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Water-Exchange Response of Downstream River–Lake System to the Flow Regulation of the Three Gorges Reservoir, China

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Abstract: Hydrological regime changes in the river–lake system and their influences on the ecological environment downstream dams have attracted increasingly more attention all over the world. The Dongting lake downstream of the Three Gorges Dam (TGD) in the Yangtze River has been experiencing a series of hydraulic and hydrological changes over the last decade. The hydrological and ecological influences of the TGD flow regulation on the Dongting river–lake system and its functional mechanism during the impounding periods remain extremely unclear. This study examines the hydrological changes in the Dongting river–lake system based on a 1D/2D coupled hydrodynamic model. In particular, the inflow boundary of the model with and without the TGD was applied with the outflow and inflow of the TGD, respectively, during the same regulation periods. The results show that the diverted flow from the Yangtze River into the Dongting lake and outflow from the lake back to the river drastically decreased during the impounding periods, especially in October. The decreased water exchange between the Yangtze River and the Dongting lake impaired the water residence capacity to some extent in the lake. Stage decrease in the lake area resulted in a significant reduction in the water volume of the Dongting lake with the same time percentage. In addition, the obvious drainage effect in Dongting lake due to the increased stage difference and current speed after the TGD operation was the essential cause of hydrological changes in the lake area. These results provide an improvement in the understanding of impoundment influences on the large river–lake system and give some practical information for ecological environment management in similar river–lake systems.

Keywords: Three Gorges Reservoir; impoundment influences; river–lake system; water exchange

1. Introduction

Lakes, as one kind of the most important water providers, widely exist on the earth. Most of these lakes connect with some rivers, so the river–lake system is the common form in natural basins [1,2]. A fifth of the world's surface freshwater was held in the five Great Lakes and their connecting rivers in North America [3]. Other lakes such as Saimaa Lake in Finland, Peace-Athabasca Delta system in

Canada, and Tonle Sap Lake in Cambodia, as part of the river–lake system, provide adequate water to their adjoining residents [4–6]. Lakes in the river–lake system receive and store plenty of water from storms and floods during flood seasons and release it steadily; this plays a significant role in flood control for the downstream rivers, as well as the nutrient substance and part of sediment deposited in the lake area while the water flows through a lake. Therefore, lakes in a river–lake system provide the necessary elements for plant growth and the important habitats for wildlife [7].

However, with the intensification of anthropogenic activities, the health of the river–lake system also faces many challenges. There are increasingly more pollutant loads in lakes all over the world, owing to the extensive human activities [8–12]. More important, a series of dams in upstream channels drastically changed the hydrological regime of a river–lake system located in the middle and lower part of catchments [13–15]. Therefore, significant water-exchange variations occurred in the river–lake system during different reservoir-impounding periods. Consequently, water-resource utilization, waterway maintenance, ecological conservation, and water environmental management in lakes are affected to some extent [16–18].

The Yangtze River, as the third longest river, contributed a lot to the integrated utilization of water resources in China [19,20]. Water-resource development based on cascade reservoirs in the Yangtze River basin has achieved great progress over the past 50 years, especially in regard to the construction of the Three Gorges Dam (TGD) [21–23]. However, a series of hydrological and hydraulic changes inevitably occurred in the downstream channels [24,25]. Therefore, the Dongting river–lake system, 260 km downstream of the TGD, suffered from severe hydrological variations during the different flow regulation periods. Increasing attention has been attracted to the hydrological changes in the Dongting river–lake system in recent years. Hayashi et al. simulated the daily runoff processes based on an integrated catchment model in the Yangtze River basin and examined the hydraulic effect of the mainstream on the outflow of the Dongting lake; the results showed a good agreement of hydrologic budget between the observed and simulated ones [26,27]. Lai et al. [28] quantified the impoundment effects of the TGD during the dry seasons, based on a coupled model, and came to the conclusion that the extremely low water level that occurred downstream of the TGD principally resulted from the reduced inflow to the Yangtze River basin and the precipitation decrease. Wang et al. recently confirmed Lai et al.'s results again and quantified the influence of human water consumption on the last decadal lake stage decline [29]. These studies significantly contributed to revealing the hydrological changes in the Dongting river–lake system. However, more work should be done to quantify the changes in the outflow volume from the Dongting lake to the Yangtze River channels and its functional mechanism.

The evaluation of hydrological changes in the Dongting river–lake system has been carried out so far from different perspectives based on various kinds of methods. Jiang et al. [30] investigated the flood response to polder restoration in Dongting lake and explored the formation mechanism of frequent flood disasters after the TGD operation, which provided vital insights into the lake ecosystem restoration downstream of dams. Using the measured hydrological data before and after the operation of the TGD, Chang et al. [31] conducted an evaluation of the influences of the TGD during its initial operation periods and quantified the annual average changes in flow and sediment discharge in the river–lake system, which provided a scientific basis for optimizing the operation program of the Three Gorges Reservoir. Sun et al. [32] examined the topographical changes downstream of TGD and analyzed its influences on the hydrological cycle around the Dongting lake basin based on the BP neural networks. The results indicated that the inundation patterns of the lake wetlands have been changing since the TGD operation. In addition, combining the observed field and remote sensing data and hydrodynamic models, Liu et al. [33] found that the TGD resulted in great downstream landscape changes, which significantly contributed to the Dongting shrinkage and its severe drought. Therefore, physically mathematical models were highly effective means to examine the hydrological changes in the complex river–lake system.

Despite several attempts that have been made to reveal the hydrological changes that occurred after the TGD operation, some problems remain unclear regarding the TGD impoundment impact on the Dongting river–lake system and their hydrodynamic mechanism of this system. In particular, whether the lake outflow during the impounding periods is increasing or not has not drawn a definitive conclusion. Current research was mainly focused on the TGD impoundment impact by comparing with hydrological data series and the fluvial processes before and after the TGR operation; little information has been provided about the different influences of the TGD inflow and outflow processes on the downstream river–lake system, let alone the studies on the root cause analysis for the hydrological variations. The research objectives of this paper are to (1) examine the changes in the water exchange with and without the TGD and to evaluate the variation in water retention capacity of the Dongting lake based on a 1D/2D coupled hydrodynamic model; (2) analyze the variations in the lake level and water volume during the impounding periods after the operation of the TGD; and (3) further explore the formation mechanism and its dominant factors of the hydraulic and hydrological changes in the river–lake system, which will be significantly conductive to relieve the adverse influences on the river–lake system.

