Water Science & Technology

Water Science & Technology Vol 85 No 9, 2601 doi: 10.2166/wst.2022.130

Demonstration study of bypass stabilization pond system in the treatment of eutrophic water body

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ABSTRACT

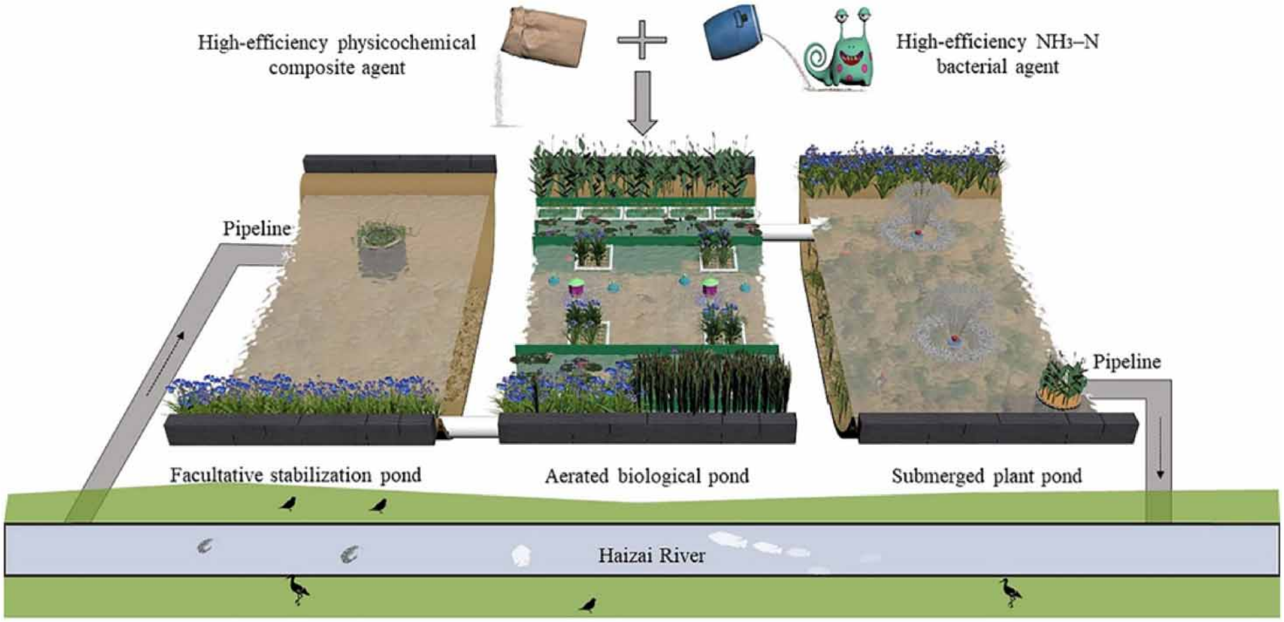
This study involved a comprehensive renovation of fish ponds to improve the water quality of a eutrophic river in Dongguan City. The abandoned fish ponds were transformed into three different types of stabilization ponds: facultative, aerated biological, and submerged plant stabilization ponds. The water of the eutrophic section of the river was pumped into the facultative stabilization pond and discharged into the Haizai River through an aerated biological pond and a submerged plant pond. In the aerated biological pond, secondary treatment was carried out using plant zoning and artificial floating island aeration system. The submerged plant pond used fountain-type aeration and an underwater forest for tertiary treatment. After four months of monitoring the water quality of the stabilization pond and the river, the ammonia nitrogen (NH_3-N), total phosphorus (TP), and chemical oxygen demand (COD_{Cr}) levels in the raw sewage reduced from 6.53 mg/L to 1.13 mg/L, 1.76 mg/L to 0.29 mg/L, and 63 mg/L to 22 mg/L, respectively; the transparency of water increased to 45 cm, and dissolved oxygen (DO) level increased to 5.32 mg/L. This study provides a reference for the ex-situ treatment of urban eutrophic waterbodies.

Key words: aquatic plant zoning, bypass circulation, eutrophic water body, stabilization pond

HIGHLIGHTS

- Ponds include facultative ponds, aerated biological pond and submerged plant ponds.
- Middle pond uses plant partition and ecological floating islands–artificial aeration.
- The final pond was treated with fountain type aeration and underwater forestry.
- The tarpaulin blocks water and plants, and the suspended filler of the floating island is conducive to the growth of microorganisms under aeration conditions.

GRAPHICAL ABSTRACT



INTRODUCTION

Eutrophication is common in rivers, lakes, coastal areas, and other regions (Tilahun & Kifle 2020; Zhou *et al.* 2020; Beretta-Blanco & Carrasco-Letelier 2021). It has become a major environmental concern in aquatic ecosystems and is one of the most challenging environmental issues worldwide (Hao *et al.* 2021). Excessive input and accumulation of nitrogen and phosphorus into a water body due to anthropogenic activities, such as discharge of industrial and agricultural wastewater and urban domestic sewage, which exceeds the ability of the water body to transform and utilize nutrients and organic matter, leads to eutrophication (Zhang *et al.* 2018). Fertilizers are also an important and significant cause of eutrophication (van Wijnen *et al.* 2015). Eutrophication of a water body often leads to the proliferation of harmful algae, and the organic matter cannot be degraded over time, resulting in the deposition of organic matter; the bottom of the water body is in an oxygen-deficient state (Rydin *et al.* 2017). The proliferation of aquatic plants and subsequent decomposition of organic matter usually result in low dissolved oxygen (DO) concentrations in the bottom water and sediments, and low water turnover rates (Zamparas & Zacharias 2014). Eutrophication reduces transparency, water quality, and DO levels of the water body; it is toxic to humans and animals, and the water body becomes black and odorous. Simultaneously, drinking water sources for urban and rural residents, and industrial and agricultural production water, face direct threats.

