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Application of the technology of water lifting and aeration on improving water quality in a Deep Canyon Reservoir – a case study from northern China

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ABSTRACT

The technology of water-lifting and aeration can be widely applied in water aeration, algal inhibition, and endogenous pollution control. The Jin-Pen reservoir has been undergoing increasing water pollution in the past few years. To solve this problem, the water-lifting aerator system was installed here in the summer of 2010, and its improving effect on water quality was investigated. The results showed that under the mixing and aeration conditions, the thermal stratification structure was disturbed but not destroyed. The vertical water temperature difference was reduced by 3–5℃, and the surface temperature fell at 2.1–3.6℃. The seasonal aerobic state was withheld at the bottom of the reservoir, and the concentration of DO was maintained above 2 mg/L at the sediment surface. The decay rate of DO in the hypolimnion decreased by 51.2 and 49.6%, respectively, compared to the same period in 2008 and 2009. The concentrations of TP and NH_3-N in the overlying water on the sediment surface decreased to 0.12 and 0.25 mg/L, respectively. The algal abundance in the surface water was reduced by more than 75–80%. However, the present cost of water improvement considering the current water supply capacity (80×10^4 m^3) was only 0.004 Yuan RMB/m^3.

Keywords: Aeration; Algal control; Water-lifting aerator; Water quality

1. Introduction

Eutrophication of lakes and water pollution have brought about serious problems in recent years for the water supply as well as for aquatic ecosystems, which causes the generation of toxic algae and deoxygenation of water, being harmful to other organisms and destroying the ecological balance. To combat the deoxygenation of water, artificial aeration is commonly used. Hypolimnetic aeration and destratification, or artificial circulation, are the two primary methods of artificial aeration. Hypolimnetic aeration involves oxygenation of the hypolimnion without disturbing the thermal density gradient associated with stratification [1]. The goal of artificial circulation is either to prevent a water body from stratifying or to mix an already stratified one by introducing sufficient energy to disrupt the thermal gradient. Various methods have been developed to achieve hypolimnetic aeration. The methods can be grouped into three different categories: mechanical agitation, oxygen injection, and air injection [2]; and different kinds of technologies for the restoration of water quality were specifically applied in different situations: the blue algae's

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multiplication restrained by the air bubble plume in the Nieuwe Meer Lake in Holland [3] and the reduced amount of plankton microorganisms in Hanningfield Reservoir in Britain [4]; the controlling of the phytoplankton's growth by the hydraulic gun approach in Daechung Lake in Korea [5]; the full-lift hypolimnetic aerator used in Prince Lake and Western Lake in America [6]; and the partial-lift hypolimnetic aerator happlied in Tagel Lake in Berlin [7].

The Jin-Pen reservoir is located in the City of Xi'an, Shaanxi Province, China, and it is the most important raw water source for the City with a daily water supply of 8.0×10^5 m^3. The storage capacity of the Jin-Pen reservoir is 2.0×10^8 m^3 with an area of 1,481 km^2. In recent years, the environmental problem aroused by eutrophication has become severe, including the periodically exceeded ammonia-nitrogen and phosphorus nutrient concentrations, which certainly causes the increasing content of organic matter and algae, leading to an acute water quality problem considering that the urban drinking water is mainly supplied by this reservoir. According to the Chinese national drinking water standard, a large amount of chlorine had to be added into the treated water which results in lots of complaints from consumers. After a series of investigations, the current water quality problem is essentially due to seasonal anoxic condition at the bottom of the reservoir.

The water-lifting and aeration technology developed by our team as a new patented technology for *in situ* restoration of water quality has been applied successfully with the improvement of water quality in emergency cases [8]. However, the Jin-Pen reservoir is characterized by a large depth, fast oxygen consumption, and stable thermal stratification, which put forward higher and stricter requirements. Most of the studies were focused on the non-stratified or weakly stratified water with a small water depth, but little is known about the effectiveness of these technologies in the lake or reservoir with a large depth and strong stratification. This paper describes the practical applications of the water-lifting and aeration technology in reservoirs with great depth (>70 m) and strong stratification, which has proved to be efficient for controlling the pollution sources and algae growth. The results could be used as a scientific basis and reference in order to optimize the restoration technologies of water quality.

2. Materials and methods

2.1. Water-lifting aerator

Two solutions are usually recommended to the anoxic condition in lower-layer water due to stratification. One is to overcome the water stratification by mixing the water of different layers. The other is to directly oxygenate the deep layer water. The former method requires equipment such as the air bubble plume and hydraulic gun. Using perforated air pipes installed on the reservoir bottom, the air bubble plume releasing from the perforations can mix the upper and lower water layers. The second method requires the hypolimnetic aerator that can directly oxygenate the deep-layer water.

The function core of technology of water-lifting and aeration calls a water-lifting aerator (Fig. 1), which consists of an anchor pier (1), air-releasing tube (2), aeration chamber (3), air vessel (5), return chamber (4), water-sealed board (10), telescopic cylinder (9), watertight compartment (8), and air supply pipe (11).