2. Materials and Methods

2.1. Study Area and Data

The Yangtze River, located in South Central China, is 6300 km long and ranks as the third longest river on the earth. The TGD in the middle Yangtze River was completed in 2003, and it is the largest dam structure in the world. One of the most important objectives of the TGD was the flood control in the Yangtze river basin. Therefore, significant hydrological changes occurred downstream of the TGD [34]. Dongting lake, situated downstream of the TGD (111°19′–113°34′ E, 27°39′–29°51′ N) with a drainage area of 2579 km^2, is the second-largest freshwater lake in China (Figure 1). The Dongting lake was mainly fed by the Yangtze River through three inlets (Ouchi, Taiping, and Songzi) and four tributaries (Zi River, Yuan River, Xiang River, and Li River,). In addition, the lake empties its water through the Chenglingji outlet (Figure 1). The climate of the lake area is characterized by hot summers and relatively mild winters, which belongs to the subtropical monsoon climate. Its annual precipitation ranges from 1100 to 1400 mm, and the wet seasons are from May to October.

According to the operation rules of the TGD, the complete run cycle was divided into four continuous flow regulating periods: (1) flood pre-discharged regulation, emptying the reservoir volume to the downstream during this period; (2) flood regulation, the floods from the upstream were regulated during this period; (3) reservoir impoundment, partial water inflow was stored in the reservoir; and (4) water supplement, the reservoir increased its outflow to the downstream in order to meet irrigation water needs and keep the ecological balance and water depth of the waterways [35]. The above operational procedure is repeated year by year. The reservoir impoundment generally began from September to October, after the main flood seasons. The water-holding capacity test of the TGD was completed in 2008, and then normal flow regulation was carried out. Figure 1 presents the inflow and outflow processes of the TGD from 2008 to 2015.

For a comparative analysis of hydrological and hydrodynamic changes in the Dongting river–lake system, the meteorological and hydrological data (e.g., water level, discharge, precipitation, and evaporation) were collected from the Bureau of Hydrology, Changjiang Water Resources Commission, and the Weather Bureau of China. In addition, the outflow and inflow data of the TGD were collected from the Three Gorges Corporation, China. The meteorological and hydrological data cover the concerned sites in this study area. The detailed locations of the gauging stations are presented in Figure 1. Moreover, the digital elevation model including rivers and lake terrain used in this study was surveyed from 2008 to 2012, which was also provided by the Changjiang Water Resources Commission (see Supplementary Materials).

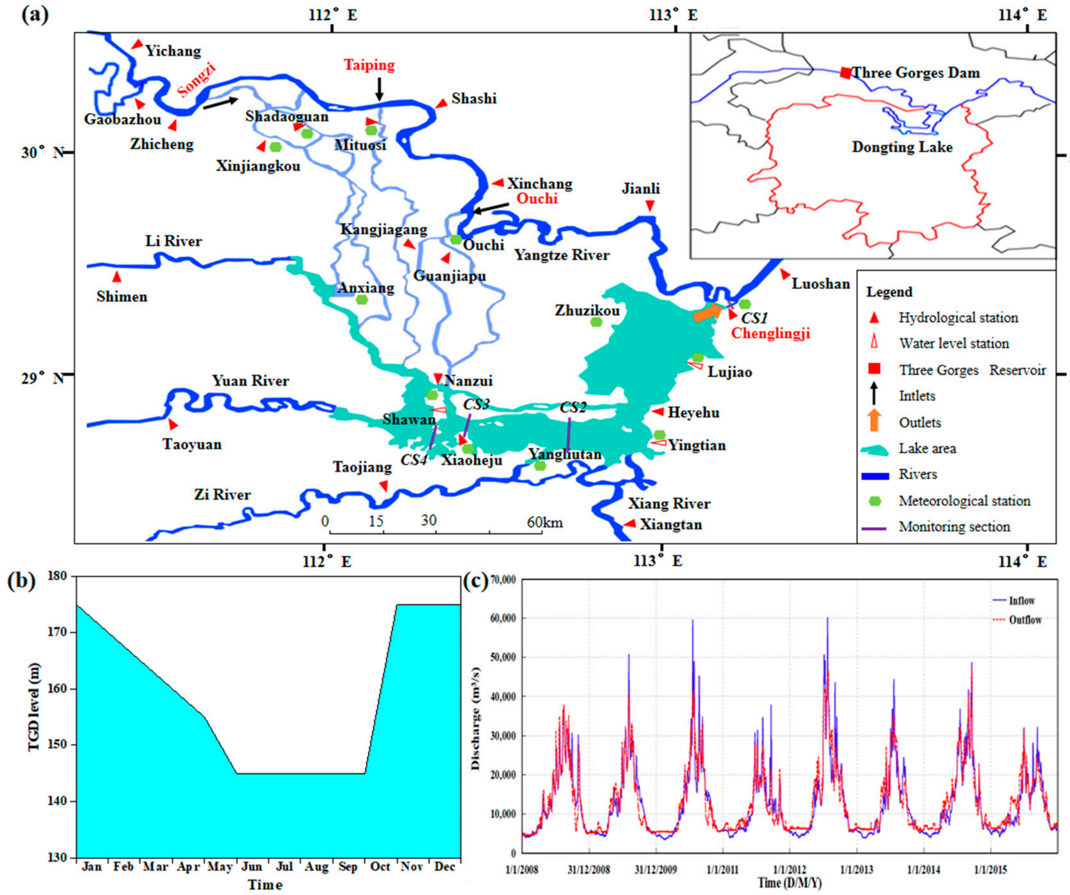

Figure 1. The physical location of the Dongting river–lake system: (**a**) sketch map with the information of gauging stations; (**b**) regular scheduling chart of the Three Gorges Dam (TGD); (**c**) the hydrograph of the inflow and outflow of the TGD from 2008 to 2015.

