The Dual Effect of Reclaimed Water Replenishment in an Urban Lake: Hydrodynamic Enhancement Versus Phosphorus Risk

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Abstract. The application of reclaimed water can be used as an important avenue of encouraging the utilization of wastewater resources and maintaining water ecological safety. This presented work centered on Tangxun Lake which is the biggest urban lake in Asia created an innovative coupled two-dimensional hydrodynamic -water quality numerical model of the basin. The model was calibrated and tested with measured data, with high reliability, and simulation errors of COD, NH_3-N, TN and TP all less than 35%. Systematically, the feasibility of the treated effluent of the wastewater treatment plant being considered as the replenishment source was evaluated and different possible replenishment situations were modeled. It could be observed that ecological replenishment has a significant positive influence on the hydrodynamic conditions of the lake bays, and the flow velocity of the Hongqi Lake Bay increased by as much as 17.5%. The improvements in the water quality had strong pollutant-specific features: it was noted that the process of dilution and degradation caused efficient reductions in TN, COD and NH_3-N concentrations. Nonetheless, the high TP concentration of the tail water caused more severe phosphorus pollution of the lake, which indicated that the replenishment of reclaimed water has a double-edged sword effect on the probability of eutrophication. The current study offers scientific evidence and optimization of the planning and risk management of such projects.

Keywords: Reclaimed water, Ecological Replenishment, Numerical Simulation, Pollutant-specific response, Eutrophication risk

1 Introduction

The definition of wastewater resource utilization is the procedure through which waste water is rendered harmless before it can be used to achieve certain water quality requirements and becomes reclaimed water to replace conventional water sources. It is

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used in industrial manufacturing, municipal purposes, household use, ecosystem recovery, agricultural irrigation, groundwater recharging, and to extract other materials and energy out of wastewater. Such a strategy is very important in terms of water supply optimization, enhancing water resources accessibility, addressing supply-demand issues, water contamination, and protecting the aquatic ecological safety [1,2]. On January 2021, the National Development and Reform Commission along with nine other ministries jointly released the guidelines on promoting wastewater resource utilization [3] thus indicating that wastewater resource utilization has been raised to a level of a national action plan. At the same time, other countries and territories such as the European Union, Japan, and Israel have included reclaimed water in urban water replenishment systems, with more than 100 million cubic meters per year being replenished, which is beneficial to the ecology of rivers and lakes [4-6]. Reclaimed water application in ecological restoration of rivers, lakes, and wetlands may improve the ecological purification ability of urban water environment systems and facilitate the inherent nature of the ecological cycle of water bodies. The past few years have seen it as one of the main solutions to urban water shortages and it has been very important in preserving aquatic ecosystems and reviving river and lake ecosystems[7-9].

The Tangxun Lake, which is the biggest urban lake in Asia, has undergone a fast-paced socio-economic progress in its basin over recent years, with recurring environmental problems such as wastewater discharges into its coastline, poor quality of water, and repeated cyanobacterial blooms[10-11]. The monitoring results of the data between October 2018-September 2020 show that the general water quality in Tangxun Lake was between Class V and lower than Class V, which is far below the Class III water quality goal. Chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) and total phosphorus (TP) were the main pollutants exceeding the standards. It is worth noting that the quality of water in the bay areas was significantly lower than that in the open water, mainly because of less hydromechanical conditions as well as the concentration of pollutants flowing into these areas.

The watershed is experiencing a range of restoration efforts such as transforming reclaimed land and fishing grounds into lakes, shoreline restoration, pollution discharge interception, separation of storm drainage and sewer systems, overall regulation of inflows, internal pollution abatement, ecological restoration, and the diversion of treated effluent out of the lake. Nonetheless, these efforts are a long-term project that will not result in significant improvement in the lake water quality in the short term.

Hence, to alleviate water quality deterioration, cyanobacterial blooms and odor problems especially in the lake bays and increase hydrodynamic flow and the environmental carrying capacity of the lake, it is important to assess the feasibility and environmental consequences of reclaimed water as an ecological replenishment.

