Potential for nutrient removal by integrated remediation methods in a eutrophicated artificial lake – a case study in Dishui Lake, Lingang New City, China

Qiuzhuo Zhang, Chi Ding, Varenyam Achal, Dan Shan, Yang Zhou, Yatong Xu and Wei-Ning Xiang

ABSTRACT

A new integrated water remediation technology, including a floating bed, a buffer zone of floating plants, enclosed 'water hyacinth' purification, economic aquatic plants and near-shore aquatic plant purification, was used in Dishui Lake to improve its water quality. A channel of 1,000 m length and 30 m width was selected to implement pilot-scale experiments both in the static period and the continuous water diversion period. The results showed that the new integrated water remediation technology exhibited the highest removal rate for permanganate index in a static period, which achieved 40.6%. The average removal rates of total nitrogen (TN), ammonia nitrogen (NH_3-N) and total phosphorus (TP) in a static period were 23.2, 21.6 and 19.1%, respectively. However, it did not exhibit an excellent removal rate for pollutants in the continuous water diversion period. The average removal rates for all pollutants were below 10%. In winter, the new integrated remediation technology showed efficient effects compared to others. The average removal rate for COD_{Mn}, TN, NH_3-N and TP were 7, 5.3, 7.6 and 6.5%, respectively. Based on our results, the new integrated water remediation technology was highly efficient as a purification system, especially during the static period in winter.

Key words | eutrophication, floating bed, integrated remediation, nutrient removal, seasonal effects, submerged plants

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INTRODUCTION

Urban lakes are an important part of city water bodies and play a crucial role in promoting social development (Zhang *et al.* 2010). Lakes provide various important functions, such as drinking water supply, irrigation, shipping, fishery, landscape, entertainment, biodiversity, conservation and energy production, whose natural, social, economic and environmental values in modern cities are irreplaceable (Cui *et al.* 2013). Unfortunately, due to human activities, such as land clearing, agriculture, forestry and urbanization, urban lakes are affected by heavy pollution and extreme degradation, especially since the Industrial Revolution (Naeher *et al.* 2012).

China has undergone dramatic development since the 1980s. The scale, intensity and speed of urbanization led to serious problems in water environments and aquatic ecosystems, especially in urban areas. The total lake area in China accounts for 30% of the global total. However, most of these lakes have been eutrophic or are eutrophying (Qin 2009). A recent investigation focusing on 67 major Chinese lakes indicated that nearly 80% of them had undergone eutrophication processes (Lu 2012). The anthropogenic (human-induced) eutrophication of lakes leads to serious ecological and environmental consequences, and poses a great threat to environmental health and human welfare (Su *et al.* 2011).

Thus, various methods have been exploited to find the ultimate solution for these lake eutrophication problems, such as physical methods (Volker *et al.* 2011), chemical methods (Vicente *et al.* 2011) and ecological methods (Huang *et al.* 2012). Of all methods, ecological restoration methods, including constructed wetland system (Özkundakci *et al.* 2010), seed band (Cui *et al.* 2013), forest

doi: 10.2166/wst.2014.453

restoration (Huang *et al.* 2012), aquatic macrophytes planting (Matthew *et al.* 2009) and zooplankton stocking (Chen *et al.* 2012) have proved successful in improving the water quality of many lakes due to low cost, high efficiency and no secondary pollution. However, every ecological restoration method has its own advantages and disadvantages. Many previous studies have proved that restoration of a degraded lake ecosystem needs to combine different ecological approaches because so many factors have caused its degradation (Ye *et al.* 2011; Coops & Hosper 2002), whereas only limited research has focused on this.

Dishui Lake (DSL), a symbolic landscape of Lingang Eco-city located at the southeast corner of Shanghai municipality, is an artificial lake designed by the German architects, GMP. The lake was completed in 2005, and its area is 5.56 km^2 with an average depth of 3.7 m (Huo *et al.* 2010). However, monitoring results indicated that severe eutrophication and other water-quality problems have arisen there since 2006. In the present research, a new integrated water remediation technology was adopted for a channel in DSL, which could cut down the nutrition loading of the lake and provide a landmark for solving similar lake eutrophication problems around the world.

