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Scenario optimization of water supplement and outflow management in Yilong Lake based on the EFDC model

Tao Wu[a,b,c], Baolin Su[a], Huaxin Wu[a,b,c], Shengrui Wang[a,b,c,d,*], Guoqiang Wang[a,c],
Harsha Ratnaweera[e], S. B. Weerakoon[f], Zhibin Zhang[g] and Bo Yao[h]

[a] Beijing Key Laboratory of Urban Water Cycle and Sponge City Technology, Institute of Water Science, Beijing Normal University, Beijing 100875, China
[b] Guangdong-Hong Kong Joint Laboratory for Water Security, Research Center of Water Science, Beijing Normal University at Zhuhai, Zhuhai 519087, China
[c] Engineering Research Center of Ministry of Education on Groundwater Pollution Control and Remediation, College of Water Sciences, Beijing Normal University, Beijing 100875, China
[d] Yunnan Key Laboratory of Pollution Process and Management of Plateau Lake Watershed, Kunming, Yunnan Province 650034, China
[e] Faculty of Science and Technology, Norwegian University of Sciences, Aas 1432, Norway
[f] Department of Civil Engineering, University of Peradeniya, Peradeniya 20400, Sri Lanka
[g] School of municipal and environmental engineering, Shandong Jianzhu University, Jinan, Shandong Province 250101, China
[h] Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
*Corresponding author. E-mail: wangsr@bnu.edu.cn

ABSTRACT

To address the problem of poor hydrodynamic conditions in Yilong Lake and to meet the water quality standards, the EFDC model was applied to propose an optimization plan for water supplement and outflow management of Yilong Lake. The model explores the impact of wind forcing, water supplement from external watersheds, outflow management and setting up an enclosure in the lake on the hydrodynamics in Yilong Lake. The results show that (1) the overall velocity of the water body of Yilong Lake is relatively slow, 90% of the area is lower than 0.01 m s^{-1}, the central and eastern areas are faster and the western is slower. During the dry period and the wet periods of the year, improves the flow velocity of the water body in 90% of the area is increased by 80% compared to no wind velocity; (2) the increase in the amount of water supplement is significant for the improvement of the hydrodynamic conditions of water body; the water supplement volume at the two water supplement points of Mafangwan is conducive to improving the hydrodynamic conditions. If the total water supplement volume is increased by 10 million cubic meters per year which corresponds to water supplement volume increases at the Pubu and the Mafangwan by 33 and 35%, respectively, then water area with flow velocity greater than 0.007 m s^{-1} can be increased to 70%; (3) based on the demand for water quality, the water level management curves for different seasons are designed. It should be dominated by the eastern outflow, during the spring, coordinated by the southern and eastern outflows during the summer, and should be dominated by the southern outflow during the autumn and winter period.

Key words: EFDC, flow field, hydrodynamic, outflow, water level management, Yilong Lake

HIGHLIGHTS

- The hydrodynamics of Yilong Lake are analyzed comprehensively.
- Water level, temperature and flow field are important factors.
- Hydrodynamic conditions are better in winter than in summer.
- Water supplement can significantly improve the hydrodynamic conditions of Yilong Lake.
- Formed the outflow management opinion.

1. INTRODUCTION

China is a country with multiple lakes, which play an important role in national economic development due to their services for irrigation, water supply, shipping, flood water storage and improvement of the regional ecological environment (Wu *et al.* 2017). With the continuous development of the river basin economy, the increased human activities and industrial and agricultural pollution have caused serious problems of lake water pollution in China (Seo *et al.* 2010; Wang *et al.* 2019a). Measures such as controlling pollution load, implementing ecological restoration and optimizing hydrodynamic conditions can all improve the water environment quality of the lake (Kim *et al.* 2017; Gao *et al.* 2018). Among these, the control of

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inflow of pollution load and the implementation of ecological restoration are generally more direct and obvious, but the investment is substantial and the implementation period is long. To improve the water quality of Yilong Lake by adopting pollution control only, the pollution load needs to be reduced by more than 50% before the water quality can meet the standards, which is difficult to task (Zhao *et al.* 2013). If the hydrodynamic conditions can be optimized through some regulations, it would be an economical solution for improving the water quality in the lake. Many studies on optimizing hydrodynamic circulation to improve water environment quality have been reported (Zhao *et al.* 2013). The hydrodynamic model of the intersection of Chongqing Yangtze river and Jialing river shows that EFDC (Environmental Fluid Dynamics Code, USEPA) model can better reflect the flow field characteristics of the research area. It has a good applicability to the analysis of flow field and hydrodynamic (Chen 2005). For example, based on the coupling model of EFDC and WASP (Water Quality Analysis Simulation Program), the hydrodynamic and water quality changes of river and lake systems in the Chicago area were simulated, indicating that the water quality could be significantly improved by optimizing the hydrodynamic conditions (Quijiano *et al.* 2017). The EFDC model was used to simulate the degradation and transport characteristics of lake nutrients, indicating that the better the hydrodynamic conditions, the lower the risk of lake eutrophication (Zhou *et al.* 2007). It can be seen that optimizing hydrodynamic conditions can improve the water quality of lakes to some extent.

The Yilong Lake is one of nine plateau lakes in Yunnan province where the water environment problem has been closely monitored, the external pollution interception, sediment dredging and enclosure have improved the water quality, but the indexes of COD, TN is still inferior of V class of standard, further improvement of water quality is the main difficulty faced by the protection and management of Yilong Lake (Zhang *et al.* 2010). Pollution control and ecological restoration measures are commonly used in lake governance in China. If the hydrodynamic conditions of lakes are optimized at the same time, the treatment effect may be better. In recent years, the hydrodynamic conditions of Yilong Lake have undergone major changes. In 2009, the lake water level dropped rapidly, and by 2013, the water level reached its lowest level in nearly 10 years. Monitoring the flow velocity of the water body and thus affecting the water quality has become an important issue of concern, that is, while further controlling the pollution load into the lake, whether the water quality can be improved by optimizing the hydrodynamic conditions. Therefore, this study has chosen the EFDC model that has been widely used in the simulation of surface water hydrodynamics and water quality in lakes, reservoirs, bays, wetlands and estuaries incorporating the good procedures reported (Seo *et al.* 2010; Peng *et al.* 2011; Shi *et al.* 2011; Wu & Xu 2011; Li *et al.* 2013), to simulate the hydrodynamic changes of Yilong Lake. It was also used to quantify the effects of wind forcing, water supplement and enclosure on hydrodynamics, and systematically analyzes the characteristics and influencing factors of the hydrodynamic changes of Yilong Lake. Additionally, exerts the optimized hydrodynamic conditions to improve the water quality of the lake, and proposes the appropriately optimized water inflow and outflow plan, in order to provide scientific support for the water resource management and protection of Yilong Lake.