2.2. 1D/2D Coupled Hydrodynamic Model

A 1D/2D coupled model constructed by Zhang et al. [36] was used to examine the hydrological impact of the TGD on the Dongting river–lake system during the water impoundment periods. The coupled model was set up based on the module of MIKE FLOOD, which is an integrated modeling and analysis platform developed by the Danish Hydraulic Institute (DHI) and extensively applied around the world [37–40]. The 1D/2D coupled model used in this study covered the Dongting lake and the connected branches in the middle Yangtze River [36]. The river network in the study area was modeled by using the MIKE 11 hydrodynamic module, while the MIKE 21 hydrodynamic module was applied to simulate the lake area. There were 862 cross-sections, and 23,436 grid cells in the 1D and 2D hydrodynamic modules respectively. The MIKE 11 and MIKE 21 hydrodynamic modules are described by the Saint-Venant equations and the 2D shallow-water equations, respectively [41,42]. The standard linkage in the MIKE FLOOD was used in this study to connect the hydrodynamic modules; thus, water exchanges between the modules occurred through the overlapped MIKE 21 grid cells and the MIKE 11 network. Therefore, the hydrodynamic processes of the Dongting river–lake system during the impounding periods were simulated by using the coupled model in this research.

The daily streamflow gauged at the tributary gauging stations (Gaobazhou, Taojiang, Taoyuan, Shimen, and Xiangtan) was specified as the upstream boundary conditions for the coupled model, while the regular inflow and outflow of the TGR were applied as the mainstream boundary conditions. The downstream boundary condition was applied as the rating curve at the Luoshan station. Zhang et al. [36] calibrated and validated the coupled model against the observed data in the study area for the periods of January–December 2008 and January–December 2011, respectively. The coupled model was quantitatively evaluated by using the Nash–Sutcliffe efficiency coefficients (NSE) and the normalized root mean squared error (RMSE); the results show that there is a fairly close agreement between the simulated and observed values at the main stream, tributaries, and the lake area. The NSE value is larger than 0.89 and RMSE is smaller than 0.025 at the river–lake system stations, which indicates that the coupled model has a high simulation accuracy to predict and evaluate the hydrological changes in the study area [36].

2.3. Hydrologic Residence

To eliminate the effects of data random fluctuation on the research results, the gauged stage and water volume data in the lake area were processed by using the moving average method, as follows:

$$h(y) = \frac{1}{5}\sum_{t=1}^{5} H(y,t) \tag{1}$$

$$v\,(y) = \frac{1}{5}\sum_{t=1}^{5} V(y,t) \tag{2}$$

where $h(t)$ and $v(t)$ are the data series of moving averaged stage and water volume, respectively, which are the results of a daily averaged sequence of $H(y,t)$ and $V(y,t)$; y and t denote the year and day in the time series.

The fluctuation of stage and water volume in the lake was on account of the flow difference between the lake inflow and outflow. Therefore, the ratio between the volume difference and the inflow volume was used to show the water residence rate as follows:

$$R_{resi} = \frac{\int (q_{in}(t) - q_{out}(t))dt}{\int q_{in}(t)dt} \tag{3}$$

where R_{resi} is the water residence rate (WRR) in the lake; $q_{in}(t)$ and $q_{out}(t)$ are the daily water inflow and outflow rate of the Dongting lake.

In addition, the residence time is an important variable to present the hydrological changes in the study area, which can be addressed as follows:

$$T_{resi} = \frac{\int t q_{out}(t)dt}{\int q_{out}(t)dt}, \left(q_{in} > q_{out}\right) \tag{4}$$

where T_{resi} is the mean residence time (MRT), which is the cumulative time that inflow is larger than the outflow.

2.4. Evaluation of Hydrologic Regime Changes during the Impounding Periods

To accurately quantify the influence of the TGD impoundment on the river–lake system, the following two research scenarios were performed: Scenario 1 (S1), simulating the actual hydrological processes under the TGD regulation during 2008–2011; Scenario 2 (S2), simulating the hydrological processes that without the operation of the TGD during the same periods. For the second scenario (S2), the flow boundary at the Yichang station was replaced by the upstream inflow of the TGD. The other boundary conditions were kept the same as scenario 1. The gauged estuary station data of the tributaries (Xiang River, Zi River, Yuan River, and Li River) were applied as the inflow boundary conditions to the lake area. Several complete scheduling cycles were covered in the selected simulation periods; therefore, the hydraulic and hydrological changes during the different run phases of the TGD can be detected by comparing the two simulation scenarios.

3. Results

3.1. Water Exchange between the Dongting Lake and the Yangtze River

There were obvious hydrological variations after the TGD was put into operation; as shown in Figure 2, the diverted flow through the Taiping, Songzi, and Ouchi inlets to the tributaries dropped obviously. Compared with the flow changes in September, the flow drop occurred much more seriously during October due to the increasing water impoundment of the TGD. The mean diverted flow through the three inlets was less than 1000 m^3/s during October, after the TGD operation. The flow drop was most serious at the Ouchi inlet, which was nearly drying up during the October 2009 and 2011. In addition, there was a high agreement between the mainstream flow and the diverted flow during the impoundment periods at the three inlets of the tributaries with and without the TGD. Consequently, there was an evident flow drop in the mainstream and diverted flow after the TGD operation. When the flow discharge in the mainstream was lower than 4800, 7200, and 6700 m^3/s, there would be no flow diversion at the Songzi, Taiping, and Ouchi inlets, respectively (Figure 2).

