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Article

Estimation of Transport Trajectory and Residence Time in Large River–Lake Systems: Application to Poyang Lake (China) Using a Combined Model Approach

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Abstract: The biochemical processes and associated water quality in many lakes mainly depend on their transport behaviors. Most existing methodologies for investigating transport behaviors are based on physically based numerical models. The pollutant transport trajectory and residence time of Poyang Lake are thought to have important implications for the steadily deteriorating water quality and the associated rapid environmental changes during the flood period. This study used a hydrodynamic model (MIKE 21) in conjunction with transport and particle-tracking sub-models to provide comprehensive investigation of transport behaviors in Poyang Lake. Model simulations reveal that the lake's prevailing water flow patterns cause a unique transport trajectory that primarily develops from the catchment river mouths to the downstream area along the lake's main flow channels, similar to a river-transport behavior. Particle tracking results show that the mean residence time of the lake is 89 days during July–September. The effect of the Yangtze River (the effluent of the lake) on the residence time is stronger than that of the catchment river inflows. The current study represents a first attempt to use a combined model approach to provide insights into the transport behaviors for a large river–lake system, given proposals to manage the pollutant inputs both directly to the lake and catchment rivers.

Keywords: hydrodynamic model; transport model; particle-tracking model; transport trajectory; residence time; Poyang Lake; Yangtze River

1. Introduction

Lakes are vitally important components of the hydrosphere that serve multiple purposes. Apart from providing clean and safe surface freshwater for local communities, lakes can be recreation centers, have high cultural value, and provide numerous ecosystem services [1]. Extensive human activities in lake catchments are responsible for increased pollutant loads in lakes around the world, e.g., Lake Canyon in the United States [2], Sugarloaf Lake in Australia [3], Lake Erie in the United States [4], and Lake Geneva in Switzerland [5]. The discharge from the catchment rivers and tributaries, including sediment, nutrient and pollutant loads, generate substantial adverse effects on the drinking water supply and water resource regulation of large river–lake systems [4,5]. The physical transport processes and associated transport time scales in many lakes strongly influence the fate of various pollutants, and may thus affect the spatiotemporal variations in the general water quality of the lake [6].

Lakes often serve as important nursery regions and feeding grounds for a large number of species. However, because of this close relationship of lakes with humans, high-intensity production activities occur near lakes and massive populations live in areas neighboring lakes. This leads to substantial deterioration of lake water quality and associated threat to human health. In China, among the 35 key lakes that were observed by the Ministry of Environmental Protection in 2012, only 37.2% satisfied the standards set for drinking water resources, 42.8% met the lower standards set for general water use in industry, recreation, or agriculture, and the remaining 20% were of a quality even lower than this [7]. Conversely, the deterioration of lake water quality has restricted the development of regions near lakes because of water security concerns. These conflicts originate from the imbalance between overly rapid socioeconomic development and asynchronous water protection efforts [7]. Environmental stewardship requires that the water quality of any lake should be heavily regulated and properly managed. Predicting the transport and fate of pollutants in lakes is one of the most important challenges.

Poyang Lake, the largest freshwater lake in China, is an example of a highly valued water resource with complex hydrological forces [8]. The lake predominantly receives surface runoffs from the lake's catchment rivers and subsequently flows into the Yangtze River [9]. Extensive efforts have been carried out to investigate the water quality status of Poyang Lake, including field measurements and analysis [10,11], the investigation of major pollutants and pollution sources [12,13], and the analysis of the factors influencing water quality [14,15], which have provided various management strategies for local governments. With the rapid economic development around the lake, an increasing numbers of factories and communities are gathering around Poyang Lake and are discharging pollutants of various types into the lake [16]. Simultaneously, with the increase in waterway transportation, the number of accidental releases of hazardous chemicals into the lake is also increasing [17]. To the best of our knowledge, the water quality and the associated ecosystem are being seriously threatened during the lake flood period (July–September), due to the continuous accumulation of catchment river-transported pollutants along with large amounts of river discharges [10]. In addition, the extent of lake flooding with slow water flows significantly increases pollution risk of the already environmentally degraded Poyang Lake [11]. It is anticipated that the biogeochemical response of the ecosystem to inflows largely depends on the distribution pathways of river water in the lake. How pollutants are transported into the lake according to their release positions and how widely and intensively the lake's hydrodynamics affect the pollutant transport behaviors within the lake is still unknown. Such knowledge is of great importance for policymakers as it may help with water quality protection and lake ecological conservation.

Field observations or experiments that explore the special importance to the knowledge of transport trajectory and residence time for any lake system are expensive [18]. Physically based numerical models have been extensively applied in the investigation of transport behaviors because they can be used to make decisions with regard to the release of contaminants into lakes and other hydrological systems [19,20]. Previous model studies of transport trajectory in lakes have mainly focused on lakes that are driven by wind (*i.e.*, wind-driven lakes), e.g., Lake Breeze in the United States [21], Lake Huron in the United States and Canada [22], Lake Ontario in the United States [23], Lake Geneva in Switzerland [5], or Lake St Lucia in South Africa [24]. Pollution transport in such wind-driven lakes indicates that the transport trajectories appear to exhibit random pathways within the lakes, which is primarily attributed to the spatiotemporal structure of wind-driven circulation patterns as a result of highly variable wind speeds and directions [24]. The residence time in an aquatic environment has long been of interest because it is an important parameter for determining ecosystem health and its sensitivity to pollution threats [25]. Numerical models have also been used to investigate the residence time in lakes and other water bodies, such as the wind-driven Lake Taihu in China [26], the semi-enclosed Lake Tanganyika in Africa [27], and the wind-driven Lake Geneva in Switzerland [5]. Poyang Lake is distinct from previous lake systems in that it is a highly dynamic river-dominated lake system, with high complexities created by the interactions of large lake with surrounding rivers. The investigation of transport behaviors in type of large river–lake systems adds to the novelty of the current study.

In this study, we build on a previously developed 2D hydrodynamic model of Poyang Lake [28]. The model was used to investigate the effects of the Yangtze River and the catchment on the seasonal changes in Poyang Lake water levels [29]. More recently, the model was adopted to explore the seasonal variations of flushing ability in Poyang Lake [30] and investigate the hysteretic relationships of the extensive floodplains of Poyang Lake [31]. Despite several efforts to improve understanding of the river–lake system, questions remain regarding the transport behaviors and causes of Poyang Lake. Additionally, the effects of the Yangtze River and the catchment have not been quantified taking into account the dominant hydrodynamic processes of the river–lake system. This paper extends previous studies by combining the hydrodynamic model with a pollutant transport model and a particle-tracking model to explore the transport behaviors in a large river–lake system. The main objectives of this paper are to: (1) investigate the influence of lake's hydrodynamics on the pollutant transport pathways within lake, using both the transport model and the particle-tracking model; and (2) examine the residence time of pollutants within lake using the particle-tracking model, evaluating the effects of lake's inflow and outflow on the residence time. The current study represents a first attempt to use a combined hydrodynamic model with transport and particle-tracking models to offer comprehensive insights into the transport behaviors due to rapid environmental changes of Poyang Lake during the flood period.

This study is critical for guiding future strategies to properly manage the pollutant inputs both directly to the lake and rivers.

2. Study Site and Background

Poyang Lake (28°4'–29°46' N, 115°49'–116°46' E), located on the south bank of the middle-lower reaches of the Yangtze River (Figure 1a), has a recognized wetland system. The Poyang Lake wetlands are of abundant biodiversity and have been registered as internationally important habitats for many species of birds [32]. The lake has a substantial influence on flood-mitigation storage, the regulation of the local climate and the protection of global biodiversity [32]. The lake receives surface inflows from five major rivers (*i.e.*, the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers) within its 1.62×10^5 km^2 catchment (Figure 1a), and the water flows into the Yangtze River through a narrow channel at northern Hukou (*i.e.*, the junction of Poyang Lake and the Yangtze River; Figure 1b). The five rivers contribute approximately 89% of the lake's inflow, while backflow from the Yangtze River contributes around 3% of the lake's inflow (backflow occurs more frequently during July–September), with the remaining 8% made up mainly of other sources such as minor streams, rainfall to the lake's surface and groundwater discharge [8]. Additionally, the five rivers account for around 87% of the annual pollutant load of the lake based on the pollutants measurement in the rivers [11,33]. Poyang Lake is controlled by both the catchment rivers and the Yangtze River, which results in seasonal water level fluctuations of 8 to 18 m and associated water surface area changes that range from less than 1000 to over 3000 km^2 [34]. It has a maximum length of 170 km and a mean width of 17 km [35]. The features of Poyang Lake are shaped by a combination of lacustrine and riverine morphological processes. That is, the lake exhibits complex topographical features, including islands, inundated floodplain areas and main flow channels. On average, the lake's main flow channels with deep lake bathymetry vary between −8 m (downstream end) and approximately 10 m (upstream end), and the inundated floodplain areas at most lake areas have relatively high bed elevation in ranges of 10–18 m (using Huanghai sea level as datum; Figure 1b). In general, the lake bottom elevation decreases from upstream (south) to downstream (north), with a difference of approximately 6.5 m (Figure 1b).

