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Research into the Eutrophication of an Artificial Playground Lake near the Yangtze River

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Abstract: Water pollution in urban rivers is serious in China. Eutrophication and other issues are prominent. Taking the artificial Playground Lake in Zhenjiang as an example, a numerical model combining particle tracing, hydrodynamics, water quality and eutrophication was constructed to simulate the water quality improvement in Playground Lake with or without water diversion by pump and sluice. Simulation results using particle tracking showed that the water residence time depended on wind direction: east wind, 125 h; southeast wind, 115 h; south wind, 95 h. With no water diversion, the lower the flow velocity of Playground Lake under three wind fields, the more serious the eutrophication. Under pump diversion, the water body in Playground Lake can be entirely replaced by water diversion for 30 h. When the temperature is lower than 15 °C, from 15 °C to 25 °C and higher than 25 °C, the water quality can be maintained for 15 d, 10 d and 7 d, respectively. During high tide periods of spring tides in the Yangtze River from June to August, the water can be diverted into the lake through sluices. The greater the Δh (the water head between the Yangtze River and Playground Lake), the more the water quality will improve. Overall, the good-to-bad order of water quality improvements for Playground Lake is as follows: pumping 30 h > sluice diversion > no water diversion. This article is relevant for the environmental management of the artificial Playground Lake, and similar lakes elsewhere.

Keywords: hydrodynamic; numerical simulation; eutrophication; water diversion

1. Introduction

Eutrophication is one of the global water environment problems. The main sign of eutrophication is the abnormal proliferation of algae in water, while dynamic changes of algae in water are affected by their internal physiological characteristics and external factors. The growth of algae is affected not only by external factors such as sunlight, nutrients, transparency, water temperature and pH value, but also by hydrodynamic conditions in the water body, such as flow velocity [1,2], flow rate [3] and water disturbance [4,5]. On the other hand, the eutrophication of lakes is closely related to human activities in the basin. Industrial, agricultural and urban domestic sewage is continuously diverted into lakes. Humans damage the natural ecological environment through lake reclamation, lakeshore construction and aquaculture, thus increasing the import of nutrients [6–9]. Although the Chinese government has devoted a great deal of manpower and material resources, some control measures have not yet achieved the desired results in some areas with frequent eutrophication of lakes. Overall regional control should be implemented to control the eutrophication of lakes [10].

In the face of agricultural non-point-source pollution, it is relevant to carry out pollution source management, nutrient transfer management and soil erosion control [11]. Some scholars have proposed the use of sediment dredging and pollution source interception methods to improve water quality [12,13]. Eutrophication control of the water body is beneficial not only to the environment but also to the survival and development of human beings [14–16].

A common phenomenon associated with the eutrophication of lakes is the abundance of phytoplankton [17]. Algae usually overgrow, form algal bloom and result in the deterioration of water quality and a series of serious water environment problems. In the formation of algal bloom, the Chl-a concentration is generally above 10 mg/m^3. Due to the widespread presence of algal bloom in freshwater ecosystems, microcystis bloom has received the highest attention as the most studied algal bloom [18,19]. At present, most researchers agree that the formation of cyanobacteria bloom is generally caused by the physiological characteristics of cyanobacteria and environmental factors such as temperature, sunlight, nutrients, and other organisms [20]. With the eutrophication of lakes, especially the increase of phosphorus concentration, the species composition of phytoplankton usually leads to the formation of algal bloom. The ratio of total nitrogen (TN) to total phosphorus (TP) in water also significantly affects the phytoplankton species composition. Generally, cyanobacterial blooms are dominant when TN:TP < 29 [21]. In the early stage of eutrophication, phosphorus is the limiting factor for algae growth, and its increased concentration can lead to the massive growth of algae. With the rapid growth of the urban population and the rapid development of industry in China, the eutrophication of urban water bodies has become a serious ecological problem in the urban environment [22–24]. Eutrophication increases the amount of organic matter in the water, multiplies pathogens, and produces harmful algal toxins, which threatens the safety of drinking water. Large numbers of algae spread over the water and block out the sunlight to the bottom of the water so that the photosynthesis of the bottom of the water is prevented, which reduces oxygen release.

When algae multiply rapidly and nutrition depletes, large-scale death occurs in underwater plants. Plants are decomposed by microorganisms, which consumes a lot of oxygen. Therefore, the concentration of dissolved oxygen in the water decreases, which can cause the death of aquatic animal, especially fish [25–28]. Some algae emit noxious odors and this can prevent a water body from being used by the public.

Ecological models are important tools for lake eutrophication research and lake ecosystem management [29–32]. The development of lake eutrophication models has developed from simple models of single layer, single component, and zero dimensions to complex, multi-layer, multi-component models with three dimensions [33–36]. According to the characteristics of complexity, lake eutrophication models are divided into simple regression models, simple nutrient balance models, water quality, ecologically and hydrodynamically complex models, as well as ecologically dynamic models [37–39]. With the advances in computing, monitoring and communication technologies, simulation and forecasting technologies for water environments are also constantly improving [40,41]. At present, there are many models for simulating hydrodynamic processes, such as QUAL2 K (River and Stream Water Quality Model), MIKE11 (Modelling System for Rivers and Channels), WASP (Water Quality Analysis Simulation Program) and EFDC (Environmental Fluid Dynamic Code). For example, Zhenjiang Magic Ocean World, a typical playground in Zhenjiang City, carried out playground hydrodynamic and water quality improvement measures, mainly using a two-dimensional, hydrodynamic/aquatic ecological model.

2. Study Area and Methods

2.1. Study Area

Located at 119°28′ E and 32°15′ N, Zhenjiang City has a monsoon climate with a transition from a warm temperate zone to the northern subtropical zone, belonging to a semi-humid zone. The average annual precipitation is 1082.7 mm and the average annual evaporation is 894.6 mm. The daily maximum evaporation during the year generally occurs in July and August [42], with the minimum in January. Over the years, the average temperature is 15.4 °C, with a highest temperature of 40.9 °C and a lowest temperature of −12 °C. The sunshine is sufficient, with an average annual sunshine h of 2073.8 h [43]. The annual sunshine percentage is 47~49%. According to statistics, the annual prevailing winds are E, ENE and ESE (9% each)—ESE in summer (13%) and ENE in winter (9%). The prevailing wind of Zhenjiang City is northeast to east by south. The average annual wind speed is 3.4 m/s [44], which is high.

The Zhenjiang Magic Ocean World project is surrounded by water on three sides. The north side is a diversion channel, the south side is the original pilot diversion river and the southeast side is Neijiang Lake, which is about 372 km away from the downriver estuary and is not affected by saltwater intrusion. Neijiang Lake is connected to the Yangtze River by the diversion channel and joins the Yangtze River downstream at the Jiaonan Sluice. The exchanged water volume per year between Neijiang and the Yangtze River is typically between 4.5×10^9 m^3 and 1.5×10^{10} m^3. More than 85% of the exchanged water volume is concentrated in the flood season. The tides in the Yangtze River result in high and low tides twice a day in Neijiang Lake, with the rising tide lasting 3.42 h and the ebbing tide lasting 9.25 h on average [36,37]. The water system of Playground Lake, the water conservation project and the surrounding land use situation are shown in Figure 1.

The total construction area of the Zhenjiang Magic Ocean World project is 101,050 m^2 [45]. The main construction items include Playground Lake, Ocean World, the Water Tourism Center and other tourism facilities, among which Playground Lake is made up of #1, #2 and #3 sections of Shuijie, the central landscape lake and Moya, which carries out flood control and ecological dispatch through three sluices and one culvert [46].

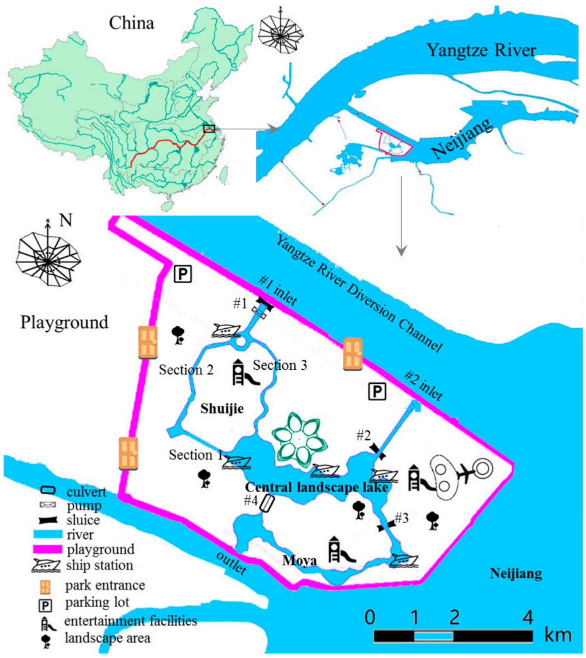


Figure 1. Study area.