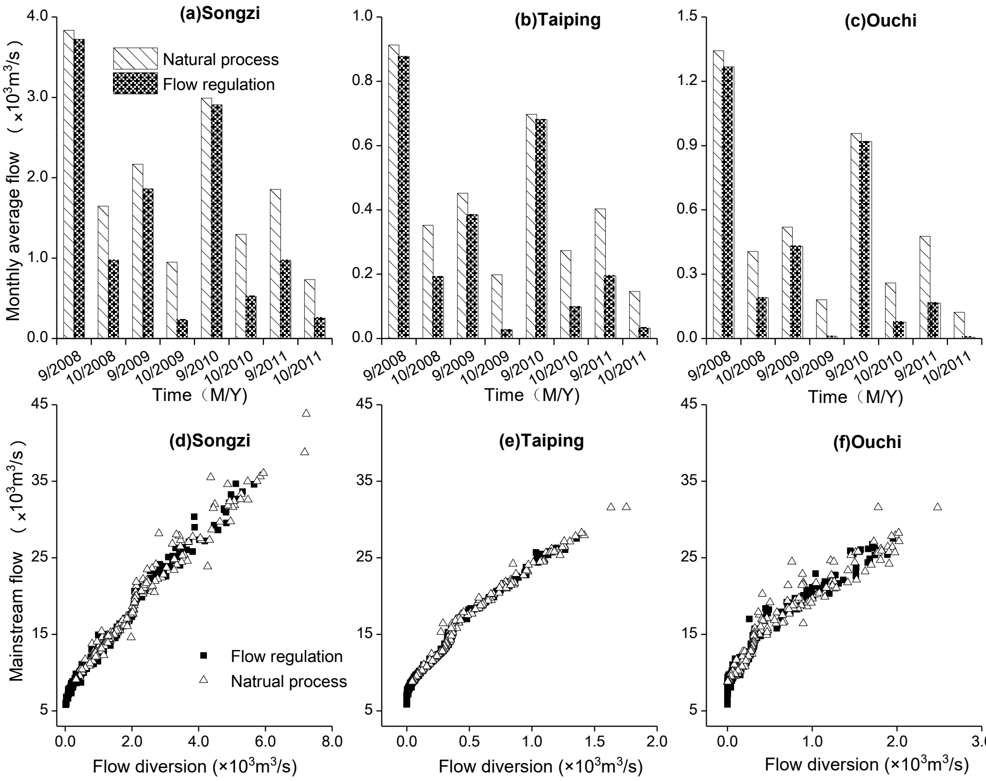

Figure 2. Monthly diverted flow through the three inlets in September and October, from 2008 to 2011, and the relationship between the mainstream flow and the diverted flow. Natural processes indicate the hydrological processes are the ones that without the TGD influences, while the regulation represents the hydrological processes that are under the TGD flow regulation. (**a**) Monthly average diverted flow through the Songzi outlet with and without the TGD, (**b**) Monthly average diverted flow through the Taiping outlet with and without the TGD, (**c**) Monthly average diverted flow through the Ouchi outlet with and without the TGD, (**d**) Relationship between the diverted flow and the mainstream flow at the Songzi outlet, (**e**) Relationship between the diverted flow and the mainstream flow at the Taiping outlet, (**f**) Relationship between the diverted flow and the mainstream flow at the Ouchi outlet.

Figure 3 presents the outflow processes at the Chenglingji outlet during September and October, from 2008 to 2011, with and without the TGD, which indicates that water impoundment of the TGD indeed leads to a series of hydrological changes in the lake outflow. Although there were both a flow increase and a flow decrease after the TGD operation, the flow decrease was more apparent on the whole compared with the processes without the TGD. During the periods of TGD impoundment from September to October in each year from 2008 to 2011, the maximum flow decrease was up to 4860, 2012, 2610, and 9551 m^3/s, and the mean flow decrease was about 1610, 790, 1029, and 1035 m^3/s than the processes without TGD. Furthermore, the dashed lines in Figure 3 present the beginning day that the TGD impoundment. There was a sharp increase in the lake outflow when the TGD began to store water. But then the outflow reduced sharply because of the water volume decrease in Dongting lake.

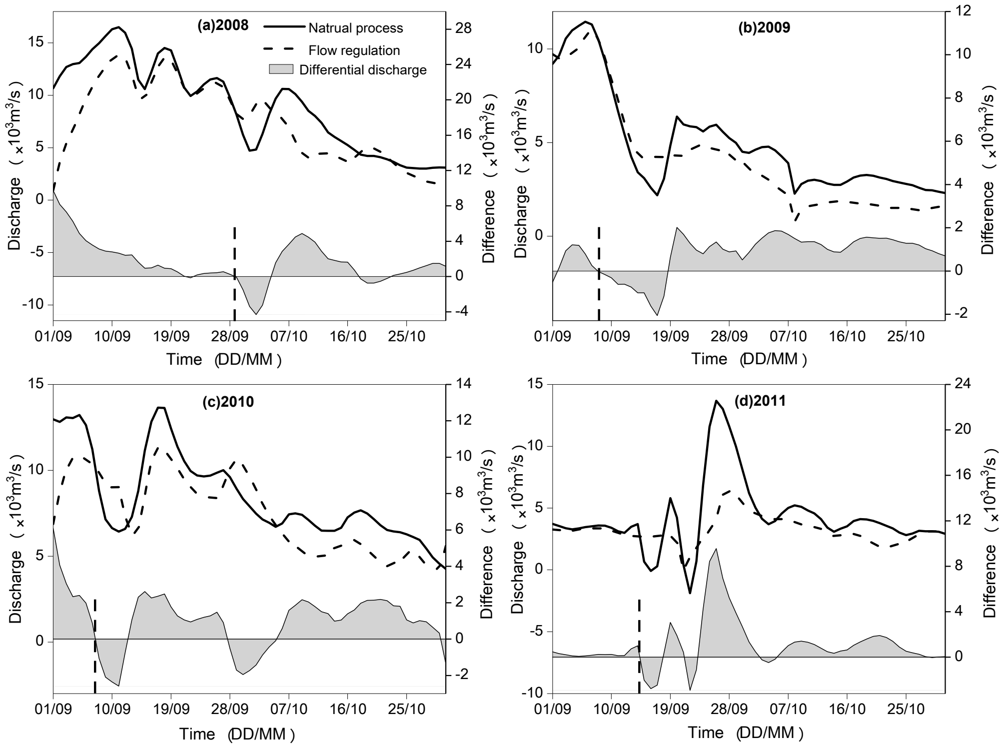

Figure 3. Hydrograph at the Chenglingji outlet during the impoundment periods from 2008 to 2011, and the flow difference with and without the TGD. The positive flow difference denotes the outflow without TGD was larger than the one under the flow regulation of TGD and vice versa.

In addition, the flow difference between lake inflow and outflow directly caused the water exchange variation in the river–lake system. Therefore, the water volume and its residence time in the lake area unavoidably changed with the water exchange. The water residence rate and mean residence time was calculated via Equations (3) and (4), and the results were presented in Table 1. The water residence rate indicates the water retention capacity of the Dongting lake; as shown in Equation (3), its negative value implies the outflow is larger than the inflow. Although there was an evident decrease in the inflow and outflow from September to October, the water residence rate under the TGD regulation was smaller than the one without TGD, which indicated the water volume gap between the lake inflow from the Yangtze River and the lake outflow to the Yangtze River increased after the TGD operation. The inflow decrease was larger than the outflow decrease after the TGD operation. Consequently, the mean residence time was also reduced due to the decreased water retention capacity. As shown in Table 1, there were about 1–2 days reduced in the water residence time after the TGD operation.