MATERIALS AND METHODS

Study site

DSL (30 °54′N, 121 °56′E), which is located in Lingang New City, is the largest artificial lake in China and it was excavated in 2003 (shown in Figure 1). The lake is a circular type and its diameter is 2.66 km, total area is 5.56 km^2, mean water depth is 3.7 m and the deepest depth is 6.2 m. The lake could play a role in flood prevention and drainage for Lingang New City. Meanwhile, it plays an important role in urban landscaping and regional microclimate optimization. According to statistical information between 1951 and 2004 for Lingang New City, the annual average temperature is 15.7 °C; annual rainfall is 1,125 mm, which is mainly concentrated between June and September every year; the annual average relative humidity is 80.8%; and annual average evaporation capacity is 953.1 mm (Zhou 2012).

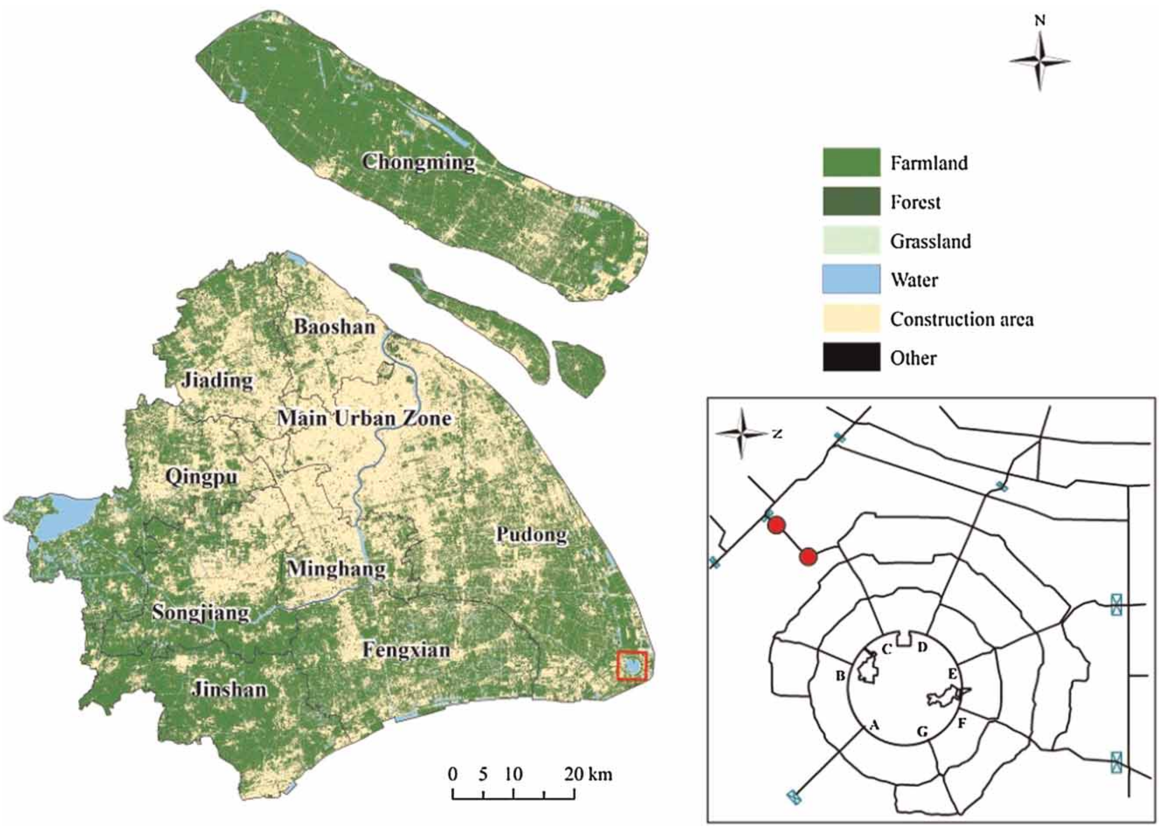

Figure 1 | Location of sampling sites.