2. MATERIALS AND METHODS

2.1. Study area

The Yilong Lake is one of the nine major plateau lakes in Yunnan Province, with an average water surface elevation of 1,414 m; the regional dry and wet seasons are distinct, the summer is rainy, the rain and heat are in the same season, the average annual temperature is 18 °C, the average precipitation is 920 mm, and the area of Yilong Lake Basin is 360.4 km^2, the lake area is 31 km^2, with an average water depth of 3.6 m. There are six main rivers entering Yilong Lake, namely Chengbeihe, Chenghe, Chengnanhe, Dashuihe, Longganghe and Yucunhe. The flow into the lake in summer is large due to other reasons; the lake has two outlets located on the south and east shores of the lake. The outflow is mainly on the south shore. Basin development and other factors lead to the poor water quality of Yilong Lake and the water quality fails to meet the stipulated standards (Wang *et al.* 2019b). There are currently four water supplement points for the water supplement project implemented to improve lake water quality, namely Pubu, Mafangwan, Renshoucun and Xian. Pubu and Mafangwan are closer to the state-controlled monitoring point, and the amount of water supplement is also larger.

2.2. Model description

EFDC is a comprehensive water quality model developed by John Hamrick at the Virginia Institute of Marine Science (Hamrick 1992). It is used to simulate the 3D numerical calculation model of surface water in lakes, reservoirs, bays, wetlands and estuaries. The integrated hydrodynamic module, sediment module, water temperature module, water quality module and tracer module can be used to simulate the one-dimensional, two-dimensional and three-dimensional physical and chemical processes of water bodies such as rivers, lakes, wetlands and coastal waters. The hydrodynamic equations in the EFDC model are based on the three-dimensional incompressible variable density turbulent boundary layer equations. In order to facilitate the handling of the buoyancy term caused by the density difference, the Boussinesq assumption and the static water assumption are often used. The horizontal orthogonal coordinate transformation and the sigma coordinate transformation in the vertical direction are adopted. The control equations after these two transformations are as follows:

$$\begin{aligned}&\frac{\partial(mHu)}{\partial t}+\frac{\partial(m_yHuu)}{\partial x}+\frac{\partial(m_xHvu)}{\partial y}+\frac{\partial(mwu)}{\partial z}\\&\quad-\left(mf+v\frac{\partial(m_y)}{\partial x}-u\frac{\partial(m_x)}{\partial y}\right)Hv=-m_yH\frac{\partial(g\zeta+p)}{\partial x}-m_y\left(\frac{\partial h}{\partial x}-z\frac{\partial H}{\partial x}\right)\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left(m\frac{1}{H}A_v\frac{\partial u}{\partial z}\right)+Q_u\end{aligned}\tag{1}$$

$$\begin{aligned}&\frac{\partial(mHv)}{\partial t}+\frac{\partial(m_yHuv)}{\partial x}+\frac{\partial(m_xHvv)}{\partial y}+\frac{\partial(mwv)}{\partial z}\\&\quad-\left(mf+v\frac{\partial(m_y)}{\partial x}-u\frac{\partial(m_x)}{\partial y}\right)Hu=-m_xH\frac{\partial(g\zeta+p)}{\partial y}-m_x\left(\frac{\partial h}{\partial y}-z\frac{\partial H}{\partial y}\right)\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left(m\frac{1}{H}A_b\frac{\partial v}{\partial z}\right)+Q_v\end{aligned}\tag{2}$$

$$\frac{\partial p}{\partial z}=-gH\frac{\rho-\rho_0}{\rho_0}=-gHb\tag{3}$$

where (u, v, w) is the horizontal velocity component in the direction of the boundary fitting orthogonal curvilinear coordinates (x, y, z); m_x and m_y are the scale factors of the horizontal coordinate transformation in different directions; $m = m_x m_y$ is the metric tensor, the square root of the determinant; A_v is the vertical turbulent viscosity coefficient; A_b is the vertical turbulent diffusion coefficient; ζ is the Coriolis coefficient; p is the pressure; ρ is the mixed density; ρ_o is the reference density; Q_u and Q_v are the source and sink items of momentum, respectively.

2.3. Establishment and verification of the hydrodynamic model of Yilong Lake

2.3.1. Grid generation

EFDC is a numerical simulation system based on finite difference solution. In order to characterize complex geometric features and meet the needs of this study, 3,682 grids of 100 m × 100 m were used.

2.3.2. Initial and boundary conditions preparation

The simulation period of the study is from January 1, 2018 to December 31, 2018 with the time step of 4 s. The monitored water level which was 1,519.63 m and the monitored water quality and the water temperature of 15 °C on January 1, 2018 were the initial conditions. In the model, the limit of the dry and wet grid was set to 0.05 m. (That is, when the water depth of the grid is greater than 0.05 m, it is treated as a wet grid for simulation calculation. When the depth of the grid is less than 0.05 m, the grid becomes a dry grid, which is not involved in calculations.)

2.3.3. Bathymetry conditions

The four water supplement points of Yilong Lake are Pubu, Mafangwan, Xian and Renshoucun. The rivers entering the lake include Chengbeihe, Chenghe, Chengnanhe, Dashuihe, Yucunhe and Longganghe, and there are two outflow places, which are located on the south bank and the east bank. There are three monitoring points in the lake, east and west of the lake (Figure 1). The hydrodynamic process of a water body is greatly affected by wind direction, wind speed, air temperature, solar radiation and other factors in the region of gentle water flow, hence, rainfall, evaporation, solar radiation, dry and wet bulb temperature, data such as cloud cover and wind speed are important boundary conditions in the simulation.