The technical property requirements and structure design scheme of this device have been introduced in previous papers [8]. Modified from the hydraulic gun, the new device called a water-lifting aerator has been developed to improve the water quality of deepwater lakes and large reservoirs. The addition of an aeration chamber enhances the oxygen transfer efficiency by increasing the contact time of bubble/water, while the aerated water is pushed to the lower water through the return chamber. The sliding tube can automatically float to adjust with the water depth. Hence, the water is oxygenated by the circulating flow and direct aeration produced by the water-lifting aerator using the aeration chamber. The circulating flow can promote the diffusion of dissolved oxygen from the superficial water to the bottom water, which destroys the water stratification and increases the dissolved oxygen concentration in the lower-layer water. Moreover, the algae can be carried to the lower layer by the circulating flow. Their growth will be restrained, when they reach the sunlight-deficient bottom. More efficient, the lower-layer water is directly oxygenated with the help of aeration chamber. Part 3 will be sacrificed to simulate and testify the performance of direct oxygenation.

2.2. The water-lifting and aeration system in the Jin-Pen reservoir

The *in situ* restoration of water quality in the Jin-Pen reservoir is composed of water-lifting aerators, air compressor system, and pipeline system. Eight water-lifting aerators are deployed separately in the area within 1.1 km from the dam of the reservoir, and there is 250–300 m spacing between the adjacent aerators. Fig. 2 shows the deployment map.

The air compressor, which forces the filtered air to the water-lifting aerator, sits on the bank, connected with each water-lifting aerator with an air supply pipeline made of stainless steel for the part onshore and polyethylene for the part underwater. The water-

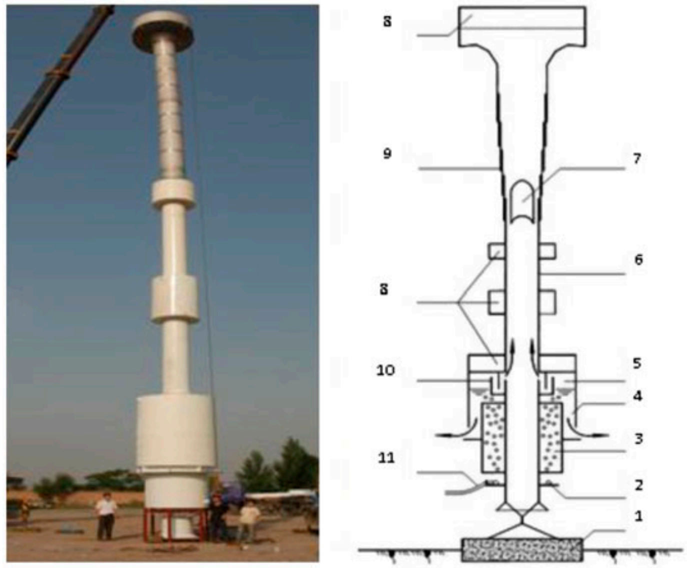

Fig. 1. Schematic diagram of the water-lifting aerator. (1) anchor pier; (2) air-releasing tube; (3) aeration chamber; (4) return chamber; (5) air vessel; (6) ascending cylinder; (7) air piston; (8) watertight compartment; (9) telescopic cylinder; (10) water-sealed board; (11) air supply pipe.

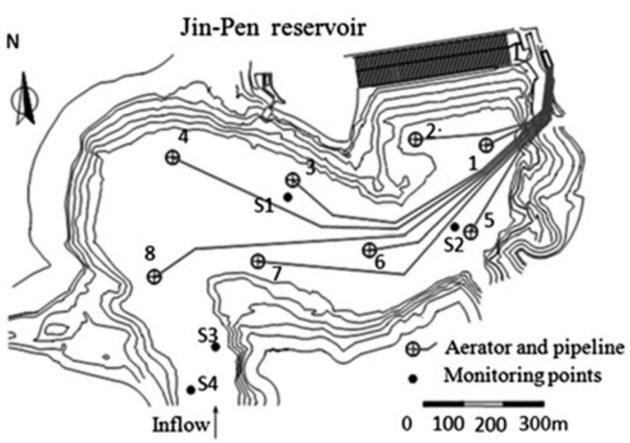

Fig. 2. Arrangement of the water-lifting aerators in the Jin-Pen reservoir.

lifting aerators began partial operation from June to December every year. The supplied rate of each water-lifting aerator is 20–30 m^3/h with a supply pressure of 0.7–1 MPa. The rate of circulating water flow produced by the water-lifting aerators is 4.5×10^4 $m^3\,d^{-1}$.

2.3. *Simulation of the oxygen transfer in the water-lifting aerator*

Many studies of the similar aerators have focused on water quality and stratification, and several researchers have attempted to testify the performance of aerators through by studying the air bubble kinetics and the oxygen transfer model in different kinds of aerators [1,9–11]. A relatively simple model was developed here to predict the increase in the dissolved oxygen concentration produced by the water-lifting aerator. Concurrent flow of water and gas, variation of the saturated dissolved oxygen concentration as a function of depth, and depletion of gaseous oxygen are accounted for in the model.