The concentrations of COD (Chemical Oxygen Demand), ammonia nitrogen, TP, TN and Chl-a of Playground Lake are 3.03 mg/L, 0.15 mg/L, 0.039 mg/L, 1.182 mg/L and 0.016 mg/L on average, respectively. According to Surface Water Class III standards [47,48], the concentrations of COD, ammonia nitrogen and Chl-a can meet the standards; the exceeding standard rates of TP and TN are 27.3% and 66.7%, respectively.

2.2. Study Methods

2.2.1. Two-Dimensional Hydrodynamic Model

The two-dimensional hydrodynamic governing equations in a Cartesian coordinate system are the continuity equation and momentum equations for the integral of the three-dimensional Renault Navier–Stokes equations [30,31] of the incompressible fluid along the direction of water depth, which can be expressed as follows:

Continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial h\overline{u}}{\partial x} + \frac{\partial h\overline{v}}{\partial y} = hQ \tag{1}$$

Momentum equation:

$$\begin{aligned} \frac{\partial h\overline{u}}{\partial t} + \frac{\partial h\overline{u}^2}{\partial x} + \frac{\partial h\overline{v}\overline{u}}{\partial y} & \\ &= fh\overline{v} - gh\frac{\partial \eta}{\partial x} - \frac{h}{\rho_0}\frac{\partial P_a}{\partial x} - \frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x} + \frac{\tau_{sx}}{\rho_0} - \frac{\tau_{bx}}{\rho_0} - \frac{1}{\rho_0}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y}\right) \\ &+ \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{xy}) + hu_s Q \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial h\overline{v}}{\partial t} + \frac{\partial h\overline{v}^2}{\partial y} + \frac{\partial h\overline{v}\overline{u}}{\partial x} & \\ &= -fh\overline{u} - gh\frac{\partial \eta}{\partial y} - \frac{h}{\rho_0}\frac{\partial P_a}{\partial y} - \frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y} + \frac{\tau_{sy}}{\rho_0} - \frac{\tau_{by}}{\rho_0} - \frac{1}{\rho_0}\left(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y}\right) \\ &+ \frac{\partial}{\partial x}(hT_{xy}) + \frac{\partial}{\partial y}(hT_{yy}) + hv_s Q \end{aligned} \tag{3}$$

where t represents time; x and y represent Cartesian coordinates; h represents total water depth; η represents water level; ρ represents water density; $\overline{u}$ and $\overline{v}$ represent average water depth; $f = 2\Omega sin\varphi$ denotes the Coriolis factor (Ω is the angular velocity of the Earth's rotation, φ is the geographical latitude); S_{xx}, S_{xy} and S_{yy} are the radiation stress tensors; P_a is the atmospheric pressure; Q is the point source emissions; g is the gravitational acceleration;

$$h\overline{u} = \int_{-d}^{\eta} udz,\ h\overline{v} = \int_{-d}^{\eta} vdz \tag{4}$$

where ρ_0 represents the relative density of water; and (u_s, v_s) represents the rate at which the outside world is released into the water body.

Transverse stress T_{ij} includes viscous resistance, turbulent frictional resistance, and differential advection frictional resistance, which can be calculated using the eddy viscosity equation with the mean vertical velocity:

$$T_{xx} = 2A\frac{\partial \overline{u}}{\partial x},\ T_{xy} = A\left(\frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{v}}{\partial x}\right),\ T_{yy} = 2A\frac{\partial \overline{v}}{\partial x} \tag{5}$$

2.2.2. Two-Dimensional Water Quality and Eutrophication Model

(1) Basic equations of the water quality model

The water quality equation is based on the mass balance equation. The three-dimensional water quality transport equation contains a lot of uncertain parameters. Under the existing conditions, the verification of this model is difficult. Considering the factors such as data and model calculation workload, the vertically average two-dimensional water quality model is adopted [49,50]. The rwo-dimensional water quality transport equation is:

$$\frac{\partial C_i}{\partial t} + U\frac{\partial C_i}{\partial x} + V\frac{\partial C_i}{\partial y} = \frac{\partial}{\partial x}\left(E_x\frac{\partial C_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y\frac{\partial C_i}{\partial y}\right) + K_iC_i + S_i \quad (6)$$

where: C_i is the pollutant concentration; u and v are the flow velocity in the x and y directions; E_x and E_y are the diffusion coefficients in the x and y directions; K_i is the pollutant degradation coefficient; and S_i is the sediment release of pollutant.

In order to introduce a quantitative relationship between sediment resuspension flux and hydrodynamic conditions in the model and reflect the change of sediment resuspension flux of pollutant with the flow velocity, the sediment resuspension flux is calculated using the relationship obtained from sediment resuspension experiments when the mathematical model is established [49,50]. This mainly reflects the handling of the source sink term S_i, as follows:

$$S_i = \frac{\alpha_i}{H} \quad (7)$$

where α_i is the sediment resuspension flux (g/(m^2·d)), $\alpha_i = \zeta_i \cdot \beta_i \exp(\xi_i \cdot P)$; H represents water depth (m); β_i is the proportion of sediment pollutants in SS (%); P represents co-velocity (cm/s), $P = \sqrt{u^2 + v^2}$; and ζ_i, ξ_i are the sediment resuspension parameters.

(2) Basic equations of the Ecolab eutrophication model

The content of Chl-a in lakes is the major parameter for evaluating the water trophic status. There are many factors affecting Chl-a content in lakes. It is generally acknowledged that sunlight, temperature, precipitation, nutrients and pH can affect it. In this paper, the impact of the nutritive salt (total nitrogen, total phosphorus) concentration on algae growth was investigated. Chl-a concentration was regarded as the evaluation index. According to the principle of mass conservation, the basic equation of eutrophication is [36–41]:

$$\frac{\partial C_{chl-a}}{\partial t} + U\frac{\partial C_{chl-a}}{\partial x} + V\frac{\partial C_{chl-a}}{\partial y} = \frac{\partial}{\partial x}\left(E_x\frac{\partial C_{chl-a}}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y\frac{\partial C_{chl-a}}{\partial y}\right) + S_{chl-a} \quad (8)$$

where:

$$S_{chl-a} = G_{PI}(t) - D_{PI}(t) - \frac{V_s}{D} \quad (8a)$$

$$G_{PI} = K_1 \cdot Phtsy \cdot F(N,P) \quad (8b)$$

$$D_{PI} = \mu \cdot F(N,P) \quad (8c)$$

In the equation, $C_{chl\text{-}a}$ represents the concentration of Chl-a; U and V respectively represent the flow velocity in the x and y directions, which can be calculated from the water volume model; E_x and E_y represent the lateral and longitudinal diffusion coefficients of algae; $S_{chl\text{-}a}$ represents the conversion of Chl-a; G_{PI} represents algae growth; D_{PI} represents algae death; V_s represents algae sedimentation ; D represents water depth; K_1 refers to the correlation coefficient between Chl-a content and photosynthesis of phytoplankton; Phtsyn refers to the photosynthesis of plants in unit water volume; μ refers to the mortality rate under optimal nutrition conditions; and F (N, P) indicates the nutrient limit function, whose model conceptual diagram is shown in Figure 2.

$$F(N,P) = \frac{2}{\frac{1}{F(N)} + \frac{1}{F(P)}} \quad (8d)$$

$$F(N) = \frac{\frac{PN}{PC} - PN_{min}}{PN_{max} - PP_{min}} \quad (8e)$$

$$F(P) = \frac{\left(\frac{PP}{PC} - PP_{min}\right) \cdot (KC + PP_{max} - PP_{min})}{(PP_{max} - PP) \cdot (KC + PP/PC - PP_{min})} \tag{8f}$$

where PN_{min} and PN_{max} are respectively the minimum and maximum nitrogen content of algae (gN/gC). PP_{min} and PP_{max} are the minimum and maximum phosphorus content of algae, (gP/gC). KC is the half-saturation phosphorus content of phytoplankton (gP/gC).