Poyang Lake serves multiple functions related to industrial production, drinking water, irrigation, ecosystem maintenance, and the regulation of environmental functions, as well as supporting cultural and recreational functions for surrounding residents [36]. However, the steadily deteriorating water quality and the associated rapid environmental changes have intensified as a result of the pollutant loads from industrial and domestic sources as well as agricultural chemical inputs from the lake's catchment [11]. For example, on a scale of Grades I to V (from best to worst), 80% of the lake water was Grade I–II before year 2000. However, 40% of Poyang Lake has a water quality of Grade III, and approximately 20% was rated as Grade IV–V in the recent 10 years [11]. The total nitrogen (TN) and total phosphorus (TP) concentrations in the lake averaged 1.8 mg/L and 0.1 mg/L, respectively, indicating severe eutrophication of the lake [11]. The region's biodiversity has also decreased due to water pollution [36]. These urgent problems concerning Poyang Lake have gained considerable attention because they have resulted in a serious threat to the approximately 12.4 million inhabitants that rely on this freshwater resource [10].

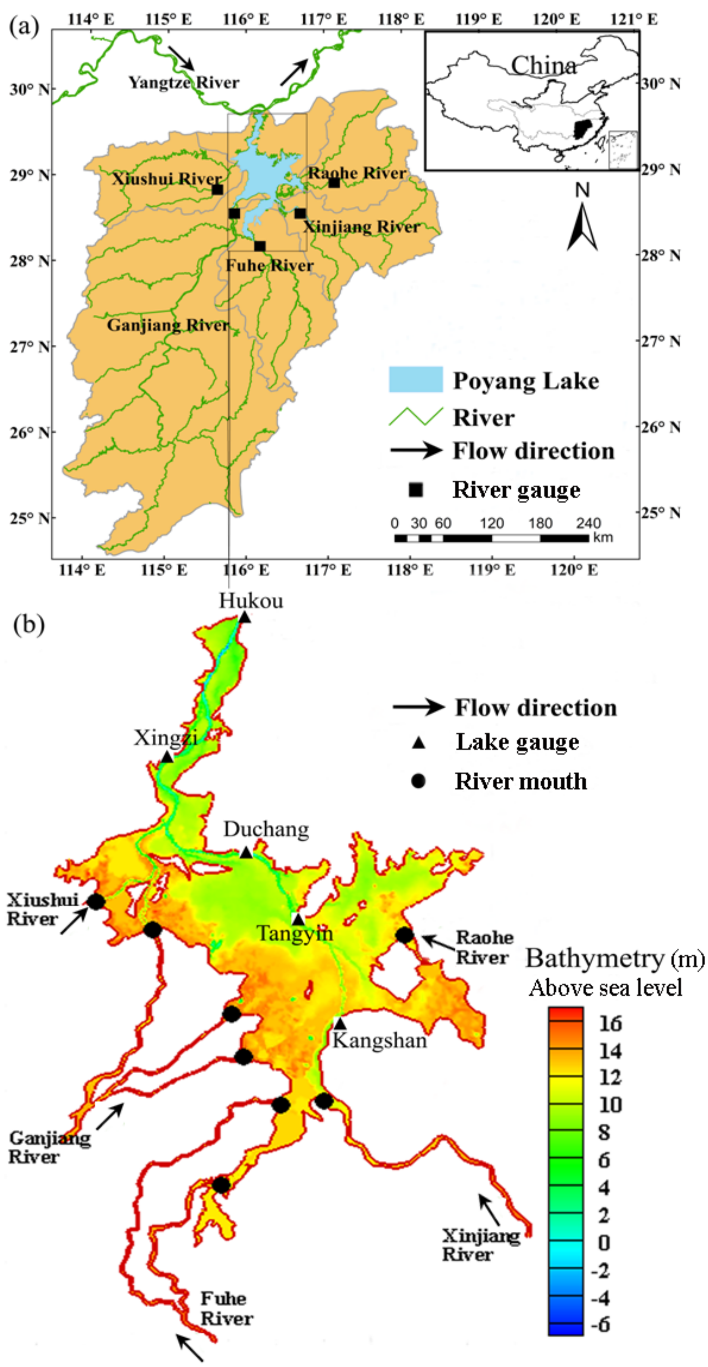

Figure 1. (**a**) Location of Poyang Lake-catchment, the main rivers and river gauging stations within its catchment; (**b**) Lake bathymetry, lake level gauging stations and river mouths.

3. Materials and Methods

A combination of hydrodynamic model, transport model and particle-tracking model was applied in this study to explore transport behaviors in Poyang Lake and provide comprehensive analysis from different perspectives. Hydrodynamic model was used to investigate flow features of the lake and thus to provide lake water levels and flow fields (*i.e.*, the model outputs) for the transport and particle-tracking models. The transport model was employed to ascertain the pollutant trajectory using dye-tracer approach, which considers the advection-dispersion processes of the lake. The particle-tracking model is expected to describe the movement of water particles and thus reproduce the transport trajectory using Lagrangian random-walk technique. A Lagrangian water residence time of the lake was examined using the particle-tracking model.

3.1. Data Availability and Model Description

The bathymetry of the lake, as used in the hydrodynamic model, was based on surveyed data updated in 2000 with 30 m × 30 m resolution (Figure 1b). The main forcing data of the hydrodynamic model include the catchment river inflows, water levels of the Yangtze River, and meteorological data on the lake surface. The observed daily river discharges at five river gauging stations in the lake's catchment (*i.e.*, the farthest downstream gauging stations of the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers; Figure 1a) were selected to represent the discharges from the lake's catchment. The observed daily water levels at the Hukou gauging station (*i.e.*, the junction between Poyang Lake and the Yangtze River; Figure 1b) were used to reflect the influence of the Yangtze River. The precipitation and evaporation rates were obtained from the five lake gauging stations (*i.e.*, Hukou, Xingzi, Duchang, Tangyin and Kangshan; Figure 1b) and used to represent the meteorological conditions on the lake surface. Wind field data were obtained from the Xingzi gauging station and used to reflect the effect of the wind. All daily hydro-meteorological data are available for the period 2001–2010. These data were obtained from the Hydrological Bureau of Jiangxi Province and the Hydrological Bureau of the Yangtze River Water Resources Commission of the Ministry of Water Resources of China.

Poyang Lake is generally shallow, with 85% of the lake less than 6 m depth during the flood seasons, as calculated from previous model results [28]. The temperature and velocity stratification can be neglected due to mostly small differences in measured vertical profiles [30,37]. Therefore, vertically averaged currents (or two-dimensional currents) are suitable to represent the wide and shallow characteristics of Poyang Lake. In response to this, a 2D horizontal depth-averaged hydrodynamic model of Poyang Lake has been implemented using MIKE 21 to investigate the seasonal dynamics of water levels, water surface areas and water flow patterns [28]. The MIKE 21 hydrodynamic model has already been successfully applied to a number of case studies, as exemplified by Poyang Lake [8,29–31]. The MIKE 21 hydrodynamic model of Poyang Lake covers the maximum historical flood inundation area of 3124 km^2, and adopts a 2D grid with variable mesh resolution to capture the complex lake bathymetry. The grid comprised 11,251 nodes and 20,450 triangular elements, with minimum and maximum element sizes of 70 m and 1500 m, respectively [28]. The upstream boundary conditions of the hydrodynamic model included five inflow sources, for which daily observed inflows from the five major rivers were used. The lake's lower boundary condition was specified as a daily series of observed water levels at the Hukou gauging station. Spatially uniform but time-varying precipitation and evaporation rates were averaged from five lake gauging stations and used for the atmospheric boundary conditions in the hydrodynamic model [28]. The minimum time step was set to 5 s to maintain the Courant–Friedrich–Levy (CFL) condition for a stable solution [28]. Other aspects of the model construction are the same as adopted by previous study [28], and therefore, only a brief description of the MIKE 21 hydrodynamic model is given here.

The performance of the MIKE 21 hydrodynamic model of Poyang Lake was successfully calibrated (for 2000–2005) and validated (for 2006–2008) with a variety of field observations [28,30], including: (1) lake water-level records at Xingzi, Duchang, Tangyin and Kangshan gauging stations; (2) flow rates at the junction of the lake and the Yangtze River (*i.e.*, Hukou gauging station); (3) lake water-surface areas (*i.e.*, 2D inundation maps) obtained from 14 MODIS images from 2004; (4) spatial distributions in the lake flow field at 4 days (*i.e.*, 15 January, 15 April, 15 September and 15 October) from 2005, respectively; and (5) ADCP (Acoustic Doppler Current Profile) velocity profile at two cross-sections of Hukou and Xingzi. The water levels at the four gauging stations produced the Nash–Sutcliffe coefficients (E_{ns}) in ranges of 0.80–0.98 for both the calibration and validation periods [28]. A comparison between the model and the gauging station estimates of the flow exchanges between the Yangtze River and Poyang Lake produced a determination coefficient (R^2) of 0.82 and 0.92 from the calibration and validation phases of model development [28]. The simulated seasonal variations in the lake water surface area produced the relative errors (R_e) of 3.3% and 16.8% for wet and dry seasons, respectively [28]. The R^2 varied from 0.79 to 0.84 for the velocity profile comparison between ADCP observations and model simulations [30]. Based on these results, the MIKE 21 hydrodynamic model was able to reproduce the major flow features of the lake, including the transient nature of flooding and recession events.