To determine the amount of oxygen transferred from the gas phase to the liquid phase, a mass balance was performed on water flowing in the riser (Fig. 3):

$$\frac{dC}{dz} = \frac{K_L a}{U_L}(C^* - C) \tag{1}$$

where C is the bulk dissolved oxygen concentration ($mg\,L^{-1}$); z is the distance from the bottom of aeration chamber (m); $K_L a$ is the volumetric mass transfer coefficient; C^* is the saturated aqueous oxygen concentration at the air–water interface. To calculate water flow rate, the following equation is used:

$$U_L = 0.7(U_G)^{0.53}(L)^{0.56} \tag{2}$$

where U_L is the superficial liquid velocity in aeration chamber ($m\,s^{-1}$); U_G is the superficial gas velocity in

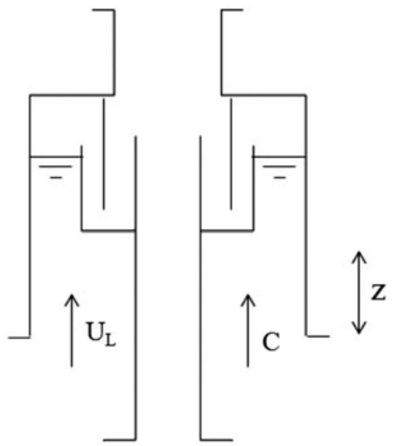

Fig. 3. Calculation diagram for the simulation of oxygen transport.

the aeration chamber ($m\,s^{-1}$); and L is the length of the aeration chamber (m).

To calculate the saturated aqueous oxygen concentration in equilibrium with the bubbles at any depth, the following formula is used:

$$C^* = MYP = MY\left[1.01325 \times 10^5 + \frac{\rho_L g(H-z)}{1.01325 \times 10^5}\right] \quad (3)$$

where Y is the mole fraction of oxygen, M is a Henry's Law constant, ρ_L is density of the liquid (kg/m^3), g is the acceleration of gravity (m/s^2), H is the distance between bottom of aeration chamber and water surface (m), and P is pressure of bubbles (Pa). The volumetric mass transfer coefficient must be known to solve the bulk dissolved oxygen concentration [12]. Little [10] used a set of four correlation equations from the literature to obtain an estimate of the mass transfer coefficient which is actually a function of gas superficial velocity U_g.

In order to validate the model, the aerator was used and running in a Plexiglas cylindrical tank with a diameter of 450 mm and a height of 4.5 m, after the dissolved oxygen concentration adjusted to zero with Na_2SO_3. The dissolved oxygen concentration was monitored with the passage of time. Three different gas velocities were used and the results were compared with the ones calculated by the model as shown in Fig. 4.

The results show that the measured and calculated values are in good agreement for three different gas velocities. When the dissolved oxygen concentration is high, the measured values are underestimated compared to the calculated ones because of the excessive Na_2SO_3 dissolved in the water, which consumes the dissolved oxygen and makes the measurements lower.

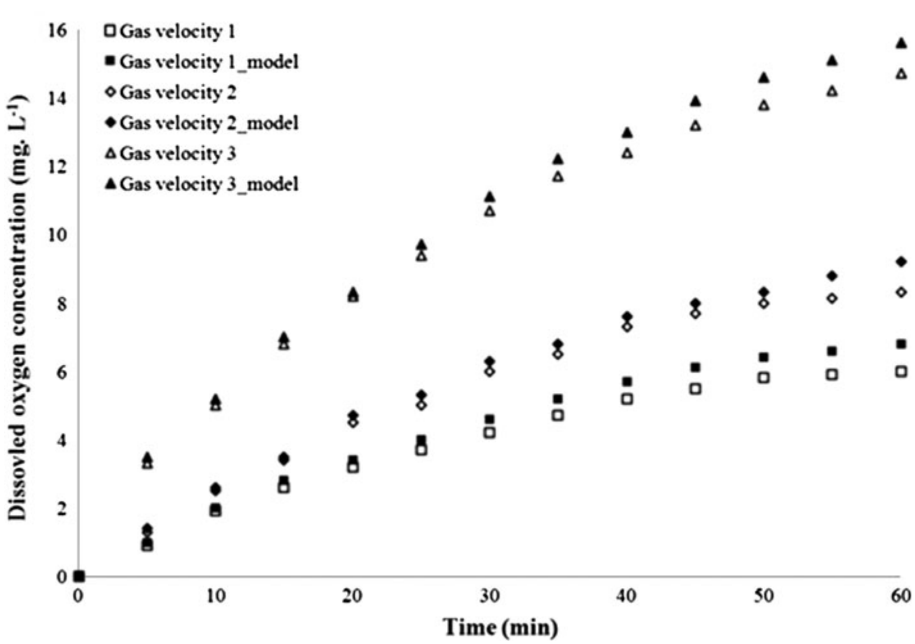

Fig. 4. Comparison between the actual dissolved oxygen concentrations and simulated values with three different gas velocity (gas velocity 1 < gas velocity 2 < gas velocity 3).

3. Results and discussion

Two sorts of data were collected to evaluate the water quality improved by the water-lifting aerator. One is the water quality distribution at monitoring point S1, 20 m from the 3# water-lifting aerator (which is a typical aerator selected for investigating the effect of water quality improvement around water-lifting aerator, the location of 3# aerator is shown in Fig. 2); the other is the water quality distribution over the whole deepwater area: S2 (20 m from the 5# water-lifting aerator); S3 (200 m from the 8# water-lifting aerator); S4 (400 m from the 8# water-lifting aerator). The tests of dissolved oxygen and chlorophyll-*a* took place on site using Multifunctional Water Quality Analyzer (HACH Hydro-Lab DS5), while the ammonia-nitrogen, phosphorus, and COD test were done in the laboratory with samplings by the chemical experiment.

