



## Study on the application of integrated eco-engineering in purifying eutrophic river waters



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### ABSTRACT

Eutrophication has become the primary water quality issue for most of the freshwater in the world. An integrated ecological engineering was applied to treat the eutrophic water of the Shuangqiao River (SQ River), one of the most heavily polluted rivers inflowing to the Chaohu Lake, China. A multi-pond constructed wetlands system was built up to treat the external loading of wastewater. Meanwhile, an in situ purification system consisted of sediment dredging, hydrophytes restoration and artificial floating islands was constructed to purify the internal loading and the river course water. By monitoring the river water quality and analyzing the samples of sediments and plants, the treatment effects and efficiencies of single and integrated ecological technique were studied. Our results indicated that the implement of ecological project notably enhanced the river's capacity of reducing total phosphorus (TP), total nitrogen (TN) and potassium permanganate index (COD), which had increased from 2.49, 33.69 and 40.32 tons per year to 3.75, 58.28 and 74.36 tons per year, respectively. As a result, the concentrations of TP, TN and COD in the river water were dropped by 10.5%, 11.8% and 8.2% respectively. The monitoring data also showed that the removal efficiency of the in situ purification system varied with the seasons, while that of the wetlands system remained at a high level throughout the year, indicating the feasibility of a combination of different techniques to reduce the impact of season on water purification. In summary, this research indicated that single ecological technique produced no satisfying results due to the limits of technique features and environmental conditions, while the integrated engineering techniques could overcome those restrictions and had the potential to remediate heavily polluted rivers.

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### 1. Introduction

Globally, aquatic ecosystems are being impaired by human activities (Gleick, 2003; Zamparas and Zacharias, 2014). The shortage of river water and the discharge of relative large quantities of wastewater directly into watercourses led to significant water pollution. Eutrophication and algal blooms, which appeared as a result of excessive input of inorganic nutrients (particularly nitrogen and phosphorus) to freshwater rivers, lakes, streams and reservoirs, have been considered as two of the most common and serious threats to the safety and security of water resources around the world (Ghadouani and Coggins, 2011; Sierp et al., 2009; Vareli et al., 2009; Zhu et al., 2011). In China, up to 27.8% and 57.4% of the lakes

were eutrophic and mesotrophic respectively, and 19.3% and 9.0% of the water quality of the river monitoring sections belonged to IV–V and inferior to V grade (*Surface Water Quality Standards of China*) in 2013 (Ministry of Environmental Protection, 2014).

As nitrogen (N) and phosphorus (P) are directly responsible for water eutrophication, removing N and P from water is an effective approach to mitigate or prevent this issue. However, conventional wastewater treatment systems, which are known to be efficient in removing COD, cannot reduce the negative impacts of nutrient pollution effectively (de-Bashan and Bashan, 2004; Paerl et al., 2011; Yin et al., 2013). Therefore, other appropriate measures should be taken to lower the impacts of nutrient pollution. Ecological technologies, such as hydrophytes restoration, artificial floating island (AFI) and constructed wetlands system (CWs), representing innovative and emerging solutions for environmental protection and restoration, have been developed worldwide (Babatunde et al., 2008; Vymazal, 2011; D.Q. Zhang et al., 2014; Zhao et al., 2012).

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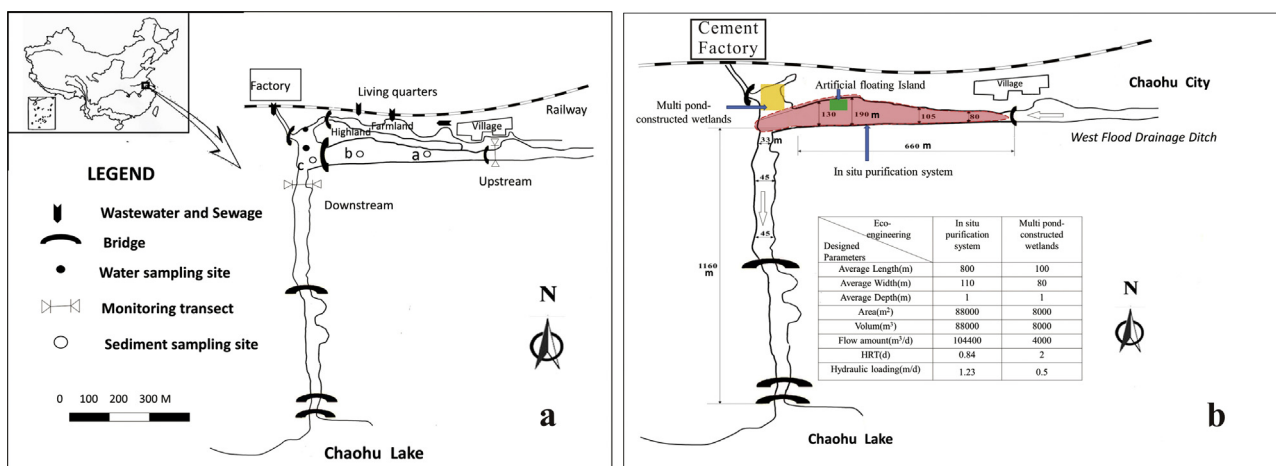