Different kinds of methods have been used for treating eutrophic water bodies, including physical, chemical and biological treatment methods. The physical measures for the treatment eutrophic water bodies include sediment dredging, mulching, and deep aeration (Richardson *et al.* 2011). If physical measures are not done properly, then secondary contamination may occur. Chemical treatment methods include flocculation sedimentation and use of chemical agents, such as aluminum salt, iron sulfate, and hydrogen peroxide, which inhibit the growth of algae in the water (Ronen *et al.* 2010; Rydin *et al.* 2017; Rybak *et al.* 2020). However, both physical and chemical methods are costly for long-term treatment and negatively impact ecosystems (Urionabarrenetxea *et al.* 2021). Bioremediation technology is inexpensive, environmentally friendly, and has a long-lasting effect. Therefore, various studies have been done to develop different methods, such as biofilm purification, stable pond purification, and aquatic plant purification (Xu *et al.* 2018; Zhuang *et al.* 2019; Su *et al.* 2020). The integrated action of microorganisms and plants in biological stabilization ponds to treat eutrophic water bodies, especially aquatic plants, has attracted attention and is considered promising because of its low cost, non-invasiveness, environmental friendliness, and safety (Zhang *et al.* 2014). Stabilization ponds offer unique advantages, including ease of operation, minimal energy input, and minimal maintenance requirements (Liu *et al.* 2018). Stabilization ponds are commonly used in many parts of the world, especially in places with mild-to-warm climates throughout the year (Butler *et al.* 2015). They are used for secondary or tertiary treatment of wastewater, and they provide effective disinfection, and reduce turbidity and nutrient load (Rey *et al.* 2021). They have been widely used in both developed and developing countries because they can provide a completely natural purification process (Ho *et al.* 2017). Moreover, they can effectively prevent secondary pollution during the treatment process and exhibit higher treatment efficacy.

In this case study, we examined a section of the Haizai River in Shipai Town, Dongguan City. Based on a detailed investigation of the river water quality and eutrophication level, the bypass stabilization pond circulation system was adopted as the treatment method, keeping in mind both the technical cost and stability. The water body of the eutrophic river section was pumped into the nearby stabilization pond, which passed through the facultative stabilization pond, aerated biological pond, and submerged plant pond in turn and was recycled into the river course. A combination of plant zoning and ecological floating island–artificial aeration was used in the aerated biological pond, whereas fountain-type aeration and underwater forest were used in the submerged plant pond. Adopting the bypass circulation process achieves the maximum synergistic effect of removing pollutants through the reasonable combination of aquatic plants, suspended fill and aeration equipment, etc., and the optimal combination of each pond controls the flow direction of the water body and achieves the gradual reduction of nutrients. The process overcomes the disadvantages of traditional stabilized ponds, such as a large floor area, low oxygen content, and poor hydraulic performance, and effectively performs ectopic treatment and remediation of polluted water bodies. This improves the ecological usability of abandoned ponds and landscape ornamental properties. The project goals were as follows: a water quality index chemical oxygen demand (COD_{Cr}) < 40 mg/L; ammonia nitrogen (NH_3-N) < 2 mg/L; total phosphorus (TP) < 0.4 mg/L; DO > 2 mg/L; and transparency > 25 cm.

METHODS

Overview of the study area

The project area is in the northeast of Dongguan City, on the south bank of the middle and lower reaches of the Dongjiang River; it has a subtropical monsoon climate (warm and rainy) and is close to the tropical ocean, and thus gets affected by the oceanic climate. It is a depression area, and the terrain is high in the northeast and low in the southwest, with abundant water systems within the jurisdiction.

The project is located in the south of the Haizai River in Dongguan City, adjacent to the Haizai River. The stabilization pond was transformed from three connected abandoned fish ponds. Earlier, the fish ponds were used for aquaculture. The depth of the fish ponds was 30–50 cm, and the fish ponds' areas were 6,120 m^2, 5,959 m^2, and 4,698 m^2. The Haizai River has already been comprehensively rejuvenated; thus, the turbidity and odor of the river have been eliminated; the water quality also improved significantly compared to that at the pre-treatment stage, and the overall water quality reached Class V standards. However, the water quality in one area of the river was unstable, and the water quality in summer did not meet the Class V standards for a long time. The district crosses urban residential areas with low-lying terrain, slow water flow, and serious non-point source pollution, causing seasonal eutrophication, reduced river water transparency, and excessive NH_3-N and TP concentrations. The geographical location of the river section that was included in the experiment and the reconstructed fish pond are shown in Figure 1.

Water quality characteristics

Long-term monitoring of the water quality of the Haizai River shows that when the temperature is high in summer, the water quality of the river deteriorates, and seasonal eutrophication occurs. The NH_3-N, TP, and DO concentrations in the Haizai River did not meet the 'Environmental Quality Standards for Surface Water' (GB3838-2002) stipulated in the Class V water quality standards. The NH_3-N and TP contents were too high, and the DO concentration was too low. The average data of the experimental river section are shown in Table 1, and the original data of the fish ponds are shown in Table 2.