3.1. Water quality improvement at monitoring point S1-the distribution of dissolved oxygen around the water-lifting aerator

Affected by the water stratification, the distribution of dissolved oxygen changed significantly (Fig. 5). During the synthermol mixed period (January to early March), the structure of stratification disappears, the entire reservoir stays in the aerobic condition, the water quality tends to be uniform. From mid-March, stratification pattern of dissolved oxygen gradually emerges. In June, the vertical water exchange is severely limited by the stable stratification structure. The oxygen consumed cannot be compensated, and the dissolved oxygen began to decrease rapidly. As shown in the Figs. 5(a) and (b), during the period from June to December in 2008 and 2009, the concentration of dissolved oxygen at the investigating point S1 decreased rapidly with the increasing water depth and the average variation gradient at the fracture surface reaches 0.06–0.12 mg/L m.

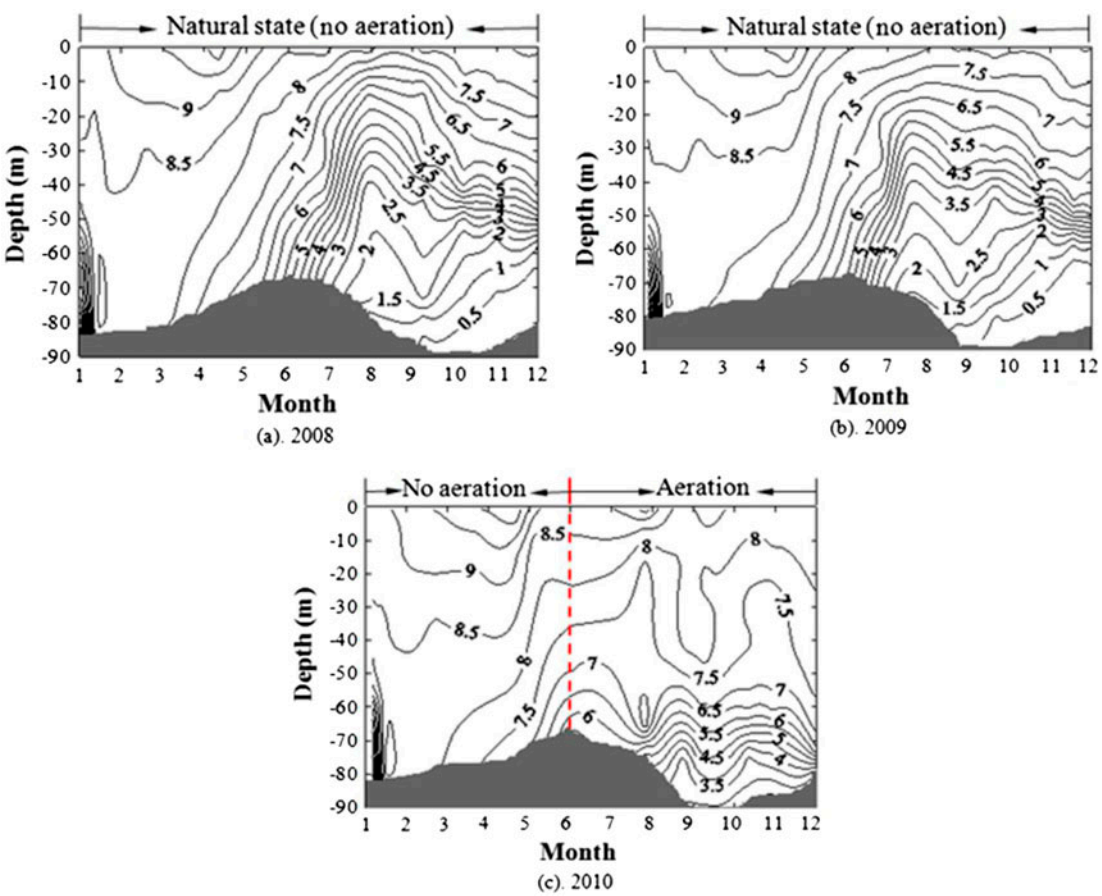

Fig. 5. Vertical dissolved oxygen distribution in the Jin-Pen reservoir from 2008–2010.

