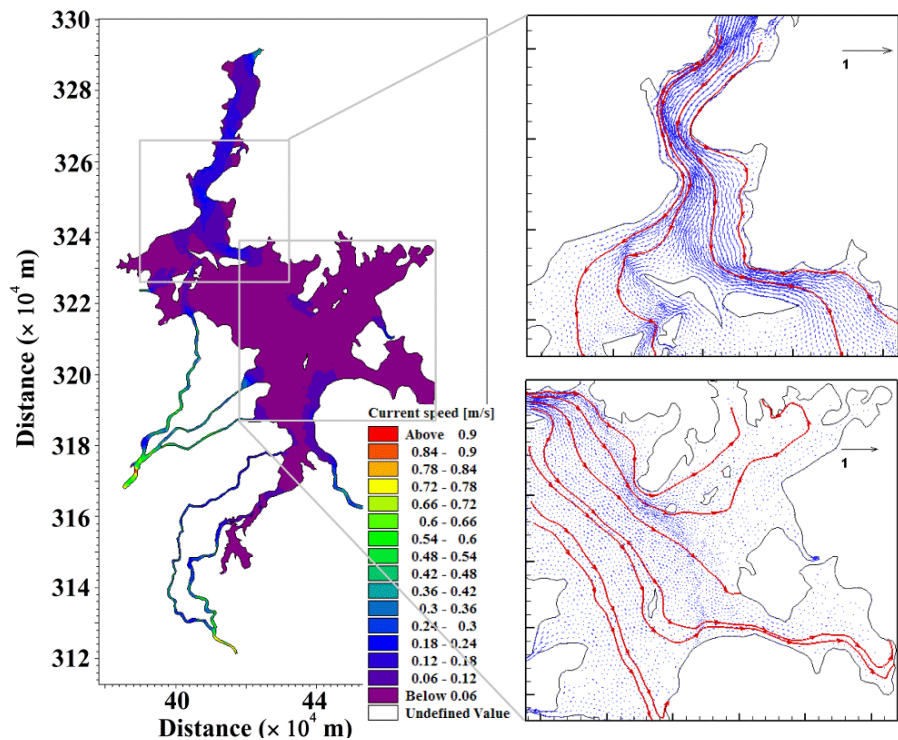


Figure 8. Map of the depth-averaged velocity (m/s) averaged over the high water level period of MIKE 21 runs and a close-up of the velocity field for the region of interest. Red arrows represent the streamlines and associated flow directions. Note that the “Undefined Value” represents dry land.

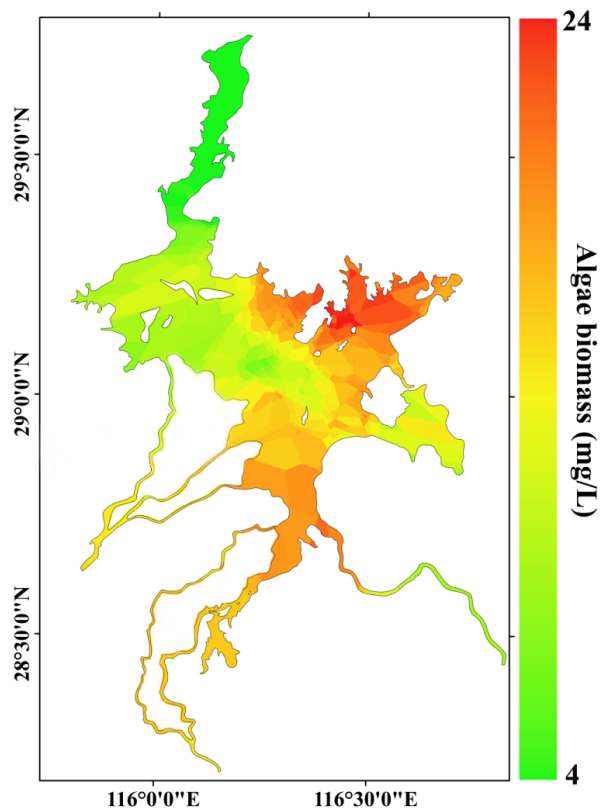


Figure 9. Spatial distribution of algae biomass (in mg/L) in Poyang Lake. Algae biomass data were obtained from 83 field samplings in July 2012.

