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In-Situ Water Quality Improvement by Hypolimnion Oxygenation and Artificially Induced Mixing in a Drinking Water Reservoir

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ABSTRACT

Faced with the problems of hypolimnion dissolved oxygen (DO) depletion and water quality deterioration, a newly designed water quality improvement technology named water-lifting aerators (WLAs) was put into utilization to solve these problems in Jinpen Reservoir. During the hypolimnion oxygenation period, after 20 days operation of 8 WLAs with compressed air volume of 10 m^3/h, the thickness of anaerobic layer was compressed from 17 m to 3.2 m. As for artificially induced mixing, after 18 days operation of 8 WLAs with compressed air volume of 50 m^3/h (full capacity), the reservoir was mixed, and DO of the bottom water increased to more than 8 mg/L. Removal rates of TN, TP, NH_4-N and TOC reached 25.5%, 50%, 29.8% and 19.4% respectively. Results of Biolog method showed that the activity of microbes and carbon source utilization were improved in the water of the controlled area compared with the uncontrolled area during the operation. WLAs have been proved to be an efficient technology in water quality improvement especially in hypolimnion oxygenation and artificially induced mixing.

INTRODUCTION

Reservoirs are aquatic systems and they are very similar to natural lakes with the exception that they are artificial impoundments (Michele & Michele 2002). In this century, most drinking water source reservoirs are suffering from the overdose input of nutrients, organic matter and heavy metals (Martin-Torre et al. 2015). As a result, eutrophication of reservoirs and lakes has progressively occurred all over the world. This results in an increase in toxic algal concentrations and dissolved oxygen depletion (Doan et al. 2015, Zhu et al. 2013, Shen et al. 2014). A lack of dissolved oxygen may increase eutrophication. In anaerobic and reducing conditions, phosphorus that bound to the sediment may be released to the water column as phosphate (Nykanen et al. 2012). Increased phosphorus concentration may also increase algal blooms leading to more severe anoxia when the algal biomass decomposes (Zhu et al. 2013). While in deep reservoirs, thermal stratification may also result in substantial hypolimnetic oxygen depletion. In source water reservoirs, hydrogen sulfide and ammonia may be produced and become soluble, and reduced iron and manganese be released from the sediment due to the low dissolved oxygen (Mcginnis & Little 2002).

Based on these problems, artificial aeration is commonly used to prevent anoxia in the hypolimnion of stratified reservoirs (Burris et al. 2002) and this helps inhibit sediment release. Hypolimnion oxygenation and destratification are the two primary methods of artificial aeration (Michele & Michele 2002, Bryant et al. 2011). The advantages of hypolimnion oxygenation over destratification are: pollutants are not transported to the surface water where they can stimulate algal growth, and the cold water habitat is not destroyed (Burris et al. 2002). The water-lifting aerator system, which is a newly designed mixing and oxygenating device, has proved to be an effective technology (Ma et al. 2015a, Sun et al. 2014a). Water-lifting aerators (WLAs) are used increasingly by drinking water reservoirs to replenish dissolved oxygen and decrease concentrations of soluble metals and other chemical species while destroying stratification which also controls the growth of algae (Chai et al. 2011).

Jinpen Reservoir is a deep (maximum depth 94 m) reservoir, and the water-lifting aerator system has successfully re-installed in 2013. In 2014 and 2015, WLAs were put into use for hypolimnion oxygenation and full layer mixing. During the operation of the WLAs, an advanced method named Biolog which could be used to determine metabolic activity and carbon source utilization of microbes was used to explore the water quality improvement mechanism.