The water in DSL inflows from Dazhi River and the water diversion channel is as long as 2.66 km. Natural rainfall and surrounding runoff are the usual main supplement for DSL and there is a water exchange every February. The whole capacity of this lake is about 16,200,000 m^3. Unfortunately, the water quality of the Dazhi River is even worse than that of DSL. Thus, the water quality in DSL is inferior and is tending toward moderate eutrophication, whose synthetical nutrition index is 54.3–60.4 (Huo *et al.* 2010). Originally, to cut down the nutrition loading from its source, a section of the water diversion channel was selected for experiment sites, which is shown in Figure 1 (between the two red dots; the full color version of this figure is available in the online version of the paper, at http://www.iwaponline.com/wst/toc.htm).

Basic information about the selected channel

The length and width of the selected channel is 1,000 and 30 m, respectively. Thus, the whole water area of the experimental channel is 3.0 ha. Its average depth is 4 m. The water quality of the selected channel before restoration is shown in Table 1 (Zhou 2011). It was found that most of the water-quality indexes were Class V or even inferior to Class V (permanganate index (COD_{Mn}), total nitrogen (TN) and NH_3-N), which indicated that the selected channel was tending toward a eutrophication state. Total phosphorus seemed to be best among these water-quality indexes.

Construction of pilot-scale experiment

Design of integrated water remediation technology

Five different kinds of single water remediation methods were chosen (as shown in Figure 2) in the pilot-scale experiment, which include: a floating bed area (*Iris pseudacorus* L., *Lythrum salicaria* Linn, *Thalia dealbata* and *Arundo donax var. versicolor*, 0.16 ha, 100 individual plant/m^2, marked as part (a)); a buffer zone of floating plants (*Alternanthera philoxeroides*, 0.45 ha, marked as part (b)); an enclosed 'water hyacinth' purification area (0.60 ha, marked as part (c)); economic aquatic plant area ('water spinach', 0.10 ha, 200 individual plant/m^2, marked as part (d)); and a near-shore aquatic plant area (*Myriophyllum spicatum* L., 25 individual plant/m^2, 1 m below the water level, *Nymphaea alba*, 1 individual plant/m^2, 0.40 ha in total, marked as part (e)). The plant grown in the lake were chosen on the basis of an indoor simulation experiment (Zhou 2011) and all proved to be the most effective and well grown among the various kinds of plants tested. In addition, the floating bed was fixed on the channel bank, followed by use of our own

Table 1 | Water quality of selected channel before restoration (Zhou 2011)

Item	COD_{Mn} (mg/L)	TN (mg/L)	TP (mg/L)	NH_3-N (mg/L)	Salinity (%)
Value	11.90–23.63	1.53–5.85	0.05–0.21	0.92–3.69	1.30–2.60
Average value	15.26	3.27	0.09	1.75	2.10
Rank	Inferior V	Inferior V	III	V	–

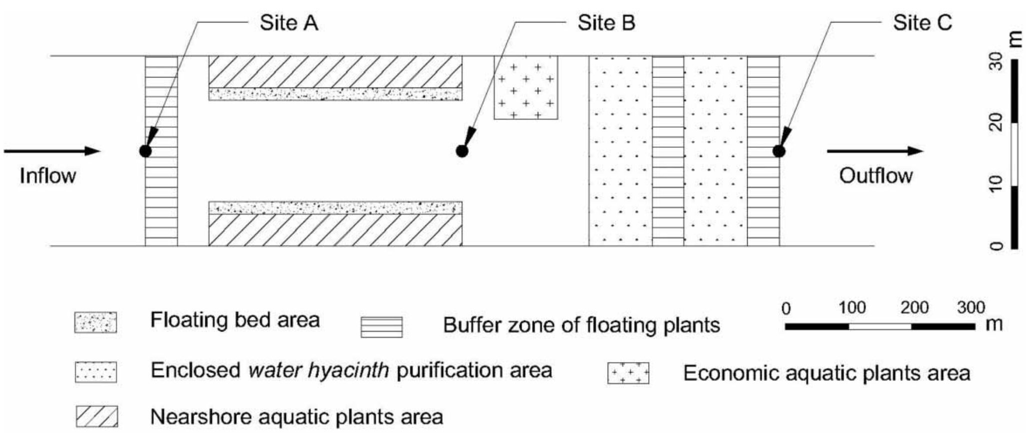

Figure 2 | Construction of new integrated water remediation project.

immobilization method (Patent No. CN201120063140.5), so it could not be influenced seriously by wind.