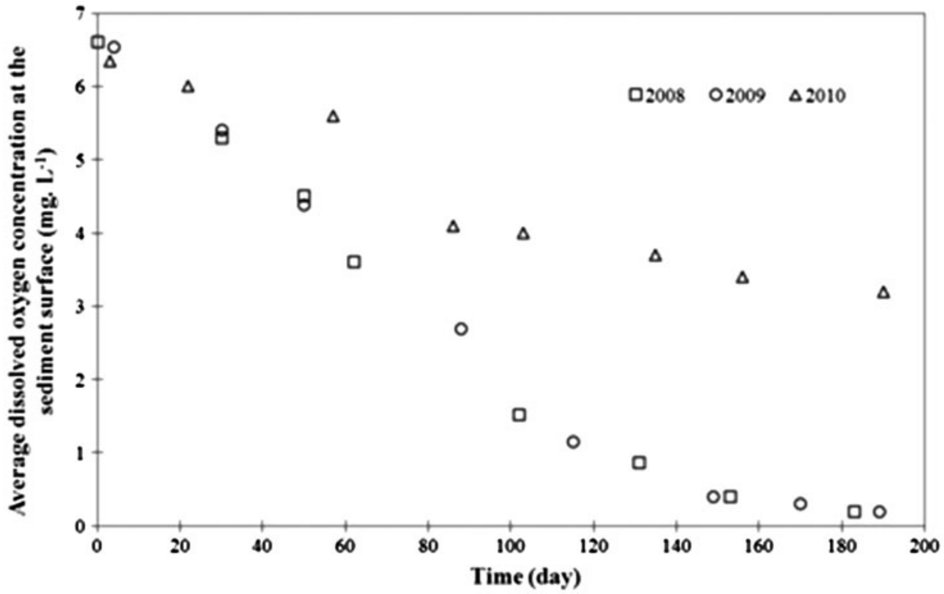

Fig. 6. Variance of dissolved oxygen concentrations at the sediment surface from 2008–2010.

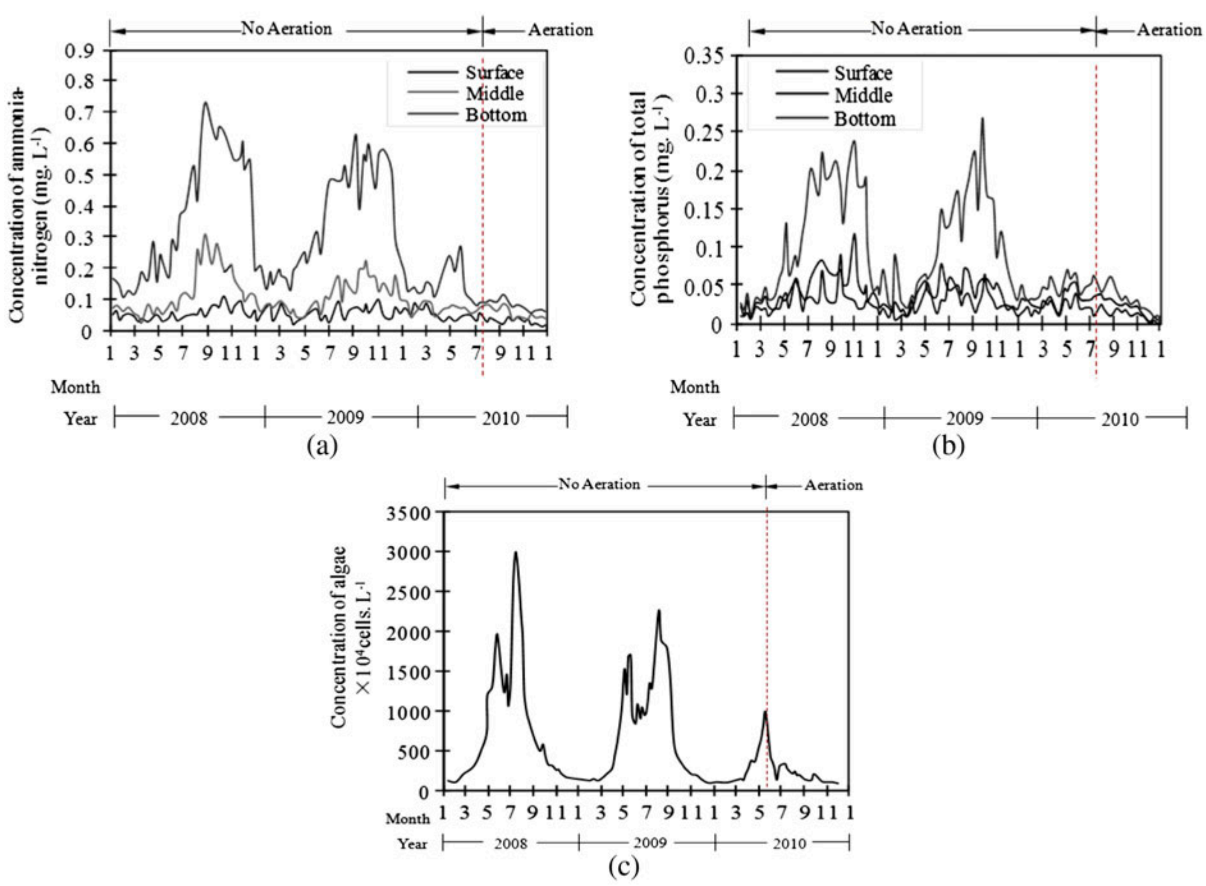

Fig. 7. Concentration variance of ammonia-nitrogen (a); total phosphorus (b); and algae (c) at different depths from 2008–2010.

The concentration of dissolved oxygen at the sediment surface decreased from 5 to 6 mg/L in June to around 2 mg/L in the middle of July, achieving the anoxic condition (Fig. 6).

After September, the dissolved oxygen concentrations continued to decline, and the entire bottom of the reservoir became anaerobic. Since the water-lifting aerators were put into operation, the vertical dissolved oxygen concentration improved significantly over the same period of 2008 and 2009 (Fig. 5(c)). With the depth range from 0 to 50 m, the dissolved oxygen concentration decreased slowly and kept relatively stable above 7 mg/L; with a water depth larger than 50 m, the dissolved oxygen concentrations stay around 2.5 mg/L without attaining the anoxic or anaerobic concentration.

The ammonia-nitrogen and phosphorus concentrations around the water-lifting aerator at three different depths from 2008 to 2010 are shown in Figs. 7(a) and (b).