Water quality analysis methods

Water quality testing mainly included pH, transparency, NH_3-N, TP, DO, and COD_{Cr} as the main water quality indicators. pH was measured using a pH meter (PHB-4 portable meter) (Lei Magnetics, Shanghai, China). Transparency was tested using the transparency meter (Sai Shi Compass) (SL87-1994); DO levels were tested by a portable DO meter 'Methods for Monitoring and Analysis of Water and Wastewater (4th edition)'; the DO meter used was a JPBJ-610L portable meter (Lei Magnetics, Shanghai, China); NH_3-N content was measured using Nessler's reagent spectrophotometric method (HJ535-2009); TP

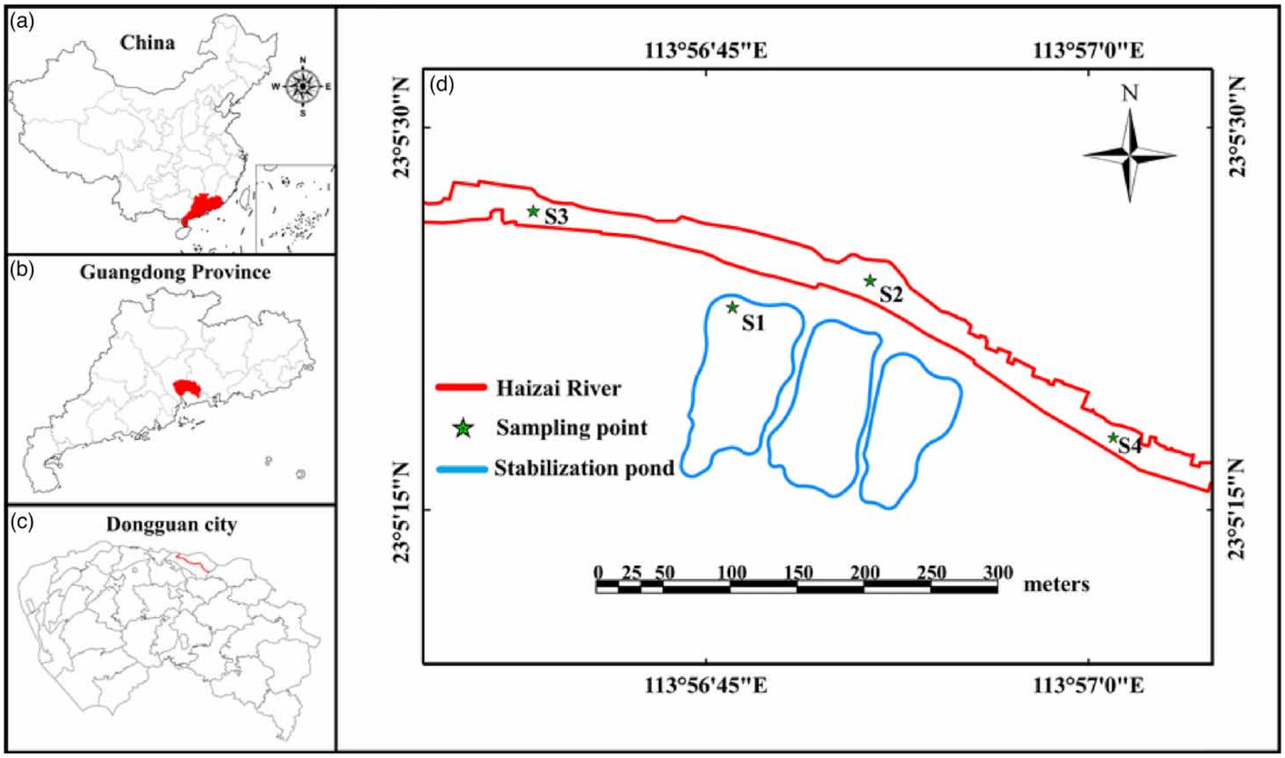


Figure 1 | Schematic diagram of the location of the river and oxidation ponds.

Table 1 | Average test results of raw data in the experimental river section

Water quality indicators	DO (mg/L)	COD_{Cr} (mg/L)	NH_3-N (mg/L)	TP (mg/L)	pH	Transparency (cm)
Average value of detection section	0.91	63	6.53	1.76	7.12	8
Class V standard of surface water	≥ 2	≤ 40	≤ 2	≤ 0.4	–	–

Table 2 | Average test results of raw data from fish ponds

Water quality indicators	DO (mg/L)	COD_{Cr} (mg/L)	NH_3-N (mg/L)	TP (mg/L)	pH	Transparency (cm)
Average value of detection section	0.64	78	7.96	2.18	7.2	5
Class V standard of surface water	≥ 2	≤ 40	≤ 2	≤ 0.4	–	–

content was measured using ammonium molybdate spectrophotometry (GB11893-89); and COD_{Cr} was measured according to potassium dichromate method (HJ828-2017).