2 Materials and Methods

2.1 Study Area

The largest urban lake in Asia, Tangxun Lake, is situated in the southeastern part of Wuhan with a water surface area of 47.62 km_2 and a catchment area of 240.48 km_2. It is a big shallow lake with an average depth of 2.2 m and is separated into east and west parts by Jiangxia Avenue. The hydrological monitoring shows the presence of different water level changes in both sections, with an average run-off of 5.1m^3/sec and water renewal time of 220 days. Seasonal hydrodynamic variations are very high in the lake: non-flood seasons have low general water mobility especially in bays such as Maque Lake and Hongqi Lake whereas the central bulk of Outer Tangxun Lake has good flow. Rainfall during flood periods significantly improves the flow conditions of important lake sections, although some bays such as Hongqi Lake and Zhongzhou Lake still remain hydrodynamically confined.

2.2 Model Setup

To create a high-precision mathematical model that can simulate hydrodynamic and water quality processes in lakes with great accuracy is an essential requirement and main task in the scientific prediction and evaluation of environmental consequences of ecological water replenishment. The internationally well-known Danish DHI MIKE 21 program was used to develop a two-dimensional hydrodynamic-water quality coupled numerical model of Tangxun Lake in this work. The model was rigorously calibrated and validated against a variety of measured data sources and it can be relied upon and has predictive ability.