The release case in the autumn (1st of October) represented the water level recession period and is shown in Figure 10. The residence times significantly decreased relative to the period with high water levels in the summer (compare Figure 10 to Figure 7), mainly due to the gradually decreasing water level of the Yangtze River, which increased the hydraulic gradient between the lake and the river (Figure 2) and intensified the lake's discharges (Figure 11). It should be noted that similar distribution patterns of the residence times are represented between the autumn and summer releases. This similarity can be partly attributed to the contraflow of the Yangtze River, although the water levels of the Yangtze River for the recession period were relatively lower than the water levels in the summer [28]. The residence time of the main flow channels of the lake is approximately 20 days (Figure 10a,b), which is slightly shorter than the residence times in the adjacent floodplain due to the relatively faster water velocities (0.3–0.4 m/s) in the main flow channels (Figure 11). The highest values (approximately 200 days or higher) were predicted for the eastern bays that are adjacent the lake shorelines (Figure 10a,c), indicating a poor flushing for local regions (the velocity ranges in magnitude from 0.1 to 0.2 m/s; Figure 11).

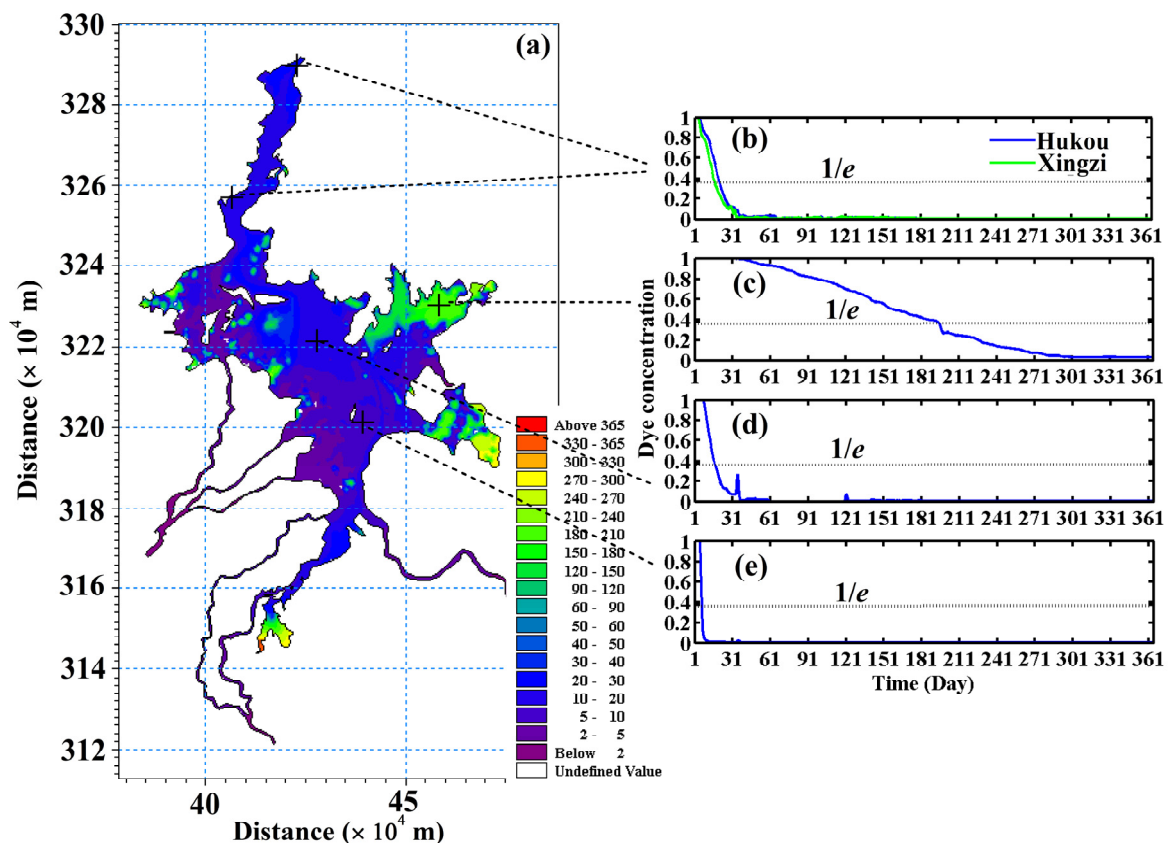


Figure 10. (a) Spatial distribution of the depth-averaged residence times (in days) for the water level recession period; (b–e) the computed dye concentrations (in kg/m³) with time for the areas of interest. Releases were performed on the 1st of October during the autumn. Note that the “Undefined Value” represents dry land.