3.2. Transport Trajectory Simulations

To calculate the transport trajectory of Poyang Lake, the 2D advection-dispersion transport sub-model [38] and the Lagrangian random-walk particle-tracking sub-model [39] of MIKE 21 were adopted simultaneously by using generated flow fields of the hydrodynamic model of Poyang Lake [28].

As noted previously, the transport behavior is of great importance during the lake flood period from July to September, this time period was selected to investigate transport trajectory of Poyang Lake. Consequently, the MIKE 21 simulations were produced for the lake flood period of a representative year from 1 July to 30 September (92 days). To define a representative year, the average of the long-term records (from 2001 to 2010) was developed for a set of hydrological gauging stations around the lake. The upstream boundary conditions of the hydrodynamic model included five inflow sources (*i.e.*, the inflows from Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers, respectively), for which the time-varying river inflows from 1 July to 30 September (*i.e.*, 10-year averaged) were used. The lake's lower boundary condition was specified using a corresponding three-month sequence of time-varying water levels (*i.e.*, 10-year averaged) at the Hukou gauging station. Additionally, the spatially uniform but time-varying 10-year climatological data records (winds, precipitation and evaporation rates) were averaged and used as atmospheric boundary conditions on the lake surface.

The authors limit the discussion to six released points near the river mouths of the catchment inflows (see Section 4.1 for more detail), given the difficulties in performing detailed analyses of pollutant transport trajectory at each river mouth. These six release points best represent the primary sources of pollution (e.g., oils, Persistent Organic Pollutants, heavy metals) entering the lake from the catchment rivers [11,40], which allows for a sufficient evaluation of distribution pathways of the catchment river-transported pollutants. In the transport model, a passive conservative tracer was released continuously (*i.e.*, covered the entire simulation period) at each of the six river mouths with a constant concentration corresponding to 100% (arbitrary units; kg/m^3 was used in this study), and a concentration of zero was imposed for the boundaries and for any other areas in the lake domain. In the particle-tracking model, 100 conservative particles were released continuously (*i.e.*, covered the entire simulation period) at each of the six river mouths for every time step of 3600 s and used to preserve the target of the study to capture the particle trajectory.

3.3. Residence Time Estimation

In this study, the particle-tracking model was used to estimate the water residence time of Poyang Lake. The mean residence time of the lake is considered to be the time required to flush out a certain percentage (*i.e.*, 67%) of the conservative particles that were evenly distributed at time zero [41,42]. It is almost impossible to assign one particle to each grid cell for use of the particle-tracking model due to large horizontal scale of Poyang Lake. Therefore, a total of 100 virtual particles were evenly distributed within the lake at the initial time, 1 July (*i.e.*, instantaneous release). The minimum residence time represents the time required to reach the lake outlet from the released points. To examine the effects of catchment inflows and the Yangtze River on mean residence time of the lake, a series of 3-month model simulations (*i.e.*, from 1 July to 30 September) were conducted based on previous MIKE 21 runs (*i.e.*, the 10-year average condition; Case 0). The catchment inflows of the major five rivers were modeled for relative changes of +25%, +50% and +75% (Case 1–3) for the upstream boundaries in the MIKE 21 model, and the downstream water-level boundary at the junction of the Yangtze River and the lake (*i.e.*, Hukou) was specified as relative changes of −5%, −10% and −15% (Case 4–6), relative to the long-term average condition (Case 0). The idea here is to quantify the effects of the Yangtze River and local catchment on the flushing ability of the lake (*i.e.*, reduce the residence time). The cases differed in major forcing functions.

The lake bottom roughness (Manning number M used in MIKE 21) and Smagorinsky factor for eddy viscosity (C_s) are the main parameters in the hydrodynamic model. The settling velocity (ω_s) and dispersion coefficients (D_H and D_V) have been shown to be the key parameters affecting the pattern of drift transport in the transport and particle-tracking sub-models of MIKE 21. The physical parameters in Table 1 were prescribed based on extensive literature survey of published studies in Poyang Lake [28,43] and other similar areas [38,39,44,45].

Table 1. Model parameters used for scenario simulations.

Parameter	Description	Purpose	Values and Reference
M	Manning number	Hydrodynamic simulation	30–50 $m^{1/3}/s$ [28,45]
C_s	Smagorinsky factor for eddy viscosity	Hydrodynamic simulation	0.28 [28,45]
ω_s	Settling velocity for particles	Particle tracking	0.0082 m/s [39,44]
D_V	Vertical dispersion	Particle tracking	0.001 m^2/s [39]
D_H	Horizontal dispersion	Particle tracking and transport simulation	0.05 m^2/s [38,39,43]

4. Results

4.1. Transport Trajectories for Different Released Sources and Physical Interpretation

Water velocities and associated water flow patterns are responsible for the transport and distribution of contaminants within lake. Therefore, simulation results should be first reviewed to understand the general flow behavior indicated by the MIKE 21 hydrodynamic model. Figure 2 shows the spatial distribution of water velocity and corresponding water depth averaged over the lake flood period during July–September. As expected from most river–lake systems, the water velocities near the catchment river mouths (up to 0.4 m/s) are distinctly higher than any other areas of the lake (approximately, <0.1 m/s), suggesting strong effect of inflows from the lake's catchment rivers (Figure 2a). Within the lake, a distinct difference in magnitude of 0.2–0.3 m/s was observed between the lake's main flow channels (*i.e.*, low lake bed elevation with deep water depth ranged from 6 to18 m; Figure 2b) and the inundated floodplain areas (*i.e.*, high lake bed elevation with shallow water depth roughly <6 m; Figure 2b), especially the downstream area of the lake (Figure 2a). The difference can be at least partly attributable to the complex topography of the lake. That is, the considerably narrower cross sections with deep lake bathymetry at the lake downstream (Figure 1b) may increase the velocity differences between the lake's main flow channels and the inundated floodplain areas, relative to the upstream areas of the lake.

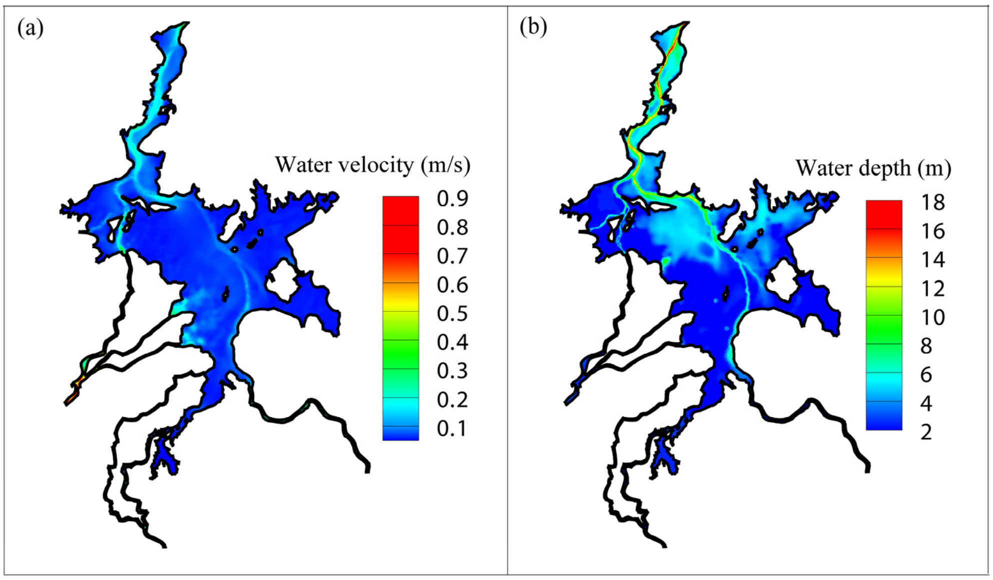

Figure 2. (**a**) Spatial distribution of water velocities and (**b**) corresponded water depths averaged over the flood period (July–September) of MIKE 21 runs.