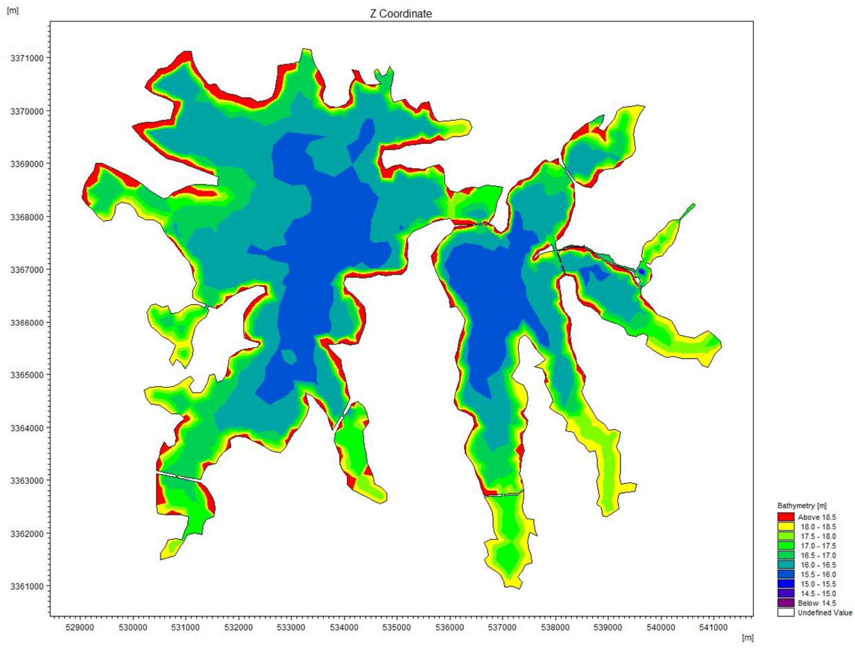

Fig. 1. Interpolation distribution of underwater terrain

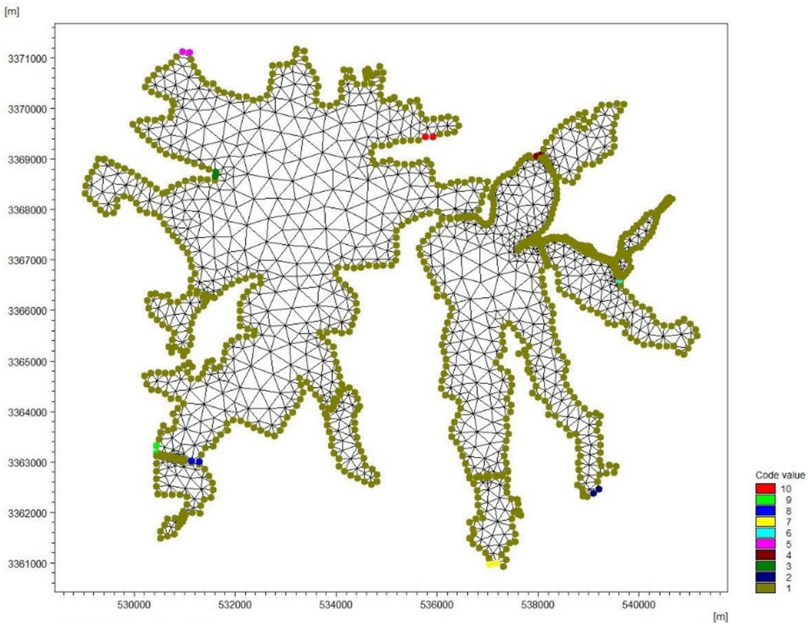

Fig. 2. Numerical model simulation scope and grid division

The simulation domain precisely covers the total water area of 47.6 km² within the blue line of Tangxun Lake. To enhance simulation accuracy, high-resolution 1:2000 underwater topographic data measured in July 2019 were adopted (Fig. 1). For computational efficiency and spatial resolution, an unstructured triangular mesh was used in flexible discretization of the computational domain. Grid size of 500 m was applied to the open water regions like the main bodies of the Outer and Inner Tangxun Lake but at the nearshore regions and lake bays where the shorelines are complex and there is a large amount of hydrodynamic variation, it was refined to 100 m grids (Fig. 2). The meshing scheme produced a total of 2,587 computational cells which were efficient in terms of representing the complex boundary features and the local flow behavior of the lake. Important model parameters such as bed roughness (Manning coefficient, M), wind drag coefficient, and diffusion and decay coefficients of different contaminants were first defined according to the available literature and the features of the lake, and then acted as calibration objects. In this model, Manning's coefficient M was set between 0.031 and 0.050 for different depth zones in Tangxun Lake.

2.3 Model Calibration and Verification

Analysis of Hydrodynamic Results. Because of the overall low rates of flow in lakes, conducting a full-scale field measurement of flow patterns is extremely difficult. Consequently, a non-direct but very persuasive validation strategy has been used in this research: testing the validity of the hydrodynamic model by testing whether the simulated wind-induced flow field structure is reasonable. The lake hydrodynamic theory states that the structure of wind-driven flows is strongly connected with water depth: in deep regions, the depth-averaged flow direction tends to be opposite to the wind direction, and in shallow regions, it tends to be aligned with the wind direction.

Figures 3 and 4 illustrate the computed average wind-induced flow fields on June 15, 2012 (SE wind, 2.3m/s) and December 15, 2012 (NE wind, 1.6m/s), respectively. The simulation findings make it clear that SE wind led to the formation of a large-scale counterclockwise circulation within open regions like most part of Outer Tangxun Lake whereas NE winds caused another flow field arrangement. However, more crucially, in both the simulations, either on June 15 or December 15, 2012, the return flow in the deep-water area and the downwind flow in the shallow region were extremely similar to classical theory. This result is not only an assurance of the appropriateness of the model in reaction to the main driving factor (wind) but also an impressive indication of its ability to recreate the essential hydrodynamics of Tangxun Lake as a shallow lake to offer a solid physical premise to the further simulation of the water quality.

Calibration and Validation of Water Quality Results. The calibration of the water quality model is necessary to assess its simulation capacity. Data on COD, NH3-N, TN, and TP were gathered on a monthly basis at the central monitoring point of the Outer Tangxun Lake throughout the whole year of 2012 to allow the model to be calibrated in detail.