MATERIALS AND METHODS

Sampling sites: Jinpen Reservoir (34°13'-34°42' N; 107°43' -108°24' E) is the main drinking water source for Xi'an City, which is the most important city in northwest China as seen in Fig. 1. Jinpen Reservoir is almost 90 km far from Xi'an city and is located in the north of Qinling Mountains. Jinpen Reservoir is a canyon-shaped deep reservoir, in the flooding season the maximum water column depth can reach 94 meters. Its stratification period and mixing period are clear. The total capacity of the reservoir is 2.0×10^8 m^3 and the effective capacity is 1.8×10^8 m^3. When full, the surface area of the reservoir is 4.55 km^2. The catchment area of the reservoir is largely unmodified and consists primarily of mountains covered with forest. However, in recent years, water quality deterioration and algal bloom problems have increased dramatically due to sediment release and storm runoffs, therefore leading to acute water quality problems for Xi'an city. Based on these problems, 8 water-lifting aerators (WLAs) have been successfully installed in Jinpen Reservoir for water quality improvement.

Field work: The water-lifting and aeration system included the air compressed system, air transport system and WLAs. The design and installation have already been reported in our early research (Ma et al. 2015b). The diagram of the water-lifting aerator structure is shown in Fig. 2.

Under normal water quality monitoring conditions, water samples were collected weekly from Jinpen Reservoir during July 2014 to August 2015. Dissolved oxygen (DO), water temperature, turbidity, pH, and chlorophyll-*a* were monitored *in-situ* using a Hydrolab DS5 multi-probe sonde (Hach, USA) at 1 meter water depth interval. Water samples from the controlled area and uncontrolled area were taken every 5 meters from the water surface to the bottom using pre-cleaned high-density polyethylene bottles with preservative already added. All samples were immediately cooled and stored at 4°C before analysis. Upon the WLAs operation period, the monitoring frequency was increased to every 3 days.

Experimental and Analytic Methods

Physical and chemical analysis: Analyses included total nitrogen (TN), ammonia nitrogen (NH_4-N), total phosphorus (TP), total organic carbon (TOC), algal enumeration and algal species identification. Concentrations of TN and NH_4-N were determined with Auto-Analyser 3 (SEAL, Germany), and TP was measured by ultraviolet spectrophotometry after potassium persulfate digestion under 121°C for 30 minutes. TOC was determined by TOC-ASL (Shimadzu, Japan). Algal enumeration and algal species identification were conducted by microscopic method.

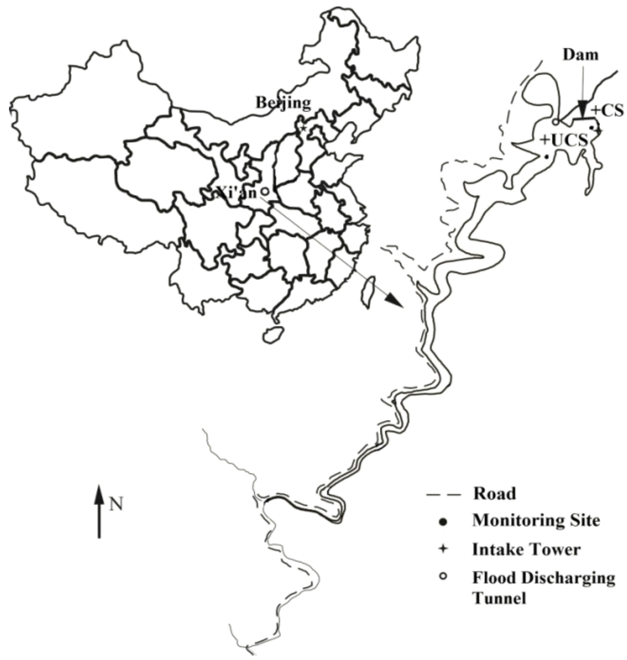

Fig. 1: Positions of Jinpen Reservoir and the water sampling sites (CS: controlled site which was 100 m far from the water-lifting aerator, UCS: uncontrolled site which was 2 km far from the water-lifting aerator).