Table 1. Computing results of the water residence rate and mean residence time in the Dongting lake with and without the TGD.

Time	Without TGD		TGD	
	WRR	MRT (Day)	WRR	MRT (Day)
2008	−0.234	18	−0.242	17
2009	−0.285	12	−0.351	10
2010	−0.191	16	−0.198	15
2011	−0.038	25	−0.05	23

Note: WRR denotes the water residence rate; MRT denotes the mean residence time, day.

3.2. Changes in the Hydrological Regime of the Dongting Lake

The changes of water exchange between the Dongting lake and the Yangtze River inevitably lead to the variation in the hydrological regime of the Dongting lake. Figure 4 shows the lake-stage changes from September to October, with and without the TGD. The water level decreased apparently at all the gauging stations during the same periods. The stage difference at the Nanzui station was more insignificant than the other lake stations. In addition, there was a similar stage-changing trend at the Heyehu, Lujiao, and Chenglingji stations. Compared with the processes without TGD, the lake level decreased greatly from late September, after the TGD impoundment. The maximum and mean lake level decrease at the Nanzui station was 2.18 and 0.46 m during the impounding periods from 2008 to 2011. Similarly, there was a larger-lake level decrease at the other stations, especially at the Chenglingji station. The maximum lake-level decrease occurred at the Chenglingji station and was up to 3.39 m, and the mean lake-level decrease at the Heyehu, Lujiao, and Chenglingji stations was about 1.17, 1.19, and 1.20 m.

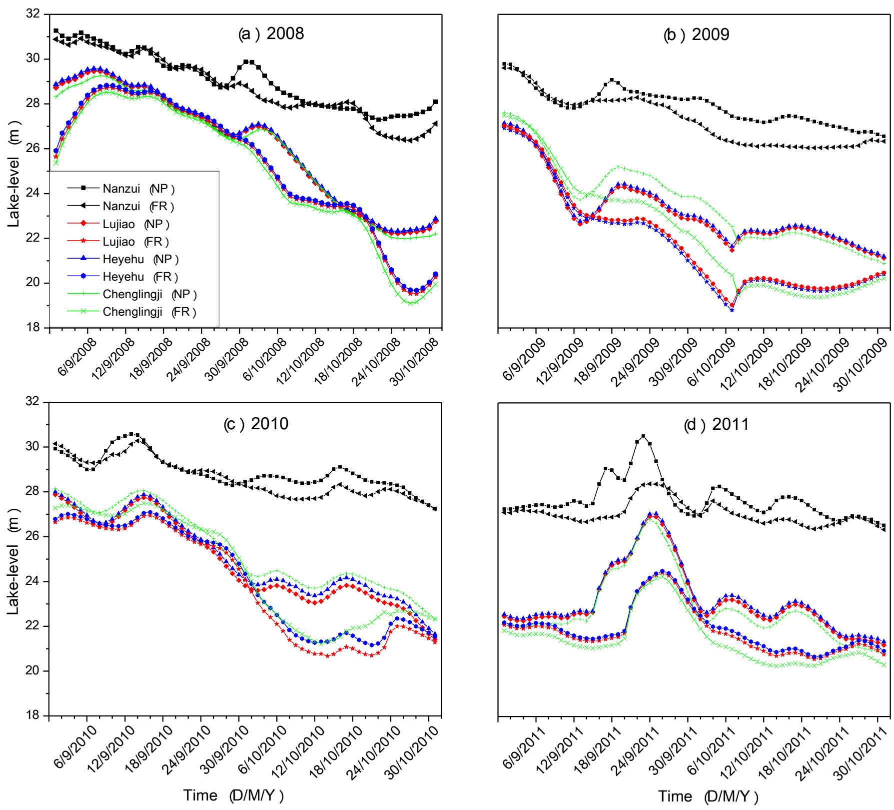

Figure 4. Lake-level changes from September to October, with and without the TGD. Continuous lines represent hydrological processes without the TGD; dashed lines denote the TGD regulated flow processes.

Figure 5 presents the stage-change rate in the lake area. The stage change rate was the daily mean water level variation from September to October. As shown in Figure 5, the stage drop under the TGD flow regulation from September to October was more severe than the one in the processes without TGD. After the TGD operation, the lake level decreased about 0~0.6 m per day, while the stage drop was only 0~0.45 m per day in the processes without TGD. It should be noted that the flood regulation of the TGD before the impoundment periods had also some influences on the stage change rate. The peak-flow reduction during the flood periods (from July to August) drastically decreased the flow diversion to the Dongting lake, which had an influence on the lake-level changes to some extent. For this reason, the stage-change rate in 2011 under the TGD operation was slightly smaller than the one without TGD.