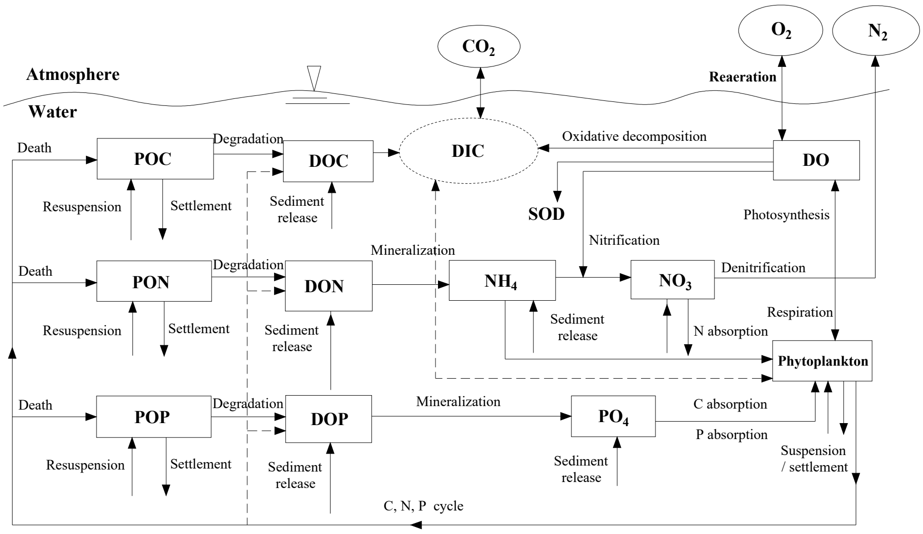


Figure 2. Model conceptual diagram.

2.3. Model Setup and Parameter Selection

2.3.1. Model Setup

In this paper, the study area was divided into 3812 grids by using mixed grids of three or four polygons. The grid spacing was about 8~10 m [30,31]. The lake was supposed to be stationary and have no disturbance at the initial time. The time step was 60 s. Figures 3 and 4 show the model grid and bathymetry of 85 elevation.

85 elevation: National Vertical Datum 1985, where the average sea level of the Yellow Sea (in Qingdao) was established as the unified base in 1956.

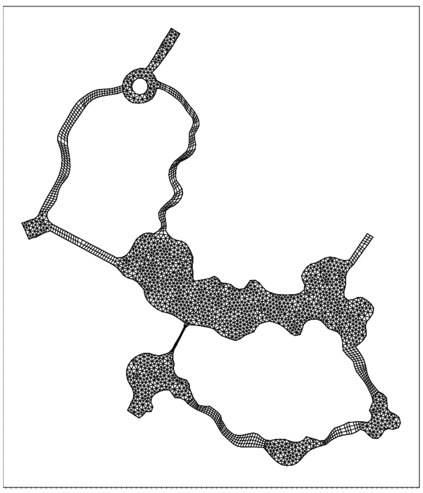


Figure 3. Model grid.

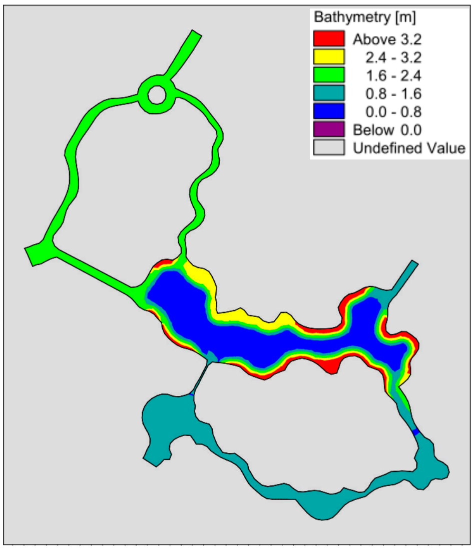


Figure 4. Model bathymetry of 85 elevation.

2.3.2. Parameter Selection

Due to the current under-planning state and no excavation operations at Playground Lake, the results of the model calculation were checked to ensure that they meet stronger relations between the real status of the park and the model to estimate the effect of changes, according to Wang Hua's in situ data and routine monitoring data of Neijiang Lake and diversion channel [22–25]. The main water quality and eutrophication parameters in the model are shown in Table 1.

Table 1. Main water quality and eutrophication parameters.

Number	Parameters	Value [22–25]	Unit
1	Chl-a growth rate	1.8	per day
2	Chl-a sedimentation rate	0.11	per day
3	Sediment oxygen consumption	0.5	per day
4	Nitrification oxygen demand of ammonia nitrogen	3.42	g O_2/g NH_4-N
5	Denitrification oxygen demand of nitrite	1.14	g O_2/g NO_2-N
6	Denitrification rate	0.1	per day
7	Phosphate degradation rate	0.06	g P/m^3/day

2.4. Calculation Programs

In order to ensure the water quality in the study area and to meet the water use requirement of landscape and recreation, two kinds of water diversion schemes were proposed to control water eutrophication, as follows:

2.4.1. Water Diversion through Sluice

During high tide periods of the spring tides in the Yangtze River, if the water level of the Yangtze River is 0.3 m higher than that of Neijiang Lake with sluice, water will be diverted into Playground Lake by gravity to improve water quality and eutrophication status by the water head between the #1 inlet, #2 inlet and outlet (Figure 5).

Model boundary conditions: The initial water level was set at 2.67 m. The temperature was 28 °C. The initial flow rate was set to zero [42–44]. The initial water head Δh (the water head between the Yangtze River and Playground Lake) was 0.2–0.3 m. The flow rate of water diversion through sluice at #1 inlet and #2 inlet were 8.27 m^3/s and 1.82 m^3/s, respectively.

Weather conditions: The measurement data show that the average temperature in 2016 was 16.8 °C; the coldest month was January when the average monthly temperature was 2.97 °C; the hottest month was August when the average monthly temperature was 29.39 °C. The average annual precipitation in the last two years was 1082.7 mm, which was unevenly distributed. The precipitation was mostly concentrated in the spring, summer and autumn [45,46]. In particular, the precipitation was the highest in the summer, exceeding 45% of the total annual precipitation. The average annual wind speed was 3.4 m/s.

Initial pollution source load: The amount of emissions by tourists and sewage produced by tourism facilities was calculated as the initial pollution source load, according to the measurement data and index establishment method [48].

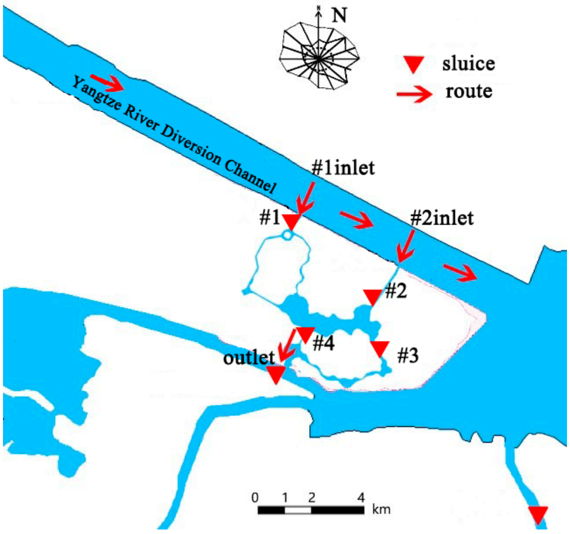


Figure 5. Route of water diversion through three sluices (#1-3) and one culvert (#4).

2.4.2. Water Diversion through Pump

Through the #1 pumping station, the diversion water will enter Playground Lake to improve its water quality and eutrophication status. The positions of the three sluices and one culvert are shown in Figure 1. The specification parameters are provided in Table 2.

Table 2. Specification parameters of three sluices and one culvert.

Number		Size
#1	sluice	Net width of 9 m, bottom elevation of 1.2 m
	pump	Single pump flow rate of 1.85 m^3/s with a total of two
#2 sluice		Net width of 10 m, bottom elevation of 1.0 m
#3 sluice		Net width of 9 m, bottom elevation of 1.5 m
#4 culvert		Net size of 2 m × 2 m

Playground Lake has a storage capacity of about 350,000 m^3. The design flow rate of a single pump was 1.85 m^3/s. Water can all be replaced within 27 h by double pump diversion, according to the initial calculation. The pump diversion will not affect recreational activities such as watercraft due to its low flow rate, so that continuous pump diversion can be used. In order to ensure that the water is completely replaced, the pump diversion was proposed to continue for 30 h. If the #1 sluice turned off and the #1 pump turned on, the #2 sluice, #3 sluice and #4 culvert will divert the water, with most of the water flowing out of the #2 sluice, so that water in the Moya area cannot be effectively changed.

Therefore, it is necessary to properly deploy the three sluices and one culvert to make sure that the water is completely replaced. As the ratio of the storage capacity of Shuijie and the central landscape lake area for the Moya area is about 3:1, the pump diversion was designed from 0:00 to 22:00 on the first day (lasting 22 h) to replace the water in Shuijie and the central landscape lake area, and from 22:00 on the first day to 6:00 on the second day (lasting 8 h) to replace the water in the Moya area. Three sluices and one culvert scheduling plan during pump diversion is shown in Table 3.