The calibration outcomes show that the simulated values were able to capture the seasonal variations of the measured pollutant concentrations in most of the months indicating that the model is able to simulate the overall processes of pollutant transport and transformation in the lake. Moreover, mean relative errors of simulated and measured values of COD (28%), NH3-N (34%), TN (21%), and TP (31) are all in the allowable error rate of modeling complex natural water bodies (usually less than 50 percent) and confirm the high quantitative simulation performance of the model.

In-depth discussion of error sources: Major errors in some months (e.g, 92 percent of TP in June) have been closely examined. Main causes are:

Model Simplifications: The two-dimensional model is not able to effectively represent the intense effects of short-term ecological mechanisms, i.e., thermal stratification and growth and death of algae, on the dynamics of nutrients.

(2) Input Load Uncertainty: The pollutant loads that will be applied to the model are estimated and the spatiotemporal accuracy of these loads will directly influence the simulation outcomes.

Monitoring Representativeness: The point measurements can be not representative of the average conditions over all the model grids.

Calibrated hydrodynamic and water quality parameters for Tangxun Lake are summarized in Table 1. To sum up, the carefully calibrated and validated hydrodynamic-water quality model was able to replicate the objective characteristics of flow field structure and water quality dynamics of Tangxun Lake. The model was adequate in terms of predicting the trends as well as quantifying them, thus offering a potent, reliable technical instrument and a novel basis of further scientific assessment of environmental impacts of various ecological water replenishment situations.

Table 1. Calibration Results of Hydrodynamic and Water Quality Parameters for the Tangxun Lake System

Parameters	Dispersion Coefficients (m^2/s)	COD Decay Rate (d^{-1})	NH_3-N Decay Rate (d^{-1})	TN Decay Rate (d^{-1})	TP Decay Rate (d^{-1})
Jan.	1	0.017	0.01	0.01	0.017
Feb.	1	0.017	0.01	0.01	0.017
Mar.	1	0.017	0.01	0.01	0.017
Apr.	1	0.017	0.02	0.02	0.017
May	1	0.017	0.02	0.02	0.02
Jun.	1	0.017	0.02	0.02	0.02
Jul.	1	0.017	0.02	0.02	0.02
Aug.	1	0.017	0.015	0.015	0.02
Sept.	1	0.017	0.015	0.015	0.02
Oct.	1	0.017	0.015	0.015	0.02
Nov.	1	0.017	0.015	0.015	0.017
Dec.	1	0.017	0.015	0.015	0.017

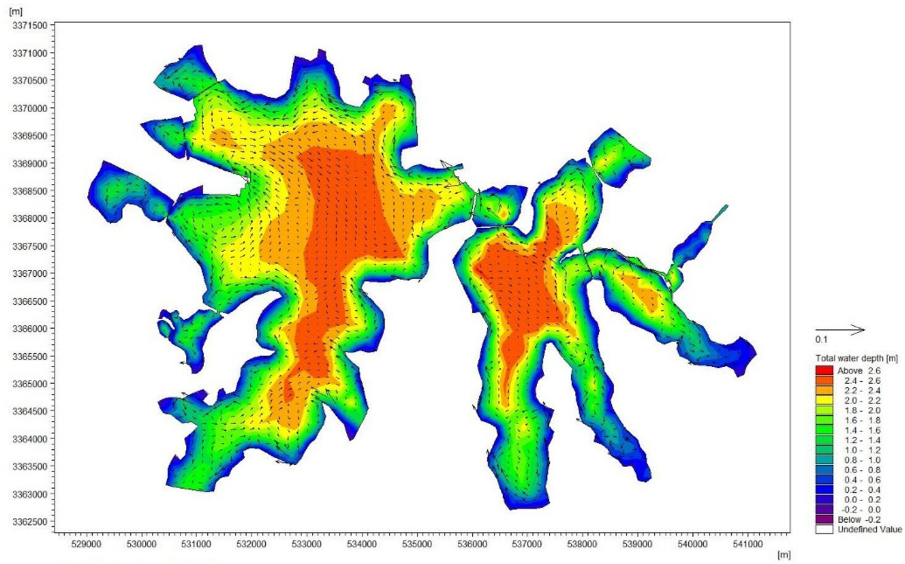

Fig. 3. Flow field validation diagram on June 15, 2012 (wind speed: 2.3m/s, wind direction: 135 degrees)