Fig. 1. Locations of sampling sites (a) and eco-engineering project (b).

Hydrophytes have been widely applied in the remediation of rivers and lakes for they are very important component part of a healthy aquatic ecosystem. Besides, the hydrophytes are also efficient in assimilating nutrients, creating favorable conditions for the microbial decomposition of organic matter and increasing water transparency and oxygen availability (Wang et al., 2009, 2010). So far, typical eco-engineering techniques including hydrophytes restoration, AFI, microbial restoration and ecological river bank, are intensively exploited the potential of aquatic plants and microorganisms to treat polluted water. However, the purification efficiency was greatly affected by the season, and the plant biomasses must be removed periodically from the water bodies, otherwise, the nutrients that have been incorporated into the plant tissues may be returned to the water during the decomposition processes (Lu et al., 2010). CW has become an increasingly novel option as the ecological restoration technique, which greatly improve the water quality by substrate adsorption and filtration, microbial assimilation and transformation as well as wetlands plant uptake (Kadlec, 2009; Scholz et al., 2007). Because of the high removal efficiency, low cost, simple operation, and great potential for water and nutrient reuse, CWs are increasingly used worldwide, especially in the developing countries. However, CWs occupy a large area of lands, which is a limiting resource in countries such as China where human population density is high. It was previously reported that the intense and persistent nutrients release from the sediment into the overlying water prevented the water quality from any improvement for a considerable period even after external loading reduction (Sondergaard et al., 2003). Therefore, sediment dredging was an effective remediation method to alleviate eutrophication for it can reduce internal nutrient loading directly, create suitable habitat conditions and promote ecological restoration (Zhang et al., 2014). However, sediment dredging has some shortcomings such as high costs, strict demand of dredging precision and instability of treatment effectiveness (Zamparas and Zacharias, 2014).

As disadvantages of single eco-engineering technique limit the success of large scale applications in river and lake restoration, techniques using combined biotechnological and engineering methods have drawn increased attention. These approaches have superiorities in maintaining the stability and longevity of the remediation effectiveness, and they usually require less time, space and cost. However, there have been only a few reports concerning the application of integrated eco-engineering in remediation of polluted rivers and most of these studies were performed with laboratory, microcosm or mesocosm experiments (Mi et al., 2014; Sheng et al., 2013; Wang et al., 2009, 2010). Particularly, the knowl-

edge about ecological river engineering is still scarce in China and neighboring Korea (Woo, 2010).

To improve future restoration practices, we herein proposed and reported an integrated eco-engineering project with in-depth analysis of results. The integrated project combined sediment dredging, hydrophytes restoration, AFI and CWs, was carried out at SQ River (one of the most heavily polluted inflows of Chaohu Lake, China) in 2010. The objectives of this study were: (1) to characterize the water purification activities and highlight strengths and weaknesses of these approaches; (2) to evaluate the water quality improvements and the removal efficiency of treatment units; (3) to assess the feasibility of applying different treatment units to remediate a polluted river. This study can make recommendations to further the application of river restoration in more broad regions.

## 2. Methods

### 2.1. Study site

The Shuangqiao River (SQ River), situated in the east of the north bank of the Chaohu Lake and approximately 1.45 kilometers (km) in length and averagely 32 meters (m) in width, was one of the most heavily polluted rivers inflowing to Chaohu Lake. The major land uses in the region were constructed land and cropland. Due to the increasing human activities, the lake suffered from serious pollution and eutrophication problems. The shortage of river water further exacerbated the problem of pollution, as a result, the water quality of the river was inferior to V grade and the sediment was polluted heavily. In the upstream of the SQ River lay the West Flood Drainage Ditch, that was 3.33 km in length and gathered municipal sewage from the Chaohu City. In addition, the SQ River also received water from farm irrigating catchments.