2.3.4. Model calibration and verification

Hydrodynamic simulation parameters include the roughness and recharging rate of the lake bottom. Because roughness has a great influence on hydrodynamic simulation, the parameterization of the roughness parameters is considered in the different areas. The roughness data was verified through simulation experiments, and the roughness of the deep water area was set to 0.025, the shallow water area was set to 0.030, and the wetland area was set to 0.040. The infiltration mainly affects the hydrodynamic conditions by changing the water volume of the water. The Nash efficiency coefficient statistics of the different

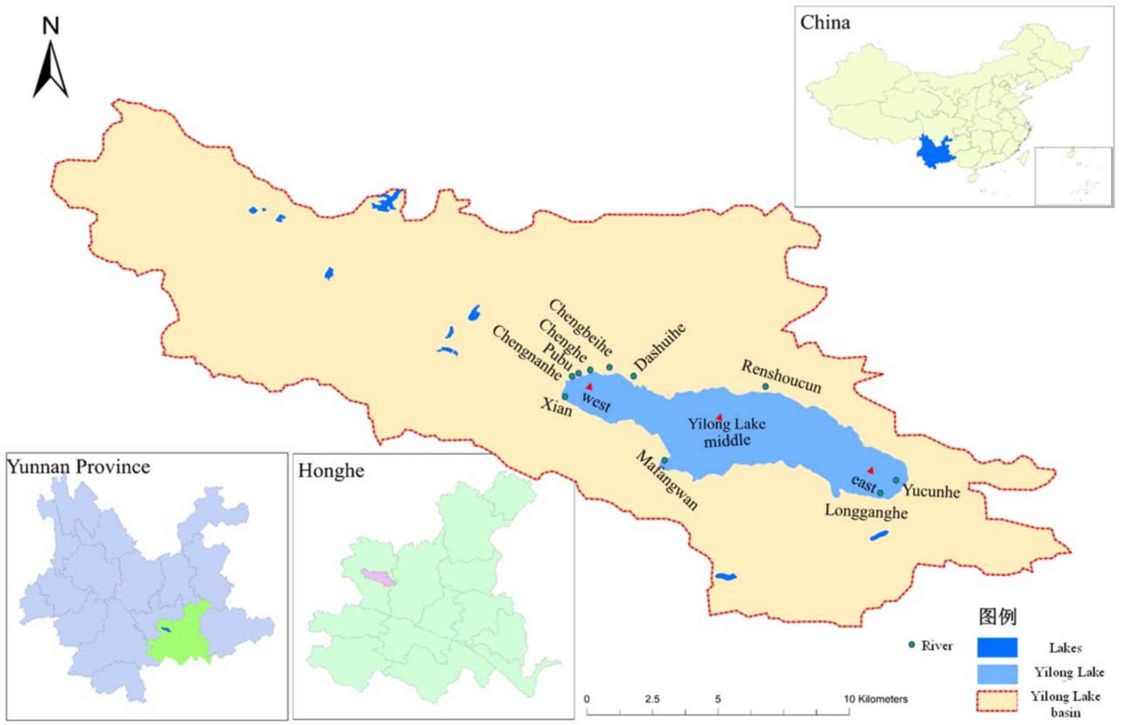


Figure 1 | The Yilong Lake watershed.

infiltration rates of Yilong Lake in 2018 on the simulated water level and the actual water level (the central point of Yilong Lake) are shown in Table 1. Using the Nash efficiency coefficient to evaluate the model results, the simulated average water level is 3.61 m, and the actual average water level is 3.62 m, and the Nash efficiency coefficient is 0.87, and the error is only 1%, indicating that the model hydrodynamic simulation accuracy is satisfactory.

2.4. Data source

The water quality and water level data of Yilong Lake are from the Honghe Prefecture Environmental Monitoring Station in Shiping County, Yunnan Province. The rainfall and evaporation data are from the China Meteorological Science Data Sharing Service Network (http://www.escience.gov.cn).

3. RESULTS AND ANALYSIS

3.1. Effects of wind-driving flow on the hydrodynamics of Yilong Lake

In recent years, due to the influence of wind-driving, dredging of sediments, the amount of water entering and exiting the lake, water supplement, and diversion engineering, the hydrodynamic conditions of Yilong Lake have undergone major changes. Among them, wind-driving are important internal factors affecting the hydrodynamic conditions of Yilong Lake. As shown in Figure 2, the northwest wind prevails in Yilong Lake Basin, with an average wind speed of 1.9 m s^{-1}. In view of how wind force affects the hydrodynamics of Yilong Lake, this study comparatively analyzes the changes in the flow field of Yilong Lake in the two scenarios of no wind and wind-driving current field (Figure 3).

Table 1 | Error table of simulated water level (central point) and measured water level for different infiltration values of Yilong Lake in 2018

Recharging rate (cm/d)	Nash efficiency coefficient	Simulated average water depth (m)	Measured average water depth (m)	Error (%)
1.21	0.494	3.37	3.62	6.91
1.49	0.774	3.73	3.62	3.04
1.37	0.870	3.61	3.62	0.28

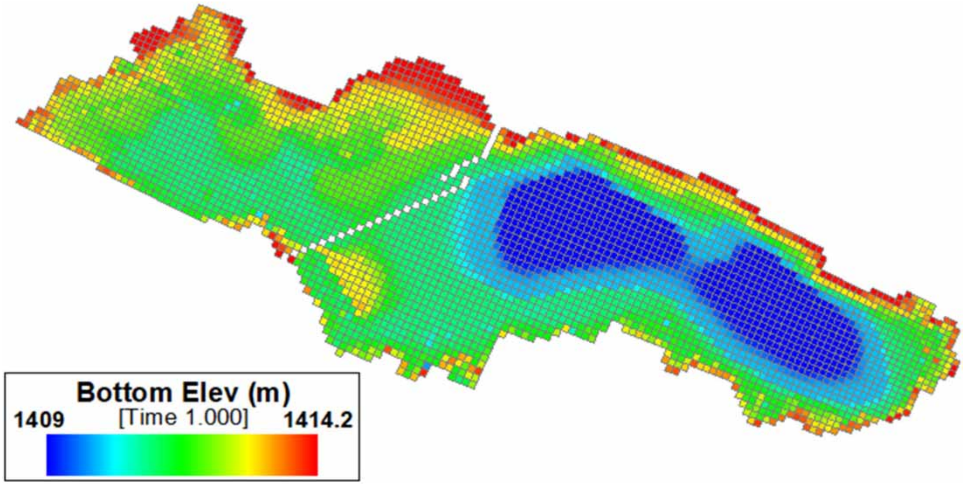


Figure 2 | The grid of Yilong Lake.