Table 3. Three sluices and one culvert scheduling plan during pump diversion.

Time (24 h)	Pump	#1 Sluice	#2 Sluice	#3 Sluice	#4 Sluice	Remarks
Before pumping	Close	Open	Open	Open	Open	/
0:00~22:00	Open	Close	Open	Close	Close	Shuijie and central landscape lake area water diversion
22:00~6:00^{+1}	Open	Close	Close	Open	Open	All areas water diversion
6:00^{+1}~7:00^{+1}	Close	Close	Open	Open	Open	Close #1 sluice for 1 h to prevent backwater
After pumping	Close	Open	Open	Open	Open	Open the flow pump

Note: time^{+1} means the next day.

Zhenjiang Magic Ocean World is affected by a wind field. However, due to the large range of variation of wind speed and direction, it is hard to form a stable flow field and the lake flow does not have a very high degree of regularity. In order to better reflect the influence of the wind field on the flow field in Playground Lake, three kinds of wind speed and direction with high frequency were used in the model simulation. The wind directions were E, SE and S, and the wind speed was 3.4 m/s. The flow field, water quality and eutrophication status under three water diversion modes in three wind fields were simulated. Owing to the small size of Playground Lake and the large diversion flow, the flow field in Playground Lake is mainly affected by water diversion. Therefore, the impact of wind direction on the flow field is almost negligible [35–39]. Thus only the flow field, water quality and eutrophication status of the water diversion through the pump and sluice under SE wind with the highest wind frequency were simulated [51,52]. The model calculation scheme is presented in Table 4.

Table 4. Model calculation scheme.

Program	Wind Direction	Wind Speed	Temperature	Water Diversion
1	E, SE, S	3.4 m/s	28 °C	No
2	SE			Pump
3	SE			Sluice

3. Results and Discussion

3.1. Particle Tracking

Four particles were located at the #2 entrance of the river. The movements and positions of each particle in the flow field [53–57] are provided in Figure 6, which shows that: ① Water residence time depended on wind direction: east wind, 125 h; southeast wind, 115 h; south wind, 95 h. ② Particles did not pass the Moya area in all three wind directions, and almost all particles entered the Shuijie area through the central landscape lake, and then entered the Yangtze River diversion channel. Only one particle reached to the east bank of Playground Lake in the east wind. ③ Particles in the central landscape lake experienced a backflow phenomenon and the water residence time was longer. However, eventually the water still flowed out through the Shuijie area to achieve water exchange.

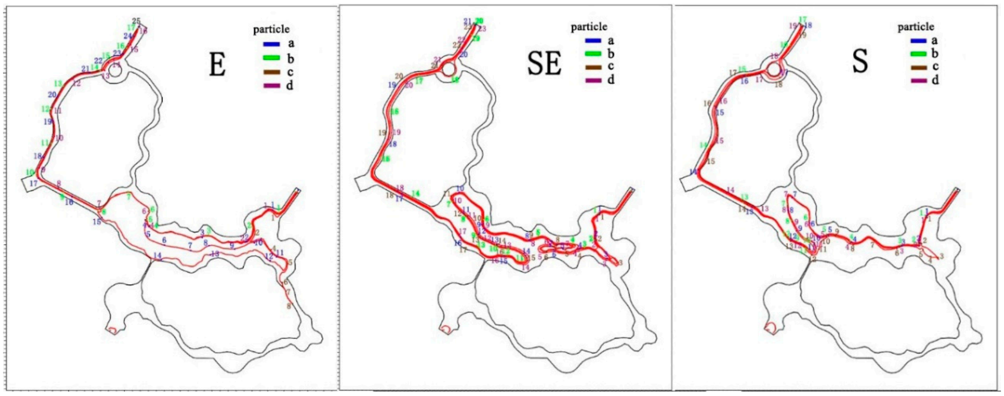


Figure 6. Particle tracking pathway and water residence time in three wind directions.

3.2. Flow Field Calculation and Analysis

3.2.1. Calculation and Analysis of Flow Field with No Water Diversion

Using the established hydrodynamic model for the artificial Playground Lake [44–46] and depending on the above calculation scheme, the flow field in different wind fields with no water diversion was calculated (Figure 7). In all kinds of wind fields [49–51], the model can simulate for ten days to form a stable flow field. Figure 7 showed that: ① The flow velocity of the central landscape lake in three wind fields is low, and the shallow depth of shore water is greatly affected by wind speed, showing slightly higher flow velocity in different wind directions. ② In three wind fields, the flow velocity in the Moya area is very low, only the surface flow moves slightly with the wind direction. ③ Under the east wind, the flow velocity is almost zero because the wind direction is perpendicular to the #1, #2 and #3 sections of Shijie. In the southeast and south wind, the flow velocity increases in the #1 and #2 sections of Shijie.

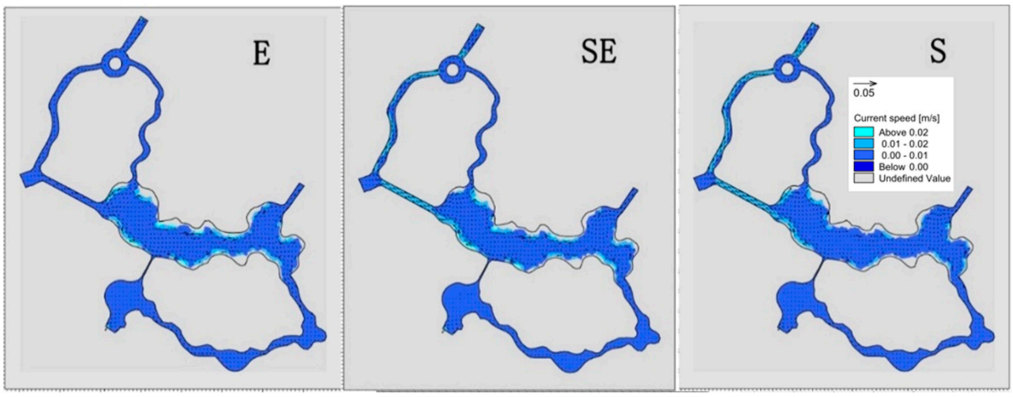


Figure 7. Velocity distribution in different wind directions without water diversion.

3.2.2. Calculation and Analysis of Flow Field with Water Diversion through Pump

Combining the wind data over the years, the flow field of Playground Lake after pumping for 22 h and 30 h was simulated in the most prevailing southeast wind [50–54]. Figure 8a,b showed that: ① After water diversion for 22 h, due to the sudden widening at the junction of Playground Lake and the west side of central landscape lake, the water flow changed from moving wave to diffusion wave. Along the direction of the diffusion wave, the flow velocity decreased. In the central and east areas of the central landscape lake, as the water flow gradually stabilized, the flow velocity increased. ② After water diversion for 30 h, the #2 sluice was closed and the #3 sluice and #4 culvert were open. The flow velocity of the Moya area and exit area became higher and the water body was soon replaced. In the southeast of Playground Lake and in the middle of the Moya area, the flow velocity was relatively slow due to the width being wider than the average wide of the channel. Due to the closure of #2 sluice, there were stagnating flow areas.

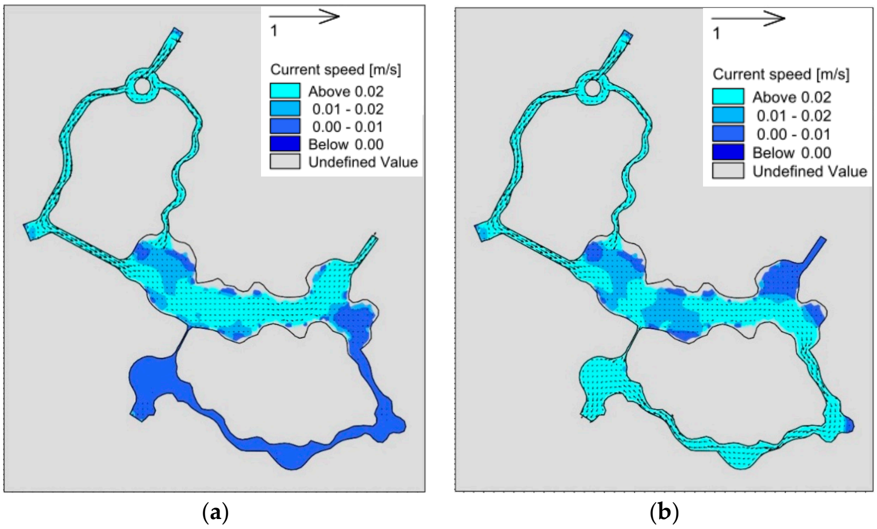


Figure 8. (**a**) Flow field with water diversion through pump for 22 h. (**b**) Flow field with water diversion through pump for 30 h.