The results indicate that, during the synthermol mixed period of 2008 and 2009, the release of pollutants from the sediment surface remains shortly stagnant, and the homogeneity of ammonia-nitrogen and phosphorus concentrations in different layers is observed. After the thermo-stratification, the concentrations of ammonia-nitrogen and phosphorus augment with increasingly severe anoxic and anaerobic conditions, extending toward the upper layers until attaining the maximum concentrations up to 0.24–0.27 and 0.63–0.73 mg/L, respectively. As the water-lifting aerator operating in 2010, the total phosphorus and ammonia-nitrogen concentrations in the lower layer decreased remarkably and stayed stable at around 0.01–0.06 and 0.05–0.12 mg/L, which indicates that the release of the phosphorus and ammonia-nitrogen from the sediment was restrained by the operation of the water-lifting aerator and that the water mixing made the phosphorus and ammonia-nitrogen concentrations in the upper and lower water layers homogeneous.

Anaerobic condition is the determining factor for the release of ammonia-nitrogen and phosphorus from the sediment. But up to now, little is known about the critical value f dissolved oxygen to trigger the massive release of these pollutants. According to Cong et al. [8], the nitrification is inhibited and begins to accumulate, when the concentration of dissolved oxygen is below 2 mg/L. The phosphorus

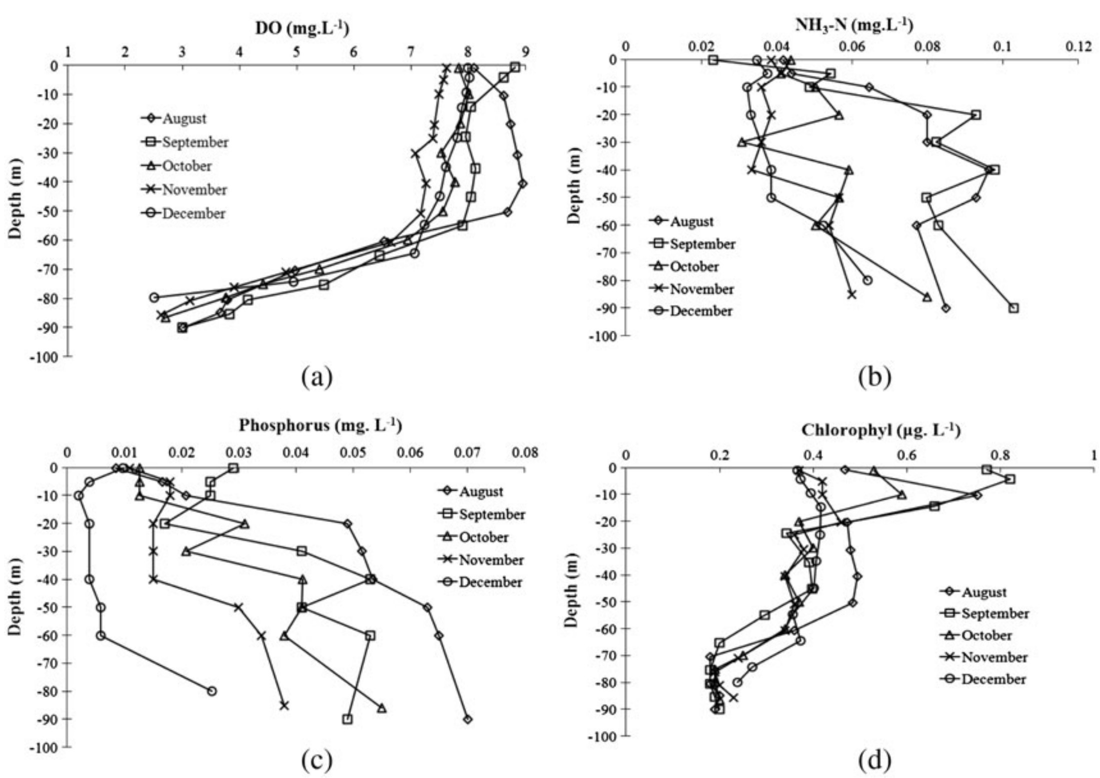

Fig. 8. Vertical water quality variance of monitoring point S1 from August 2010–December 2010. (a) dissolved oxygen; (b) ammonia-nitrogen; (c) phosphorus; (d) chlorophyll-*a*.

begins to release when the concentration of dissolved oxygen is below 1 mg/L in acidic and neutral conditions or 2 mg/L in alkaline conditions. Based on this theory, the dissolved oxygen concentration should be kept below 2 mg/L to control and restrict the release of phosphorus and ammonia-nitrogen from the sediment. As shown in Figs. 5–7, the water-lifting aeration enhanced effectively the dissolved oxygen concentration level of the sediment–water interface in the reservoir (DO > 2.5 mg/L) in order to prevent the high-loaded pollution problems caused by the seasonal anoxic environment in the reservoir.

Eutrophication causes the generation of toxic algae which, in addition to causing the deoxygenation of water, is harmful to other organisms and destroys the ecological balance. The variance of concentration and community composition indicates and affects directly the dynamics of the reservoir water quality.