This study select the normal season (day 30), dry season (day 120) and wet season (day 180) to compare and analyze the changes of the flow field of Yilong Lake under the windless and current wind scenarios. Velocity, due to the large wind speed (the average wind speed is 2.3 m s^{-1}), and the relatively high water level, the hydrodynamic conditions of the lake are good; the water velocity of the water bodies on both sides of the lake is relatively large during the dry season. There is an increase in the water velocity in the central water area when there is no wind, but the increase is small. It may be due to the slow wind speed during the dry season (the average wind speed is only 1.6 m s^{-1}) and that the water level is also low, and the hydrodynamic conditions are more than the normal season and the wet season. The overall water velocity of the lake during the wet season is significantly higher than when there is no wind. Since the average wind speed in the wet season reaches

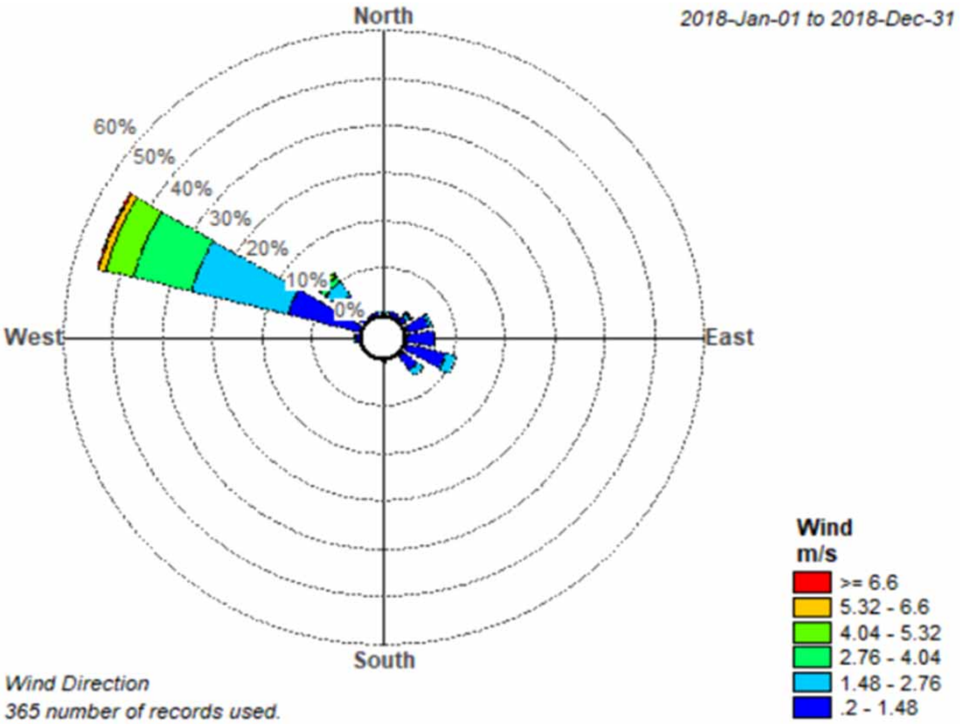


Figure 3 | Wind rose.

$1.8\ \mathrm{m\ s^{-1}}$ and the average water level is 0.2 m higher than the dry season, the hydrodynamic conditions during this period are better than those during the dry season (Table 2).

Based on the above analysis, it can be seen that the current wind compared with that of without wind, the flow field of Yilong Lake has improved significantly in different periods, especially in the flat water season and the wet season. Except for the enclosure area in the middle and local area, the water velocity is greater than $0.005\ \mathrm{m\ s^{-1}}$, the overall velocity in the lake area is $0.0025\ \mathrm{m\ s^{-1}}$ in the no wind scenario. The possible reason for the significant influence of wind flow on the hydrodynamic conditions of Yilong Lake is that the lake is oriented east–west direction, and the northwest wind prevails in the basin. The wind direction is consistent with the direction of the water flow. Under the action of wind-driving currents, the velocity of the water body can be increased; and it mainly affects the surface velocity of the water body. The water level is relatively high during the wet season, which has a significant effect on the water flow rate. The wind flow has a significant effect on the water velocity on both sides of Yilong Lake. The main reason is that there are water supply points on both sides of the lake and the rivers enter the lake. Under the influence of the wind, the flow velocity on both sides increases faster. It can be seen that due to the combined effects of wind-driving currents, water supplement and the amount of water entering the lake, the current hydrodynamic conditions of Yilong Lake under wind are better than when there is no wind, and the flow velocity of 90% of the water area in the normal and wet season is increased by 80% compared to when there is no wind, to improve the self-purification ability of the lake a certain extent.

3.2. Effects of water supplement on the hydrodynamics of Yilong Lake

The hydrodynamic conditions of Yilong Lake have undergone significant changes after implementation of the water supplement project. Due to the large amount of water supplement and high investment, further quantification of the impact of water supplement on the lake's hydrodynamics is of guiding significance for the protection and management of Yilong Lake. The contribution rate of each water supply point to the water level is shown in Figure 4. If only Pubu, Xian, Renshoucun and Mafangwan make up water separately, the year of Yilong Lake average water levels are 3.41, 3.34, 3.37 and 3.42 m, mainly due to the different distances between the water supply points and the national control monitoring section. The rates of water supply at each water supply points are equal – the Mafangwan has the most water supply, reaching 15.34 million cubic meters. The Xian has the least amount of water supplement – only 4.14 million cubic meters, resulting in different contribution of water supplement points to the lake water level. The simulation results show that the two water supplement points of Pubu and Mafangwan have a greater impact on the water level of Yilong Lake, reaching 33.6 and 35.7%, respectively. If there is no water supplement, COD concentration reaches 49.4 mg/L, which increases by 22.5%. The water quality improvement effect is more obvious, and the two supplement points have more supplement volume, which has a greater impact on the water level. It can be seen that if new water supplement can be added, the water volume of the two supplement points of Pubu and Mafangwan should be given priority.

In order to reveal the effect of water supplement on the hydrodynamic conditions of Yilong Lake, the effects of the two scenarios without water supplement and current water supplement on the hydrodynamic conditions of Yilong Lake were comparatively studied. The water level comparison between the scenario of no water supplement and the current water supplement scenario is shown in Figure 5. The average annual water level of Yilong Lake is 3.35 m without water supplement, the annual average water level is 3.62 m when the current supplement is present, and the annual average water level is increased by 0.27 m; the water velocity of the lake is gentle, and 90% of the regional basins are lower than $0.01\ \mathrm{m\ s^{-1}}$. Under the current situation of water supplement, the overall flow velocity of the lake is twice that of the one without water supplement. Lake water level is unevenly distributed during the year, and can be divided into three stages. January to April is a period of flat water, and the water level is slowly reduced in this stage to prevent floods and floods. May to July is the dry season. Due to human factors and high temperatures, the evapotranspiration is greater than the precipitation, and the water level is low at this stage. August to December is the wet season. This stage has more water supplement and less evaporation, resulting in a higher lake water level. The results show that the water supplement project has a significant effect

Table 2 | Monthly average wind speed data ($\mathrm{m\ s^{-1}}$)

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Wind	2.1	2.3	2.3	2.3	2.1	1.7	1.7	1.5	1.6	1.6	1.7	1.9