3.2.3. Calculation and Analysis of Flow Field with Water Diversion through Sluice

Combining the historical wind field data [42–44], the water head between the #1 inlet, #2 inlet and outlet (Δh) was simulated to be 0.3 m in the most prevailing southeast wind [35–37]. The steady flow field in Figure 9. showed that:①The flow velority of Moya area was the highest in Playground Lake, followed by the Shuijie area. The flow velocity in central landscape lake was relatively low, and the flow velocity in some areas was lower than 0.01 m/s. There were some stagnating flow areas.②For Shuijie area, the water flow entered through #1 inlet, and most water flowed into the central landscape lake through the #1 and #2 sections of Shuijie. A small part of the water flowed through the #3 section of Shuijie. It can be known that the flow rate in the #1 and #2 sections was larger than that of the #3 section.

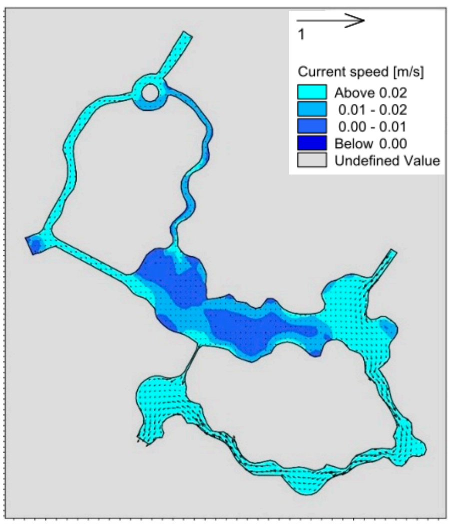
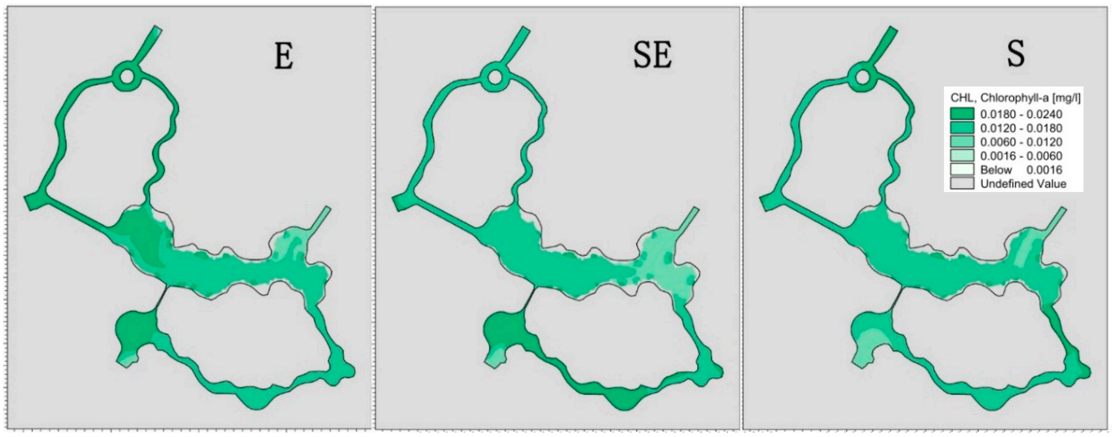


Figure 9. Flow field with water diversion through sluice.

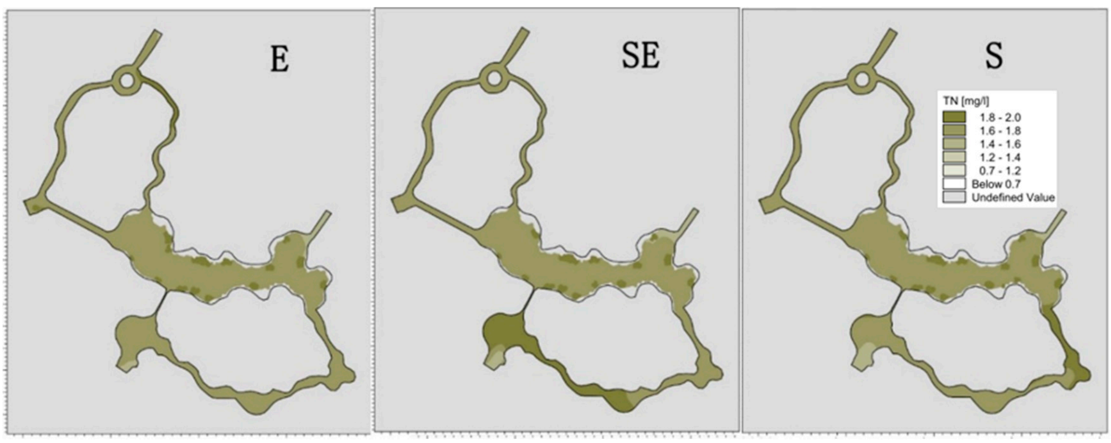
3.3. Water Quality and Eutrophication

3.3.1. Calculation and Analysis of the Water Quality and Eutrophication with No Water Diversion

The distribution of Chl-a, TN and TP in Playground Lake were obtained after the model reached a fully stable state [38–41], as shown in the Figure 10a–c. The comprehensive score of the eutrophication assessment is shown in Figure 10d. The results showed that: ① The concentrations of Chl-a, TN and TP and the comprehensive score of eutrophication assessment in three wind directions were 0.014 mg/L, 1.49 mg/L, 0.11 mg/L and 58.0, respectively. With no water diversion and in three kinds of wind field, the water of the Shuijie area, Moya area and the outlet area connected with the culvert cannot be effectively replaced, which was consistent with the flow field. Water retention led to higher Chl-a, TN and TP contents. ② In the case of no water diversion and the east wind, as the wind direction was perpendicular to the #1, #2 and #3 sections of Shuijie, the contents of Chl-a, TN and TP in the water body in this area were higher than those under the other two wind directions. Under the east and southeast winds, the contents of Chl-a, TN and TP in the water body in the central landscape lake were higher than that under the south wind, because the water was more affected by the inflow from #2 sluice in the first two wind directions, which improved the water quality of the central landscape lake. While affected by the inflow of the outlet, the water quality in the outlet area was the best under the south wind, followed by the southeast wind and finally the east wind.

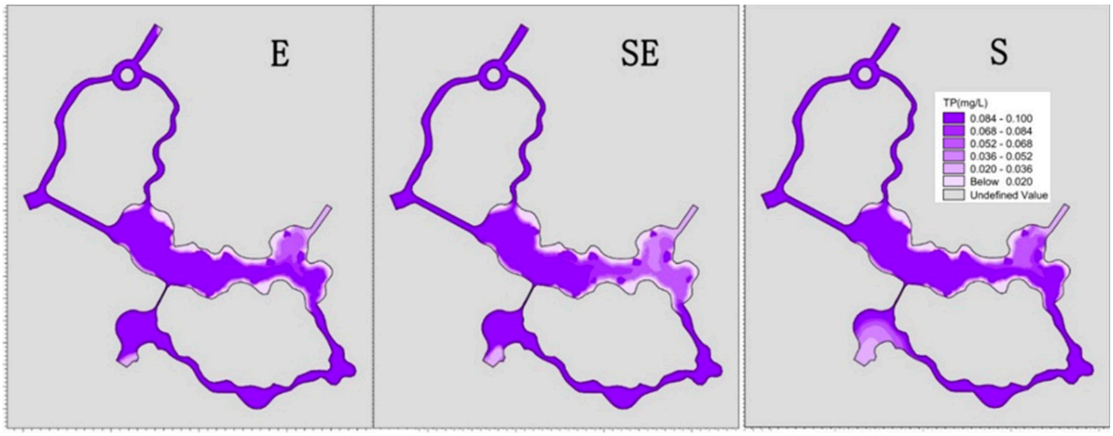


(**a**)

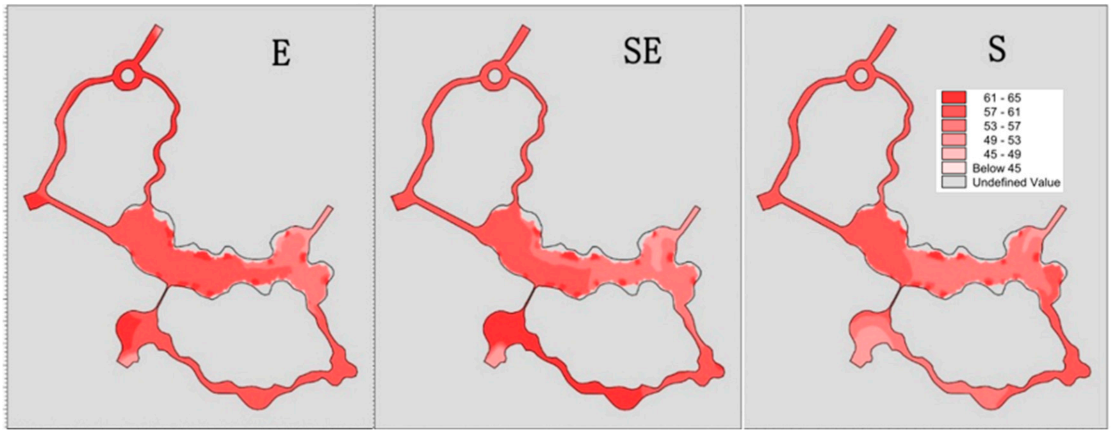


(**b**)