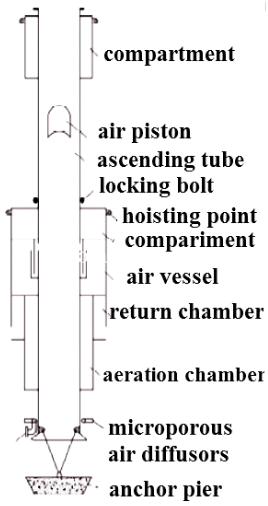

Fig. 2: The diagram of water-lifting aerator.

The water-lifting and aeration system included the air compressed system, air transport system and WLAs. The design and installation have already been reported in our earlier research (Ma et al. 2015b). The diagram of the water-lifting aerator structure is shown in Fig. 2.

Carbon metabolism characteristics and diversity of microbes: As is well known, Biolog is an advanced method of investigating carbon metabolism, community structure, and diversity of microbes in different environments (Zhou et al. 2016). Using Biolog ECO Micro Plate, metabolic characteristics and functional diversity of carbon in microflorae of the reservoir were studied based on *in situ* operation of WLAs.

Average well colour development (AWCD) of microbe average activity was used to determine the utilization of carbon sources and metabolism characteristics (Zhou et al. 2016). As per the references, absorbance values at wavelengths of 590 and 750 mm per hole subtracted the absorbance values in control groups, respectively, and then the absorbance value of 590 nm subtracted the value of 750 nm in the same group, respectively ($C_{590\text{-}750}$). Hence, the absorbance value per hole can be obtained. It is notable that a number below 0.06 was recorded as 0. The formula can be determined as follows:

$$AWCD_{590\text{-}750} = \Sigma\ (C_{590\text{-}750})/31 \quad ...(1)$$

Where 31 represents the number of carbon source variety in the Biolog ECO Micro Plate. The Shannon index, H, is used to evaluate the abundance and evenness of microbes, as follows:

$$H = -\Sigma\ P_i \ln P_i;\ P_i = n_i/N,\ n_i \quad ...(2)$$

Considering the optical density of i well, and N is the sum optical density of all wells. The McIntosh index, U, is used to evaluate the diversity of n dimension space, as follows:

$$U = \sqrt{(\Sigma\ n_i^2)} \quad ...(3)$$

In this research, data within 120 h were used to compute AWCD, the Shannon index (H), and the McIntosh index (U) in different sites.

RESULTS AND DISCUSSION

Variation of Water Quality

Thermal stratification and DO depletion: Based on early research of Jinpen Reservoir, it was considered to be a canyon-shaped stratified reservoir (Huang et al. 2014). And the thermal stratification intensifies since every April. The temperature variation of Jinpen Reservoir is shown in Fig. 3. From July to September, the reservoir was in stable stratification period, the temperature difference between the bottom and the surface could enlarge to18.28°C. After the operation of WLAs, the reservoir entered the period of mixing in November. From December to March, the vertical temperature of the water column was nearly the same, and the temperature decreased from 14°C to 6°C.

Meanwhile, DO of the bottom water decreased from 8 to 0 mg/L gradually since April (Fig. 4). From middle March to early June 2014, volume-weighted hypolimnion DO concentrations steadily declined at a mean rate of 0.069 mg/L/d, which was less than 0.130 mg/L/d of Falling Creek Reservoir in USA (Gerling et al. 2014) and more than 0.034 mg/L/d of Lake Qiandaohu in China (Zhang et al. 2015). It is clear that the DO depth profiles and stratification are closely linked to the water temperature and thermal stratification. Our results are similar to those observed in Haviva Reservoir (Milstein & Feldlite 2015) and Muga Reservoir (Casamitjana et al. 2003).