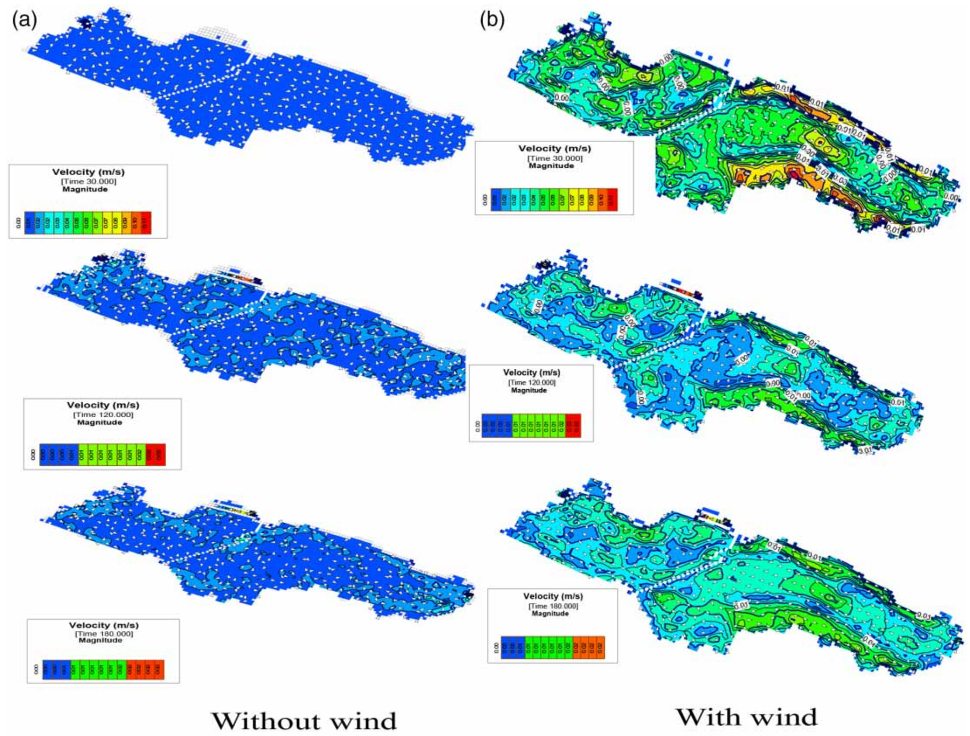


Figure 4 | Variations of the simulated flow field in Yilong Lake with and without wind.

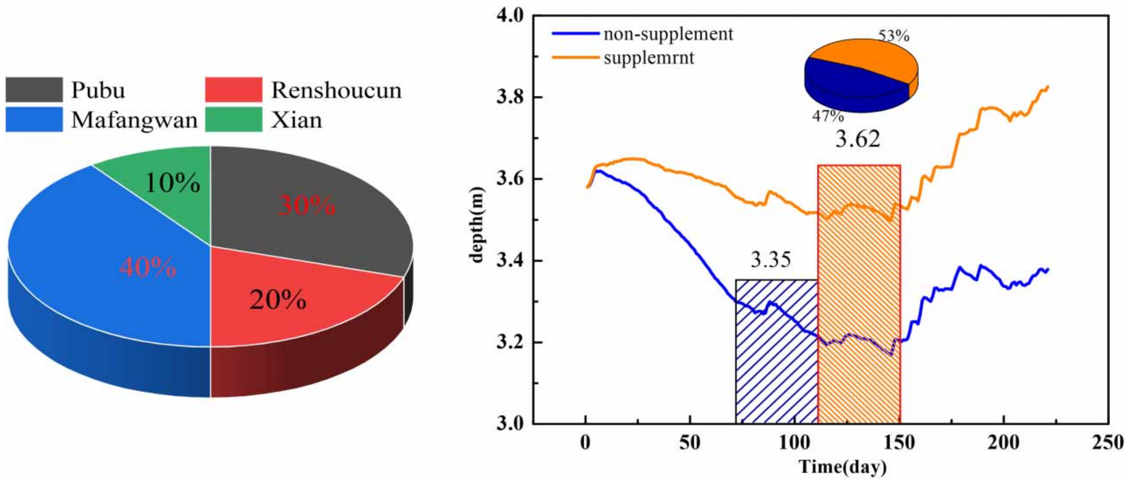


Figure 5 | Contributions of different supplementary water points and changes of water level in Yilong Lake with and without supplementary water.

on the water level rise of Yilong Lake. The rise of water level can accelerate the flow of water, promote the absorption and degradation of nutrients, and the sedimentation of suspended substances (Tang *et al.* 2021; Wu *et al.* 2021), which can improve the water environment of Yilong Lake.

Based on the above analysis, it can be seen that water supplement has a significant effect on the hydrodynamic conditions of Yilong Lake. Different water supplement points have different contributions to the water level records at monitoring points due to the difference in the distance between the geographical location and the monitoring point and the difference in water supplement. The water supply quality is better than the lake water quality. The average value of the water supply quality indicators such as COD and TN for many years is 10 and 1.2 mg/L, respectively, and the concentration of COD and TN in the lake are 35 and 0.8 mg/L, respectively. On the other hand, water supplementation can increase the water level of Yilong Lake, accelerate the flow of water, promote the circulation of water and optimize the hydrodynamic conditions of the lake to improve the water environment of Yilong Lake to a certain extent.

3.3. Effects of enclosure on the hydrodynamics of Yilong Lake

In 2018, a water-conducting enclosure was built in the central area of Yilong Lake, its purpose was to influence the hydrodynamic conditions of Yilong Lake through enclosure, increase the flow velocity of water in some areas, and improve the water quality of the lake (Van Maren *et al.* 2015). The effect can be seen in Figure 6, and the enclosure is located in the middle of Yilong Lake, which has a greater impact on the flow velocity of the central and southeast water bodies, a relatively small effect on the flow velocity of the west water body. Before the enclosure was established, the average flow velocity in the west of Yilong Lake was 0.0047 m s^{-1}, the average flow velocity in the middle was 0.0060 m s^{-1}, and the average flow velocity in the east was 0.0052 m s^{-1}; after the enclosure was established, the average flow velocity in the west of Yilong Lake increased by 6.9%, the average flow velocity in the central region increased by 10.2% and the average flow velocity in the eastern region increased by 7.8%. There are differences in the increase of flow velocity in different periods. The flow velocities on both sides of the lake increases significantly, and the overall flow velocity in the lake area increases but is slower than that in both sides.

In order to reveal the influence of the enclosure on the hydrodynamic conditions of Yilong Lake, the changes of the lake flow field before and after the establishment of the enclosure were comparatively studied. The flow field can be divided into three stages. During the dry season, the flow velocity on both sides increases rapidly, indicating that the establishment of the enclosure may hinder the flow of water from west to east, and more water flow will change to flow to both sides of the lake. During the normal and wet seasons, due to the relatively high water level of the lake, the influence of the enclosure on the flow velocity rate is relatively small, indicating that the water level and enclosure affect the lake hydrodynamic conditions together, and the establishment of the enclosure diversion can change Yilong Lake's flow field and thus affects the algae's drift and accumulation. When the water level is low, the enclosure has a more significant effect on hydrodynamics.