Technology route

Functional division of stabilization ponds

The technical process of bypass stabilization pond repair is shown in Figure 2. The stabilization ponds were divided into facultative ponds, aerated biological ponds, and submerged plant ponds. The submersible horizontal screw pump pumps the water of the Haizai River into the facultative pond through bypass circulation, which precipitated suspended materials and degraded refractory organic pollutants. Sewage entered the aerated biological pond and was treated by the combined treatment of aquatic plant zoning and ecological floating islands–artificial aeration system. The DO concentration in the water

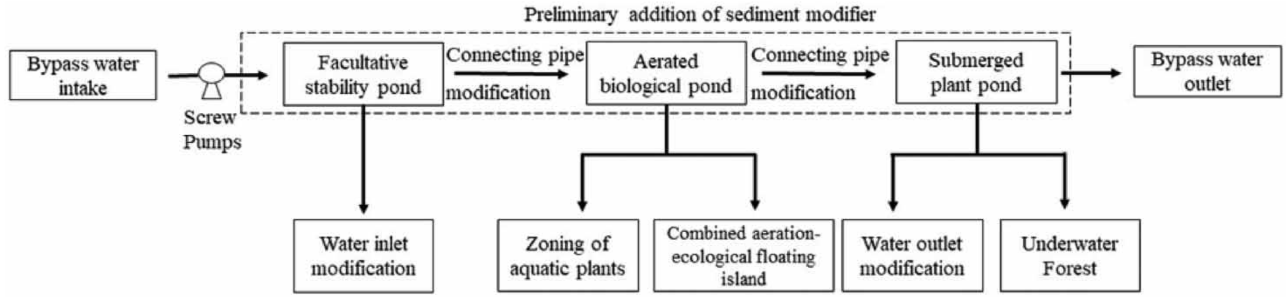


Figure 2 | Bypass stabilization pond restoration technology process.

increased while the concentration of pollutants, such as NH_3-N, decreased. Finally, the sewage passed through the submerged plant pond and was further purified by the fountain-type aerator and underwater forest treatment method to reach Class V water quality standards.

Substrate improvement

The stabilization ponds were transformed from three fish ponds. The sediments in fish ponds are an integral part of the aquatic ecosystem and also the main reservoir of nitrogen, phosphorus, organic matter, metals, and toxic substances (Li *et al.* 2019). In addition to the external input of nitrogen and phosphorus, the release of nitrogen and phosphorus from internal sediments is sufficient to maintain eutrophication (Zhong *et al.* 2021). The direct removal of sediments can effectively reduce the sources of nutrients (Jing *et al.* 2019); however, its cost is high and it causes resuspension of fine sediment particles, which damages the original ecological environment of the bottom of the fish pond (Lurling & Faassen 2012). Sediments can provide nutrients for emergent plants (Liu *et al.* 2021), and direct removal leads to the lowering of the river bed, which is not conducive to the subsequent growth of aquatic plants. Therefore, an in-situ repair method was used to improve the physical and chemical properties of the sediments. The original water volume of the fish pond was 30–50 cm. A bottom mud modifier was added to the fish pond using manual and mechanical methods. A high-pressure water gun stirred the bottom mud, and the modifier was mixed simultaneously. The dosing amount was 0.3–0.6 kg/m^2, applied four times once every five days.

Modification of connecting pipes and water inlet and outlet

The original fish ponds were connected by two DN1500 reinforced concrete pipes, and because of the low embedding position, the water storage capacity was insufficient. The water storage depth was approximately 30–50 cm, and the connecting pipe required modification. The cement part (two-thirds) of the first coagulation pipe was used to block the fish pond at a depth of 1.3–1.5 m, ensuring that the first fish pond could maintain the characteristics of a facultative pond. One-third of the second coagulation pipe was blocked to ensure that the highest water level of the last two fish ponds was maintained within 1 m, in a stable aerobic state.

The drainage outlet of the submerged plant pond was too low, which blocked water circulation, and the sewage from the Haizai River was recharged. It was necessary to intercept the suspended matter at the water inlet and increase the height of the water outlet simultaneously to modify the water inlet and outlet (Figure 4). Double-layer pine stakes were installed at the water inlet; small gravel, pebbles, and clay were placed in the middle of the pine stakes, and *Myriophyllum elatinoides Gaudich* was planted on the upper layer of the pine stakes. The water outlet used a horizontal outlet pipe of DN1500 reinforced concrete pipe to connect the vertical pipe. Pine piles were placed around the pipeline and were set into a semicircular cofferdam with a radius of 2 m, filled with schist, quartz sand, pebbles, clay, and other materials. *Thalia dealbata Fraser* and other emergent plants were planted above the cofferdam.

Zoning of aquatic plants

The zoning of aquatic plants was mainly used in the second stabilization pond, which acted as the biological aeration pond (Figure 3).

Aquatic plants can promote species diversity at the ecosystem level and reduce nutrient levels and water turbidity (Vanacker *et al.* 2016). Emergent plants reduce the concentration of nitrogen by ingesting excessive nutrients, particularly