Figure 3 further shows the spatial distributions of velocity fields at four selected time slices during July–September. In general, the large-scale patterns of the water flows produced by the hydrodynamic model show distinct south–northward flow in the entire lake (see the streamlines in Figure 3), representing the prevailing flow pattern of the lake. The water flow patterns coincide with the fact that the inflows from the lake's catchment rivers pass through the inundated floodplain areas and further flow into the lake's main flow channels. It can therefore be found that the water velocities along the lake's main flow channels are obviously higher than those of water velocities in the inundated floodplain areas (Figure 3). Additionally, the local water flow patterns in the lake could be caused by sharp bathymetric features and relatively large velocity gradients, such as those found in the eastern and center portions of the lake, generally cause gyres to form (*i.e.*, the streamlines are closed; Figure 3). The gyres in these local regions lasted for most of the flood period of the lake (*i.e.*, it can be observed from July to September; Figure 3).

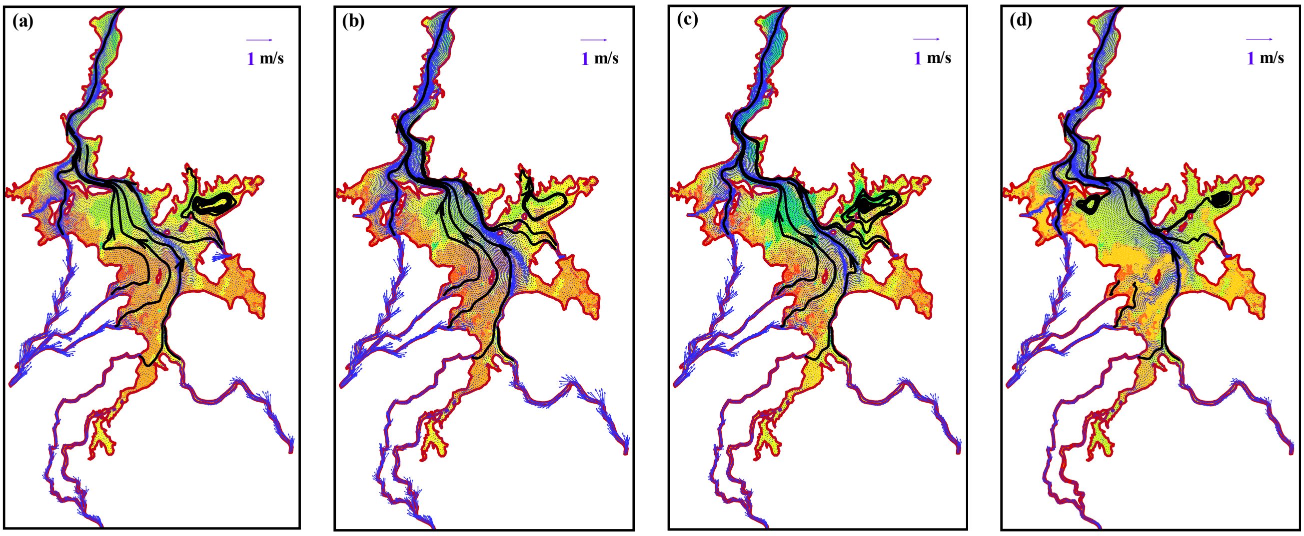

Figure 3. Map of the velocity fields (in blue arrows) overlapped the lake bathymetry at selected time slices: (**a**) 15 July; (**b**) 15 August; (**c**) 15 September; and (**d**) 30 September. The black lines with arrows represent the streamlines generated by the flow fields.

Figure 4 shows the spatial distribution of dye-tracers and particles released from each river mouth of the catchment inflows at three selected time slices. Simulation results demonstrate that the transport trajectories simulated by the dye tracer approach (*i.e.*, the transport model) show good agreement with the results produced by the Lagrangian particle-tracking approach (*i.e.*, the particle-tracking model) from visual inspection (Figure 4). The simulated results from both the transport model and particle-tracking model reveal that the pollutant transport trajectories develop from each river mouth, moving northward along the lake's main flow channels to the downstream extremity of the lake (Figure 4), similar to a river-transport behavior. This distribution pattern suggests that the transport trajectories within the lake strictly follow the dominant water flow pattern of the lake, using the velocity field of the lake as a reference (see the streamlines in Figure 3). Compare to the inundated floodplain areas with shallow water depth (*i.e.*, the water depth < 6 m; Figure 2b), the relatively fast water flows in the lake's flow channels are favorable to pushing the pollutants travelling away from the released points and towards the north side of the lake (Figure 4), indicating strong effects of river inflows from the lake's catchment (Figure 3). This coincides with the transport trajectories (Figure 4) and the water flow patterns (Figure 3), indicating the pollutants are more likely to be constrained in the lake's main flow channels during this flood period. A substantial amount of the released dyes and particles are also found in the inundated floodplain areas (Figure 4). It is likely that the inundated floodplain areas with shallow water depth at least partly slow down the pollutant transport because they function as a buffer when the fast flows pass through the deep water areas of the lake's main flow channels or flow into the floodplain areas. It was noted that the dyes and particles were also trapped in the eastern bay of the lake (e.g., Figure 4p–r), mainly due to influence of the clock-wise gyre (Figure 3). These results demonstrate that the water flow patterns play an important role in controlling the transport trajectory across the lake.