4. DISCUSSION

4.1. Optimization of water supplement scenario of Yilong Lake based on water quality

4.1.1. Influence and optimization of water supplement on Yilong Lake hydrodynamics

In order to reveal the impact of water supplement on the hydrodynamics of Yilong Lake and optimize the water supplement plan, comprehensively consider the future water supplement plan and discuss four water supplement scenarios. In order to explore the relationship between water supplement methods and the hydrodynamic conditions of Yilong Lake, the effects of

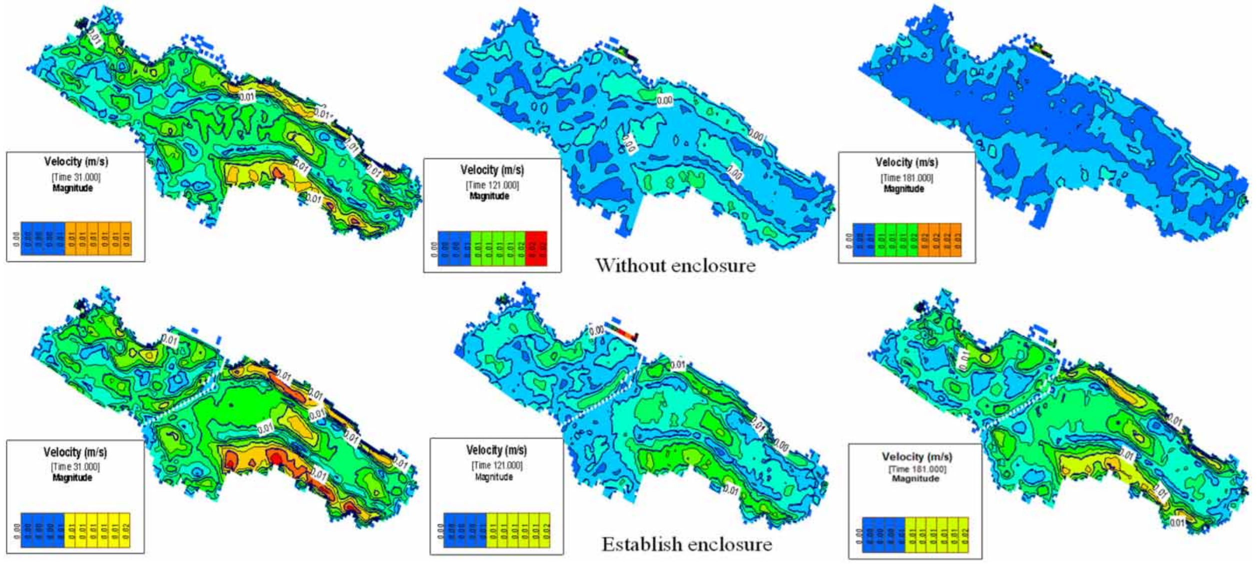


Figure 6 | Distribution of flow field of Yilong Lake before and after containment.

four different water supplement scenarios on the water level of Yilong Lake were compared and analyzed through the EFDC model. The amount of water supplement in each scenario is shown in Table 3. The results are shown in Figure 7.

Both scenario 1 and scenario 2 have a total water supplement volume of 10 million cubic meters. The simulated water level of scenario 1 is 0.05 m higher than scenario 2 which indicates that different water supplement methods have significant differences in the hydrodynamics of Yilong Lake (Figure 4). Scenario 2 adds new supplement volume based on the current supplement ratio. The results show that the contribution of the new supplement volume to the water level of Yilong Lake according to the supplement point is more conducive to optimizing the hydrodynamic conditions of the lake; supplement volume of rice, of which the two supplement points of Pubu and Mafangwan are 3.37 and 3.57 million cubic meters, respectively, that is, if additional supplement of 10 million cubic meters can be added, the water volume of two supplement points of waterfall and Mafang Bay should be increased, respectively, by 33 and 35%.

The total water supplement in scenario 3 and scenario 4 is 20 million cubic meters, and the simulated average water level is 3.81 m, which is 0.11 m higher than the average water level in scenario 1. This shows that the increase in water supplement can increase the lake water level, but when the total water supplement reaches a certain amount, the contribution of water points to water level is almost the same, and the effect is not significant (Figure 8).

4.1.2. Influence and optimization of water supply position on hydrodynamic

There are two outlets on the south bank and the east bank of the lake and the two water supplement points of Pubu and Mafangwan are close to the outlets. The principle of setting the simulated water supplement position is to set one water supplement point in the east, west, north and south of Yilong Lake, mainly to increase the flow velocity.

The purpose of changing the water supplement location of Yilong Lake is to affect the hydrodynamic conditions of the lake by changing the flow field (Li *et al.* 2014). The model simulates that the overall temperature change of Yilong Lake at different supplement locations is less than 5%, indicating that changing the location of water supplement has only little effect on the hydrodynamics of Yilong Lake. It is better to increase the amount of water supplement on the lake's hydrodynamics. In the

Table 3 | Water distribution at each water supply point (thousand cubic meters)

Total	Scenario	Pubu	Xian	Renshoucun	Mafangwan
1,000	1	337	96	210	357
1,000	2	200	350	300	150
2,000	3	674	192	420	714
2,000	4	400	700	600	300