Three sampling sites, including A (water inlet), B (middle) and C (water outlet) were chosen, from which water samples were selected and then taken to the laboratory for water index determination.

Characteristics of new technology using in the floating bed area

A new technology has been used in the floating bed area. To increase the landscape effect and improve nutrient removal efficiency, two different kinds of frame-softening methods were tried for the floating bed, including using plastic pipes and by twinning plants (Figure 3) and some additional small plastic pipes were fixed on the frame of the floating bed. Various kinds of floating plants (including plants that can bear low temperatures in winter) could grow in the extra plastic pipes, which could increase the biomass of the floating bed. On the other side, the diameter of the additional pipes was small enough to prevent fishes in the channel from preying on the tender roots of the plants. Figure 3 depicts that both use of plastic pipes and twinning plants could improve the visual effect of the floating bed, but could also enlarge the biomass, thus increasing the removal efficiency of the new integrated water remediation projects, especially in winter.

METHODS

Water-quality analysis in the static period

The water in DSL only exchanges once per year. If wind-driven current is not considered, DSL is in an almost static period for most of the year. In the static period, although it is not affected by upstream pollutants, the increasing point source pollution and non-point source pollution could threaten the water quality in DSL drainage. It was found that there are two-point sources near Site A, which is a sewage conduit and storm sewer conduit that originated from a parking lot.

To observe the removal efficiency of the integrated water remediation project on surrounding point-source pollution and non-point source pollution, water quality on Sites A, B and C was determined in the static period. The experiment lasted from 13 April to 17 December 2010. Water samples were selected every two weeks from a depth of 0.5 m below water level. Then, the samples were taken to the laboratory for water index determination, including TN, total phosphorus (TP), ammonia nitrogen (NH_3-N) and COD_{Mn} (SEPA 2002). The analyses were conducted in triplicate and the mean values were adopted.

The removal rate for different pollutants was calculated by Equation (1). C_A stands for pollutant concentration in Site A (inlet of the selected channel). C_C stands for pollutant

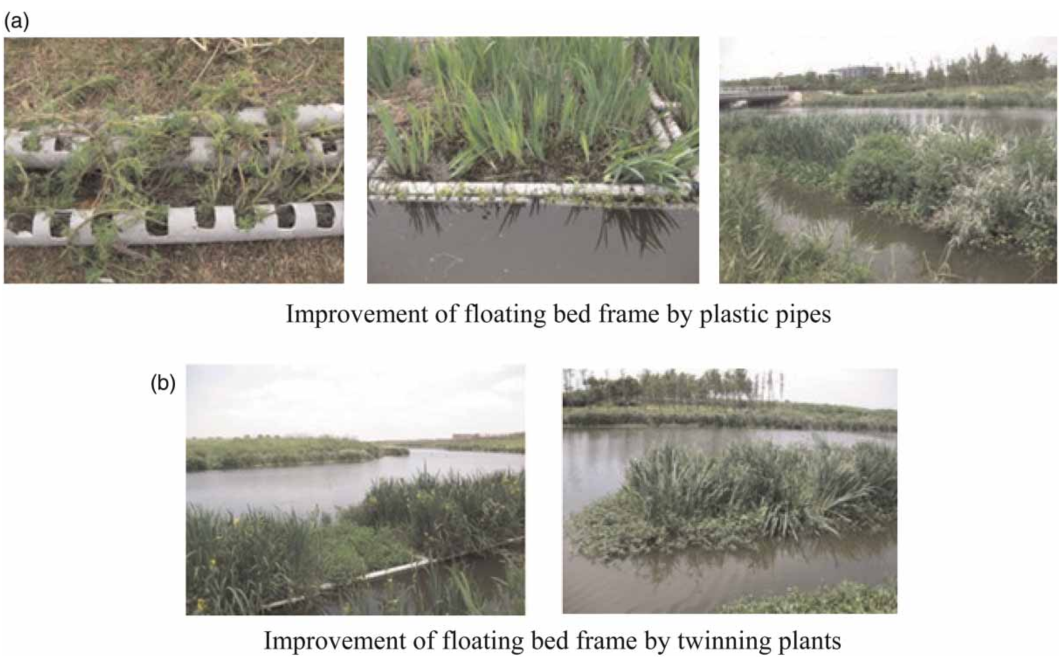

Figure 3 | Two different novel ways to improve the frame of the floating bed.