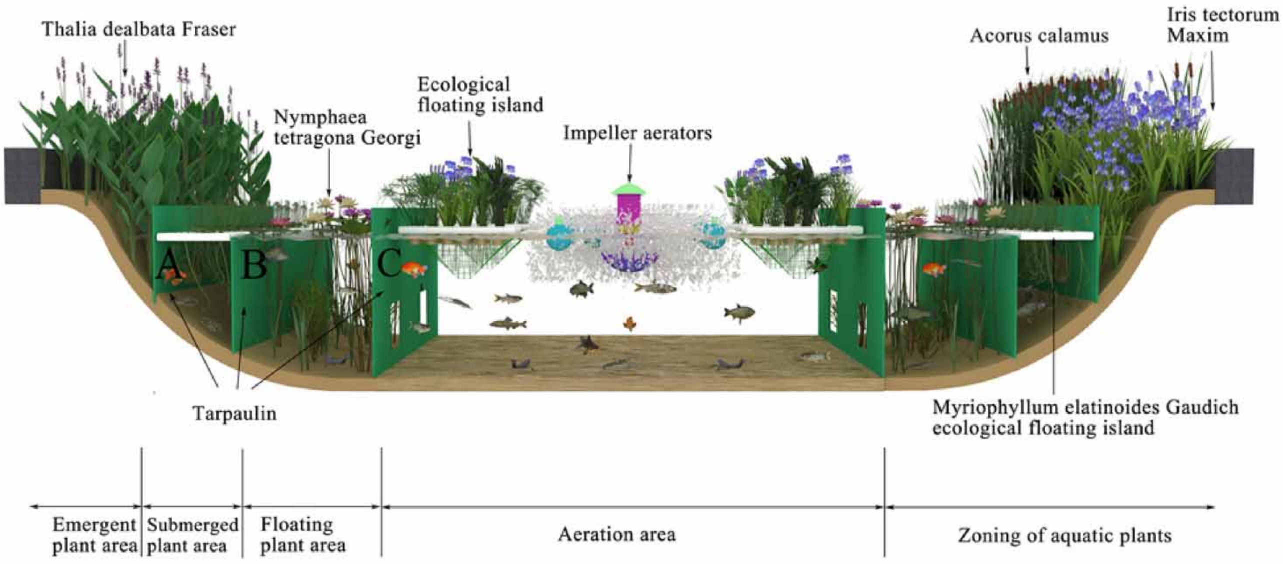


Figure 3 | Schematic diagram of the structure of aerated biological pond.

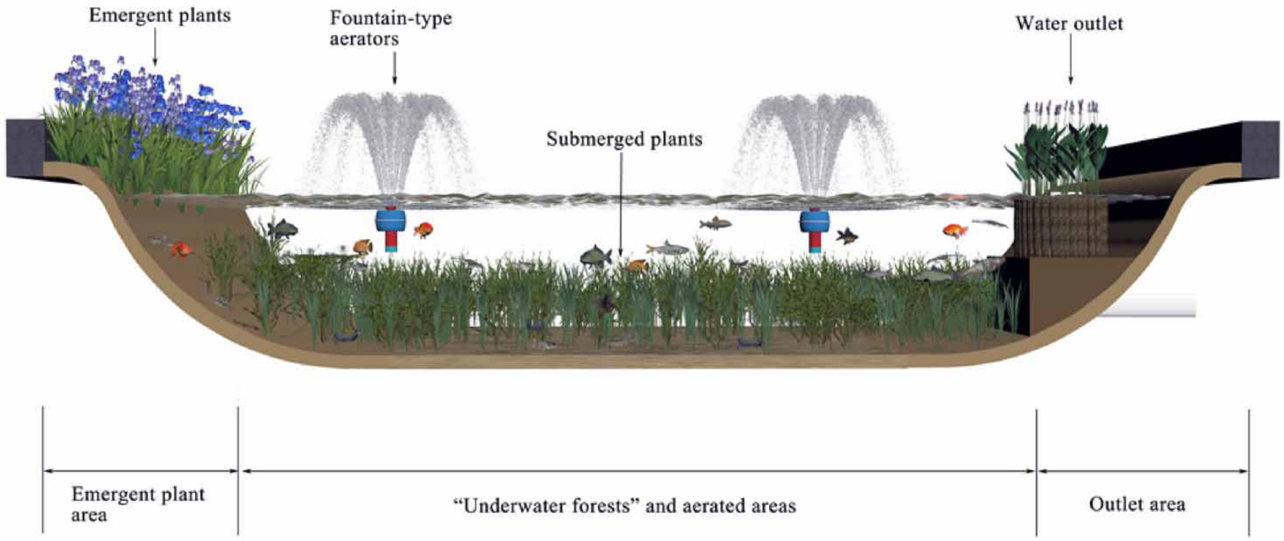


Figure 4 | Schematic diagram of the structure of the submerged plant pond.

through nitrification and denitrification, and can stimulate the activity of microorganisms, thereby improving water quality (Fujibayashi *et al.* 2020). Submerged plants can increase water clarity and prevent sediment resuspension (Wang *et al.* 2017). They also exhibit allelopathy, which involves competition with phytoplankton, and inhibit the growth of phytoplankton (Hilt & Gross 2008). Floating plants are more adaptable than submerged plants and have better ornamental landscape qualities. The integrated treatment of wastewater was carried out in different areas through the combined action of emergent, floating, and submerged plants.

The water depth of the biological aeration pond was approximately 1 m, and three tarpaulins, A, B, and C, were set along one side of the biological aeration pond; the distances from the shore of the three tarpaulins were 5, 15, and 25 m, respectively. The height of tarpaulin A was set to 1.5 m, and two $0.5 \times 0.5\ \text{m}^2$ water outlets were set at the bottom. The height of tarpaulin B was set to 0.7 m, and the treatment method of tarpaulin C was the same as that of tarpaulin A.

In the aerated biological pond, at a depth of 5 m (within tarpaulin A), seedlings of emergent plants *Thalia dealbata Fraser*, *Acorus calamus*, and *Iris tectorum Maxim* were transplanted at a density of 10 plants/m^2. The water body flowed from the connecting pipe of the biological aeration tank and flowed out from the water outlet at the bottom end of tarpaulin (A) to prevent short currents and the wild growth of emergent plants; sewage and the emergent plants were in full contact. The *Myriophyllum elatinoides Gaudich* ecological floating island was placed between tarpaulins (A) and (B). PVC pipes were used to form ten squares (10×2 m^2), the fishing net was fixed as a support layer around the PVC pipes, and nylon ropes were used to connect the PVC pipes to form a 50×4 m^2 floating island. The upper layer of the floating island contained *Myriophyllum elatinoides Gaudich*, at a density of 45 plants/m^2. Tarpaulins (B) and (C) were placed between the submerged plants *Vallisneria natans*, *Myriophyllum elatinoides Gaudich*, and the floating-leaf plant *Nymphaea tetragona Georgi*. The emergent plants, floating-leaf plants, and submerged plants were in complete contact with sewage, and pollutants in the water were removed to a greater extent. The connecting pipe on the other side does the same thing.