Figure 10. *Cont.*



(**c**)



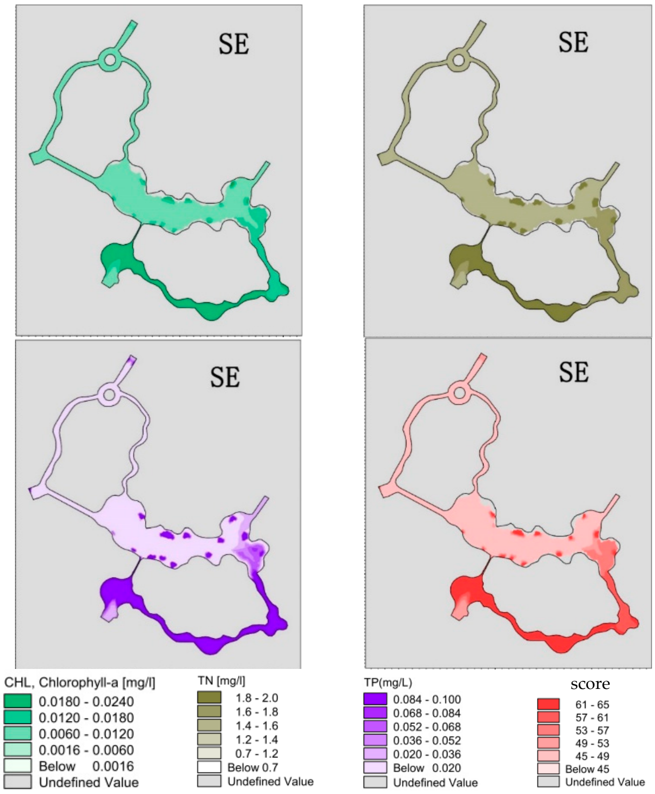
(**d**)

Figure 10. Chl-a distribution (**a**), TN distribution (**b**), TP distribution (**c**) and comprehensive score of eutrophication assessment (**d**) with no water diversion under different wind conditions.

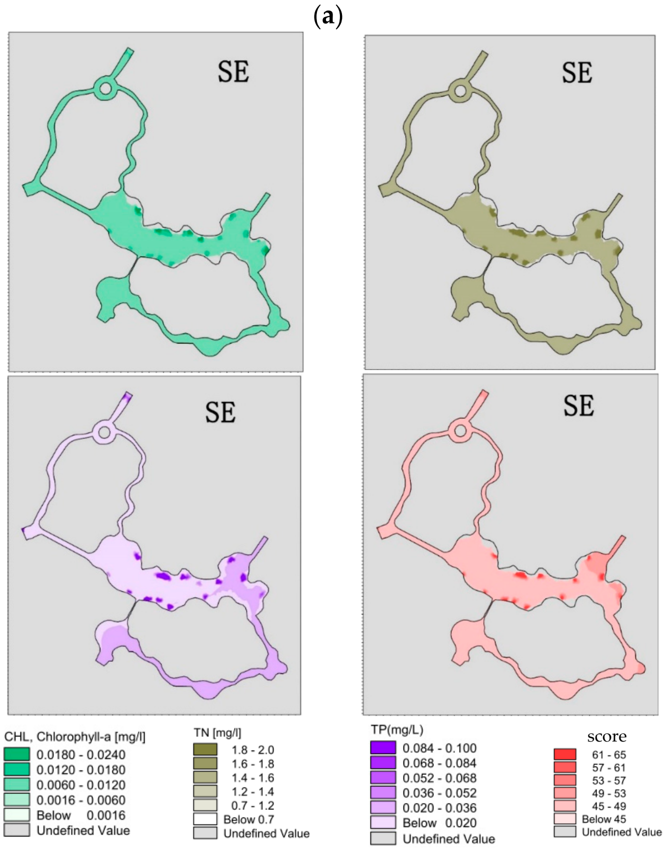
3.3.2. Calculation and Analysis of Water Quality and Eutrophication with Water Diversion through Pump

After water diversion for 22 h, the Chl-a, TN and TP concentrations and eutrophication comprehensive score of Playground Lake were presented in Figure 11a. The overall water quality in the eastern lake area had been significantly improved, except the local shore stagnant area. The Chl-a, TN and TP concentrations of the Shuijie and central landscape lake were significantly reduced, and were 0.01 mg/L, 1.42 mg/L and 0.06 mg/L, respectively, and the eutrophication score significantly decreased to 51.4, showing mild eutrophication.

After water diversion for 30 h, the remaining water in the Moya area was replaced. The Chl-a, TN and TP concentrations and eutrophication comprehensive score of Playground Lake are presented in Figure 11b. The water quality in the Moya area improved. The Chl-a, TN and TP concentrations in the Shuijie and central landscape lake reduced to 0.009 mg/L, 1.36 mg/L and 0.02 mg/L, respectively. The eutrophication comprehensive score decreased to 47.7. The results showed that water diversion had an obvious effect on water quality improvement in Playground Lake.



(a)



(b)

Figure 11. (**a**) Chl-a, TN and TP concentrations and eutrophication comprehensive score after water diversion for 22 h. (**b**) Chl-a, TN and TP concentrations and eutrophication comprehensive score after water diversion for 30 h.

3.3.3. Calculation and Analysis of Water Quality and Eutrophication with Water Diversion through Sluice

Under water diversion through the sluice, the Chl-a, TN, TP concentrations and eutrophication comprehensive score presented in Figure 12 show that: ① The improvement of water quality with sluice diversion was very rapid and obvious. The water quality was consistent with the regulation of the flow field. The greater the Δh, the higher the flow velocity. The better the water quality, the lower the eutrophication evaluation score. ② For the whole Playground Lake, the Chl-a, TN and TP concentrations and eutrophication comprehensive score were 0.01 mg/L, 1.57 mg/L, 0.03 mg/L and 49.8, respectively. The water quality of central landscape lake and the Shuijie area were relatively poor and prone to eutrophication.

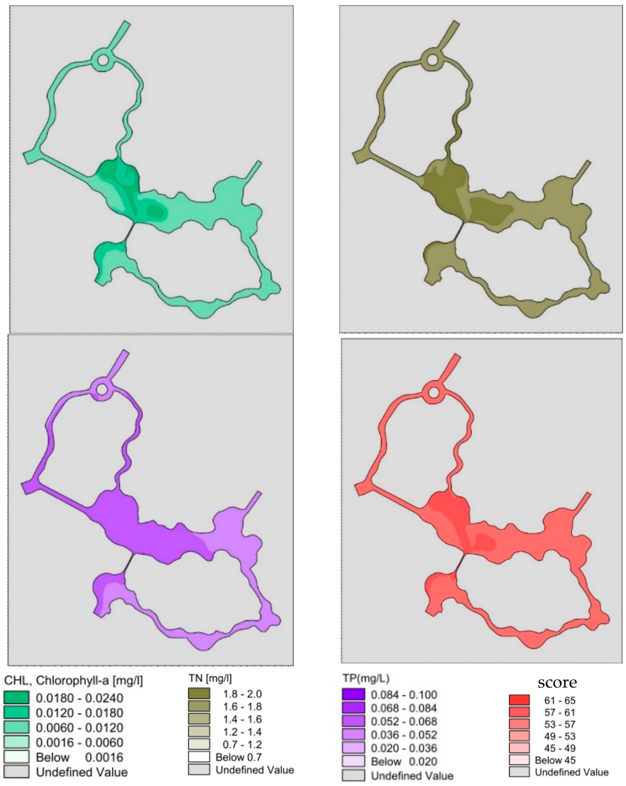


Figure 12. Chl-a, TN and TP concentrations and eutrophication comprehensive score with water diversion through sluice.

4. Water Ecological Protection Measures

Priority 1—Water diversion by sluice: When the tide level of the Yangtze River is higher than that of Neijiang Lake (3.9~4.1 m), the sluice in diversion channel and three sluices and one culvert are open to replace water in Playground Lake.