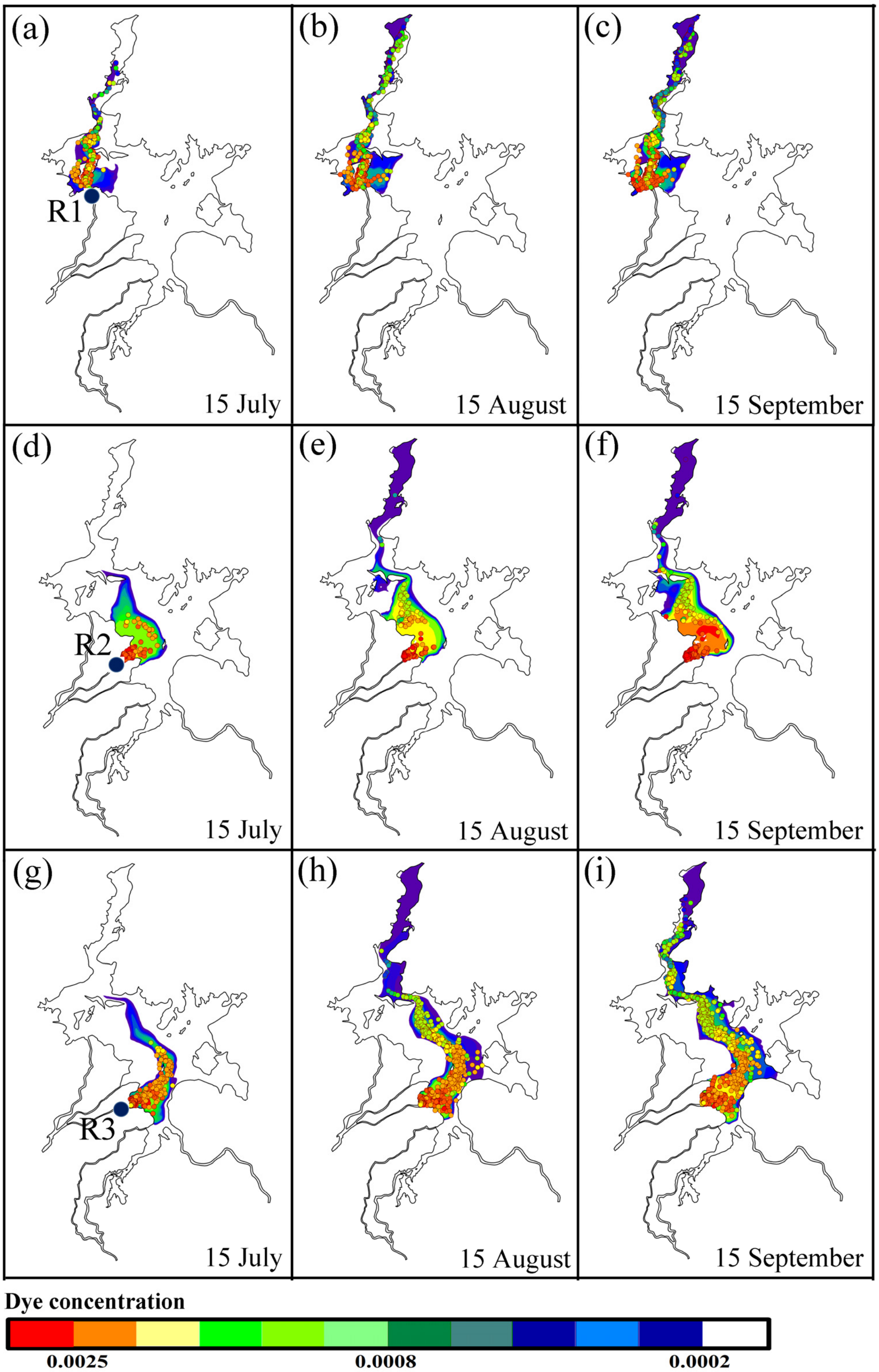

Figure 4. *Cont.*

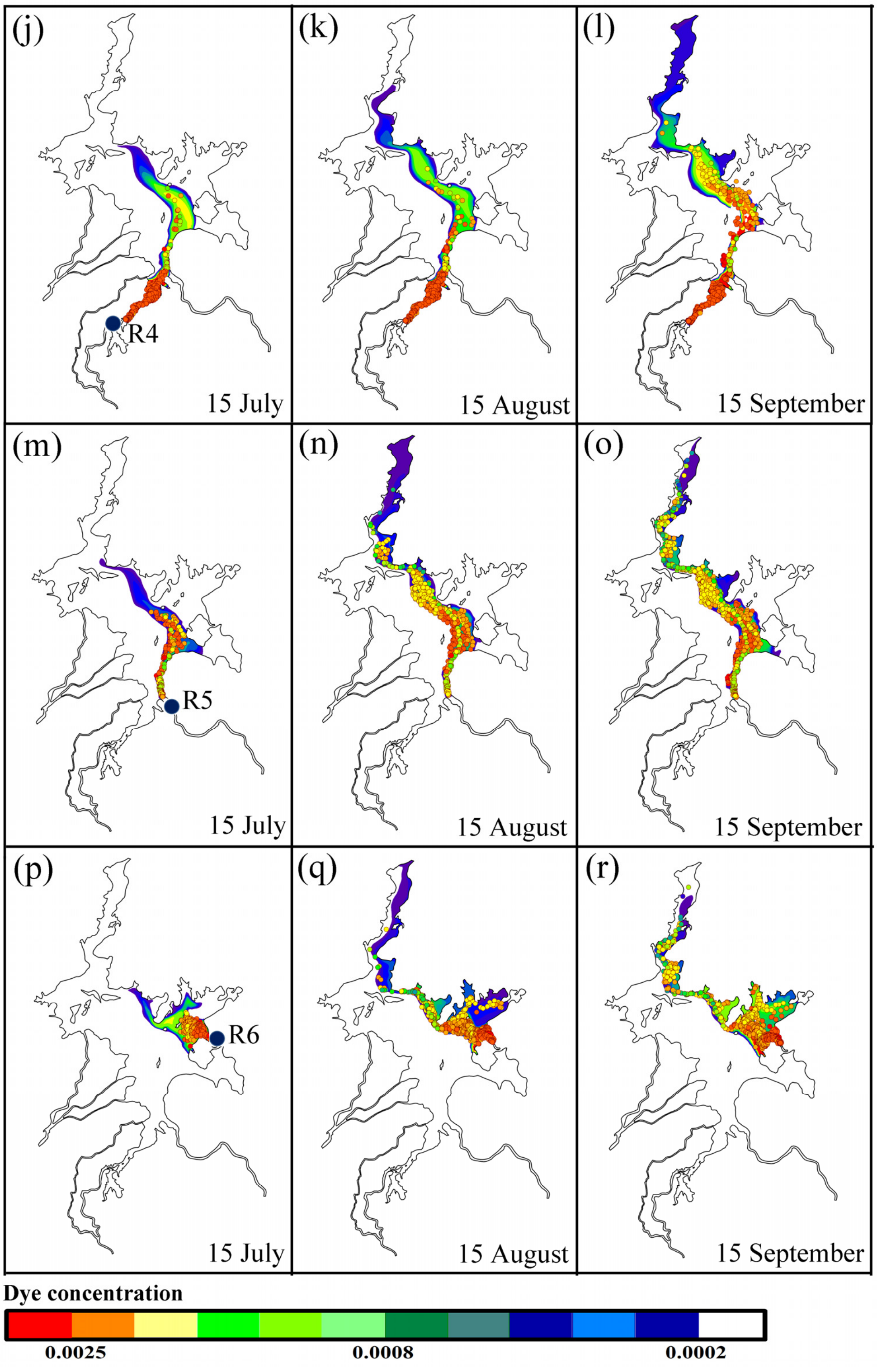

Figure 4. Spatial distribution of dye concentration (in kg/m^3) and particle trajectories (colored dots) at selected time slices during July–September. (**a**–**c**) represents the releases at river mouth of the northern branch of the Ganjiang River (marked by R1); (**d**–**f**) represents the releases at river mouth of the middle branch of the Ganjiang River (R2); (**g**–**i**) represents the releases at river mouth of the southern branch of the Ganjiang River (R3); (**j**–**l**) represents the releases at river mouth of the eastern branch of the Fuhe River (R4); (**m**–**o**) represents the releases at river mouth of the Xinjiang River (R5); and (**p**–**r**) represents the releases at river mouth of the Raohe River (R6).

4.2. Residence Time for the Lake Flood Period

Figure 5 illustrates the simulation results of mean residence time for the lake flood period during July–September.

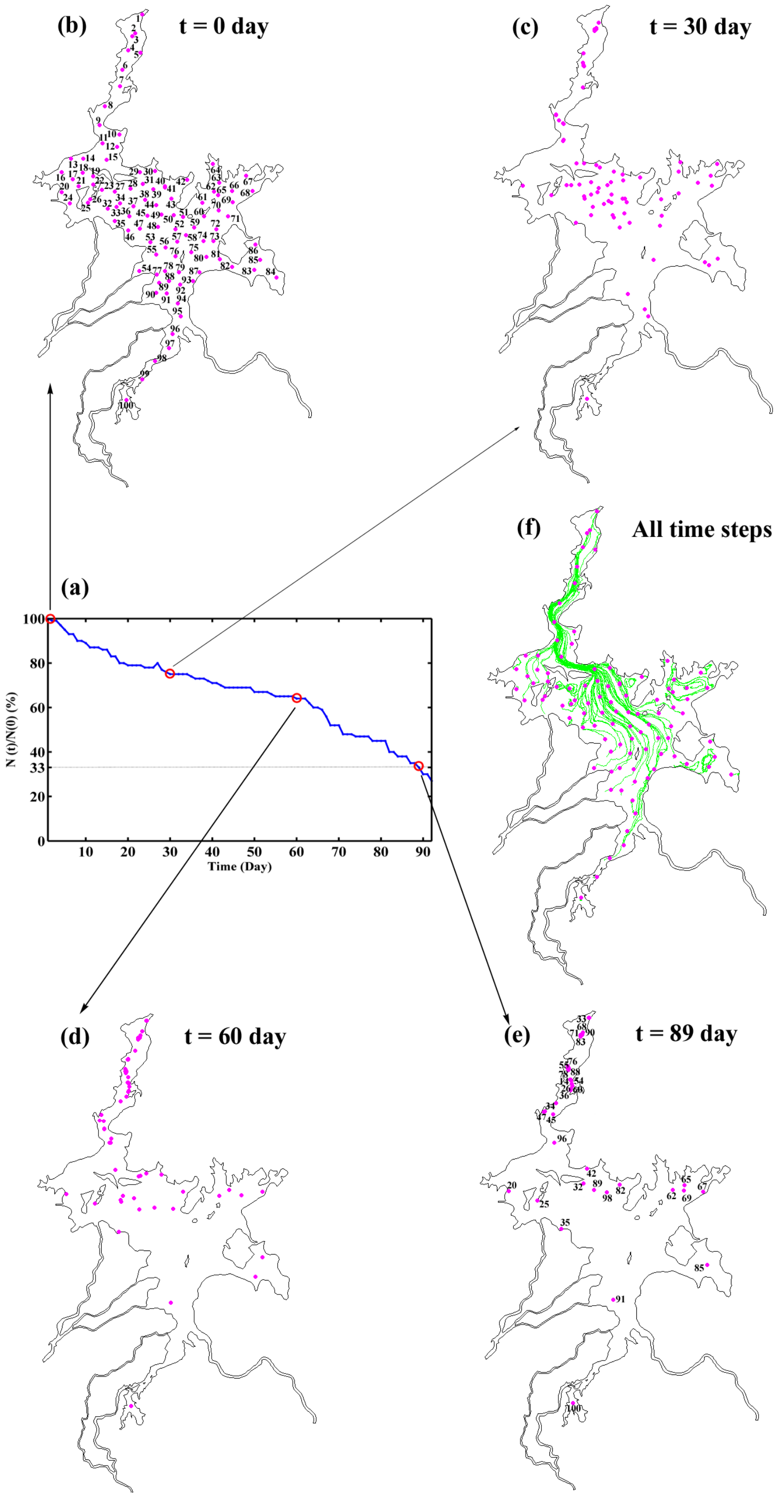

Figure 5. (**a**) The number of particles left in the lake relative to the initial numbers (in pink dots). Particle patterns after (**b**) 0, (**c**) 30, (**d**) 60, and (**e**) 89 days and (**f**) trajectories of all particles (in green lines) during the simulation periods. The marked numbers represent the Particle ID.