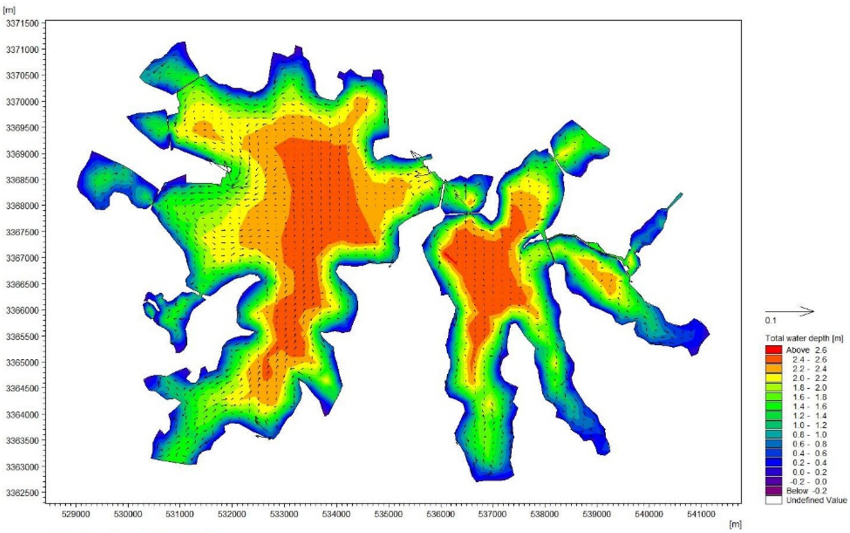

Fig. 4. Flow field validation diagram on JDecember 15, 2012 (wind speed: 1.6m/s, wind direction: 45 degrees)

3 Results and Discussion

3.1 Analysis of Replenishment Water Sources

The scientific choice and appraisal of reclaimed water sources are the basis of environmental advantages and ecological safety in ecological water replenishment projects. Under the guidance of an overview of the Tangxun Lake basin, the present work has reviewed the current, under construction, and proposed wastewater treatment plants to identify four large sources of potential reclaimed water (Table 2). These sources form a hierarchical and complementary water supply system in terms of spatial distribution, treatment capacity, effluent quality, and the stage of implementation.

Table 2. Basic information of sewage treatment plants and water purification plants around Tangxun Lake

Name	Status	Current Capacity ($10^4m^3/d$)	Planned Capacity($10^4m^3/d$)	Effluent Standards
Tangxun Lake Wastewater Treatment Plant	Existing	10	20	Quasi Class IV
High-tech Zone Integrated Wastewater Treatment Facility	Existing	6	-	Grade A
Canglong Island Underground Water Purification Plant	Planned	-	10	Quasi Class IV
Miaoshan Water Quality Purification Plant	Planned	-	3.5	Grade B

In order to properly prove that the chosen water replenishment source is feasible, the present study centers on the Tangxun Lake Wastewater Treatment Plant, which has been chosen because it has the biggest capacity of water treatment and is highly representative, as a main object of research. An overall assessment was performed in three main aspects: water quality compliance stability, compliance with the requirements of the receiving water body, and engineering-economic feasibility.

Assessment of Water Quality Compliance Capability and Stability. On the basis of 153 successive days of recorded effluent quality in the plant during April 1 through August 31, 2019, important indicators were statistically analyzed (Table 3). The findings show that the effluent produced by the plant is consistently at the Grade A level as set by the discharge standard of pollutants in municipal wastewater treatment plants (GB 18918-2002) with a 100-per cent compliance rate on all indicators. It confirms the reliability of the source of water in terms of the stability of its quality and the maturity of the operations.