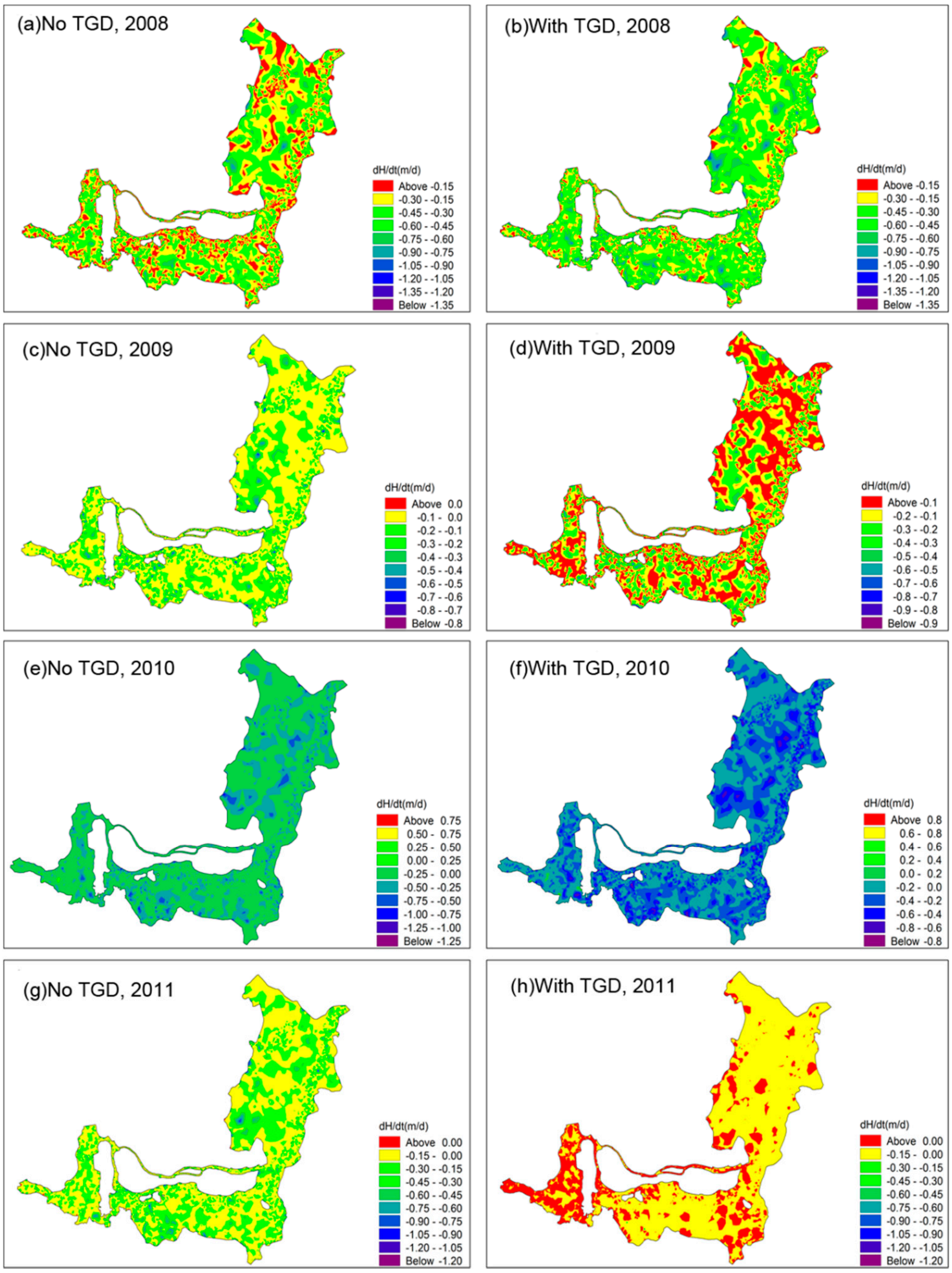

Figure 5. Rate of stage change in the Dongting lake area from September to October with and without the TGD.

Water exchange in the river–lake system also had a direct impact on the water volume in the lake area. The relationship between the water volume of the Dongting lake and the stage at the Chenglingji outlet from September to October was shown in Figure 6. The Chenglingji outlet is situated at the lowest lake site, and its stage changes greatly depended on the lake volume. Therefore, the relationship shown in Figure 6 showed the volume changes due to the water exchange in the Dongting river–lake system. The water volume decreased more or less after the TGD operation, especially during the impoundment periods in 2011. The decrease in the smallest lake volume during the impounding periods was about 3.61×10^9 m^3, 1.47×10^9 m^3, 0.93×10^9 m^3, and 0.63×10^9 m^3 in each year, from 2008 to 2011, which contributed a lot to the severe drop of lowest lake level in the Dongting lake.

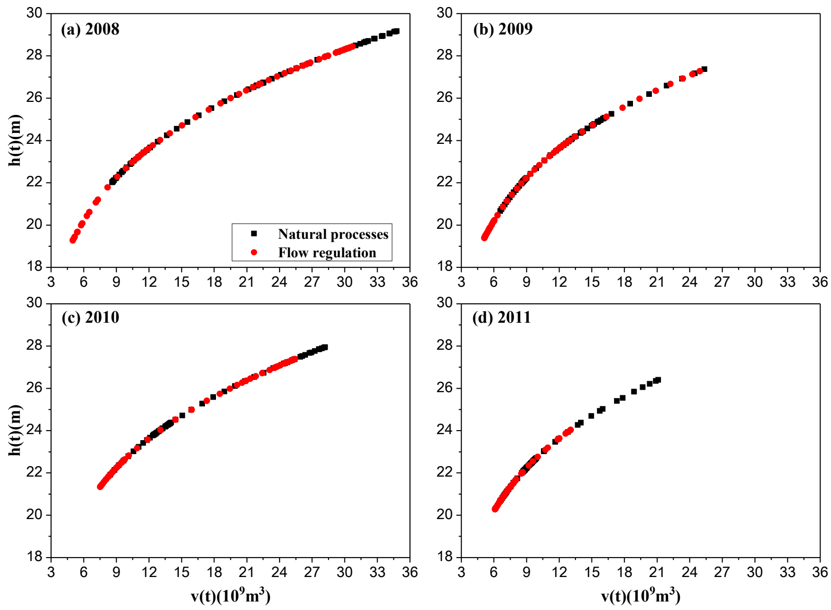

Figure 6. Relationship between water volume of the Dongting lake and stage at the Chenglingji outlet.

The impoundment impact on the water volume of the Dongting lake was not instantaneous but lasted all the impounding periods. As shown in Figure 7, compared with the processes without TGD, there was a significant decrease in the water volume during most time periods under the TGD flow regulation from September to October. The mean water-volume decrease with the time percentage from 50%–80% was about 3.32×10^9 m^3, 3.27×10^9 m^3, 3.72×10^9 m^3, and 2.05×10^9 m^3 in each year, from 2008 to 2011. In addition, the water volume with the largest time percentage of the Dongting lake was still smaller than the one during the same periods of processes without TGD, which resulted from the drastic water exchange between the Dongting lake and the Yangtze River. The TGD impoundment not only increased the outflow from the Dongting lake but also seriously decreased the inflow to the lake area.

Flow-field variation inevitably occurred due to the variations in lake level and water volume in the lake area. Figure 8 presents the flow velocity variations at the gauging stations of lake area, with and without the TGD. The changes in the flow velocity did not maintain consistency, because of the complicated hydraulic relation in the great lake area. The mean flow velocity at the Chenglingji, Lujiao, Heyehu stations increased to some extent after the TGD operation, while mean flow velocity reduced at the Shawan and Nanzui stations, to a different degree, with an especially drastic decrease at the Nanzui station. The maximum velocity increase, about 0.067 m/s in 2008, occurred at the Chenglingji outlet of the eastern part of the Dongting lake. There was a high agreement of current speed variation between the Lujiao and Heyehu stations. On the contrary, the maximum velocity decrease at the Nanzui station was about 0.128 m/s in 2009.