Water quality deterioration in the hypolimnion: As known, sediments act as a sink for toxic substances (heavy metals, organic pollutants), consequently dredged materials released from sediment often contain pollutants which are above safe limits (Pía Di Nanno et al. 2007). Under aerobic conditions or redox potential changes create a favourable convenience for pollutants release, resulting in potential toxic metals and organic matters concentration increase (Pía Di Nanno et al. 2007, Jensen et al. 1992). DO of hypolimnion decreased to 0 mg/L since June in Jinpen Reservoir. In the end of the stratification (25 August) the thickness of anaerobic layer reached 20 meters (Table 1), and TOC, TN and TP

Table 1: Vertical distribution of DO, Fe, TN and TP in Jinpen Reservoir at CS in 2014.

Elevation (m)	DO (mg/L)			TOC (mg/L)			TN(mg/L)			TP(mg/L)		
	3-Jul	1-Aug	25-Aug	3-Jul	1-Aug	25-Aug	3-Jul	1-Aug	25-Aug	3-Jul	1-Aug	25-Aug
560	8.36	8.91	8.3	3.68	3.94	3.52	1.34	1.45	1.38	0.025	0.028	0.018
540	8.31	5.83	5.4	3.32	3.02	3.33	1.55	1.75	1.81	0.025	0.024	0.032
520	3.93	0	0	3.21	2.85	3.61	1.70	1.83	1.85	0.035	0.029	0.035
510	0	0	0	3.05	3.12	3.82	1.69	1.80	1.92	0.031	0.045	0.042
505	0	0	0	3.01	3.15	3.85	1.75	2.04	2.24	0.037	0.049	0.075
500	0	0	0	2.85	3.24	3.90	1.82	2.11	2.69	0.055	0.071	0.125

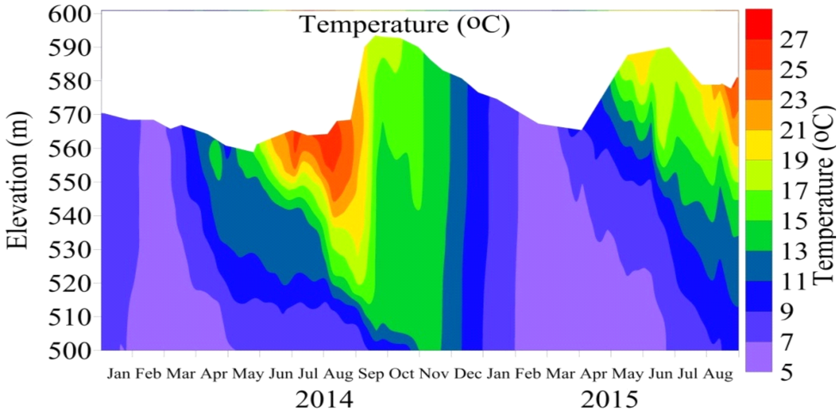

Fig. 3: Temperature variation of Jinpen Reservoir.

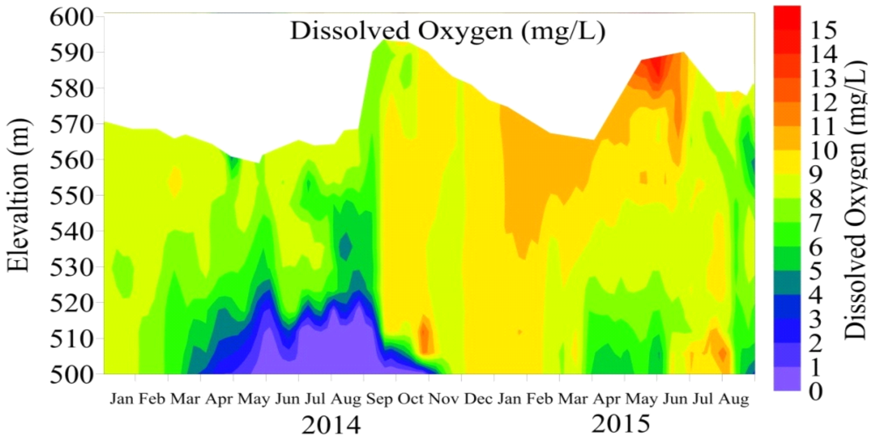

Fig. 4: Dissolved oxygen variation of Jinpen Reservoir.

concentrations in the bottom water increased to as high as 3.90 mg/L, 2.69 mg/L and 0.125 mg/L, respectively. However, concentrations of TN and TP concentrations were already beyond the safe standard. Especially, Fe had exceeded 2.2 times compared with the Chinese drinking water standard. That is to say, without any improvement technology, during the stratification period, the quality of the hypolimnion water would seriously deteriorate.