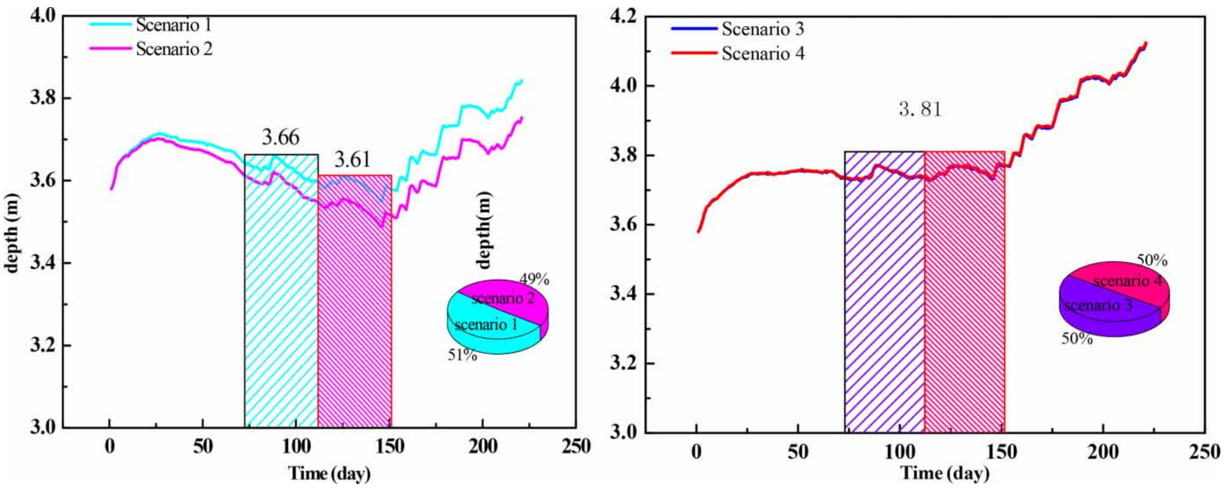
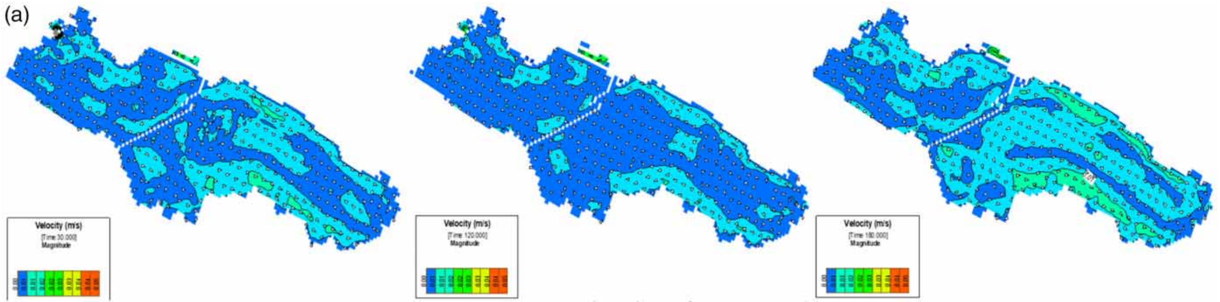
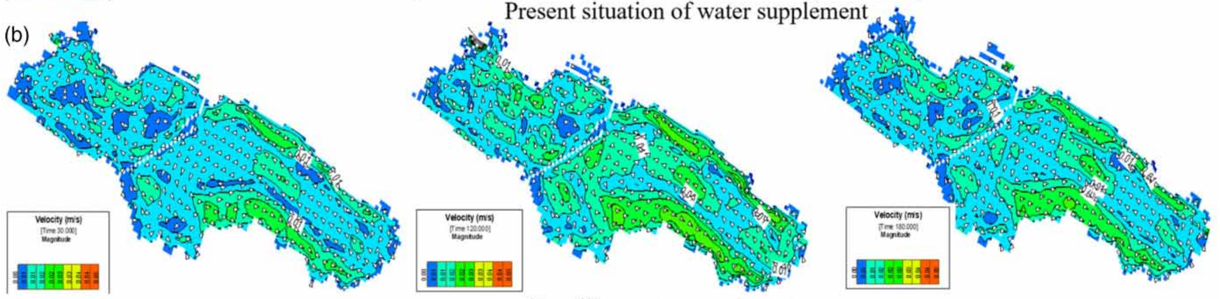


Figure 7 | Diurnal water depth variation chart of different water supplement scenario in Yilong Lake.



Present situation of water supplement



20 million water supplement

Figure 8 | Variation diagram of flow field of different water supplement in Yilong Lake.

normal season, the average temperature in the east is significantly higher than the average temperature in the western region. During the wet season, the temperature in the local area of the north bank is relatively high, and the local area reaches 19 °C, indicating that the annual temperature distribution of Yilong Lake Basin is different. The trend of water temperature and atmospheric temperature is the same, showing the characteristics of high in summer and low in winter (Yang *et al.* 2018), the water temperature in the western region is low, so the western region should be given priority in the protection and management of Yilong Lake. The effect of changing the water supplement position on the water velocity of Yilong Lake is relatively small. The west velocity of the monitoring point only increased by 4.2%, the east of the monitoring point and the national control monitoring point increased by 4.5 and 5.2%, respectively. The effect of water supplement on the improvement of the hydrodynamic conditions of Yilong Lake is more obvious.

Based on the above analysis, it can be seen that different water supplement schemes have different impacts on the hydrodynamics of Yilong Lake. One is that the location of each water supplement point is different, and the distance from the national control monitoring cross-section is large. The second is the uneven water supply at each water supply point, which has a different contribution to the lake water level, which affects the hydrodynamic conditions of the lake water level and flow rate, which in turn affects the lake water quality. Among them, increasing the amount of water supplement has a more significant impact on the hydrodynamic conditions of Yilong Lake than changing the location of the water supplement.

When supplying water in Chinese lakes, only the ecological benefits brought by the amount of supplement are generally considered, and the importance of the location of replenishment for improving the quality of the monitored cross-section water environment is underestimated (Yan *et al.* 2012). The water supplement position can improve the water quality of the point of interest faster and more effectively by shortening the distance. If the water quality of the monitoring section needs to be prioritized, the water can be refilled closer to the monitoring section. Among them, the amount of water supplement is more obvious for the improvement of lake hydrodynamics. If the water quality needs to be improved in a short time, priority can be given to increasing the amount of water supplement.

4.2. Outflow management of Yilong Lake based on water quality improvement

Seeking outflow optimization schemes, the purpose of which is to improve water quality by rationally controlling water levels and optimizing hydrodynamic conditions, thereby facilitating the management and protection of water resources at Yilong Lake (Yao *et al.* 2019). The Yilong Lake is east–west and northwest wind prevails. The wind-induced current simulation results show that the wind direction and wind speed will affect the hydrodynamic process of Yilong Lake. The velocity of flow has a significant impact on pollutants and algae discharge time. It can be seen that the rational management of the outflow plan is one of the important ways to improve Yilong Lake water environment.

The effects of wind-induced currents, water supplement and enclosure diversion on the hydrodynamic conditions of Yilong Lake are analyzed to form an outflow management plan based on water quality objectives. Reasonable outflows are expected to cause substances such as algae outbreaks to flow out of the lake more quickly, thereby improving the lake water environment. The results are shown in Figure 9, where the water flow velocity is the slowest during the dry season (middle), the average flow velocity in the eastern region is $0.013\,\mathrm{m\,s^{-1}}$, and the average flow velocity in the western region is $0.009\,\mathrm{m\,s^{-1}}$. It takes a long time for algae to flow from the west to the east bank outlet; the velocity in the central area during the normal season (left) is faster, and the velocity in the central and southern areas during the wet season is relatively uniform, maintained at $0.018\,\mathrm{m\,s^{-1}}$.