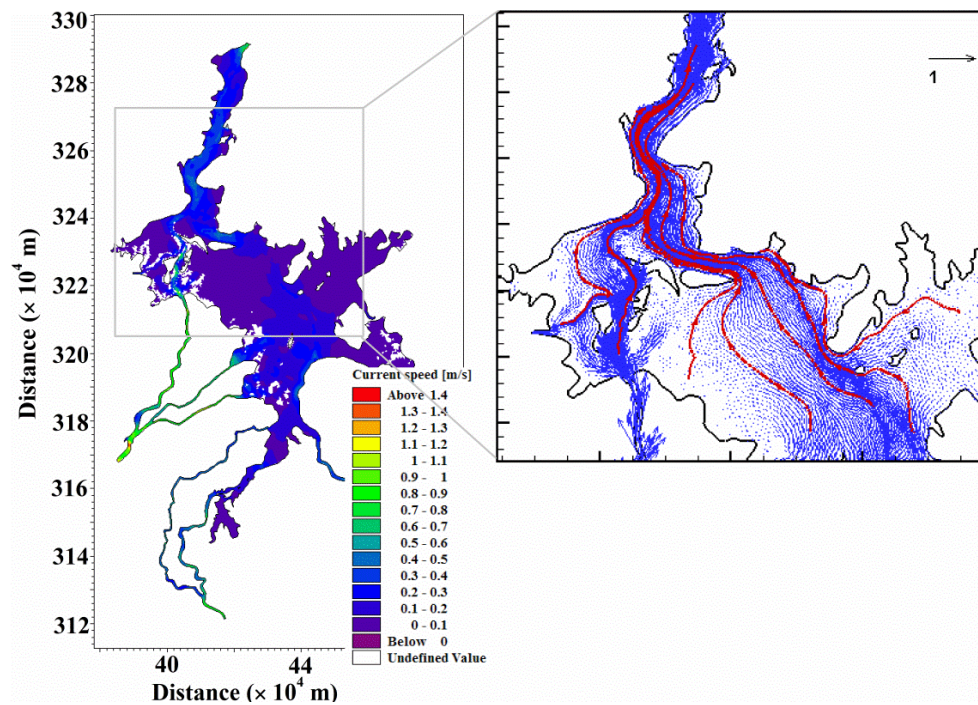


Figure 11. Map of the depth-averaged velocity (m/s) averaged over the water level recession period of MIKE 21 runs and a close-up of the velocity field for the region of interest. Red arrows represent the streamlines and associated flow directions. Note that the “Undefined Value” represents dry land.

Figure 12 demonstrates the high spatial variability of the residence times based on the winter release simulation (1st of January) during the low water level period. For this low lake water level regime with dominated gravity flow (the considerably greater water level gradient increases the horizontal component of gravity) [28], a relatively shorter residence time of approximately 10 days was observed for the main flow channels (Figure 12a,b), which agrees with the previous result for mean conditions in winter [44]. This finding is not unexpected because during the period with extremely low water levels, the along-channel water movement is northward and moves quickly from the shallower (upstream) to the deeper regions (downstream) of the lake channels (the velocity is up to 1.2 m/s; Figure 13) [26,37]. In addition, the water surface area of the lake decreases and the tracer removal is intensified in this area (Figure 12). It is interesting to note that the sublakes are separated from the main flow channels and exhibit significantly different residence times at magnitudes of 30–100 days (Figure 12); this pattern strictly coincides with the slower water movements in these relatively closed water bodies than in the main flow channels (Figure 13), in which tracer drift depends primarily on meteorological conditions (e.g., precipitation, evaporation, and winds). The highest residence times occurred in some bays that are adjacent to the lake shorelines, which indicated weak flushing (Figure 12). These results can be further explained with the water environmental factors [47], *i.e.*, the TN, TP and COD_{Cr} (chemical oxygen demand, measured by potassium dichromate) concentrations in the eastern and southern bays of the lake are higher than the concentrations in the main flow channels during the low water level period (in February 2008), which is consistent with the spatial pattern of the residence times shown in Figure 12. As noted previously, the concentration distribution can be partly supported the spatial patterns of the residence times [26,32].