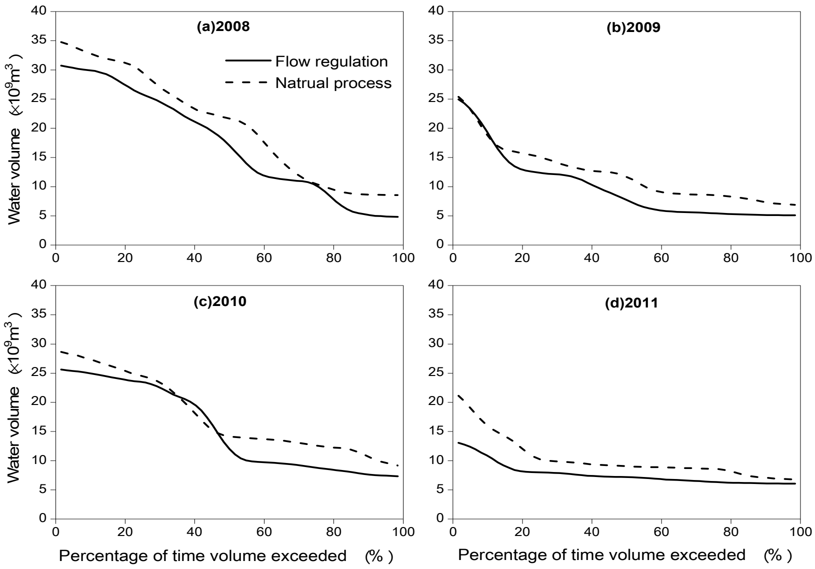

Figure 7. Volume duration curves from September to October, with and without the TGD.

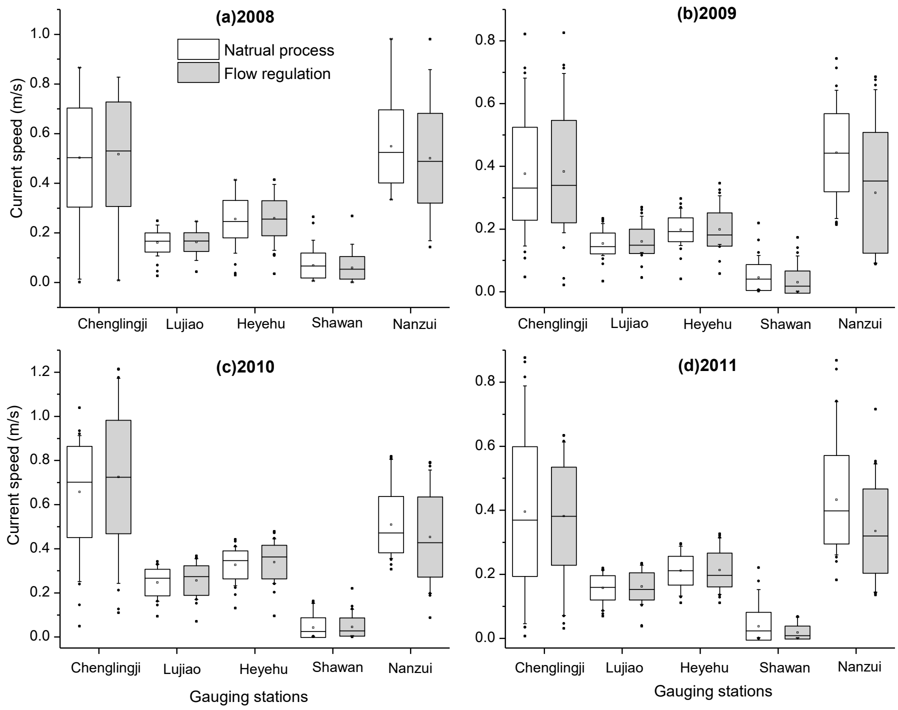

Figure 8. Flow-velocity variations at the gauging stations of the lake area, with and without the TGD.

4. Discussion

Impoundment of the TGD reduced the outflow to the downstream during its impounding periods, which had a complex influence on the hydraulic interaction between the Yangtze River and the Dongting lake. There was a positive correlation between the mainstream flow and the diverted flow at the three inlets of the Dongting lake (Figure 2). The reduced outflow from the TGD significantly decreased the diverted flow during impounding periods, which contributed a lot to the volume reduction of the lake area. Moreover, there was an evident stage decrease at the Chenglingji lake outlet that resulted from the reduced flow discharge in the Yangtze River. As presented in the Figure 9, the water-head difference increased to a different degree after the TGD was put into operation; there was especially a larger water-head difference between the eastern and western part of the Dongting lake, e.g., the maximum water-head difference was much higher than 1.5 m between the Chenglingji and Nanzui (Shawan). It was the very reason that the outflow from the Chenglingji outlet had a transitory increase at the beginning of TGD impoundment. However, limited to the water volume and the rapid stage reduction in the lake area, the lake outflow significantly decreased subsequently (Figure 3, Figure 5 and Figure 7).