As the River was located in the suburban regions of the Chaohu city, pollution interception had not been started. In the engineering area, besides the pollutants brought by the upstream water and surface runoff, 4 wastewater inflows receiving domestic sewage and agricultural wastewater from the towns and villages, were situated in the North Bank of the river (Fig. 1a). The Sewage Outlet No. 1 was 30 m away from the downstream of a village and Sewage Outlet Nos. 2, 3 and 4 went through a railway culvert. These four sewage inflows passed farmland and channels separately and finally converged at the northern corner of the crook of the river and together flowed into the SQ River.

## 2.2. Description of eco-engineering units

### 2.2.1. Multi-pond constructed wetlands

In order to treat the agricultural wastewater and the sewage came from the nearby villages and living quarters, a multi-pond CWs was built and began to run in Dec. 2010 (Figs. 1 b and S1). This system contained three different types of ponds (sedimentation, oxidation and stabilization pond) and two units of artificial wetlands (subsurface-flow CWs and surface-flow CWs). The sedimentation pond covered an area of 1200 m<sup>2</sup> and was 2 m deep, and inside the pond were floating-leaved plants (mainly *Eichhornia crassipes*. and *Hydrocharis dubia*) with the function of enhancing the sedimentation of suspended particles in the water. Covering an area of 1800 m<sup>2</sup> and being 1 m in depth, the oxidation pond was set up for the purpose of increasing the content of dissolved oxygen in water, mainly had submerged plants (*Vallisneria natans* and *Hydrilla verticillata*) in it. The area of the subsurface-flow CWs was 2400 m<sup>2</sup> and its average depth was 1.3 m. From the top to the bottom, the broken stone used as substrate, was 6–10 millimeters (mm), 10–20 mm and 20–30 mm in diameter, and inside the wetlands emergent aquatic plants such as *Canna indica* L., *Arundo donax* var. *versicolor*, *Iris pseudacorus* L. and *Cyperus alternifolius* L. were planted. The surface-flow CWs, covering an area of 1400 m<sup>2</sup> and being 0.2 m deep, had emergent aquatic plants (*Phragmites australis*, *Nelumbo nucifera* Gaertn. and *Lythrum salicaria* L.) planted as well. Inside the stabilization pond, which covered 1200 m<sup>2</sup> and was 1 m in depth, were submerged plants and emerged plants primarily (mainly *Vallisneria natans*, *Hydrilla verticillata* and *Nelumbo nucifera* Gaertn.).

Before introduced into this system, the domestic sewage and agricultural wastewater were first collected by the agricultural drainage ditch, which was rebuilt as ecological ditch to reduce the pollutants and the suspended particles. Then the effluent was discharged into the sedimentation pond, and next poured continuously into the oxidation pond. Afterwards, the wastewater was pumped into the subsurface CWs to receive further treatment. At last, the effluent was dropped into the surface flow CWs, and then the stabilization pond. The area of this whole system was 8000 m<sup>2</sup> and totally 4000 m<sup>3</sup> wastewater was treated per day.

### 2.2.2. In situ purification system

To control the internal contamination and treat the polluted water, the river was dredged in Apr. 2010 to get rid of the heavily polluted sediments, and then an in situ purification system including a hydrophytes restoration zone along the river bank and an AFI in the north river bay was constructed in Oct. 2010 (Fig. S2). The area of this whole system was 88,000 m<sup>2</sup> and the average flow of the river was 104,400 m<sup>3</sup> per day (m<sup>3</sup>/d) (Fig. 1b).

The sediment dredging covered an area of 90,000 m<sup>2</sup> and the depth was 0.4 m averagely. Dredging of the middle part was deeper, about 0.6 m while the sections close to both banks were shallow, approximately 0.2 m. Hence, capacity of discharging floodwater was secured and aquatic plants near the banks were adaptive to recover. After completion of the dredging, average depth of water within this area was 1 m approximately. As the watercourse was made deeper, the hydraulic retention time was extended and pollutants were degraded more effectively.

In Feb. 2011, another project was carried out for restoring the aquatic plants from the banks to the center of the river, where hydrophytes, emergent aquatic plants and submerged aquatic plants were planted successively to reduce the runoff pollution and purified the river water. The project covered an area of 40,000 m<sup>2</sup>, with the south bank being 800 m long and 20 m wide and the north bank being 1000 m long and 20–30 m wide. To satisfy the capacity of discharging floodwater and provide a favorable growing environment for aquatic plants, submerged plants of 5 m approximately in

width were recovered near the banks, where depth of the water was shallower than 1 m. Since the river bend in the north was deeper and aquatic plants grew hardly, an AFI covering an area of 3000 m<sup>2</sup> was adopted to purify the water.