Fig. 7(c) shows that during the period of 2008 and 2009 the seasonal variance in quantity and composition of algae showed a typical "saddle-type" distribution. For the first peak in spring, the diatom species dominate with a concentration greater than 10×10^6 cells/L. After the second peak in summer, the proportion of blue-green algae rises rapidly and becomes the dominant population with a concentration of 22–30 $\times$ 10^6 cells/L. However, after the aeration in 2010, the quantity of algae reduces substantially compared with previous years ($<4.5 \times 10^6$ cells/L) and continues to decline with the system running. This inhibitory effect is caused by multiple or combined mechanisms: (1) The mixing caused by the vertical circulation has an influence on the light climate of the algae by carrying large amounts of algae to the lower layer and decreasing the proportion of the population residing in the euphotic zone, reducing the effect of photosynthesis. (2) The destratification carries the bottom sediment to the top, which decreasing the relative availability of light. (3) The formation of the mixed layer decreases the surface temperature, reducing the phytoplankton activities. (4) At the same time, the aeration inhibits the sediments from releasing the organic pollutants, especially the content of phosphorus, reducing the nutrient supply for the algae.

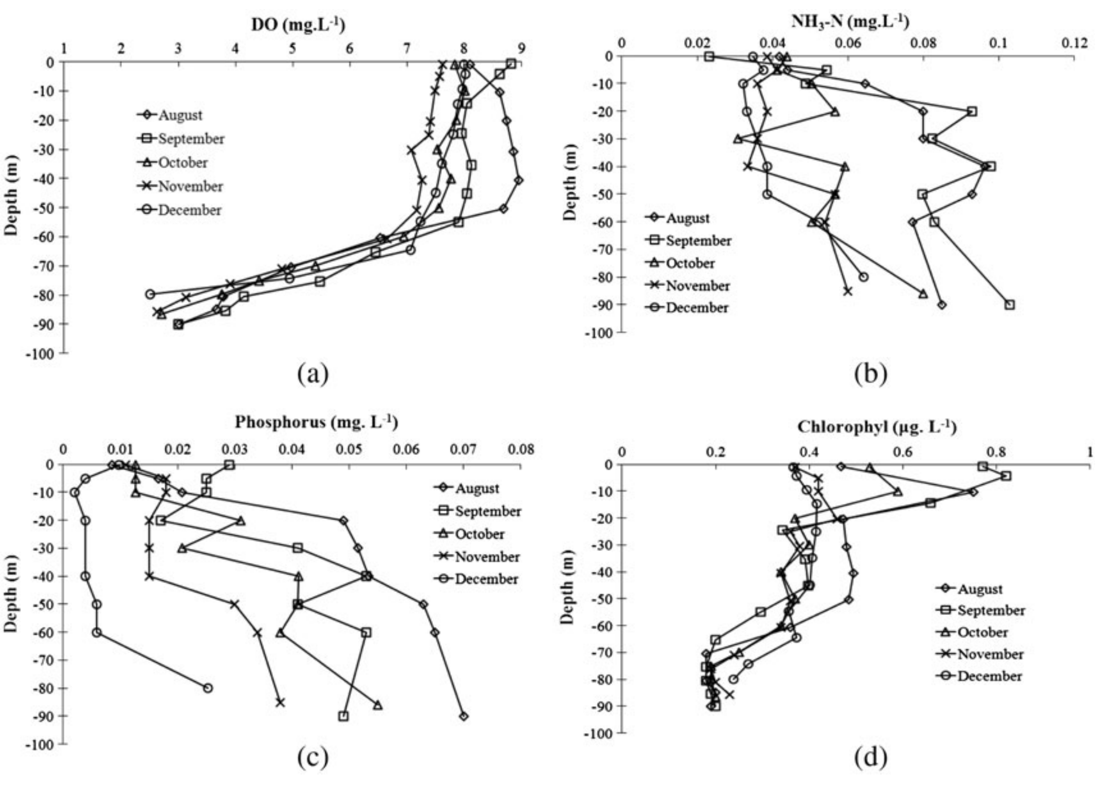

Fig. 9. Comparison of vertical water quality in November between monitoring points S1 and S4. (a) dissolved oxygen; (b) ammonia-nitrogen; (c) phosphorus; (d) chlorophyll-*a*.