concentration in Site C (outlet of the selected channel)

$$\text{Removal rate} = (C_A - C_C)/C_A \times 100\%. \quad (1)$$

Influence of impact load on water quality

DSL exchanged water between 23 February and 9 March in 2010, which lasted for 15 days. From 23 to 28 February, DSL drained off its water by harbor A and harbor C and the water level lowered to 1.9 m on 28 February. On 1 and 2 March, it stopped water exchange and started to channel water from 3 March. To observe the removal efficiency of the integrated water remediation project in the continuous water diversion period, water quality from 3 to 9 March was detected every day. Water samples were obtained from 0.5 m below water level. The determination of the water-quality index, including COD_{Mn}, TN, NH_3-N and TN, was followed by standard method (SEPA 2002) and the analyses were conducted in triplicate.

Moreover, the water level increase (H) was detected by water gauge and the water velocity (v) was determined by flow velocity exterminator. The flow volume (Q) and hydraulic retention time (HRT) were calculated by Equations (2) and (3), respectively, in which W stands for the average width of the channel (30 m) and L stands for the length of the selected channel (1,000 m)

$$Q = v \times (H \times W) \quad (2)$$

$$\text{HRT} = (H \times W \times L)/Q. \quad (3)$$

Seasonal effects of new integrated remediation methods on nutrient removal in experimental sites

To investigate the removal efficiency of new integrated water remediation technology in different seasons (1 March to 31 May was defined as Spring; 1 June to 31 August was defined as Summer; 1 September to 30 November was defined as Autumn; 1 December to 28 February was defined as Winter), the average removal rate for each pollution index was calculated and was also compared with experimental sites. The analyses were conducted in triplicate.

RESULTS AND DISCUSSION

Water-quality analysis in static period

The variation of water quality during a static period is shown in Figure 4. The pollutant concentration was highest