If the initial percentage of conservative particles is set to 100% (*i.e.*, N (t = 0)/N (0) = 1), the percentage of the total number of the tracer particles remaining in the lake (*i.e.*, N (t = 0)/N (0)) decreases and is recorded, as shown in Figure 5a. Particle-tracking results show that the slope of the time-dependent particle curve is very flat, indicating a weak flushing during this flood period. The estimated mean residence time of Poyang Lake is up to 89 days (*i.e.*, 67% of the original particles leave the lake; Figure 5a). Figure 5b–e shows snapshots of the particle distributions at 0, 30, 60, and 89 days after the particle release. Although the majority of particles move northward along with the prevailing water flows (Figure 3), unexpectedly large numbers of tracer particles are retained for much longer periods in some bays (e.g., the northeastern, southeastern and southern bays; Figure 5b–e). This retention is at least partly attributable to local gyres of the lake (Figure 3), indicating substantially poor flushing for these local regions (*i.e.*, the trajectories indicated by green lines are considered closed; Figure 5f).

Figure 6 shows the spatial distribution of algae biomass and chlorophyll *a* within Poyang Lake. It can be found that the distribution patterns of algae biomass and chlorophyll *a* show good agreement with the pollutant distributions of Poyang Lake produced by the particle-tracking model (compare Figure 6 to Figure 5b–e). That is, the lake regions with high concentrations of algae biomass and chlorophyll *a* tend to coincide with the trapped areas of particles, especially in the eastern bays. While the areas with low concentrations appear to be in agreement with the lake's main flow channels since the particles are easy to be transported downstream along with fast water flows. This similarity may at least partly corroborate the residence time estimation because the residence time has important environmental implications for local ecological and biological components in the lake [18].

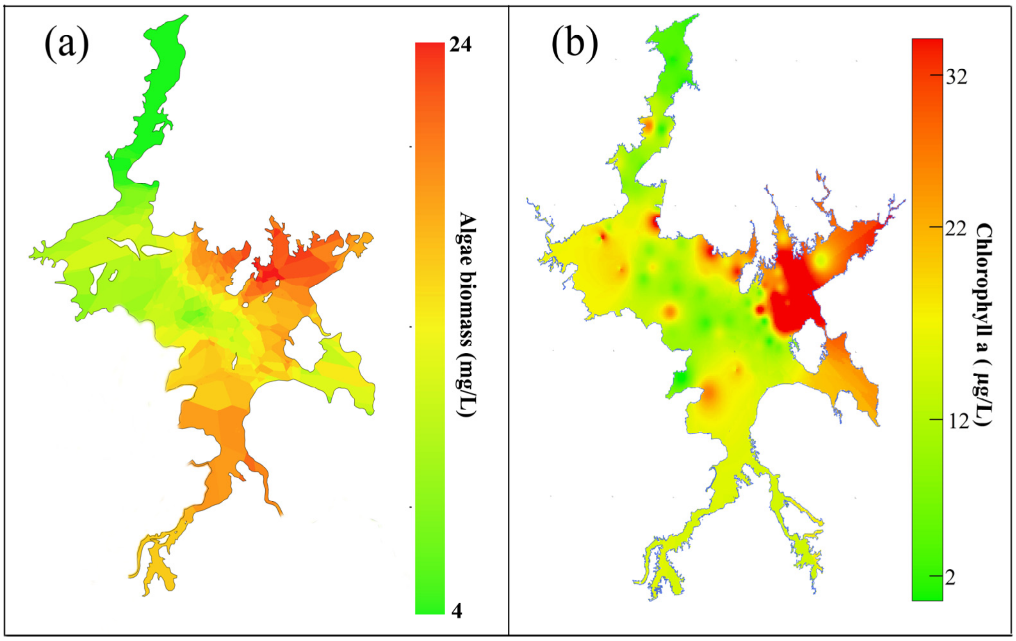

Figure 6. Spatial distribution of (**a**) algae biomass and (**b**) chlorophyll *a* within Poyang Lake. The algae biomass data were calculated from 83 field sampling sites in July 2012 (black dots) and the figure of chlorophyll *a* was modified from previous published study [46].

Figure 7 further shows the residence time distributions (*i.e.*, the minimum residence time) for the selected river mouths. Simulation results reveal that, on average, the minimum residence time from each released river mouth (R1–R6) to the lake outlet (*i.e.*, Hukou) is approximately 50 days (except R4; Figure 7). Although the water velocities and associated flow patterns of the lake should be responsible for the residence times, the transport distance (*i.e.*, the distance from the river mouth to the lake outlet; see the insert in Figure 7) appears to have a large effect on the spatial differences in residence time (*i.e.*, the minimum residence time varies between 46 and 88 days) during this flood period, as expected. Overall, the model results demonstrate that the pollutants (*i.e.*, the dye tracers and particles) from each river mouth can reach up to the lake outlet and further escape the lake.

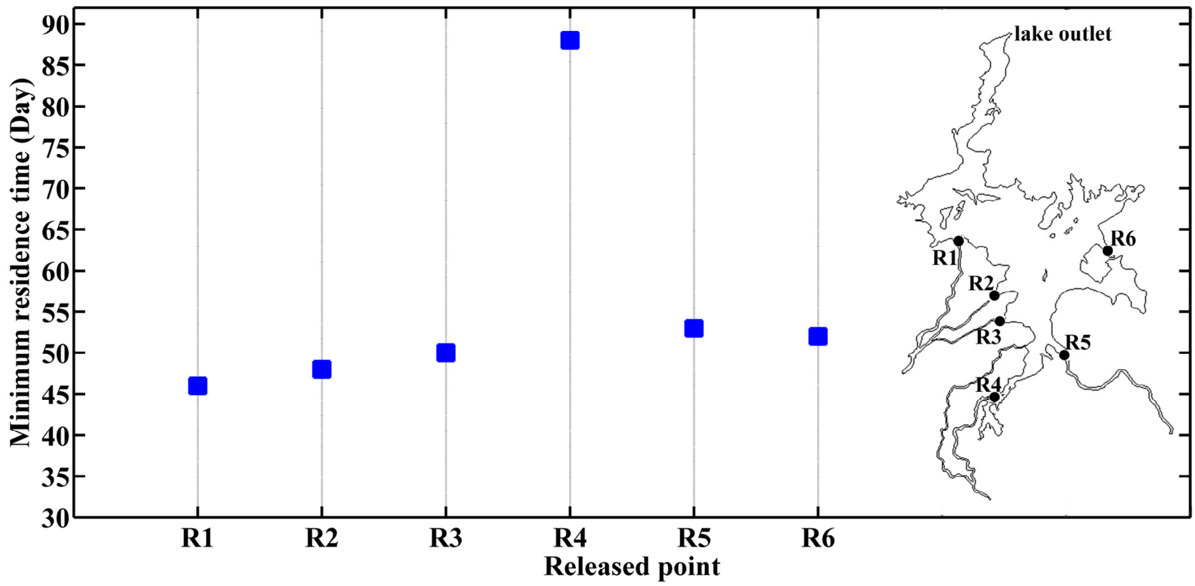

Figure 7. Distribution of residence times for the selected river mouths (R1–R6).

4.3. Comparison of the Effects of Local Catchment and the Yangtze River on Mean Residence Time

Table 2 shows a summary of simulation cases to evaluate the effects of the Yangtze River and local catchment on average residence time of Poyang Lake. The simulation results indicate that as the catchment discharge at each river increases, the residence time of Poyang Lake exhibits small changes within the range of several days (compare Cases 1–3 to Case 0; Case 0 is same to the residence time in Figure 5), suggesting a minor effect of the catchment inflows on the lake hydrodynamics and associated residence time (Table 2). In contrast, the average residence times of the lake in Cases 4–6 are significantly shorter than the average condition (Case 0) and the variable catchment river discharges (Cases 1–3), and a −5% to −15% changes in the Yangtze River water levels can result in a distinct reduction in the residence time of 5–12-day (see Case 4 in Table 2). Based on the comparison of Cases 1–6 to Case 0, the effect of the Yangtze River on the residence time is clearly much stronger than that of the catchment river inflows, *i.e.*, the decreased water levels of the Yangtze River result in a distinctly shorter residence time than the increased catchment inflows. This finding demonstrates the remarkable contribution of the Yangtze River to the hydrodynamics of Poyang Lake during this flood period, which coincides with previous investigations of the lake and the Yangtze River interactions [29,47]. It was concluded that the reduction in the Yangtze River discharge enhances the "emptying effect" of the Yangtze River, which increases the lake outflows and may thus strengthen lake flushing ability.

Table 2. Cases examined at model boundaries to evaluate the effects of the catchment rivers and the Yangtze River on lake mean residence time.