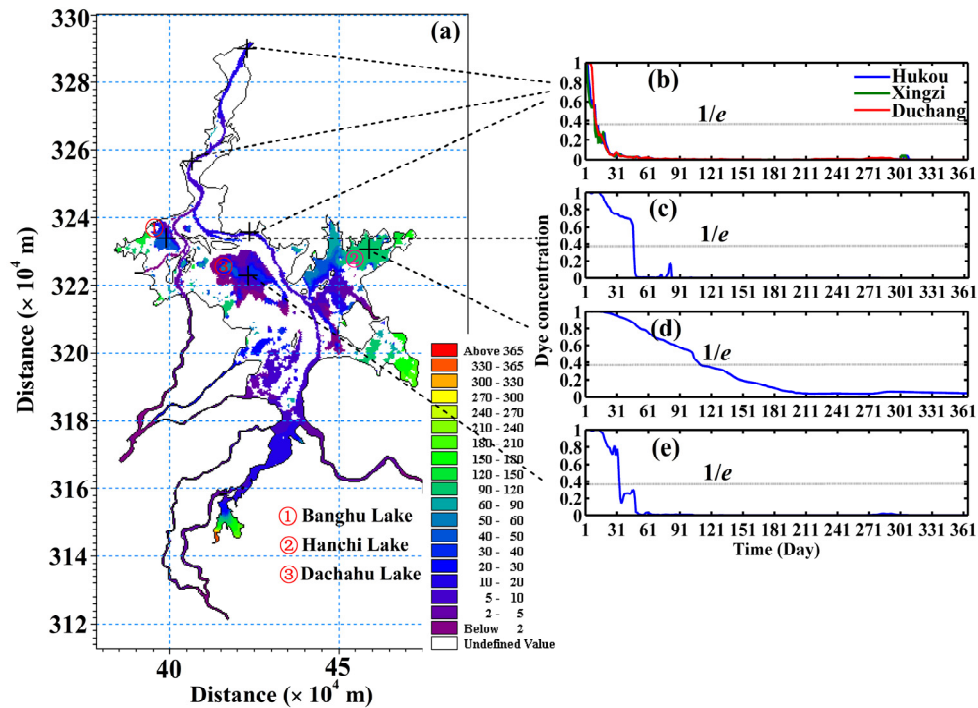


Figure 12. (a) Spatial distribution of the depth-averaged residence times (in days) for the low water level period; (b–e) the computed dye concentrations with time (in kg/m^3) for areas of interest. Releases were performed on the 1st of January during the winter. Note that the “Undefined Value” represents dry land.