Operation of WLAs

Hypolimnion oxygenation: Water quality of the bottom 10 meter water in the hypolimnion was deteriorated due to DO depletion. In order to replenish DO to the bottom water and inhibit the pollutants releasing from the sediment, 8 WLAs were turned on since 25 August. The purpose of the operation was to oxygenate the hypolimnion. During this operation period, the maximum compressed air volume was controlled to less than 10 m^3/h.

As shown in Fig. 5, during the 20 days of the 8 WLAs operation, the thickness of anaerobic layer decreased from 17 m to 3.2 m. So the oxygenation effect was quite obvious. Meanwhile, the temperature of bottom water increased by 1.39°C and the surface water decreased by 5.30°C. Water temperature difference narrowed from 15.03°C to 8.34°C. Higher hypolimnion temperature may be responsible for increased sediment oxygen uptake (Singleton et al. 2010). But as seen in our study (Fig. 4), the oxygen uptake rate of the bottom water and sediment was just at the normal level during 15 September to 15 October. This was because the near-sediment water velocity had not been increased (Arega & Lee 2005, Bryant et al. 2010), and the near-sediment water temperature increased little. This showed that the design of the WLAs was successful and effective.

The operation was discontinued by storm runoff from 15 September to 15 October. Our previous study had already drawn a conclusion that the operation of WLAs would increase the turbidity of the whole reservoir due to the high turbidity underflow (Ma et al. 2015a, Ma et al. 2015b).

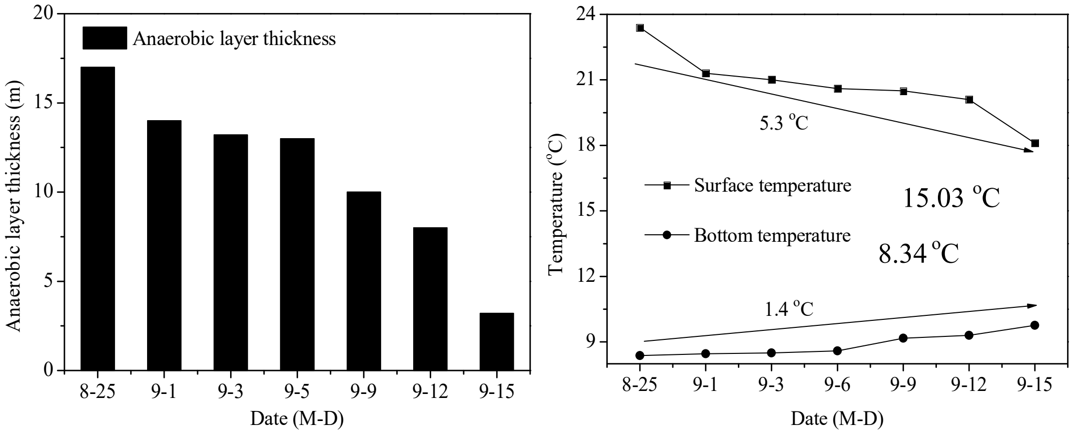

Fig. 5: Anaerobic layer thickness reduction and water temperature difference variation during bottom aeration period.