Priority 2—Water diversion by pump: According to the temperature and the corresponding interval days, when the temperature higher than 15 °C and there is no water diversion by pump, in order to speed up the water replacement in stagnating and slow flow areas, the ecological scheduling scheme should be implemented, as shown in Table 5.

Table 5. Ecological scheduling scheme.

Sluice Diversion	Water Temperature Pumping	
Open the sluice in the diversion channel		1 # pump diversion
Note: Sluice diversion is generally carried	<15 °C	15 d/time, each time 30 h
out in June, July and August (temperature	15 °C~25 °C	10 d/time, each time 30 h
above 23 °C), twice per month.	>25 °C	7 d/time, each time 30 h

According to the model calculations, the following ecological operation was planned: During high tide periods of spring tides in the Yangtze River from June to August, the water level of the Yangtze River is higher than that of Playground Lake. In other time, the water is pumped by #1 pump. Under pump diversion, the water body in Playground Lake can be replaced by water diversion for 30 h. When the temperature is lower than 15 °C, from 15 °C to 25 °C and higher than 25 °C, the water quality can be maintained for 15 d, 10 d and 7 d, respectively.

5. Conclusions

The purpose of this paper was to predict the eutrophication of the planned Playground Lake. Some targeted water quality protection measures were put forward according to possible eutrophication or poor water quality. The eutrophication model presented in this paper was used to simulate the scenarios under different water diversions and wind directions. According to the simulation results and numerical analysis, the main conclusions are as follows:

(1) Simulation results using particle tracking showed that the water residence time depended on wind direction: east wind, 125 h; southeast wind, 115 h; south wind, 95 h. Particles did not pass the Moya area under all three wind directions. Particles in central landscape lake experienced a backflow phenomenon and the water residence time was longer. However, eventually the water still flowed out to achieve water replacement. With no water diversion, the flow velocity in Playground Lake under the three wind fields was low, and the shallow depth of shore water was greatly affected by wind speed.

(2) The Chl-a, TN, TP concentrations and eutrophication comprehensive score under the three wind directions were 0.014 mg/L, 1.49 mg/L, 0.11 mg/L and 58.0, respectively. In conformity with the flow field, the water retention caused the Chl-a, TN, and TP contents to be higher. Under pump diversion, the water replacement result of water diversion for 30 h was better than that of water diversion for 22 h. Following water diversion for 22 h, the eutrophication comprehensive score was 51.4, showing mild eutrophication. Following water diversion for 30 h, the eutrophication comprehensive score was 47.7 points, so the water quality improvement effect was more obvious. Under sluice diversion, the flow field scope of the Moya area was the largest in Playground Lake, followed by the Shuijie area. The flow velocity in central landscape lake was low, and in some areas it was lower than 0.01 m/s. The improvement of water quality with sluice diversion was very rapid and obvious. The water quality was consistent with the regulation of the flow field. The greater the Δh, the higher the flow velocity. The better the water quality, the lower the eutrophication evaluation score. The central landscape lake and three sections of Shuijie had relatively poor water quality leading to eutrophication. Overall, the good-to-bad order of water quality improvements for Playground Lake is as follows: pumping 30 h > sluice diversion > no water diversion.

(3) According to the model calculations, the following ecological operation was planned: During high tide periods of spring tides in the Yangtze River from June to August, the water can be diverted into the lake through sluices. At other time, the water is pumped by the #1 pump. Under pump diversion, the water body in Playground Lake can be replaced by water diversion for 30 h. When the temperature is less than 15 °C, from 15 °C to 25 °C and higher than 25 °C,

the water quality can be maintained for 15 d, 10 d and 7 d, respectively. These water quality improvement measures can effectively control the occurrence of eutrophication.

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References

1. Marshall, H.G.; Burchardt, L. Phytoplankton composition within the tidal freshwater region of the James River, Virginia. *Proc. Biol. Soc. Wash.* **1998**, *111*, 720–730.
2. Ha, K.; Cho, E.A.; Kim, H.W.; Joo, G.J. Microsystis bloom formation in the lower Nakong River, South Korea. Importance of hydro-dynamics and nutrient loading. *Mar. Freshw. Res.* **1999**, *50*, 89–94. [CrossRef]
3. Lung, W.S.; Paerl, H.W. Modeling blue-green algal blooms in the lower Neuse River. *Water Res.* **1988**, *22*, 895–905. [CrossRef]
4. Steinberg, C.; Hartmann, H. Planktonic bloom forming cyanobacteria and the eutrophication of lakes and rivers. *Freshw. Biol.* **1988**, *20*, 279–287. [CrossRef]
5. Eldridge, M.; Sieracki, M.E. Biological and hydrodynamic regulation of the microbial food web in a periodically mixed estuary. *Limnol. Oceanogr.* **1993**, *38*, 1666–1679. [CrossRef]
6. Qin, B. Approaches to Mechanisms and Control of Eutrophication of Shallow Lakes in the Middle and Lower Reaches of the Yangze River. *J. Lake Sci.* **2002**, *14*, 193–202. [CrossRef]
7. Qin, B.; Wang, X.; Tang, X.; Feng, S.; Zhang, Y. Drinking Water Crisis Caused by Eutrophication and Cyanobacterial Bloom in Lake Taihu: Cause and Measurement. *Adv. Earth Sci.* **2007**, *22*, 896–906.
8. Zhu, G. Eutrophic status and causing factors for a large, shallow and subtropical Lake Taihu, China. *J. Lake Sci.* **2008**, *20*, 21–26. [CrossRef]
9. Liang, P.; Wang, X.; Ma, F. Effect of hydrodynamic conditions on water eutrophication: A review. *J. Lake Sci.* **2013**, *25*, 455–462. [CrossRef]
10. Zhao, Y.; Deng, X.; Zhan, J.; Xi, B.; Lu, Q. Progress on Preventing and Controlling Strategies of Lake Eutrophication in China. *Environ. Sci. Technol.* **2010**, *33*, 92–98.
11. Qu, W.; Yan, L. Effects of Agricultural Non-point Source Pollution on Eutrophica tion of Water Body and Its Control Measure. *Acta Ecol. Sin.* **2002**, *22*, 291–299.
12. Pu, P.; Wang, G.; Hu, C.; Hu, W.; Fan, C. Can We Control Lake Eutrophication by Dredging? *J. Lake Sci.* **2000**, *12*, 269–279. [CrossRef]
13. Song, W.; Pang, Y. The Calculation of Water Environment Capacity of Qinhuai River Basin Based on the National Test of QB-CS Water Quality Standards. *China Rural Water Hydropower* **2017**, *10*, 80–84. [CrossRef]
14. Conley, D.J.; Paerl, H.W.; Howarth, R.W.; Boesch, D.F.; Seitzinger, S.P.; Havens, K.E.; Lancelot, C.; Likens, G.E. Ecology. Controlling eutrophication: Nitrogen and phosphorus. *Science* **2009**, *323*, 1014. [CrossRef] [PubMed]
15. Cloern, J.E. Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Prog.* **2001**, *210*, 223–253. [CrossRef]
16. Smith, V.H. Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environ. Sci. Pollut. Res. Int.* **2003**, *10*, 126–139. [CrossRef] [PubMed]
17. Shapiro, J. Blue-green algae: Why they become dominant. *Science* **1973**, *179*, 382–384. [CrossRef] [PubMed]
18. Dokulil, M.T.; Teubner, K. Cyanobacterial Dominance in Eutrophic Lakes: Causes-Consequences-Solutions. *J. Lake Sci.* **1998**, *10*, 357–370. [CrossRef]
19. Dokulil, M.; Chen, W.; Cai, Q. Anthropogenic impacts to large lakes in China: The Tai Hu example. *Aqu. Ecosyst. Health Manag.* **2000**, *3*, 81–94. [CrossRef]