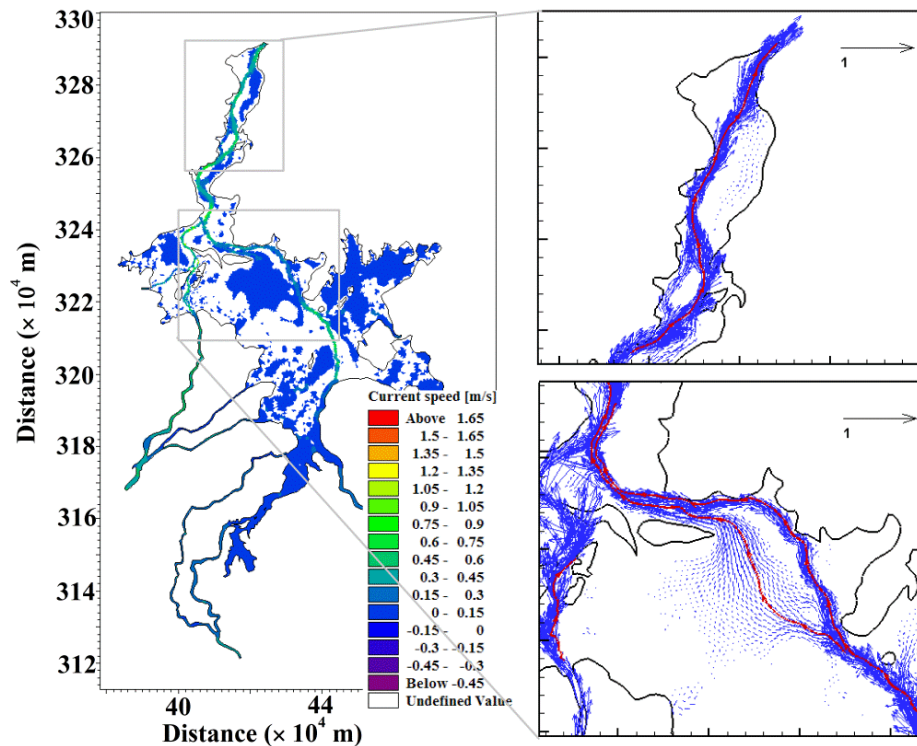


Figure 13. Map of the depth-averaged velocity (m/s) averaged over the low water level period of MIKE 21 runs and a close-up of the velocity field for the region of interest. Red arrows represent the streamlines and associated flow directions. Note that the “Undefined Value” represents dry land.

4.2. Frequency Distribution Curves

Figure 14 shows the frequency distribution curves of the four water level regimes calculated from the spatial distributions of the residence times. Generally, the steeper the frequency distribution curve, the less variation in the residence time values for any hydrological system [3]. The characteristic shapes of the curves indicate that although large portions of the lake are characterized by similar residence times, places with sharp τ_e gradients can be expected (Figure 14). This finding is represented as a characteristic ‘step’ in the frequency distribution curves. Figure 14 shows that a large percentage of the area (approximately 80%) features τ_e values of between a few days and approximately 1 month. For τ_e values of more than 1 month, the gradient of the curves is significantly shallower. The characteristic shapes of the frequency distribution curves with apparent contraflexure points were similar for all of the tracer release cases, which indicated the transition of the flushing characteristic (Figure 14). The most pronounced feature of the frequency distribution curves was the characteristic ‘step’ that indicated that Poyang Lake is a mixing system, which can be divided into fast (the main flow channels of the lake) and slow flushing (some bays adjacent to the lake shorelines) systems during different water level regimes (Figure 14).