Based on the above analysis, it can be seen that reasonable management of outflow is an important measure for governance and protection of Yilong Lake. In the dry season, the flow velocity is slow. At this time, the lake water level is the most restrictive factor of the flow velocity. In the southern region, there are water supplement points, the water body exchanges are frequent, and the flow velocity is relatively fast. Therefore, during the dry season, the outflow is mainly from the south bank, and the outflow from the east bank is auxiliary; during the normal season, the water level is relatively high, while the wind speed is relatively slow. The central diversion guide makes the central area of Yilong Lake to have a faster flow rate, and the water can flow to the east bank outlet faster. During the wet season, the water supply is large and the water level is high, which leads to the rapid flow of the lake. Then, the average flow rate of the whole lake can be increased by $0.0025\,\mathrm{m\,s^{-1}}$, the average concentration of the water quality indicator COD at the national monitoring point can be reduced from 45.86 to 37.74 mg/L, a decrease of 17.7%.

The change of water level is a dynamic reflection of the hydrological process and water balance of a lake, which has an important influence on the ecological environment elements such as water quality, sediment and aquatic organisms (Coops *et al.* 2003; Zohary & Ostrovsky 2011). One of the most difficult problems facing Lakes in China is how to manage water resources, that is, how to manage the lake water level and outflow under the influence of multiple factors while improving lake water environment quality and optimize lake hydrodynamic conditions. At the same time, due to the implementation of such projects as water interception and pollution control, the lake water level drops, and reasonable water level management is more important. Water supplement can increase the self-purification capacity of lakes by regulating the water level of lakes, and also accelerate the discharge of nutrients from lakes, thus improving the water environment quality of lakes. Erhai Lake transfers water mainly through the three-reservoir connection project to increase lake water storage and raise running water level of Erhai Lake (Wu *et al.* 2019). The Taihu Basin is located in the plain river network area, and the flood disaster has caused great economic losses to the local area (Li *et al.* 2014; Hu *et al.* 2017; He *et al.* 2019). With the continuous advancement of urbanization, the river regulation and storage capacity has decreased significantly, which further weakens the ability of the Taihu Basin to cope with the flood disaster. Its changes have a significant impact on regional flood and drought disaster prevention and ecological environment protection (Liu *et al.* 2015; Zhu *et al.* 2017; Zhang *et al.* 2018; He *et al.* 2019). Weather conditions and different lakes and lake relations factors, such as water level and discharge management is also different, but the reasonable management flow management should consider the following aspects:

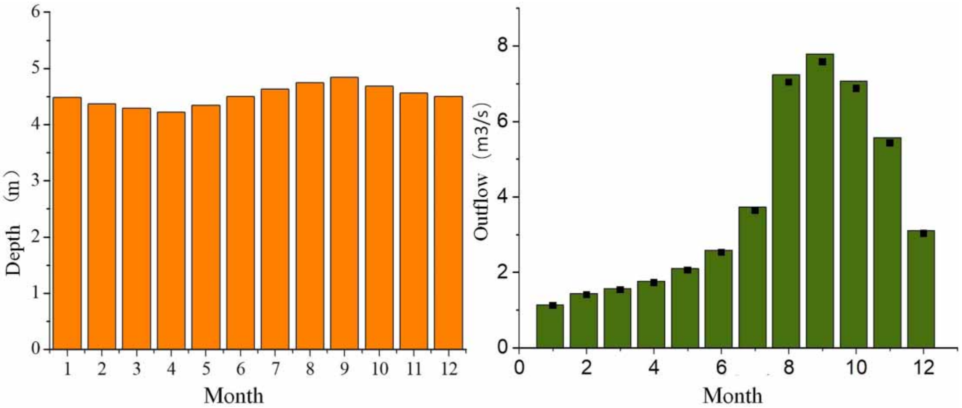


Figure 9 | Water depth management and outflow management.

(1) Discharge location choice: According to the direction of the wind speed to determine the best discharge position, because water and nutrients could move in the wind direction, the LiuKou location choice will affect nutrient retention time in the lake and water environmental quality. (2) Discharge selection: The discharge is determined according to the hydrodynamic conditions of the lake. Since optimizing the hydrodynamic conditions can improve the water quality of the lake, the lake discharge should be selected when the hydrodynamic conditions are good. (3) Selection of outflow time: The optimal outflow time should be determined according to the water quality of the lake. Since the water quality of the lake is spatial-temporal variable, more outflow should be selected when the lake water quality is poor to improve the water environmental quality of the lake (Grace *et al.* 2019).

5. CONCLUSION

Based on the EFDC numerical model, a hydrodynamic model of Yilong Lake is established in this research. The effects of wind forcing, supplement and enclosure on the hydrodynamics of Yilong Lake are studied. Based on the water quality objectives, the supplement and outflow schemes are optimized. The simulation results show that:

1. Wind forcing, water supplement and enclosure can affect the hydrodynamic conditions of Yilong Lake. Among them, wind forcing and enclosure diversion works mainly affect the hydrodynamic characteristics by changing the velocity and direction of the water body. The water flow velocity, in turn, affects hydrodynamic conditions. The current hydrodynamic conditions of the water body in Yilong Lake are generally poor, with an average annual water level of 3.62 m and a fluctuation range of 3.49–3.85 m. The flow velocity of the water body is gentle, and the flow velocity in 90% of the area is less than 0.01 m s^{-1}. The flow velocity in the central lake area is relatively high, while that in the east and west lake areas is relatively low.
2. The water supplement project can improve the water quality of Yilong Lake to a certain extent. Among them, the increase of water supplement is more obvious than the optimization of the water supplement position; priority is given to increasing the water supplement at the Pubu and Mafangwan. If 10 million cubic meters of additional water is added, and the Pubu and the Mafangwan are increased by 33 and 35%, respectively, the average water level can be increased by 0.15 m, and the average flow rate can be increased by 0.002 m s^{-1}.
3. Based on the goal of improving water quality, due to the faster outlet velocity on the south bank during the dry season, the south bank should be the main outlet. During the normal season, the outflow from the east bank is mainly used for the surrounding diversion. When the water level is high and the flow rate is high, and the two outlets in the east and the south should be operated at the same time. The water level management from January to mid-April gradually decreased from 4.48 to 4.20 m in Yilong Lake, and then slowly increased to 4.82 m. The outflow increased in autumn and winter the water level is gradually reduced to the same level as the water level at the beginning of the year. The water quality improvement effect is more significant in this outflow mode where the average concentration of water quality index COD at the national control monitoring point decreased from 45.86 to 37.74 mg/L, a decrease of 17.7%.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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