Integrated ecological floating islands and artificial aeration

Artificial ecological floating islands are a variant of wetland treatment systems that can be used to purify water (Chang *et al.* 2017). Due to the large area of the fish ponds, two impeller aerators with a voltage of 220 V and a power of 2.2 kW were used to increase the DO concentration in the water after the plant was partitioned (Figure 3). Addition of high-efficiency NH_3-N bacteria and installation of the aerators were done simultaneously. The bacterial strain was isolated from a eutrophic water body and it belonged to the genus *Achromobacter*, which has heterotrophic nitrification and aerobic denitrification capabilities, can efficiently remove NH_3-N from water bodies, and has a strong ability to adapt to the river environment. During the laboratory experiment phase, the strain achieved 88% efficiency in removing NH_3-N. The optimal growth conditions for this strain are pH 7–8, 150–210 r/min, and 25–35 °C. The bacterium has stable physiological properties, strong mechanical strength, and good storage stability. The best dosage of the bacterium was 100 m^3/1–2 kg of domesticated bacterial culture, twice a week (Li *et al.* 2021; Xiao *et al.* 2021). The synergistic effect of artificial aeration and a microbial agent can effectively enhance the anti-pollution ability of the experimental river water ecosystem, improve the self-purification ability of the water body, and thus improve the river water quality. One ecological floating island (3 m × 2 m) was set up on both sides of the aerator, and the emergent water plants *Cyperus alternifolius*, *Pontederia cordata*, and *Iris tectorum Maxim* were planted on the floating island. The bottom of the floating island was surrounded by fishing nets, and volcanic rocks and watermelon-like fillers were placed in the fishing nets to improve water quality. Two fountain-type aerators with a voltage of 220 V and a power of 3 kW were installed in the submerged plant pond (Figure 4). In addition, through combination and collocation, submerged plants, such as *Vallisneria natans*, *Hydrilla verticillata*, and *Myriophyllum elatinoides Gaudich*, were planted underwater to form an ‘underwater forest’. The submerged plants can reduce the nitrogen and phosphorus levels, absorb nutrients, inhibit the growth of algae, provide a living space for aquatic animals, and improve the landscape of the water body.

RESULTS AND DISCUSSION

The project continued for four months, from the start-up stage to stable operation. A sampling point was set at every 200 m in the middle of the Haizai River, with three sampling points. Sampling points in the stabilization pond were set near the outlet of the submerged plant pond. Samples were taken every ten days, and the sampling time was set from 7:00 a.m. to 8:00 a.m. The testing factors included pH, transparency, and DO, COD_{Cr}, NH_3-N, and TP levels. All experimental data were the average of the values from the three points. DO levels and transparency were measured at the experimental site. The samples for the remaining indices were collected at a depth of 30 cm under the surface layer and 2 m from the river against the current, and then sent to the laboratory for immediate testing.

Effectiveness of NH_3-N removal in the water body

Figure 5(b) demonstrates that due to the addition of the sediment modifier, the concentration of NH_3-N in the detection section of the stabilization pond decreased from 7.96 mg/L (original) to 4.23 mg/L, and the removal rate reached 47%. On the 30th day, sewage from the Haizai River was pumped into the stabilization pond through a bypass cycle, resulting in a rapid increase in the concentration of NH_3-N in the stabilization pond. On the 40th day, the NH_3-N removal effect was not apparent, mainly because the aquatic plants need time to adapt to the new environment; the aeration generated by the newly activated aerator resuspended the sediments. After 40 days of operation of the stabilization pond, the concentration of NH_3-N dropped sharply. The main reason could be that the aquatic plants had absorbed NH_3-N in the water for their