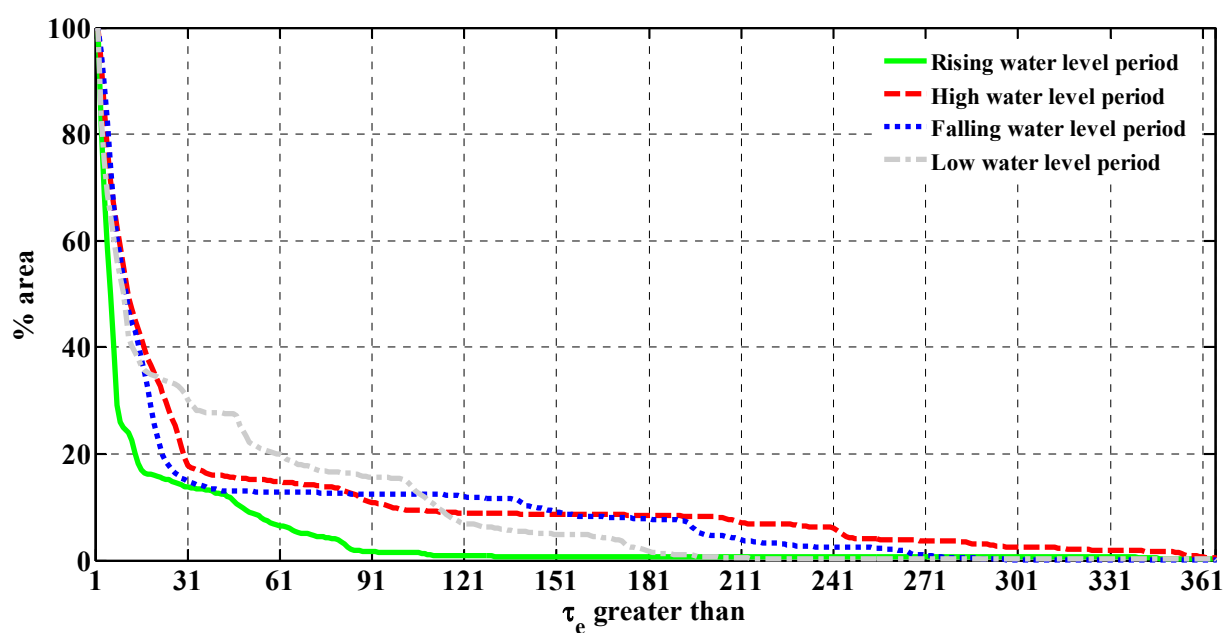


Figure 14. Residence time frequency distribution curves of the four water level regimes obtained from the MIKE 21 hydrodynamic modeling runs.

4.3. Travel Time for the Potential Pollution Sources and Physical Interpretation

A travel time analysis was conducted to further investigate the flushing ability of Poyang Lake. For the transport from the C1 release point to the Hukou outlet, the travel times fell within a range of 4–17 days, with higher values occurring during the periods of high and falling water levels (see Figure 15i). It took nearly four times longer for the tracer to arrive at the lake outlet during these periods relative to the periods with rising and low water levels (Figure 15i). In addition, this phenomenon can be observed in Figure 15ii (C2 release point; travel time ranging from 7 to 32 days) and Figure 15iii (C3

release point; travel time ranging from 6 to 30 days). The seasonal behaviors of the travel times are consistent with previous results [45], *i.e.*, the travel times (in year 2008) were approximately 15 days for periods of rising and low water levels and approximately 40 days for high and falling water levels.

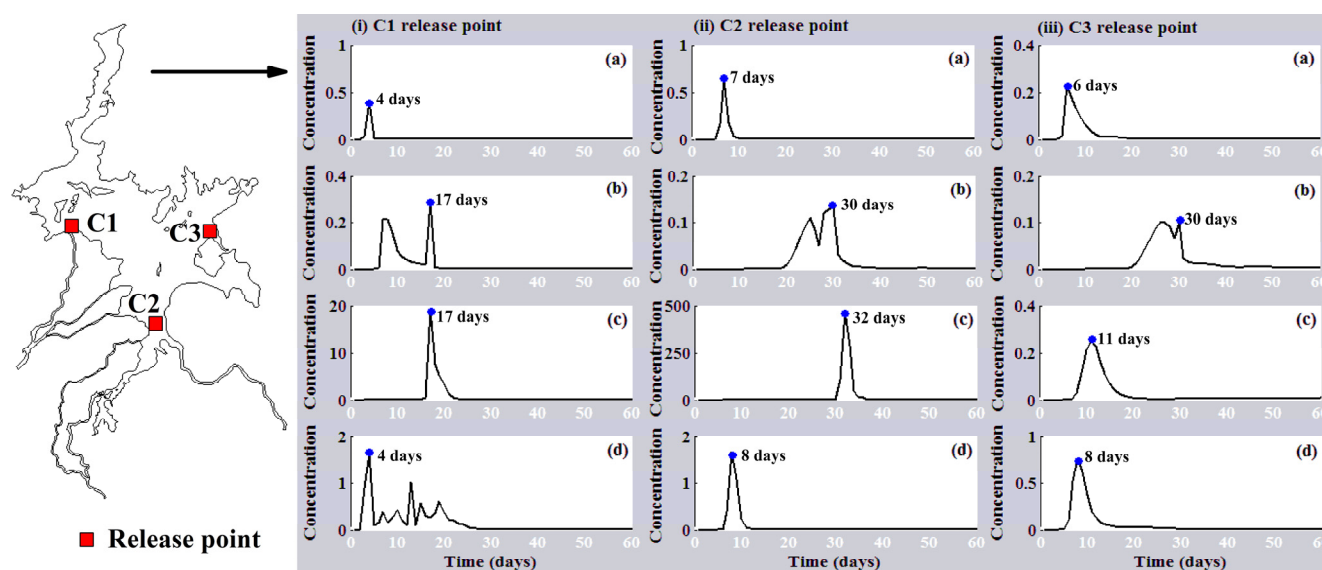


Figure 15. Time series of tracer concentrations at the Hukou lake outlet (concentrations after 60 days are not shown due to low values). Releases were performed during (a) the water level rising period on the 1st of April during the spring; (b) the high water level period on the 1st of July during the summer; (c) the water level recession period on the 1st of October during the autumn; and (d) the low water level period on the 1st of January during the winter. Here, time represents the time elapsed since the release. The blue dot represents the peak concentration and the associated travel times that are defined in this study. A unit dye concentration of 10^{-4} kg/m^3 was used.