## 2.3. Field sampling and analysis

### 2.3.1. Water

The water was sampled and analyzed monthly from Dec. 2009 to Nov. 2010 prior to the project and from Dec. 2010 to Nov. 2011 after the project. Sampling sites were established in the inlet and outlet (after the operation of the project) of the multi-pond CWs. Three monitoring sections were also set up in the upstream, the midstream and the downstream of the river respectively. Water was sampled in the left, the middle and the right part of each section and then mixed (Fig. 1a). The monitored indices including TP, TN, COD and SS (Suspended solids), were tested using standard laboratory method (State Environmental Protection Administration, 2002). Data on the flows of the SQ River and the north bank wastewater were provided by Chaohu Branch of Anhui Provincial Center for Water Environment Monitoring and Measurement.

### 2.3.2. AFI plants

The plants were transplanted in Feb. 2011. Measurements were conducted to obtain the biomasses and the contents of TN and TP in the plants (at the time point of being transplanted and growing for 9 months). The biomasses of dwarf plants were calculated by multiplying the fresh weight and the growing area of the plants. However, to obtain the biomasses of tall plants, such as *Canna indica* L., three typical *Canna* plants: tall, medium and short, were selected to obtain average unit fresh weight. The biomass for unit area of tall plants was worked out on the basis of the density of planting (9 plants/m<sup>2</sup>) and the average unit fresh weight. Dry weight analysis was performed by drying plants for 8 h at 105 °C. Besides, the loft dried plants samples were grinded and preserved after going through a screen of 0.25 mm. TN and TP in the plants were tested according to USEPA method 351.1 and method 365.2, respectively.

### 2.3.3. Sediments

The sediments at a, b and c points of the SQ River were sampled and analyzed separately on Mar. 2010, May 2010 and Nov. 2011 with a Petersen sampler. The sediments collected were dried naturally indoor and then grinded, screened (100 mesh), enclosed in bags and preserved in a refrigerator at 4 °C. The methods of detecting water content, TN and TP in sediments were the same as the analysis of plants, which were mentioned above. Organic matter content was determined following the standard methods (APHA et al., 1998).

## 2.4. Data analysis

The amount of the pollutant ( $P$ ) was determined by Eq. (1):

$$P = C \times F \times 365 / 1,000,000 \quad (1)$$

where  $P$  was the total amount of pollutants (tons per year, tons/year);  $C$  was the average concentration of pollutants (mg/L).  $F$  was the average flow rate (m<sup>3</sup>/d), which was 104,400 m<sup>3</sup>/d for the river water and was 4000 m<sup>3</sup>/d for the wastewater of the North Bank.

As for the multi-pond CWs, the reduction amount of pollutants was calculated using Eq. (2):

$$Q = Q_1 - Q_2 \quad (2)$$

where  $Q_1$  was the total amount of pollutants (tons/year) at the influent, and  $Q_2$  was the total amount of pollutants at the effluent.

As for the whole project, the reduction amounts of pollutants before and after the engineering implementation were calculated using Eq. (3):

$$R = R_1 + R_2 - R_3 \quad (3)$$

where  $R_1$  was the total amount of pollutants (tons/year) of the influent from the upstream before or after the engineering implementation.  $R_2$  was the total amount of pollutants (tons/year) of the effluent of the whole project before or after the engineering implementation.  $R_3$  was the total amount of pollutants (tons/year) of the influent before or after the running of pond-wetlands.

After the implementation of the engineering, the difference of the pollutants amount between the upstream and downstream ( $S$ ) was constituted of the self-purification of the river ( $S_1$ ), the reduction amount of the in situ system ( $S_2$ ) and the reduction amount of the CWs ( $S_3$ ), thus:

$$S = S_1 + S_2 + S_3 \quad (4)$$

One-way ANOVA and Tukey's comparison of means were performed with SPSS (Version 16.0). The confidence level at 95% was used to establish significance ( $p < 0.05$ ).