Case	Catchment Inflows (Unit: m^3/s)	Yangtze River Water Level (Unit: m)	Lake Residence Time (Unit: Day)
Case 0	Averaged over 2001–2010	Averaged over 2001–2010	89
Case 1	+25%	Averaged over 2001–2010	89
Case 2	+50%	Averaged over 2001–2010	87
Case 3	+75%	Averaged over 2001–2010	86
Case 4	Averaged over 2001–2010	–5%	84
Case 5	Averaged over 2001–2010	–10%	81
Case 6	Averaged over 2001–2010	–15%	77

5. Discussion

Numerical models are typical components of environmental flow assessments. Forecasting the effects of flow on transport behaviors is an increasingly important objective for many river–lake systems, due to the substantial influences of flow on the water quality and associated ecosystem of the lakes [44]. Previous model studies mainly used physically based hydrodynamic models to explore the flow features of river–lake systems. Generally, hydrodynamic models have the ability to investigate the variations in water levels and flow fields within any lake system. Environmental stewardship requires that any pollutant released into the lake should be heavily regulated and properly managed. Therefore, hydrodynamic models need to combine other model components (e.g., transport model, particle-tracking model) to achieve the investigation of pollutant transport behaviors within lake. The combined model includes various dynamic models and exploits their complementary advantages, and thus provides comprehensive insights into a complex river–lake system from different perspectives. For example, the dye-tracer transport models are well suited for problems involving substantial contamination gradients of a large river–lake system regarding the advection-dispersion processes of the lake [30]. The particle-tracking models do not introduce numerical diffusion. They can also be computationally efficient and used to reconstruct the movement of water [48]. However, both the transport model and particle-tracking model cannot simulate individually, they need to use the hydrodynamic outputs as their major forcings. The combined model is a very useful predictive tool that can help us assess pollutant transport after the accidental or deliberate release of pollution [48].

The current study represents the first attempt to use a combined model approach to provide unique insights into the transport behaviors of large river–lake system (Poyang Lake) relative to previous wind-driven lake systems [21,22,24]. It is also the first time to employ a combined model to quantify the mean residence time of Poyang Lake. Some areas of particular interest are the bays adjacent the lake shoreline with substantially longer residence times, exhibiting distinct retention of large numbers of tracer particles, which may have important implications to the high concentrations of algae biomass and chlorophyll *a* (see Figure 6). It can be inferred that these local areas may be heavily polluted if the released pollutant is reactive and non-conservative. The findings are extremely important for understanding the relationship between the chemistry of the original tributary waters and that of the waters within the lake, as well as the sensitivity of the lake to direct pollution. Additionally, a potential application of the combined model method is to evaluate the movement of algae blooms through the specification of a known starting location. Alternatively, the combined model can be used to determine the possible source location for algae. Unfortunately, the current combined model (*i.e.*, the particle-tracking model) does not incorporate algae population dynamics and cannot run in back-tracking mode. However, the simulations indicate that the potential for the current combined model in answering questions such as finding possible responses of water quality and associated lake ecosystem in space. Further extensions of this type of combined model will require coupling with an ecological model, making it possible to improve restoration efforts of the lake.

This study involves very practical combined model approach, which can be applied to solve pollutant transport trajectory and residence time problems for similar river–lake systems with some cautions: (1) The assumption of 2D depth-averaged flow in the lake applies to conditions where the water column is not stratified. However, the depth of the lake may reach up to 29 m near the lake downstream area during the extreme high water level conditions; hence, it is reasonable to expect some amount of velocity (and temperature) stratification. As such, the current study could be extended to a 3D representation of the lake to account for vertical structure in the hydrodynamic field. Nonetheless, the present model is considered to be adequate as a first attempt to explore the transport properties of Poyang Lake. (2) The purpose of the simulation using an average settling velocity (chosen to be 0.0082 m/s; Table 1) to investigate the transport behaviors of the released pollutants. However, a faster settling velocity for the particles has been tested to examine shorter transport distances than the average settling velocities of the present simulation [24,44]. (3) 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 considerably larger role than the variable dispersion coefficient for pollutant transport [49,50]. Because the current 2D hydrodynamic model has the ability to represent the velocity field of Poyang Lake [28,30], thereby the spatial pattern of transport trajectory and the magnitude of residence time cannot produce large changes. However, future work should validate the transport and particle-tracking models for more accurate estimation using some specific objects, such as pollution and suspended sediment concentrations.

6. Conclusions

The catchment rivers and tributaries along with sediment, nutrient and pollutant loads have been shown previously to generate substantial adverse effects on the water quality and ecosystem of large river–lake systems. Physically based numerical models have been used to explore the transport behaviors within lakes and other hydrological systems. The combination of a 2D hydrodynamic model (using MIKE 21), an advection-dispersion transport model and a Lagrangian particle-tracking model was successfully applied to the large river–lake system (Poyang Lake), performed for the flood period of the lake. The study site is known to experience steadily deteriorating water quality depended on combined role of the local catchment and the Yangtze River, although the importance of lake's hydrology and hydrodynamics on the pollutant transport has not been examined previously. The combined model approach presented in this study, aimed at exploring both the transport trajectory and the residence time of Poyang Lake, is the first attempt to integrate lake hydrodynamics to provide insights into the transport behaviors of the lake.

Model results reveal that the prevailing water flow patterns drive the transport pathways that develop from each river mouth to the lake downstream along the lake's main flow channels, exhibiting a river-transport behavior. Although the velocities across the lake are substantially lower during the flood period, the river-transported pollutants from the local catchment can reach up to the downstream extremity of the lake and the corresponding minimum residence times vary from over one month to less than three months. Simulation results indicate that although the average residence time of the lake is 89 days, substantially longer residence time may occur at some bays, depending on the topographically controlled flow patterns related to the gyres for local lake areas. The average residence time of the lake largely depends on the flow variations in the Yangtze River during the flood period, rather than the catchment river inflows.

The current work shows for the first time transport behaviors and their major causal factors in a large river–lake system. It is suggested that this study would be worthwhile to provide insights into the ultimate purpose of possible impacts on the lake's ecological system. While investigated specifically for Poyang Lake, the derived scientific knowledge can be used to support the decisions that need to be made by responsible authorities in deciding how to create a strategic lake management plan for other similar river–lake systems.

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Author Contributions

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

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Zedler, J.B.; Kercher, S. Wetland resources: Status, trends, ecosystem services, and restorability. *Annu. Rev. Env. Resour.* **2005**, *30*, 39–74.

2. Kristal, D.; Anderson, M.A.; Yates, M.V. Distribution of indicator bacteria in Canyou Lake, California. *Water Res.* **2005**, *39*, 1277–1288.
3. Hipsey, M.R.; Antenucci, J.P.; Brooks, J.D. A generic, process-based model of microbial pollution in aquatic systems. *Water Resour. Res.* **2008**, *44*, doi:10.1029/2007WR006395.
4. Leon, L.F.; Smith, R.E.H.; Hipsey, M.R.; Bocaniov, S.A.; Higgins, S.N.; Hecky, R.E.; Antenucci, J.P.; Imberger, J.A.; Guildford, S.J. Application of a 3D hydrodynamic-biological model for seasonal and spatial dynamics of water quality and phytoplankton in Lake Erie. *J. Great Lakes Res.* **2011**, *37*, 41–53.
5. Razmi, A.M.; Barry, D.A.; Lemmin, U.; Bonvin, F.; Kohn, T.; Bakhtyar, R. Direct effects of dominat winds on residence and travel times in the wide and open lacustrine embayment: Vidy Bay (Lake Geneva, Switzerland). *Aquat. Sci.* **2014**, *76*, 59–71.
6. Cucco, A.; Umgiesser, G.; Ferrarin, C.; Perilli, A.; Canu, D.M.; Solidoro, C. Eulerian and lagrangian transport time scales of a tidal active coastal basin. *Ecol. Model.* **2009**, *220*, 913–922.
7. Liu, H.; Benoit, G.; Liu, T.; Liu, Y.; Guo, H. An integrated system dynamics model developed for managing lake water quality at the watershed scale. *J. Environ. Manag.* **2015**, *155*, 11–23.
8. Li, Y.L.; Zhang, Q.; Werner, A.D.; Yao, J. Investigating a complex lake-catchment-river system using artificial neural networks: Poyang Lake (China). *Hydrol. Res.* **2015**, in press.
9. Shankman, D.; Heim, B.D.; Song, J. Flood frequency in China's Poyang Lake region: Trends and teleconnections. *Int. J. Climatol.* **2006**, *26*, 1255–1266.
10. Huang, J.; Xu, Q.; Xi, B.; Wang, X.; Jia, K.; Huo, S.; Su, J.; Zhang, T.; Li, C. Effects of lake-basin morphological and hydrological characteristics on theeutrophication of shallow lakes in eastern China. *J. Great Lakes Res.* **2014**, *40*, 666–674.
11. Wang, S. *Poyang Lake: Ecological Security*; Science Press: Beijing, China, 2014. (In Chinese)
12. Luo, M.B.; Li, J.Q.; Cao, W.P.; Wang, M.L. Study of heavy metal speciation in branch sediments of Poyang Lake. *J. Environ. Sci.* **2008**, *20*, 161–166.
13. Yuan, G.L.; Liu, C.; Chen, L.; Yang, Z.F. Inputting history of heavy metals into the inland lake recorded in sediment profiles: Poyang Lake in China. *J. Hazard. Mater*. **2011**, *185*, 336–345.
14. Gao, G.; Ruan, R.; Ouyang, Q. Water quality status and changing trend in Poyang Lake. *J. Nanchang Ins. Technol*. **2010**, *29*, 50–53. (In Chinese)
15. Wu, Z.; Lai, X.; Zhang, L.; Cai, Y.; Chen, Y. Phytoplankton chlorophyll a in Lake Poyang and its tributaries during dry, mid-dry and wet seasons: A 4-year study. *Knowl. Manag. Aquat. Ecosyst.* **2014**, *412*, 1–13.
16. Lv, T.; Wu, C. Study on coupling degree and optimal path between land water resources and economic dvelopment in Poyang Lake Ecological Zone. *Int. J. Environ. Sci. Dev.* **2013**, *4*, 569–575.
17. Wu, G.; De, Leeuw, J.; Skidmore, A.K.; Prins, H.H.T.; Liu, Y. Concurrent monitoring of vessels and water turbidity enhances the strength of evidence in remotely sensed dredging impact assessment. *Water Res.* **2007**, *41*, 3271–3280.
18. Wan, Y.; Qiu, C.; Doering, P.; Ashton, M.; Sun, D.; Coley, T. Modeling residence time with a three-dimensional hydrodynamic model: Linkage with chlorophyll *a* in a subtropical estuary. *Ecol. Model.* **2013**, *268*, 93–102.
19. Patgaonkar, R.S.; Vethamony, P.; Lokesh, K.S.; Babu, M.T. Residence time of pollutants discharged in the Gulf of Kachchh, northwestern Arabian Sea. *Mar. Pollut. Bull.* **2012**, *64*, 1659–1666.