Table 3. Analysis of effluent quality of Tangxun Lake sewage treatment plant

Project / Item	COD	BOD	NH_3-N	TN	TP
Number of data points	153	148	153	153	153
Maximum(mg/L)	37.07	9.8	4.71	14.92	0.45
Minimum(mg/L)	11.04	5.09	0.02	4.3	0.02
Mean value(mg/L)	19.8	6.94	0.96	10.35	0.17
85% Assurance Rate(mg/L)	26.52	8.75	1.84	12.8	0.21
90% Assurance Rate(mg/L)	27.90	9.12	2.15	13.2	0.23
95% Assurance Rate(mg/L)	29.97	9.42	2.61	13.74	0.28
Grade A Standard(mg/L)	50	10	5 (8)	15	0.5
Compliance Rate with Grade A (%)	100	100	100	100	100
Surface Water Class IV Standard(mg/L)	30	6	1.5	1.5	0.3 (0.1 for lakes/reservoirs)
Compliance Rate with Class IV(%)	95.42	33.11	77.78	0	13.07

Analysis of Environmental Compatibility and Potential Risks with the Lake Ecosystem. The comparison between the tail water quality and the Environmental Quality Standards of Surface Water (GB 3838-2002) is a very important factor to consider when evaluating the ecological compatibility of the former. The analysis indicates:

Positive Indicators: COD and NH3-N both achieved Class IV surface water requirements in 95.42 percent and 77.78 percent of the time respectively, which means that the tailwater of the plant is near the Class IV standard on these two parameters with regard to its water usage in the landscape and environment.

The most significant limiting factors: Total nitrogen (TN) and total phosphorus (TP) are the main limiting pollutants and possible environmental risks. The median level of TN (10.35 mg/L) is much higher than the Class V lake and reservoir standard (2.0 mg/L) and has a 0 percent compliance rate. Even though TP has a value that complies with the limit of the Class IV surface water standard (0.3 mg/L), it has an assurance concentration of 95 percent (0.28 mg/L) which is very close to the top end of that standard and considerably above the limit allowed by the Class V standard of lakes and reservoirs (0.1 mg/L).

The result indicates that the direct application of such reclaimed water in lake replenishments despite adding more water volume and some dilution ability will always bring high levels of nitrogen and phosphorus nutrients that could possibly trigger an increased level of eutrophication in the water body.

Engineering Economy and Locational Advantages. Based on the engineer implementation point of view, both the Tangxun Lake Wastewater Treatment Plant and the proposed Canglong Island Underground Water Purification Plant are located at a relatively higher elevation. This geographical benefit ensures that the treated effluent will flow into Tangxun Lake by gravity, making it unnecessary to build lifting pump stations and long-distance water conveyance systems. As a result, there are substantial reductions in initial capital costs and long-term operational energy usage with economic benefits specific to this option.

As indicated in a comprehensive assessment, it is evident that the tail water of Tangxun Lake Wastewater Treatment Plant can be used as an ecological replenishment source due to its stability and economic feasibility of the water source and engineering cost. Nonetheless, in terms of water quality compatibility, the significant values of TN and TP pose the fundamental limitation that should be taken into consideration in the implementation of ecological replenishment. Hence, the planning of water replenishment projects has to build upon the advantages and reduce the disadvantages - through improving the position, manner, and level of water replenishment to achieve maximal positive hydrodynamic effects and at the same time actively watch and scientifically measure the marginal effect on the amount of nutrients in the lake. The next set of scenarios in this study are the specific strategy explorations because they are based on this careful insight.