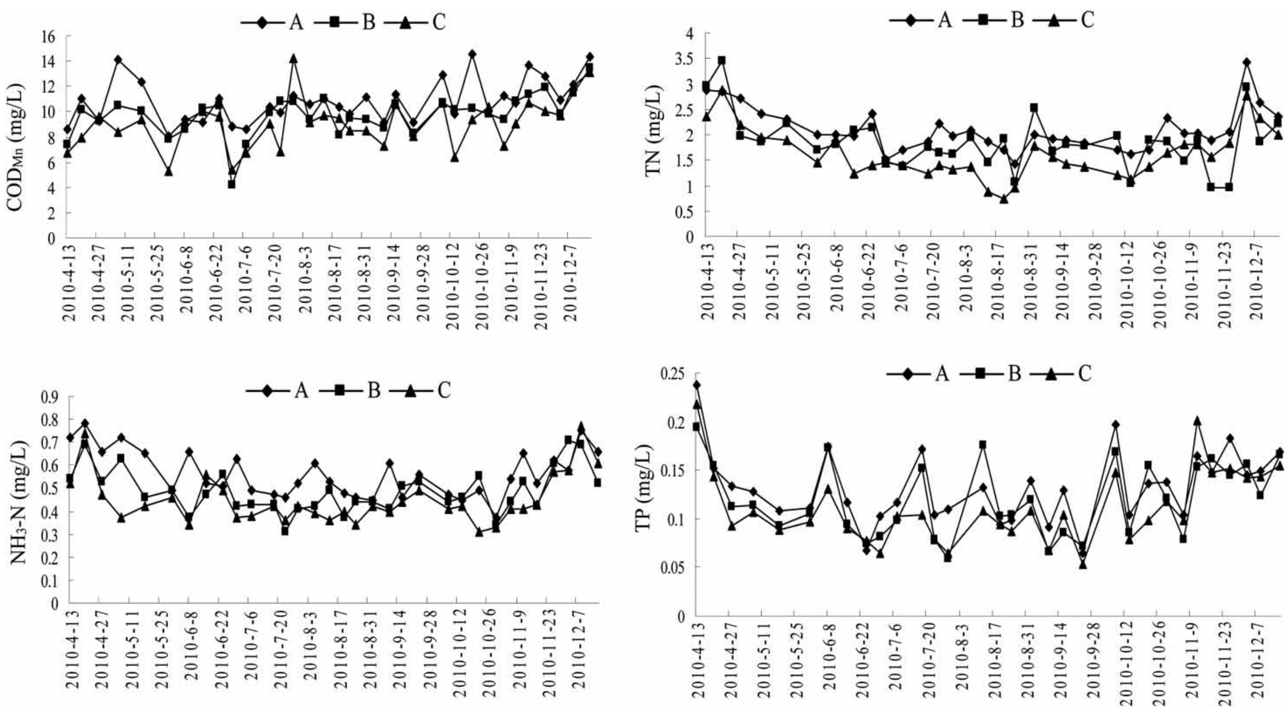

Figure 4 | Variation of water quality in static period.

in Site A, whereas it was significantly lower in Sites B and C, which indicated that the new integrated water remediation technology is effective. The removal rate was calculated for each of these four water-quality indexes, including COD_{Mn}, TN, NH_3-N and TP.

In terms of the COD_{Mn} removal rate, the highest removal efficiency occurred between April and May at 40.6%. It exhibited the lowest efficiency in December, when the removal rate was only 8.9%. This might be due to the much lower biological activity of microorganisms and plants in winter than in other seasons. Moreover, part of these plants began to die and decay in winter, which could increase the organic matter concentration because of the sedimentation of these dead bodies in the bottom of pipes.

TN concentration in Site A varied from 1.52 to 3.46 mg/L, which belonged to rank V or inferior to V, while in Site C it varied from 1.23 to 3.32 mg/L. The average TN removal rate was 23.2%. As for NH_3-N vibration, most of the NH_3-N concentration in Site A varied from 0.45 to 0.78 mg/L, which belonged to rank II or III, while in Site C it varied from 0.34 to 0.77 mg/L. The average NH_3-N removal rate was 21.6%. Meanwhile, it was found that NH_3-N only occupied a small percentage of TN, which indicated that most of the nitrogen pollutants are nitrate nitrogen or nitrite nitrogen. This might be because there were not enough effective nitrifying bacteria and denitrifying bacteria existing in the system (Zhang *et al.* 2014). The structure of nitrogenous bacteria should be observed in future to discuss the mechanism of nitrogen removal.

The concentration of TP was relatively lower among all sites, which showed that phosphorus was not the main pollutant in the experimental area. The highest TP concentration appeared in April in Site A, which was 0.227 mg/L, whereas the lowest TP concentration appeared in September in Site C, which was 0.053 mg/L. The high concentration of TP in Site A might be due to the presence of a parking lot nearby and the generated detergent wastewater could be a pollution source. The average TP removal rate was 19.1%.

Influence of impact load on water quality

Variation of water level and velocity during the continuous water diversion period is shown in Table 2. The water flowed quickly in this period; however, the velocity decreased every day. Meanwhile, the flow volume decreased and HRT increased. It should be pointed out that the highest flow volume in this period was 64,152.0 m^3/d, while the longest HRT was only 0.150 d.

Table 2 | Velocity and flow volume in continuous water diversion period

Date	Water level increase (*H*, m)	Velocity (*v*, m/s)	Flow volume (*Q*, m^3/d)	Hydraulic retention time (HRT, d)
3 March 2010	0.15	0.165	64,152.0	0.070
4 March 2010	0.14	0.154	55,883.5	0.075
5 March 2010	0.14	0.154	55,883.5	0.075
6 March 2010	0.12	0.129	40,124.2	0.090
7 March 2010	0.11	0.122	34,784.6	0.095
8 March 2010	0.09	0.101	23,561.3	0.115
9 March 2010	0.07	0.077	13,970.9	0.150

Variation of water quality in the continuous water diversion period is shown in Figure 5. The removal efficiency of COD_{Mn} was not obvious in the dynamic period, and the average removal rate was below 10%. The COD_{Mn} concentration was even higher in Site C than that in Site A on 3 March, which illustrated that the system used in the present study could not remove organic matter effectively when suffering from an impact load. This might be due to a low initial COD_{Mn} concentration and short retention time.