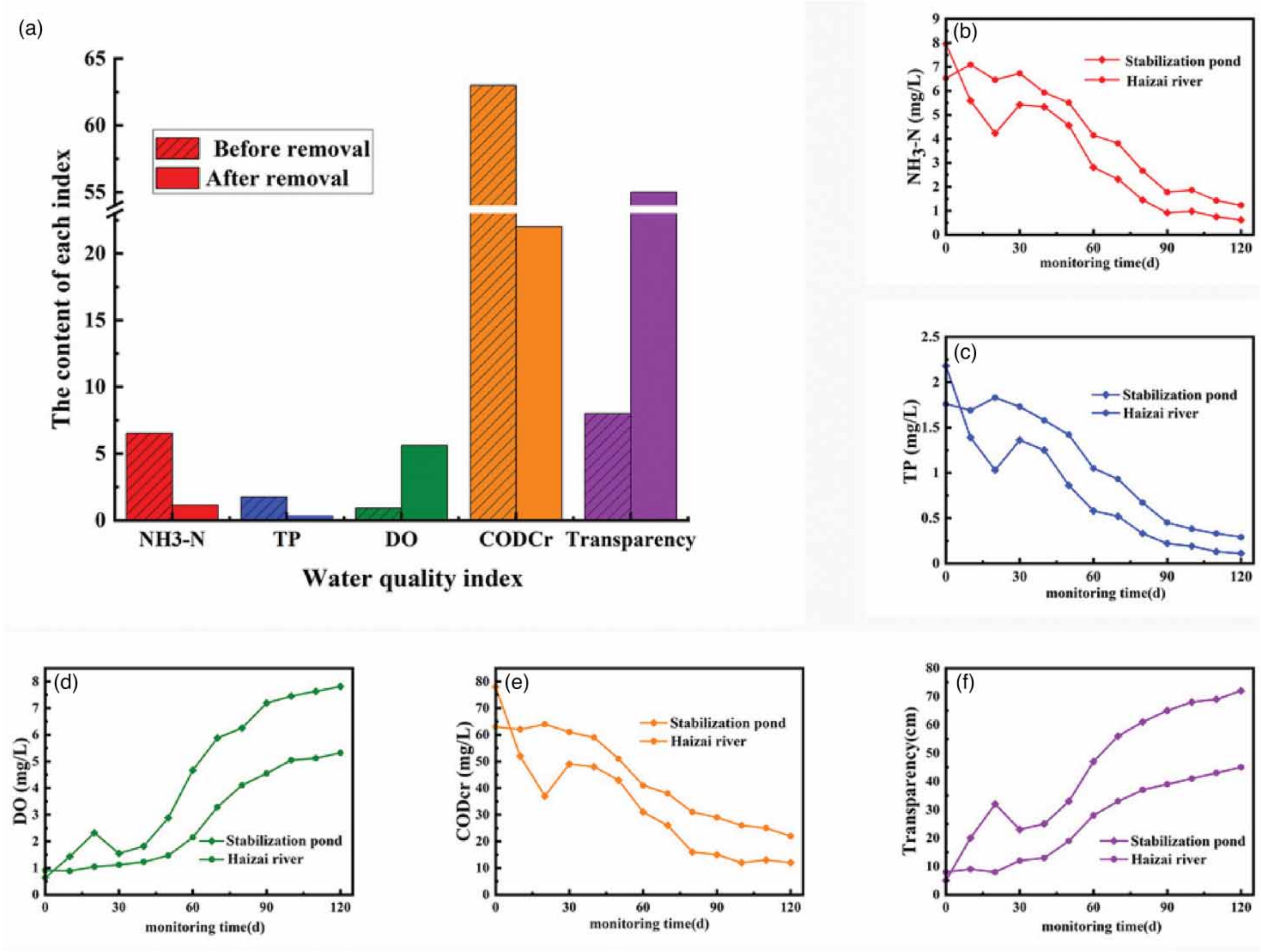


Figure 5 | Changes before and after the indicators of the Haizai River (a); in the Haizai River and the stabilization pond, ammonia nitrogen (NH_3-N, b), total phosphorus (TP, c), dissolved oxygen (DO, d), chemical oxygen demand (COD_{Cr}, e) and transparency (f) changes over time.

growth and development, and the added ammonia nitrogen bacteria successfully developed a film on the ecological floating island, which provided more surfaces for the attachment of microorganisms. Intermittent aeration increased the DO level in the water, which is beneficial for aerobic microorganisms. The proliferation of aquatic plants and microorganisms exhibited the greatest synergy and accelerated the degradation of NH_3-N. On the 90th day, the concentration of NH_3-N stabilized; the average value of NH_3-N in the water body was 1.12 mg/L, and the removal rate was 86%.

The NH_3-N concentration was maintained at a relatively stable state in the first 30 days because the Haizai River water did not pass through the bypass cycle. After the 30th day, the NH_3-N concentration in the Haizai River continued to decrease and finally stabilized due to the decrease of the NH_3-N concentration in the oxidation pond. As shown in Figure 5(a), NH_3-N concentration decreased from 6.53 mg/L (initial) to 1.13 mg/L, and the removal rate reached 83%.

Effectiveness of TP removal in the water body

In the first 30 days, due to the addition of the sediment modifier, the phosphorus content in the oxidation pond drastically reduced from 2.18 mg/L to 1.03 mg/L, and the removal rate reached 53% (Figure 5(c)). The influx of sewage from the Haizai River on the 30th day caused an increase in the TP content in the oxidation pond. The removal of TP was still not apparent on the 40th day, mainly because the aquatic plants require time to adapt to the new environment, and the aeration and agitation generated by the newly activated aerator resuspended the sediments. After 40 days of the experiment, the TP concentration decreased sharply in the stabilization pond, which could be because aquatic plants absorb phosphorus during their growth and development. Simultaneously, the planting of aquatic plants promoted the settlement of phosphorus-containing substances in the stabilized pond and inhibited the resuspension of surface sediments, thereby reducing the phosphorus content of the water body. The increase in the TP removal rate in the later period was constant, mainly because of the lower concentration of inorganic nutrients in the water body in the later period and the absorption ability of the plants reaching a saturation point. On the 90th day, the average TP concentration in the water body was 0.22 mg/L, and the removal rate reached 90%.

After the 30th day, due to the operation of the oxidation pond bypass cycle, the TP content of the Haizai River continued to decrease. As the Haizai River continues to be polluted by external sources, the reduction in TP is slower than that of the oxidation pond and eventually tends to balance. As shown in Figure 5(a), TP concentration reduced from 1.76 mg/L (initial) to 0.29 mg/L, and the removal rate reached 84%.