3.2 Design of Replenishment Scenarios

According to the near-term baseline year of 2021, assuming that the external load reduction, internal pollution control, and water systems connectivity projects are implemented in Tangxun Lake, three simulation scenarios (Table 4) have been developed by taking into consideration the discharge of treated effluent of the Tangxun Lake Wastewater Treatment Plant to the river or to the lake (the near-term and long-term capacities were 100,000 m^3/d and 200,000 m^3/d respectively). The three scenarios were applied to discuss the positive impacts of ecological replenishment through treated effluent of the plant (water quality parameters in Table 3) on the hydrodynamics and water quality of Tangxun Lake.

Table 4. Simulation scenario of ecological water replenishment effect for tail water of Tangxun Lake sewage treatment plant

Number	Simulation Scenario	Simulation Content	Replenishment Flow Rate(m^3/s)
Scenario 1	External load reduction + Internal pollution control + Internal water system connectivity	Simulates the hydrodynamic and water quality changes in each lake under the conditions of external load reduction (point and non-point sources), internal pollution control, and internal water system connectivity in 2021.	0
Scenario 2	External load reduction + Internal pollution control + Internal water system connectivity + Tail water ecological replenishment	Simulates the hydrodynamic and water quality changes in each lake under the conditions of external load reduction, internal pollution control, internal water system connectivity, and tail water ecological replenishment in 2021.	1.16
Scenario 3	External load reduction + Internal pollution control + Internal water system connectivity + Tail water ecological replenishment	Simulates the hydrodynamic and water quality changes in each lake under the conditions of external load reduction, internal pollution control, internal water system connectivity, and tail water ecological replenishment in 2021.	2.31

3.3 Analysis of Replenishment Effects

The analysis of the simulation results of three scenarios in a systematic way is used to obtain an in-depth understanding of the multifaceted impact of reclaimed water ecological replenishment on the hydrodynamic and water quality conditions of Tangxun Lake.

Significant Improvement in Hydrodynamic Conditions. The simulation findings clearly indicate that ecological replenishment as an external driver can be used to improve the mobility of lake water. In the case when no replenishment took place (Scenario 1), the average flow speed in the whole Tangxun Lake and in the Hongqi Lake Bay did not exceed 0.008 m/s, which means that the flow was almost stagnant and prevented dissipation and transport of pollutants. Following ecological replenishment, the flow regime in the lake bays was successfully stimulated. It should be noted that the improvement was especially significant in the regions initially having bad hydrodynamic conditions. With the replenishment rate of 200,000 m^3/d (Scenario 3), the average flow velocity in Hongqi Lake Bay rose by 12.87 -17.51 percent relative to the no-replenishment condition, much larger than the 1.98 -4.20 percent increase in the whole lake. This implies that ecological replenishment has an indispensable role in solving hydrodynamic dead zones created by morphological enclosure, which provides a physical basis to the further improvement in water quality by increasing the water exchange capacity.

Differentiated Water Quality Responses: The Interplay of Dilution, Mixing, and Input Pollution. Post-replenishment trends in various water quality indicators reveal inherent differences in their environmental behaviors:

COD and NH3-N: Dominance of "Purification".

Following the replenishment, COD and NH_3-N in both the whole lake and the bay zones tended to improve, which is expressed in the increase of the share of Class IV water bodies area and decrease of Class III water bodies area. The reason behind this phenomenon could be the increased hydrodynamics that led to the formation of an aerobic environment, facilitating the breakdown of organic matter and the conversion of ammonia nitrogen into nitrate and nitrite forms. While the tailwater contains a specific level of COD and NH_3N, their concentration is less or almost equal to the initial levels in the lake. Consequently, the beneficial impact of the dilution and mixing was higher than the bad influence of the input pollution and this caused a general improvement in both of these indicators.

TN: Notable "Dilution-Driven Improvement" Effect.

The overall nitrogen (TN) improvement is amongst the most encouraging results of this research. HKL Without replenishment, TN in Hongqi Lake was classified as almost entirely worse than Class V (66.42-99.97%). The percentage of Class IV water bodies has risen significantly after replenishment to 55.22% (mean of Scenario 3). It is clear to observe that the TN concentration in the tailwater (mean 10.35 mg/L) was much higher than the Class V surface water limit (2.0 mg/L) but it had the ability through dilution to reduce the peak TN concentrations in localized regions due to dilution as well as the mixing process caused by the movement of water. This confirms the success of the environmental engineering strategy of substituting highly polluted stagnant water with less polluted reclaimed water.