The most notable finding obtained from the modelling results is that the travel times were nearly the same during the periods of rising and low water levels and during the periods of high and falling water levels (Figure 15). This phenomenon can be explained by the advection-dispersion processes of the lake. Due to the substantial influences of the Yangtze River, the lake water surface is almost horizontal with relatively small water level differences for the high and falling water level periods (Figure 2), and the resulting small flow velocities across the lake (Figures 8 and 11) increase the dispersion process of the dye tracer. Although the average travel time is generally determined by the advection process of the horizontal transport, the dispersion process plays a considerable role during the high and falling water level periods of the lake, which is similar to previous reports [48,49]. However, the relatively small dispersion in the lake can be neglected for the rising and low water level releases. The dye quickly arrived at the northward outlet, attributed to the along-channel advection-dominated regime, which is mostly due to the rapid along-channel water flows from shallower to deeper regions of the lake (Figures 6 and 13) as a result of the large water level gradients (Figure 2). It should be noted that although the dispersion coefficient changes with time and location (this is the same as the flow velocity), flow velocity changes may play a larger role than the variable dispersion coefficient of the hydrodynamic model [49,50].

Overall, our results demonstrate that the travel times are mainly determined by the highly dynamic water level regimes of Poyang Lake.

5. Summary and Conclusions

This study presents detailed research that contributes to a better understanding of the flushing characteristics of the large floodplain of Poyang Lake with complex water level regimes. This study is the first to use hydrodynamic modeling combined with tracer release experiments to study transport time scales for this naturally hydraulic-linked lake system. The aim of this research was limited to revealing the spatial variability of the residence time, the seasonal behaviors of the travel time, and the water level dynamics controlling the residence and travel times. This study provides important information regarding the sustainable management of Poyang Lake given its deteriorating water quality. The main conclusions are summarized as follows:

(1) The residence times with highly spatial variability that differed in hydrographically sub-regions within Poyang Lake, which varies roughly from less than 10 days along the lake channels to 365 days in some bays adjacent to the lake shorelines. Relatively large spatial residence time variations between the periods of high (falling) and low (rising) water levels were observed in the lake depending on the seasonal water level regimes as a result of the combined effects of catchment rivers and the Yangtze River. Generally, the results indicate that Poyang Lake exhibits strong but spatially heterogeneous residence times that vary with its highly seasonal water level dynamics.

(2) The frequency distribution curve of the lake's residence time provides useful generic information regarding the degree of variation in flushing across the lake domain. The curves of the shallow gradients for Poyang Lake indicated higher spatial variability in residence times. Additionally, the characteristic 'step' of the frequency distribution curve demonstrates that the Poyang Lake domain is divided into fast (the main flow channels of the lake) and slow (some bays adjacent to the lake shorelines) flushing systems.

(3) The results indicated that the travel times from the potential pollution sources to the lake outlet varied seasonally. Nearly identical travel times occurred during the periods of high and falling water levels (up to 32 days), and these were four times longer than the travel times observed during the periods of low and rising water levels (less than 8 days), which is attributed to the advection-dispersion processes of the lake dependent on changes in the seasonal water level regime.

Our modeling effort represents a first step in integrating lake hydrodynamics to provide a better understanding of residence and travel times, information that is extremely important for spatially and temporally managing the chemical and ecological processes in Poyang Lake and for managing the responses of the lake to potential pollution sources. The findings of this study make it possible to conduct further ecological modeling experiments, as the transport of pollutants and their transport time scales depend largely on hydrodynamic fields. In addition, the future work should divide the lake domain into sub-regions with distinct flushing characteristics because this investigation may be beneficial for better understanding the local water environment of the lake. It is expected that the current study will eventually aid decision makers in creating a strategic lake management plan for Poyang Lake.

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Author Contributions

Yunliang Li performed the modelling simulations, results analysis and prepared the manuscript; Qi Zhang and Jing Yao contributed to the development and editing of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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