Artificially induced mixing: So after rainy days, WLAs were put into operation again for artificially induced mixing with full air volume (each aerator air volume was 50 m^3/h) on 16 October. However, the main purpose of the operation was to mix the reservoir, so the compressed air volume was the maximum, and the 8 WLAs were all in full capacity. During this state, the gas bombs were bigger than those of hypolimnion oxygenation state. The effect of oxygenation rate of the full layer water was also greatly improved. On 2 November, the temperature difference decreased to less than 1°C (Fig. 4). From then on, the whole main reservoir was in mixing state, which was advanced 2 months compared with natural mix of the reservoir. Along with the further decrease of temperature, the mixing process continued until next March. DO in the bottom water increased from 0 to 8.9 mg/L. Compared with Lake Bard (Debroux et al. 2012), after 14 days operation of hypolimnion oxygenation system, DO concentration of the bottom water was only increased by 4 mg/L. However, our field observation also indicated that DO concentration of area where the microporous aeration plates were placed was always in oversaturated state, which reached 13 mg/L.

With the operation of the WLAs, the mixing process of Jinpen Reservoir had been advanced about 2 months, and the mixing temperature was 14.6°C. While as for natural mix, it always occurred in late December or next January, and the mixing temperature was about 6°C. The mixing temperature has been increased by 8.6°C by the artificially induced mixing process. So the complete mixing process had lasted for 4 months. And as well, the good water quality also has been maintained for a longer time. The hypolimnion temperature was increased by 4°C during the operation. Compared with the research in Lake Serraia (Debroux et al. 2012), the hypolimnion temperature was increased by 9°C.

During the artificially induced mixing period, the reservoir water quality was gradually improved due to the adequate DO since sufficient DO is essential for good water quality (Wei-Bo & Wen-Cheng 2014). The activity of denitrification bacteria was probably improved (Huang et al. 2015a, Huang et al. 2015b). So the TN concentration decreased from 1.8 mg/L to 1.4 mg/L, and during the natural mixing period, TN concentration decreased further (Fig. 6). As for TP, NH_4-N and TOC, the concentrations had decreased from 0.039 mg/L, 0.20 mg/L and 3.9 mg/L to 0.021 mg/L, 0.14 mg/L and 3.1 mg/L, respectively. Removal rates of TN, TP, NH_4-N and TOC were 25.5%, 50%, 29.8% and 19.4%.

During the continuing mixing period, TN, TP, NH_4-N and TOC concentrations were maintained at low levels. Good water quality has been prolonged two months by the operation of WLAs.

In order to understand the relationship between improvement of water quality and the activity of microbes, Biolog method was also used to explore the carbon metabolism, community structure, and diversity of microbes in CS and UCS during the operation of WLAs.

The AWCD value reflected microflorae with different carbon sources and the change rate showed the metabolic activity of the microflorae (Zhou et al. 2016). The higher the AWCD value grows, the higher the metabolism of the microflorae, as shown in Fig. 7-A. The mean AWCD value experienced increase from 10-15 (0.9±0.1) to 11-2 (1.24±0.07), suggesting that the utilization of the carbon source increased during the WLAs operation. Based on comparisons of data from CS and UCS, the increase of the AWCD value varied significantly. The data also indicated that the metabolic activity of microflorae in the CS has been signifi-