TP: Prominent "Input Pollution" Risk.

Conversely, total phosphorus (TP) revealed a significant decline following the refilling of TN. The share of water bodies of Class V and lower than Class V in the entire lake and Hongqi Lake rose sharply by about 40 percent to almost 100 percent. The reason behind this is that the TP concentration in the tailwater (mean 0.17 mg/L) is below the Class IV surface water criteria (0.3 mg/L) but above the Class V level of lakes and reservoirs (0.1 mg/L). This result clearly underlines a fundamental paradox in the existing practice of reclaimed water replenishment: the discrepancy between regulations on rivers and more stringent regulations on lakes and reservoirs. Thus, should reclaimed water be employed as a lake ecological replenishment source, it will have to be raised to an increased priority level, and sometimes it might need to meet the more stringent lake and reservoir standards.

Marginal Effects of Replenishment Scale. When comparing Scenario 2 (100,000 m^3/d) and Scenario 3 (200,000 m^3/d), it is clear that the improvement in replenishment effects is not linear. Although the hydrodynamic conditions also kept improving along with the scale of replenishment, the water quality, especially TN, demonstrated a diminishing return between Scenario 2 and Scenario 3. This indicates a presence of an optimum range of the scale of replenishment. In this zone, environmental benefits per unit of extra replenishment can reduce whereas environmental risks related to pollutants such as TP can keep accumulating. It offers a critical scientific foundation on which cost-effective ecological replenishment strategies will be developed in the future.

Cost-Benefit Analysis of Water Replenishment Schemes. This method proves that engineering can save a lot of money on cost by using elevation discrepancies to gravity feed the replenishment water, removing pumping stations and long distance pipeline installations. Nevertheless, such advantages will be offset by environmental risk costs caused by continual phosphorus introduction that might raise the rates of eutrophication and require the removal of algae in the future and emergency management. The plans offer significant environmental advantages, including better hydrodynamic conditions, which enhance the dispersion and degradation of pollutants and decrease the COD, NH_3-N, and TN concentration values and the cost of other pollution control methods. The best policy would be to focus on replenishing the near term scale (100000 m^3/d) to reap hydrodynamic advantages at a lower cost and focus more on advanced phosphorus treatment to address the main risk. The balanced solution would have the highest combined cost-efficiency of the ecological replenishment program.

4 Conclusion

The present work is a systematic analysis of the viability of ecological replenishment with reclaimed water in the urban lake system of Tangxun Lake and its impact on the environment. A scientifically sound, high precision 2D hydrodynamic-water quality model was created and used to analyze various replenishment scenarios, offering scientific information to support sustainable urban water management.

The key conclusions can be summarized as follows:

A powerful numerical model was developed and calibrated to show that it was reliable in terms of predictive performance on important water quality parameters (COD, NH_3-N, TN, TP) with relative errors that were less than 35%. This model is a useful instrument in assessing ecological refilling measures in the presence of complex hydrodynamics.

Reclaimed water replenishment has a double effect; it is highly effective in improving hydrodynamic conditions as well as minimizing the COD, NH_3-N and TN levels through dilution and biochemical reactions, while simultaneously rising the TP values because of concentration discrepancies between tail and lake water requirements.

Mechanistic analysis showed that TN improvement is mainly caused by physical dilution, but TP decline occurs due to constant input at standard misalignment. This indicates the necessity to have different approaches in controlling nitrogen and phosphorus in regeneration schemes.

(4) The advantages of replenishment are not proportional to scale, which implies that there is an optimal level of operation. Such results can be used as a scientific

justification of planning economically sound replenishment strategies able to ensure the improvement of water quality and at the same time, minimize the risk of pollution.

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