The concentrations of TN were very high among Sites A, B and C, all of which were inferior to rank V. The highest removal rate of TN was 13.7%, when the HRT was longest on 9 March. Other TN removal rates were all below 10%. The concentrations of NH_3-N were better than that of TN, the quality of which belonged to ranks III and IV. The highest removal rate of NH_3-N was 21.2%, when the HRT was 0.095 d on 7 March. Meanwhile, the new integrated water remediation system did not exhibit removal ability for TP.

In the continuous water diversion period, the system did not show an ideal removal ability for all pollutants, including COD_{Mn}, TN, NH_3-N and TP. The high pollutant load and short HRT might be the main attribution. Compared to the high speed of the water velocity and the large area of the water body, the effect of plants and microorganisms on pollutant elimination seemed to be indistinct (He 2009). The biological membranes that were attached to the plant roots are constituted by various types of nitrogenous bacteria (ammonifying bacteria, nitrifying bacteria and denitrifying bacteria) and dephosphorization bacteria, which could transfer organic nitrogen and organic phosphorus to inorganic nitrogen and inorganic phosphorus, respectively. However, these effective bacteria would be struck by high-speed water flows and then fall off, thus resulting in the

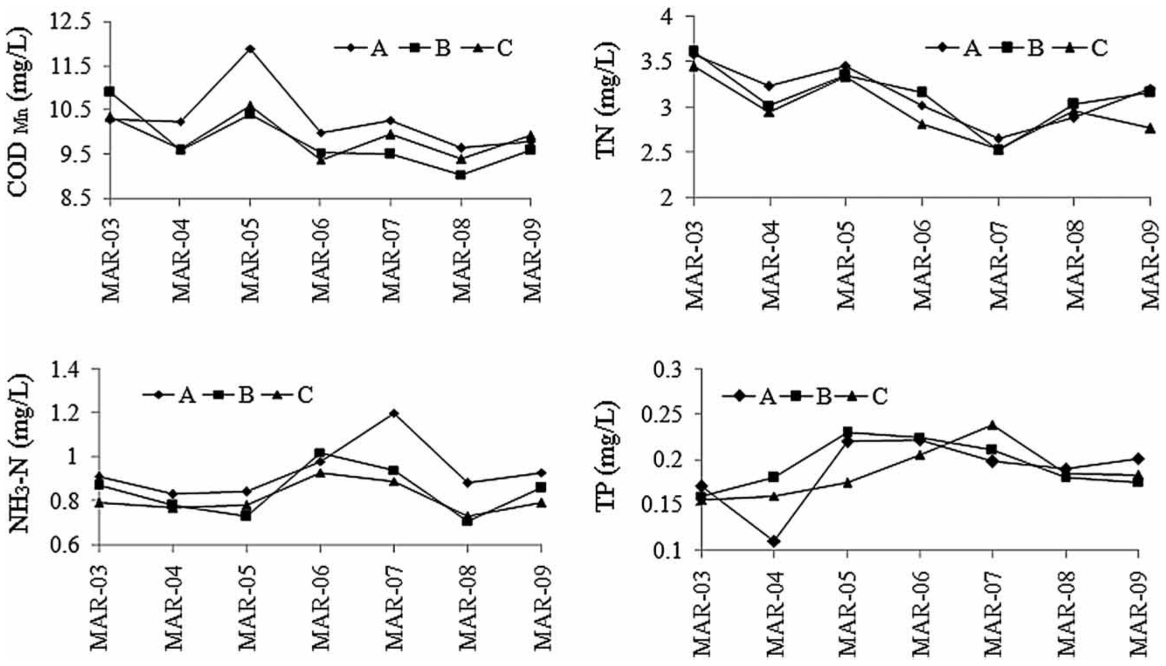

Figure 5 | Variation of water quality in the dynamic period.

reduction of nutrient removal efficiency. Another possible reason is that the bottom sediment in the channel was stirred by the fast water stream and released some deposited nutrients. Thus, it is important to make sure that new ecological systems could achieve their highest potential even when suffering from impact load. Future work is needed in this area.