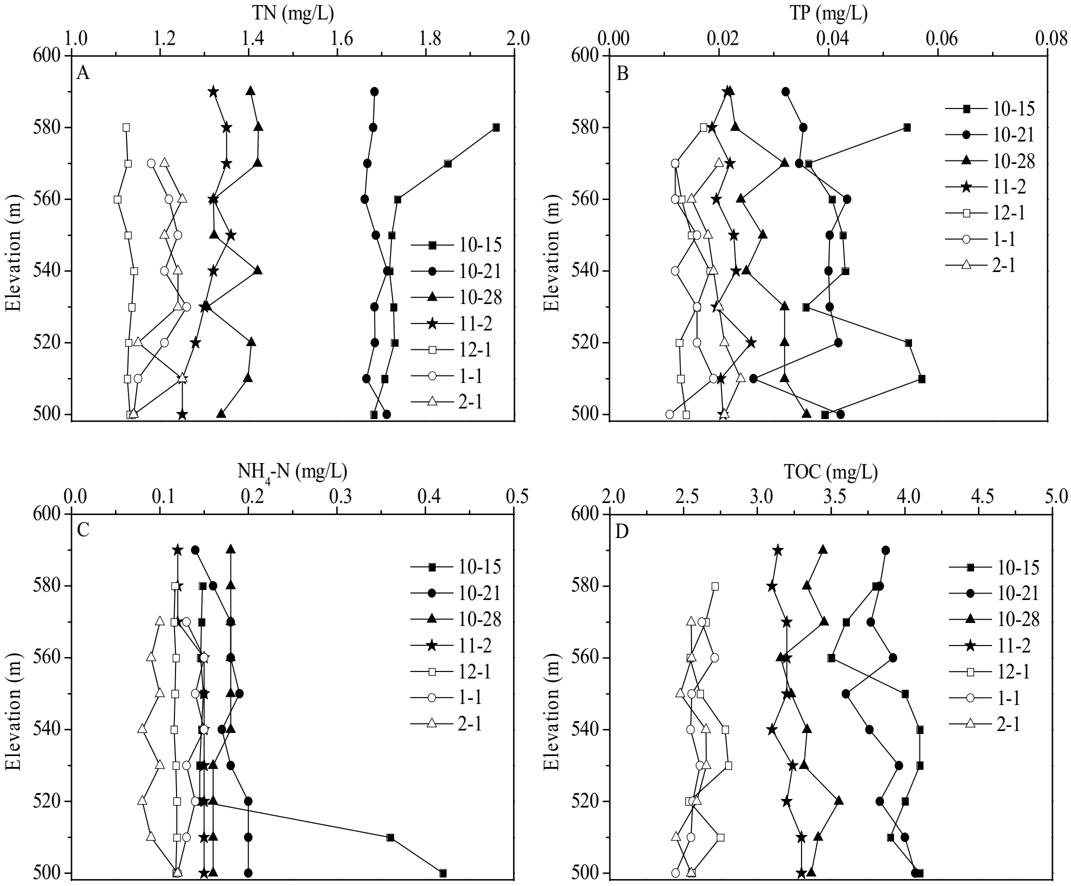

Fig. 6: Water quality variation during artificially induced mixing period (2014) and the good water quality maintained in the mixing state of the reservoir.

cantly improved compared with that in the UCS.

The absorbance of water samples cultured for 120 h was calculated with the Shannon index (*H*) and McIntosh index (*U*) in the CS and UCS. Abundance and diversity of *n* dimension space of microbes was evaluated with the Shannon index (*H*) and McIntosh index (*U*). On 11-2, the Shannon index and McIntosh index of all water layers (0 m, 40 m, 90 m) in the CS reached 3.3 ± 0.11 and 5.6± 0.30, while that of the UCS 3.1± 0.27 and 4.1± 0.56.

The absorbance of water samples that reflected the average carbon source utilization (120 h) is shown in Fig. 7-D. Total utilization of the six carbon sources in the CS showed an increasing trend, however, that of the UCS showed a decreasing trend. The results were consistent with the decreasing trend of TOC (Fig. 6-D).

From all these results, it was concluded that microbial metabolism activity (as AWCD) and the diversity index and average carbon source utilization in the CS were higher than those of the UCS. And the results were consistent with Zhou et al. (2016). Therefore, it was effective to improve the microbial metabolism activity and metabolism functional diversity of microflorae via *in situ* operation of WLAs for reservoir source water. And this was also the main reason for the removal of TN, TP, NH_4-N and TOC.