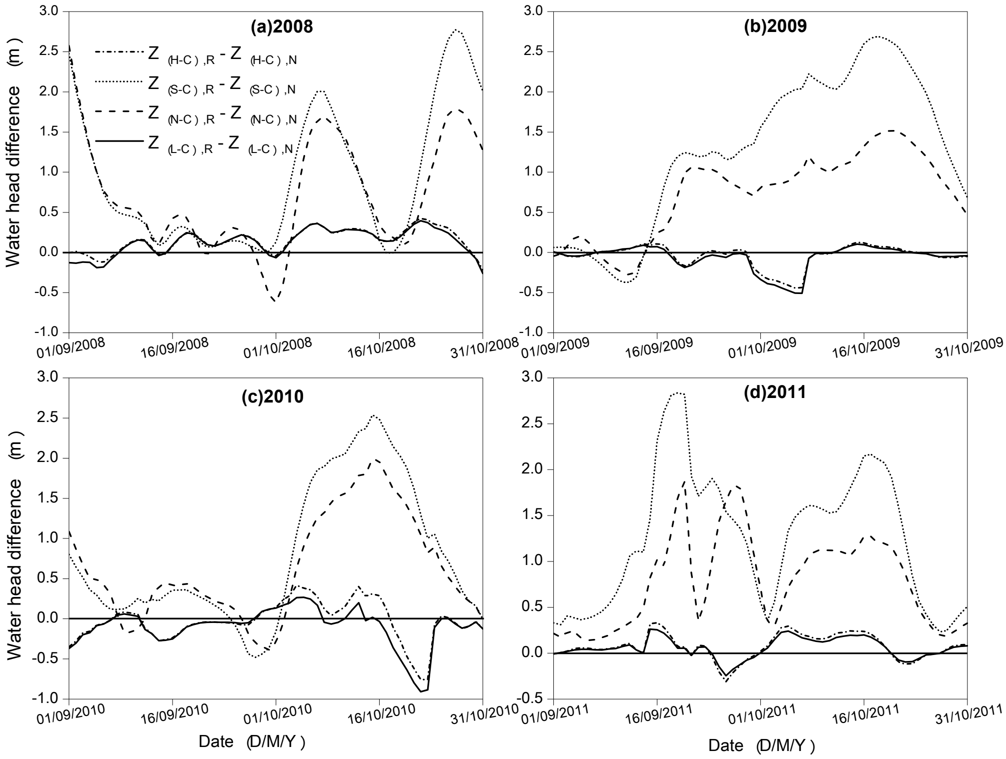

Figure 9. Water-head difference between the stations, with and without the TGD. The water-head difference was the value that the water head between the stations without the TGD subtracted from the water head between the stations with the TGD. $Z_{H\text{-}C,\,R}$, $Z_{S\text{-}C,\,R}$, $Z_{N\text{-}C,\,R}$, and $Z_{L\text{-}C,\,R}$ denote the water head between one of the stations (Heyehu, Shawan, Nanzui, and Lujiao) and the Chenglingji station, respectively, under the flow regulation, and the $Z_{H\text{-}C,\,N}$, $Z_{S\text{-}C,\,N}$, $Z_{N\text{-}C,\,N}$, and $Z_{L\text{-}C,\,N}$ present the water head between one of the stations (Heyehu, Shawan, Nanzui, and Lujiao) and the Chenglingji station, respectively, without the TGD.

On the other hand, the decrease in the water volume and lake level of Dongting lake also had an impact on the hydrological regime of the Dongting river–lake system. Lacking adequate water supply, the Dongting lake provided much less water to the downstream channels to maintain the water depth of the waterway in the following dry seasons [43]. The increased volume gap between the inflow and outflow of the Dongting lake contributed greatly to the low stage of the lake area. Furthermore, the decrease in the lake level and water volume greatly changed the hydrodynamic conditions in the lake area, which were precisely necessary conditions for the migration and transformation of nutrient content in the lake flow [44]. The abrupt hydrological changes during the impoundment periods were extremely adverse to the stability of the lake ecological environment, e.g., the 1–2 days difference in residence time indicated the time decrease that the lake inflow from the Yangtze River was larger than the lake outflow to the Yangtze River, which means the aquatic environment of the Dongting lake changed acutely within two months impoundment periods. The increased water head between the stations contributed to the increase in the flow velocity and shorting the water cycle duration, which reduced the risk of water eutrophication in the lake area. The water-head difference near the lake outlet resulted in an increase in the hydraulic gradient, which significantly contributed to the velocity increase in the eastern lake area. It is well-known that enough current speed is the necessary hydrodynamic conditions for nutrient transport. Therefore, the ecological environment will be influenced by the velocity variation in the eastern Dongting lake area. In addition, the change of the hydrological regime did not show well consistent among subareas of the lake due to the complicated hydraulic relationship in the river–lake system. Therefore, the influencing mechanism of the reservoir impoundment to the river–lake system should be further researched. It should be noted that this study examined the impoundment impact, but the other influence factors remain unchanged. The inflow and outflow of the TGD, as the flow boundary conditions in the model research, more directly revealed the impoundment impact on the river–lake system. In spite of some results that have been achieved based on the effective analysis in this paper, more research on the influence of other factors is still worth carrying out.

5. Conclusions

Impoundment impact, generally, is one of the most important influence factors to the hydrological regime of the river basin. In this study, a physically coupled hydrodynamic model and extensive hydrological data were combined to quantify the impoundment influences on the Dongting river–lake system. The TGD inflow and outflow, as the upstream flow boundary conditions, were the first attempt to explore the impoundment impact in the large Dongting river–lake system, which provided insights into the changes in the hydrological regime. The results revealed that water volume and lake level in the lake area decreased to a different degree under the flow regulation of the TGD, which resulted from the water-exchange changes in the river–lake system. The water inflow to the Dongting lake drastically decreased in total during the impounding periods of the TGD, which not only resulted in a great reduction in water volume and lake stage in the Dongting lake but also decreased the outflow to the downstream channels.

In addition, compared with the different upstream flow conditions for the coupled hydrodynamic model, the impoundment impact on the hydraulic interaction between the Yangtze River and the Dongting lake during the impounding periods was examined. The results implied that the flow velocity in the eastern part of the Dongting lake increased due to the enlarged water head to the lake outlet. However, the flow velocity decreased in the western lake area due to the drastic inflow reduction from the mainstream and the weak hydraulic relationship between the western and eastern parts of the Dongting lake. It indicated that the hydraulic and hydrological regime in the Dongting river–lake system was complicated, which also had some other influence factors worthy of further investigation.

Moreover, the results indicated that the water residence rate decreased to some extent during the different impounding periods, which implied the water retention capacity of the Dongting lake was impaired. Consequently, the water residence time also decreased during impounding periods. This study focused on the impoundment impact on the hydrological and hydraulic regime changes in the Dongting river–lake system and allowed us to better understand the potential influences of the changes in the water exchange after the TGD operation. Finally, the scientific knowledge derived from this study can provide a reference for the administrative departments to make a scientific and rational decision for water-resource, water–ecological, and environmental management in the similar river–lake systems.

Supplementary Materials: The model input data of the two scenarios investigated in this paper can be accessed through the following websites: http://www.cjh.com.cn and http://sw.hubeiwater.gov.cn.

Author Contributions: J.Z. conducted the modeling, performed the analysis, and drafted the manuscript; T.H. acquired, processed, and analyzed the data. L.C. conceived of and designed the study and interpreted the results; X.L. and L.F. prepared the input data for the simulations. L.Z. provided observational data and helped with the analysis; Y.Y. gave constructive comments on the results in this study. All the authors edited the manuscript.

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