20. Paerl, H.W.; Rd, F.R.; Moisander, P.H.; Dyble, J. Harmful freshwater algal blooms, with an emphasis on cyanobacteria. *Sci. World J.* **2001**, *1*, 76–113. [CrossRef] [PubMed]
21. Smith, V.H. Low Nitrogen to Phosphorus Ratios Favor Dominance by Blue-Green Algae in Lake Phytoplankton. *Science* **1983**, *221*, 669–671. [CrossRef] [PubMed]
22. Wang, H.; Pang, Y. Investigation of internal pollutant loading for a tide-influenced waterbody. *Water Environ. Res.* **2009**, *81*, 2437–2446. [CrossRef]
23. Wang, H.; Zhou, Y.; Pang, Y.; Wang, X. Fluctuation of Cadmium Load on a Tide-Influenced Waterfront Lake in the Middle-Lower Reaches of the Yangtze River. *Clean Soil Air Water* **2015**, *42*, 1402–1408. [CrossRef]
24. Wang, H.; Zhou, Y.; Pang, Y.; Wang, X. Influence of dredging on sedimentary arsenic release for a tide-influenced waterfront body. *J. Environ. Qual.* **2014**, *43*, 1585–1592. [CrossRef] [PubMed]
25. Wang, H.; Xia, K.; Zhou, Y.; Mu, W. Impact of Water-Sediment Exchange on Underwater Terrain Shaping Process for a Tide-Influenced Waterfront Lake. *J. Hydrol. Eng.* **2014**, *20*, 04014093. [CrossRef]
26. Li, Y.; Wang, Y.; Anim, D.O.; Tang, C.; Du, W.; Ni, L.; Yu, Z.; Acharya, K. Flow characteristics in different densities of submerged flexible vegetation from an open-channel flume study of artificial plants. *Geomorphology* **2014**, *204*, 314–324. [CrossRef]
27. Li, Y.; Tang, C.; Wang, C.; Tian, W.; Pan, B.; Hua, L.; Lau, J.; Yu, Z.; Acharya, K. Assessing and modeling impacts of different inter-basin water transfer routes on Lake Taihu and the Yangtze River, China. *Ecol. Eng.* **2013**, *60*, 399–413. [CrossRef]
28. Li, Y.; Tang, C.; Wang, C.; Anim, D.O.; Yu, Z.; Acharya, K. Improved Yangtze River Diversions: Are they helping to solve algal bloom problems in Lake Taihu, China? *Ecol. Eng.* **2013**, *51*, 104–116. [CrossRef]
29. Zhao, X.; Shen Z, Y.; Xiong, M.; Qi, J. Key uncertainty sources analysis of water quality model using the first order error method. *Int. J. Environ. Sci. Technol.* **2011**, *8*, 137–148. [CrossRef]
30. Piermay, J.L. Long-term simulation of the eutrophication of the North Sea: Temporal development of nutrients, chlorophyll and primary production in comparison to observations. *J. Sea Res.* **1997**, *38*, 275–310.
31. Nobre, A.M.; Ferreira, J.G.; Newton, A.; Simas, T.; Icely, J.D.; Neves, R. Management of coastal eutrophication: Integration of field data, ecosystem-scale simulations and screening models. *J. Mar. Syst.* **2005**, *56*, 375–390. [CrossRef]
32. Sagehashi, M.; Sakoda, A.; Suzuki, M. A mathematical model of a shallow and Eutrophic Lake (The Keszthely Basin, Lake Balaton) and simulation of restorative manipulations. *Water Res.* **2001**, *35*, 1675–1686. [CrossRef]
33. Madden, C.J.; Kemp, W.M. Ecosystem model of an estuarine submersed plant community: Calibration and simulation of eutrophication responses. *Estuaries* **1996**, *19*, 457–474. [CrossRef]
34. Karim, M.R.; Sekine, M.; Ukita, M. Simulation of eutrophication and associated occurrence of hypoxic and anoxic condition in a coastal bay in Japan. *Mar. Pollut. Bull.* **2002**, *45*, 280–285. [CrossRef]
35. Huang, Y.L.; Huang, G.H.; Liu, D.F.; Zhu, H.; Sun, W. Simulation-based inexact chance-constrained nonlinear programming for eutrophication management in the Xiangxi Bay of Three Gorges Reservoir. *J. Environ. Manag.* **2012**, *108*, 54–65. [CrossRef] [PubMed]
36. Wang, H.; Zhang, Z.; Liang, D.; Du, H.; Pang, Y.; Hu, K.; Wang, J. Separation of wind's influence on harmful cyanobacterial blooms. *Water Res.* **2016**, *98*, 280–292. [CrossRef] [PubMed]
37. Wang, H.; Zhao, Y.; Liang, D.; Deng, Y.; Pang, Y. 30+ year evolution of Cu in the surface sediment of Lake Poyang, China. *Chemosphere* **2017**, *168*, 1604–1612. [CrossRef] [PubMed]
38. Wang, J.; Pang, Y.; Li, Y.; Huang, Y.; Jia, J.; Zhang, P.; Kou, X. The regularity of wind-induced sediment resuspension in Meiliang Bay of Lake Taihu. *Water Sci. Technol.* **2014**, *70*, 167–174. [CrossRef] [PubMed]
39. Han, F.; Chen, Y.; Liu, Z. Advance in the eutrophication models for lakes and reservoirs. *Adv. Water Sci.* **2003**, *14*, 785–791.
40. Lu, X.; Xu, F.; Zhan, W.; Zhao, Z.Y.; Tao, S. Current situation and development trends in lake eutrophication models. *Adv. Water Sci.* **2003**, *14*, 792–798.
41. Quan, W.; Yan, L.; Yu, Z.; Jiao, L. Advance in study of lake eutrophication models. *Chin. Biodivers.* **2001**, *9*, 168–175.
42. Cai, Y. Study on the Characteristics of Molecular Weight Distributions of Organic Matters in Zhenjiang City's Drinking Water. *Water Purif. Technol.* **2005**, *24*, 12–16.
43. Wang, G.S.; Shi, J.J.; Ling, L.U. Evaluation and Measures of Building Zhenjiang into an Eco-city. *J. East China Shipbuild. Inst.* **2005**, *5*, 54–59.

44. Chen, S.; Qu, F.; Ni, S.; Liu, Y. City land price distribution researching in GIS spatial analysis—A case study of Zhenjiang City. *J. Nanjing Agric. Univ.* **2005**, *28*, 119–122. [CrossRef]
45. Wan, Y.L.; Zhang, B. Analysis on the Pollution Characteristics of Surface Runoff in Zhenjiang City. *Meteorol. Environ. Res.* **2011**, *5*, 76–78.
46. Ruan, H.; Ye, J.; Xu, X. Restoration of plant community in degradation riparian zone of Jinshan Lake in Zhenjiang city. *J. Nanjing For. Univ.* **2008**, *32*, 107–110.
47. Chinese Std. *GB3838-2002, Environment Quality Standards for Surface Water*; SEPA of China: Beijing, China, 2002.
48. Chinese Std. *The Evaluation Method of Eutrophication and Classification of Lake (Reservoir)*; China Environment Monitoring Station: Beijing, China, 2001.
49. Scavia, D.; Powers, W.F.; Canale, R.P.; Moody, J.L. Comparison of first-order error analysis and Monte Carlo Simulation in time-dependent lake eutrophication models. *Water Resour. Res.* **1981**, *17*, 1051–1059. [CrossRef]
50. Geng, J.; Jin, X.; Wang, Q.; Niu, X.; Wang, X.; Edwards, M.; Glindemann, D. Matrix bound phosphine formation and depletion in eutrophic lake sediment fermentation-simulation of different environmental factors. *Anaerobe* **2005**, *11*, 273. [CrossRef] [PubMed]
51. Okada, M.; Aiba, S. Simulation of water-bloom in a eutrophic lake—II. Reassessment of buoyancy, gas vacuole and Turgor pressure of Microcystis aeruginosa. *Water Res.* **1983**, *17*, 877–882. [CrossRef]
52. Xu, M.J.; Yu, L.; Zhao, Y.W.; Li, M. The Simulation of Shallow Reservoir Eutrophication Based on MIKE21, A Case Study of Douhe Reservoir in North China. *Procedia Environ. Sci.* **2012**, *13*, 1975–1988. [CrossRef]
53. Wang, X.Q.; Zhe, L.I. Swat and MIKE21 coupled models and three application in the Pengxi watershed. *Resour. Environ. Yangtze Basin* **2015**, *24*, 426–432.
54. Qian, H.; Sheetz, M.P.; Elson, E.L. Single particle tracking. Analysis of diffusion and flow in two-dimensional systems. *Biophys. J.* **1991**, *60*, 910–921. [CrossRef]
55. Malik, N.A.; Dracos, Th.; Papantoniou, D.A. Particle tracking velocimetry in three-dimensional flows. *Exp. Fluids* **1993**, *15*, 279–294. [CrossRef]
56. Maas, H.G.; Gruen, A.; Papantoniou, D. Particle tracking velocimetry in three-dimensional flows Part 1. Photogrammetric determination of particle coordinates. *Exp. Fluids* **1993**, *15*, 133–146. [CrossRef]
57. North, E.W.; Schlag, Z.; Hood, R.R.; Li, M.; Zhong, L.; Kennedy, V.S. Vertical swimming behavior influences the dispersal of simulated oyster larvae in a coupled particle-tracking and hydrodynamic model of Chesapeake Bay. *Mar. Ecol. Prog.* **2008**, *359*, 99–115. [CrossRef]