CONCLUSIONS

1. Results of the operation of WLAs (20 days) for hypolimnion oxygenation showed that the thickness of anaerobic layer decreased by 14 meter. And the temperature difference of the surface and bottom water reduced to 6.7°C.
2. During the artificial inducing mixing period, DO concentration was increased to 8.9 mg/L and temperature difference was narrowed to 1°C. Removal rates of TN, TP, NH_4-N and TOC reached 25.5%, 50%, 29.8% and 19.4%. Meanwhile, the activity of microbes and carbon

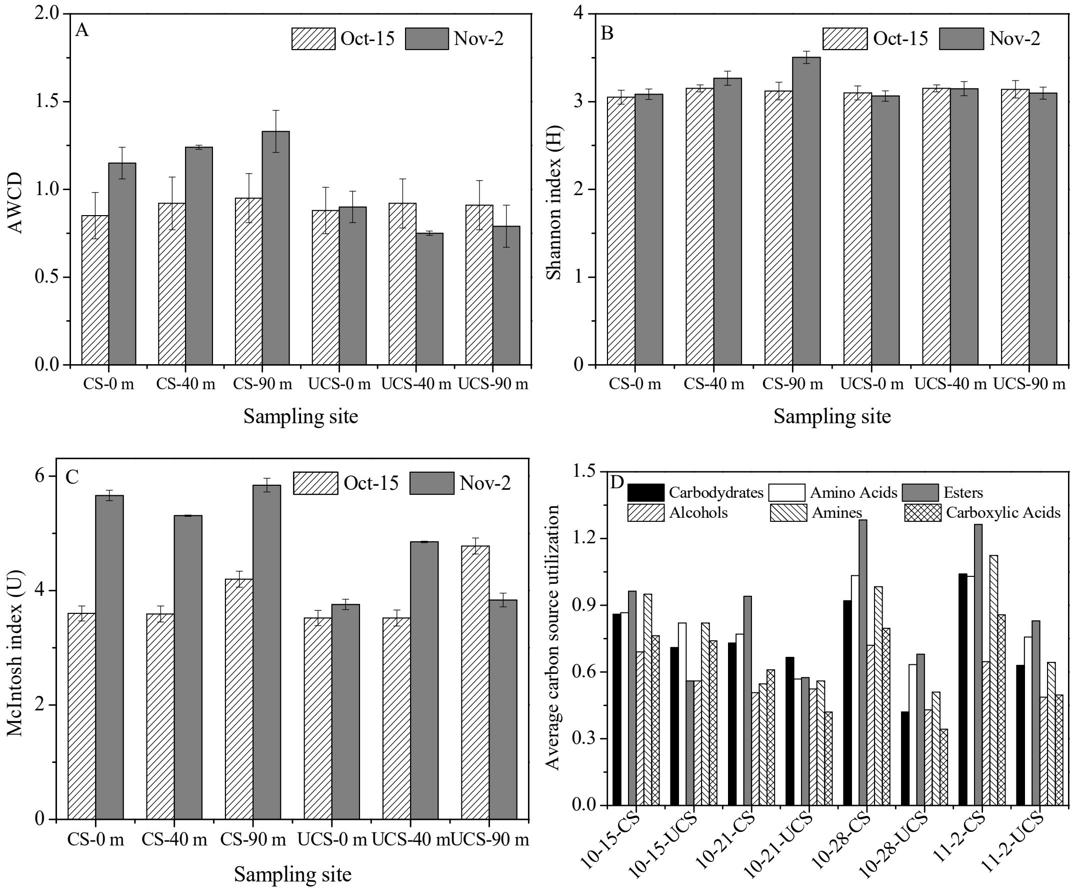

Fig. 7: Changes of AWCD and Shannon index (H) and McIntosh index (U) and average carbon source utilization during artificially induced mixing period.

source utilization were also increased by the operation of WLAs.

3. The microbial metabolism activity and metabolism functional diversity of microflorae were improved by WLAs operation, and this was a main reason of TN, TP, NH_4-N and TOC removal.

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