Table 1
Water quality variance at the outlet of the Jin-Pen reservoir

Water quality index	Months	Reduction level of the water pollutants						
					Reduction (%)		Average reduction (%)	
		2008	2009	2010	Compared to 2008	Compared to 2009	Compared to 2008	Compared to 2009
Total phosphorus (mg/L)	July	0.06–0.07	0.06–0.08	0.04–0.05	30.8	35.7	46.7	47.2
	August	0.07–0.08	0.06–0.07	0.03–0.04	53.3	46.2		
	September	0.06–0.07	0.05–0.06	0.03–0.04	46.2	36.4		
	October	0.04–0.05	0.05–0.06	0.02–0.04	33.3	45.5		
	November	0.04–0.05	0.03–0.05	0.01–0.02	66.7	62.5		
	December	0.02–0.04	0.03–0.04	0.01–0.02	50	57.1		
Ammonia-nitrogen (mg/L)	July	0.11–0.16	0.1–0.18	0.05–0.07	55.6	57.1	69.5	67.1
	August	0.20–0.25	0.11–0.17	0.06–0.08	68.9	50		
	September	0.24–0.26	0.18–0.25	0.07–0.09	68.0	62.8		
	October	0.18–0.25	0.2–0.23	0.03–0.06	79.5	79.1		
	November	0.14–0.16	0.17–0.19	0.04–0.05	70	75		
	December	0.10–0.14	0.12–0.16	0.02–0.04	75	78.6		
COD_{Mn} (mg/L)	July	4.12–4.36	4.78–5.01	3.22–3.54	20.3	30.9	22.4	25.8
	August	4.14–4.78	4.23–4.89	3.43–3.67	20.4	22.1		
	September	4.82–5.26	4.86–5.14	3.72–3.94	24.0	23.4		
	October	4.12–4.35	4.08–4.53	3.39–3.54	18.2	19.5		
	November	3.78–4.00	3.93–4.02	2.65–3.33	23.1	24.8		
	December	3.14–3.72	3.58–3.87	2.34–2.58	28.3	34		
Chlorophyll (μg/L)	July	0.88–1.02	0.91–1.05	0.32–0.38	63.2	64.3	53.6	56
	August	1.09–1.28	1.11–1.32	0.40–0.53	60.8	61.7		
	September	0.86–1.05	0.91–1.08	0.44–0.47	52.4	54.3		
	October	0.74–0.82	0.83–0.96	0.37–0.44	48.1	54.7		
	November	0.65–0.72	0.71–0.76	0.34–0.36	48.9	52.4		
	December	0.55–0.65	0.52–0.68	0.28–0.34	48.3	48.3		

3.2. Water quality improvement of different regions in the Jin-Pen reservoir

The data of monitoring point S1 were taken as an example to demonstrate the results which show that, from August to December 2010, the water quality near the monitoring points was significantly improved compared to that in 2008 and 2009: The dissolved oxygen concentration at the sediment surface was maintained above 2 mg/L, and the concentrations of pollutants (ammonia-nitrogen, phosphorus, and algae) reduced as well in varying degrees (Fig. 8).

The changes in water quality distribution are consistent for monitoring points S1 and S2 because of the same distance from the aerator (20 m): The dissolved oxygen concentration at the sediment surface is between 2.5 and3.3 mg/L, while the concentrations of total phosphorus, ammonia-nitrogen, and chlorophyll-*a* are around 0.02–0.08, 0.06–0.12 and 0.8 μg/L, respectively. In contrast, the monitoring points S3 and S4 are less affected because of longer distances from the aerators: the dissolved oxygen concentration at the sediment surface was kept between 2.1–2.5 mg/L, while the concentration fluctuations of total phosphorus, ammonia-nitrogen, and chlorophyll-*a* are, respectively, 0.05–0.12, 0.08–0.25, and 0.6–3 μg/L. The comparisons of vertical water quality in November at monitoring points S1 and S4 are shown in Fig. 9. A much better effect observed in monitoring point S1 is clearly shown. Therefore, the closer the monitoring point is to the aerators, the better the effect of aeration is, leading to a faster reduction in pollutants concentrations and a better improvement of water quality.

3.3. Water quality improvement at the outlet of reservoir

In order to investigate the improvement of water quality during the operation of water-lifter aeration, the water quality at the reservoir outlet was continually monitored for 6 months from 1 July 2010. According to legislative norms in China, the maximal allowed concentrations of total phosphorus, total nitrogen, ammonia-nitrogen, and COD_{Mn} are 0.05, 1.0, 1.0, and 6.0 mg/L, respectively. The results are reported in Table 1, which shows that the improvement is obvious, hypolimnetic aeration can control the pollutants released from the sediment in the drinking water reservoir, in 2010, COD_{Mn} is 3.22–3.54 mg/L, lower than that of 2008 is 4.12–4.36 mg/L. The total phosphorus, ammonia-nitrogen and COD_{Mn} concentration are maintained lower than 0.05, 0.1, and 4.0 mg/L which are remarkable reduced by 47.3, 68.7, and 24.2% as compared to the same period during 2008 and 2009, which accords with the Chinese national surface water quality standard (GB3838-2002) type III, I, and II, respectively, as well as a significant reduction in chlorophyll-*a* concentrations by 53.6%.

4. Conclusions

The water-lifting aerator is able to directly oxygenate the deep-layer water, and the seasonal anoxic and anaerobic conditions are restrained. The dissolved oxygen concentration at the sediment surface was kept above 2 mg/L. The aeration is more efficient when the monitoring points are located closer to the aerators (>2.5 mg/L, with a radius of 20 m from aerator). Besides, the ammonia-nitrogen and total phosphorus concentrations at sediment surface decline obviously as compared to the same period in 2008 and reduced to 0.12 and 0.25 mg/L. During the operation of water-lifter aeration, the total phosphorus, ammonia-nitrogen, COD, and chlorophyll-*a* concentrations from the water at the outlet of reservoir were reduced by 47.3, 68.7, 24.2, and 54.8% at the outlet of reservoir compared to the same period during 2008 and 2009, corresponding to the Chinese national surface water quality standard Type III, I, and II, respectively, for the content of phosphorus, ammonia-nitrogen, and COD. The improvement of water quality in the reservoir is quite obvious considering the depth of the Jin-Pen reservoir. The successful application for the water quality improvement in the Jin-Pen reservoir during the initial running of water-lifting aeration system testifies the feasibility and effectiveness of this technology in *in situ* restoration of water quality in reservoirs with great depth, which could also be used in other lakes and reservoirs.

Acknowledgements

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