Changes in DO in the water body

It can be seen from Figure 5(d) that the DO level in the submerged plant ponds increased significantly in the first 20 days, and the DO level of the monitored section increased from 0.64 mg/L to 2.32 mg/L, meeting the Class V requirements of surface water. This was mainly due to the oxygen producer present in the sediment modifier, which strengthens the ability of aerobic microorganisms to degrade pollutants and significantly increases the DO level in the water body. On the 30th day, the sewage from the Haizai River entered the stabilization pond, and the activation of the aerator suspended parts of the pollutants deposited in the bottom sludge. The decomposition process of organic matter in the stabilization pond consumed a large amount of DO, and the oxygen consumption rate was greater than that of reoxygenation, resulting in a decrease in the DO concentration in the stabilization pond. With the maturity of plants, photosynthesis of aquatic plants, and aeration of aerators to increase oxygen levels, the water body gradually restored its self-purification ability. On the 90th day, the DO level in the submerged plant pond increased to 7.19 mg/L. After the 30th day, due to the operation of the stabilizing pond bypass circulation technology, the DO content of the Haizai River continued to rise, as shown in Figure 5(a), from 0.91 mg/L at the beginning to 5.32 mg/L, and was finally maintained at a constant concentration.

Effectiveness of COD_{Cr} removal in the water body

Figure 5(e) exhibits that during the early stage of the stabilization pond, COD_{Cr} level reduced from 78 mg/L to 37 mg/L owing to the addition of sediment modifiers, and the removal rate reached 53%. On the 30th day, sewage from the Haizai River was drained into the stabilization pond, causing the concentration of COD_{Cr} to increase. After the 40th day, the COD_{Cr} level in the stabilization pond began to decrease, mainly because the roots of the plants could increase the attachment area for the microorganisms. Aeration is beneficial for the growth and reproduction of aerobic microorganisms in water, and it accelerates the decomposition of organic matter by the microorganisms. In the later period, the rhizomes of the aquatic plants were more developed, and the removal rate showed a trend of slow decline at first, then rapid decline, and finally became constant. On the 90th day, the COD_{Cr} level in the oxidation pond was reduced to 15 mg/L, and the removal rate reached 81%. The COD_{Cr} content in the Haizai River decreased after the 30th day due to the operation of the stabilization pond bypass cycle. As external sources continuously pollute the Haizai River, the reduction of COD_{Cr} is slower than that of the oxidation ponds; as shown in Figure 5(a), it reduced from 63 mg/L to 22 mg/L at the beginning, and the removal rate reached 65%.

Changes in transparency of the water body

As shown in Figure 5(f), the transparency of the submerged plant pond during the first 20 days was significantly improved. The transparency of the monitored section increased from 5 to 39 cm, and the rate of increase was 680%, mainly because of the highly efficient flocculant present in the sediment modifier, which flocculated with the suspended particles in the water body to form flocs. After the flocs gathered to obtain a particular volume, they settled out of the water phase due to gravity. On the 30th day, the Haizai River water body began to flow into the stabilization pond, and the aerator began to aerate. Because of the disturbance due to aeration, the covering layer formed at the mud-water interface was destroyed and some unrepaired sediments floated up, increasing the concentration of the suspended particles in the water body and decreasing water transparency. With the stable operation of the aerator, the DO content continued to increase, which promoted the growth and reproduction of microorganisms and enhanced the self-purification ability of the water body. The concentration of suspended particles in the water body gradually decreased, and water transparency steadily increased. On the 90th day, the transparency of the submerged plant pond increased to 65 cm. After the 30th day, due to the stable pond bypass circulation technology, the transparency content of the Haizai River continued to increase (Figure 5(a)), from 8 cm at the beginning to 45 cm, and finally became constant.

Figure 6 | Comparison of river water restoration. Left: Before restoration (eutrophication); Middle: After restoration (Class V); Right: Submerged plant pond outlet.

CONCLUSIONS

In this study, based on the bypass circulation technology, the eutrophic portion of the Haizai River was passed through a facultative pond, an aerated biological pond, and a submerged plant pond in that sequence, and the contaminated river section was treated ex-situ. After four months of treatment, the NH_3-N, TP, and COD_{Cr} levels in the original sewage of the Haizai River decreased to 1.13 mg/L, 0.29 mg/L, and 22 mg/L, respectively. The water quality of the Haizai River significantly improved, i.e., the self-purification capacity and the transparency of the water body also improved, and the concentrations of pollutants such as NH_3-N and TP decreased. The quality of the river water was upgraded from an inferior Class V water body to a Class V water body, achieving the project's governance goals. A comparison of river restoration is shown in Figure 6. The results show that the bypass stabilization pond process can achieve a stepwise reduction of nutrients levels through an optimal combination of ponds, which is conducive for a stable degradation process and improves the pollutant treatment efficiency of conventional stabilization ponds. The combined technology is practical, effective, stable, strong in operability, cost-effective, and causes low levels of secondary pollution. It provides a reference for the ex-situ treatment of eutrophic water bodies in other cities. However, difficult operational management and maintenance of aquatic plants continues to be an issue with this process, which is similar to that in the case of traditional stabilization ponds. Therefore, it is necessary to reinforce or prune fallen plants in time, replant damaged plants, and strengthen monitoring and maintenance to ensure that the efficient operation of the pond purification system is stabilized.

In this study, we used a bypass stabilization pond system to establish an experimental model to explore the remediation technology for urban eutrophic water bodies. However, owing to the limitations of field and experimental conditions, the following aspects should be investigated in future studies: (1) the microbial community structure of the bypass stabilization pool system and (2) the effect of the combined action of artificial aeration and microbial agents on water body remediation.

DATA AVAILABILITY STATEMENT

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

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First received 21 January 2022; accepted in revised form 6 April 2022. Available online 18 April 2022