20. Dabrowski, T.; Hartnett, M.; Olbert, A.I. Determination of flushing characteristics of the Irish Sea: A spatial approach. *Comput. Geosic. UK* **2012**, *45*, 250–260.
21. Harris, L.; Kotamarthi, V.R. The characteristics of the Chicago Lake Breeza and its effects on tracer particle transport: Results from an episodic event simulation. *J. Appl. Meteorol*. **2005**, *44*, 1637–1654.
22. He, C.; Droppo, I. Numerical modeling of fine particle plume transport in a large lake. *J. Great Lakes Res.* **2011**, *37*, 411–425.
23. McCombs, M.P.; Mulligan, R.P.; Boegman, L.; Rao, Y.R. Modeling surface waves and wind-driven circulation in eastern Lake Ontario during winter storms. *J. Great Lakes Res.* **2014**, *3*, 130–142.
24. Schoen, J.; Stretch, D.; Tirok, K. Wind-driven circulation patterns in a shallow estuarine lake: St Lucia, South Africa. Estuar. *Coast. Shelf Sci.* **2014**, *146*, 49–59.
25. Andutta, F.P.; Ridd, P.V.; Wolanski, E. The age and the flushing time of the Great Barrier Reef waters. *Cont. Shelf Res*. **2013**, *53*, 11–19.
26. Li, Y.; Acharya, K.; Yu, Z. Modeling impacts of Yangtze River water transfer on water ages in Lake Taihu, China. *Ecol. Eng.* **2011**, *37*, 325–334.
27. Gourgue, O.; Deleersnijder, E.; White, L. Toward a generic method for studying water renewal, with application to the epilimnion of Lake Tanganyika. *Estuar. Coast. Shelf Sci.* **2007**, *74*, 628–640.
28. Li, Y.L.; Zhang, Q.; Yao, J.; Werner, A.D.; Li, X.H. Hydrodynamic and hydrological modeling of Poyang Lake-catchment system in China. *J. Hydrol. Eng.* **2014**, *19*, 607–616.
29. Zhang, Q.; Ye, X.C.; Werner, A.D.; Li, Y.L.; Yao, J.; Li, X.H.; Xu, C.Y. An investigation of enhanced recessions in Poyang Lake: Comparison of Yangtze River and local catchment impacts. *J. Hydrol*. **2014**, *517*, 425–434.
30. Li, Y.L.; Zhang, Q.; Yao, J. Investigation of residence and travel time in a large floodplain lake with complex lake-river interactions: Poyang Lake (China). *Water* **2015**, *7*, 1991–2012.
31. Zhang, Q.; Werner, A.D. Hysteretic relationships in inundation dynamics for a large lake-floodplain system. *J. Hydrol.* **2015**, *527*, 160–171.
32. Kanai, Y.; Ueta, M.; Germogenov, N.; Nagendran, M.; Mita, N.; Higuchi, H. Migration routes and important resting areas of Siberian cranes (Grus leucogeranus) between northeastern Siberia and China as revealed by satellite tracking. *Biol. Conserv.* **2002**, *106*, 339–346.
33. Gao, J.; Jia, J.; Kettner, A.J.; Xing, F.; Wang, Y.P.; Xu, X.N.; Yang, Y.; Zou, X.Q.; Gao, S.; Qi, S.; *et al*. Changes in water and sediment exchange between the Changjiang River and Poyang Lake under nature and anthropogenic conditions, China. *Sci. Total Environ.* **2014**, *481*, 542–553.
34. Feng, L.; Hu, C.; Chen, X.; Cai, X.; Tian, L.; Gan, W. Assessment of inundation changes of Poyang Lake using MODIS observation between 2000 and 2010. *Remote Sens. Environ.* **2012**, *121*, 80–92.
35. Wei, Y.; Zhang, J.; Zhang, D.; Tu, T.; Luo, L. Metal concentrations in various fish orgrans of different fish species from Poyang Lake, China. *Ecotox. Environ. Safe* **2014**, *104*, 182–188.
36. Zhen, L.; Li, F.; Huang, H.; Dilly, O.; Liu, J.; Wei, Y.; Yang, L.; Cao, X. Households' willingness to reduce pollution threats in the Poyang Lake region, southern China. *J. Geochem. Explor.* **2011**, *110*, 15–22.

37. Cheng, S.; Ru, B. The Characteristics of the lake current of Poyang Lake. *Jiangxi Hydrau. Sci. Technol*. **2003**, *29*, 105–108. (In Chinese)
38. Danish Hydraulic Institute (DHI). *MIKE 21 Flow Model FM: Transport Module User Guide*; DHI Water and Environment: Hørsholm, Denmark, 2014; pp. 1–42.
39. Danish Hydraulic Institute (DHI). *MIKE 21 Flow Model FM: Particle Tracking Module User Guide*; DHI Water and Environment: Hørsholm, Denmark, 2014.
40. Zhang, D.W.; Wei, Y.H.; Zhang, L.; Lin, G.G.; Chen, Y.W.; Tu, T.T. Dsitribution of heavy metals in water, suspended particulate metetr and sediment of Poyang lake, China. *Fresen. Environ. Bull.* **2012**, *21*, 1910–1919.
41. Miller, R.L.; McPherson, B.F. Estimating estuarine flushing and residence times in Charlotte harbor, Florida, via salt balance and a box model. *Limnol. Oceanogr.* **1991**, *47*, 1545–1553.
42. Liu, W.; Chen, W.; Hsu, M. Using a three-dimensional particle-tracking model to estimate the residence time and age of water in a tidal estuary. *Comput. Geosci UK* **2011**, *37*, 1148–1161.
43. Fan, X. The Study of Hydrodynamic Simulation of Poyang Lake Based on Delft3D Model. Master's Thesis, Jiangxi Normal University, Nanchang, China, June 2010. (In Chinese)
44. Anderson, K.E.; Harrison, L.R.; Nisbet, R.M.; Kolpas, A. Modeling the influence of flow on invertebrate drift across spatial scales using a 2D hydraulic model and 1D population model. *Ecol. Model.* **2013**, *265*, 207–220.
45. Danish Hydraulic Institute (DHI). *MIKE 21 Flow Model: Hydrodynamic Module User Guide*; DHI Water and Environment: Hørsholm, Denmark, 2014.
46. Wu, Z.; He, H.; Cai, Y.; Zhang, L.; Chen, Y. Spatial distribution of chlorophyll *a* and its relationship with the environment during summer in Lake Poyang: A Yangtze-connected lake. *Hydrobiologia* **2014**, *732*, 61–70.
47. Guo, H.; Hu, Q.; Zhang, Q.; Feng, S. Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003–2008. *J. Hydrol.* **2012**, *416*, 19–27.
48. Chen, W.; Liu, W.; Kimura, N.; Hsu, M. Particle release transport in Danshuei River estuarine system and adjacent coastal ocean: A modeling assessment. *Environ. Monit. Assess.* **2010**, *168*, 407–428.
49. Jia, X.; Zeng, F.; Gu, Y. Semi-analytical solutions to one-dimensional advection-diffusion equations with variable diffusion coefficient and variable flow velocity. *Appl. Math. Comput.* **2013**, *221*, 268–281.
50. Zeinoddini, M.; Tofighi, M.A.; Vafaee, F. Evaluation of dike-type causeway impacts on the flow and salinity regimes in Urmia Lake, Iran. *J. Great Lakes Res.* **2009**, *35*, 13–22.