Seasonal effects of new integrated remediation methods on nutrient removal in experimental sites

The average removal rate of pollutants in different seasons is shown in Figure 6. The average removal rate for all indexes in four seasons were between 17 and 20%, which illustrated the high efficiency of the new integrated water remediation technology located in the experimental site. The highest average removal rate of COD_{Mn} was in spring, at 21.7%. However, the highest average removal rates for TN, NH_3-N and TP were in summer, up to 32.1, 25.3 and 28%, respectively. In winter, the efficiency decreased to the lowest rates, with the average removal rates for COD_{Mn}, TN, NH_3-N and TP being 7, 5.3, 7.6 and 6.5%, respectively. The results were consistent with most of the previous studies where the ecological water remediation method was reported with lower efficiency in winter than other seasons (Nie *et al.* 2006; Moreno *et al.* 2007). This seasonal influence on the remediation process might be due to the community change of zooplankton, fish, aquatic plants, etc. (Chen *et al.* 2012). However, compared to most of the findings where the average removal rate for ecological water remediation methods in winter was below 5% (Li *et al.* 2008; Zhang *et al.* 2010), this new integrated water remediation technology seems more efficient.

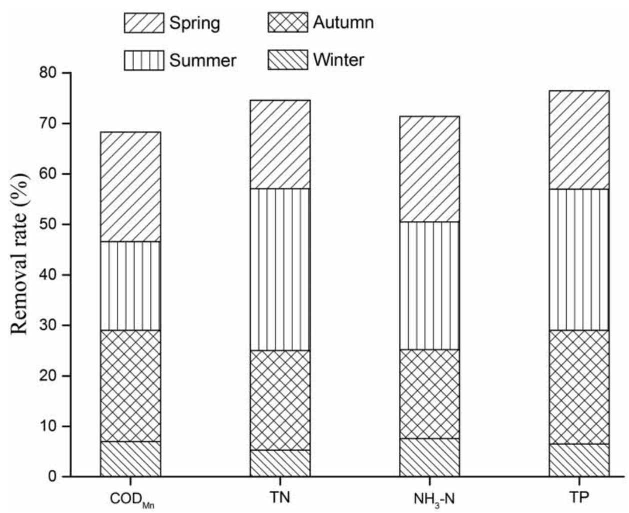

Figure 6 | Average removal rate for pollutants in different seasons in the selected channel.

Furthermore, the plants grown on the experimental channel, especially for the various plants that were grown on the floating bed area, were harvested in December. The residual plants were then taken to the laboratory to investigate their potential for methane production, which could make full use of these residuals and solve the problem of secondary pollution. The fermentation of harvested residual plants to methane was proved to be feasible on an indoor experiment scale (Qin *et al.* 2008). Moreover, the methane could be used as clean energy, which might provide a sustainable route in water remediation and in the biomass utilization field.

CONCLUSIONS

Five different kinds of single water remediation methods, including a floating bed, a buffer zone of floating plants, enclosed 'water hyacinth' purification, economic aquatic plants and near-shore aquatic plant purification, were selected as an integrated remediation technology to cut down the nutrition loading of a selected channel in DSL, China. The static period experiment showed that the integrated water remediation technology exhibited the highest removal rate for COD_{Mn}, at rates of 40.6% between April and May. The average removal rates for TN, NH_3-N and TP in the static period were 23.2, 21.6 and 19.1%, respectively. However, in the continuous water diversion period, the integrated water remediation technology did not exhibit an excellent removal rate for pollutants because of the high-impact load and short HRT. In winter, the average removal rate of COD_{Mn}, TN, NH_3-N and TP were 7, 5.3, 7.6 and 6.5%, respectively, which are more effective compared to other results in the same season.

In conclusion, the new integrated water remediation technology was successfully utilized as an effective nutrient removal function, especially during the static period. The new integrated remediation technology also exhibited more effectively compared to other technologies in winter. Nevertheless, there is a need for future investigation into how to manage its function to resist high-impact loads in addition to investigating the contribution and mechanism of every single part to the whole water remediation system.

ACKNOWLEDGEMENTS

This research was supported by grants from the Ministry of Education of the People's Republic of China (No. 20120076120019), Shanghai Science and Technology Committee (Nos. 12ZR1409100 and 12231205300). The authors would like to thank them for funding this work.

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First received 21 March 2014; accepted in revised form 29 October 2014. Available online 10 November 2014