### 3. Results and discussion

#### 3.1. Purification performance of single eco-engineering unit

##### 3.1.1. Dredging

Fig. 2 shows the contents of TN, TP and organic matters in the sediments before and after the dredging of the SQ River. The data showed that the contents of TN, TP and organic matter in the sediments were decreased immediately after dredging, and TP was dropped significantly ( $P < 0.05$ ). However, these indices were increased again after 2 years, and the contents of organic matters were significantly higher than those before the dredging ( $P < 0.01$ ).

Generally speaking, dredging is able to reduce internal load of sedimentation effectively, control the release of phosphorus and nitrogen and relieve the eutrophic status of water. However, it is still a controversial technology for eutrophication control (Gustavson et al., 2008; Jing et al., 2013). Ryding's (1982) study on the field of dredging of the Trehorningen Lake in Sweden indicated that the internal phosphorus was well controlled at the initial stage after dredging, while two years later, both phosphorus concentration and biomass of algae returned to the levels before the dredging. Our results also showed that dredging could remove the heavily polluted surface sediments in a short term. However, as the pollutants continuously entered into the West Flood Drainage Ditch without interception, the pollutants tended to accumulate on the surface of the sediments again, resulting in an increase of pollutants two years later.

##### 3.1.2. Artificial floating islands

As the AFI plants reduce the concentrations of nitrogen, phosphorus and hazardous substances in water through the absorption of their roots and the biological membrane adherent to their roots (Bu and Xu, 2013; Zhao et al., 2012), we determined the biomasses and TN and TP absorbed by the plants. After grown for 9 months (Table S1), the floating plants achieved a sharp increase in their biomasses, especially the dwarf plants whose biomass reached  $62.2 \text{ kg/m}^2$ .

Table 1 shows that the contents of nitrogen and phosphorus in AFI plants differed obviously from each other. Sequence of the contents of nitrogen and phosphorus was: *Hydrocotyle Verticillata* > *Myriophyllum aquaticum* (Vell.) Verdc. > *Canna indica* L. More adept at absorbing nitrogen and phosphorus from water, the contents of nitrogen and phosphorus of *Hydrocotyle Verticillata*, were

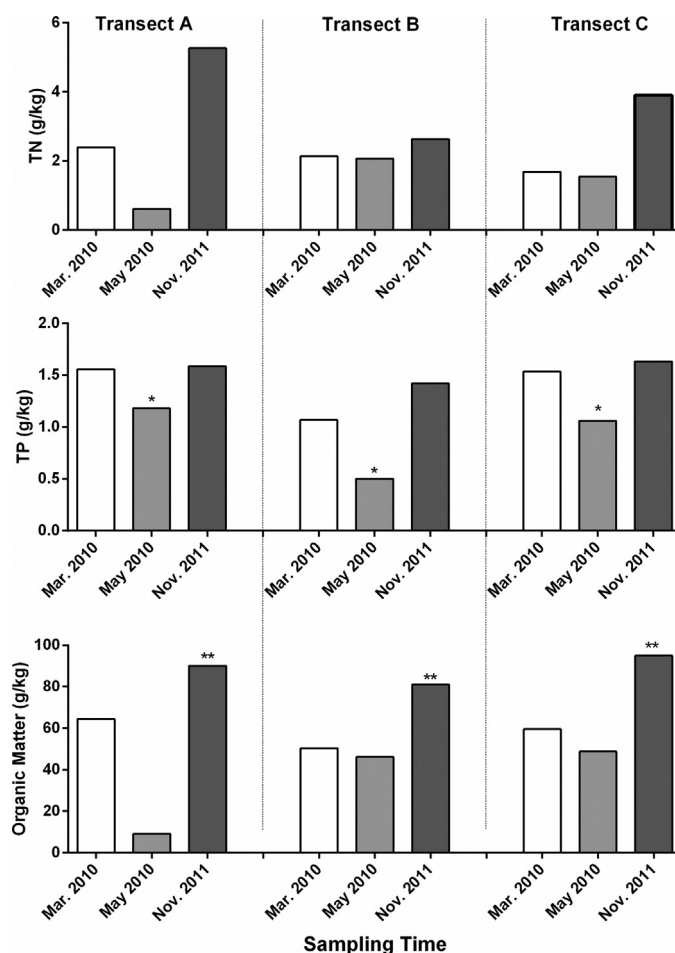


Fig. 2. Variations of nutrients in the sediments of different sampling sites before and after dredging. Statistically significant differences from the control (Mar. 2010) were determined by Student's  $t$ -test (\* $P < 0.05$ , \*\* $P < 0.01$ ).

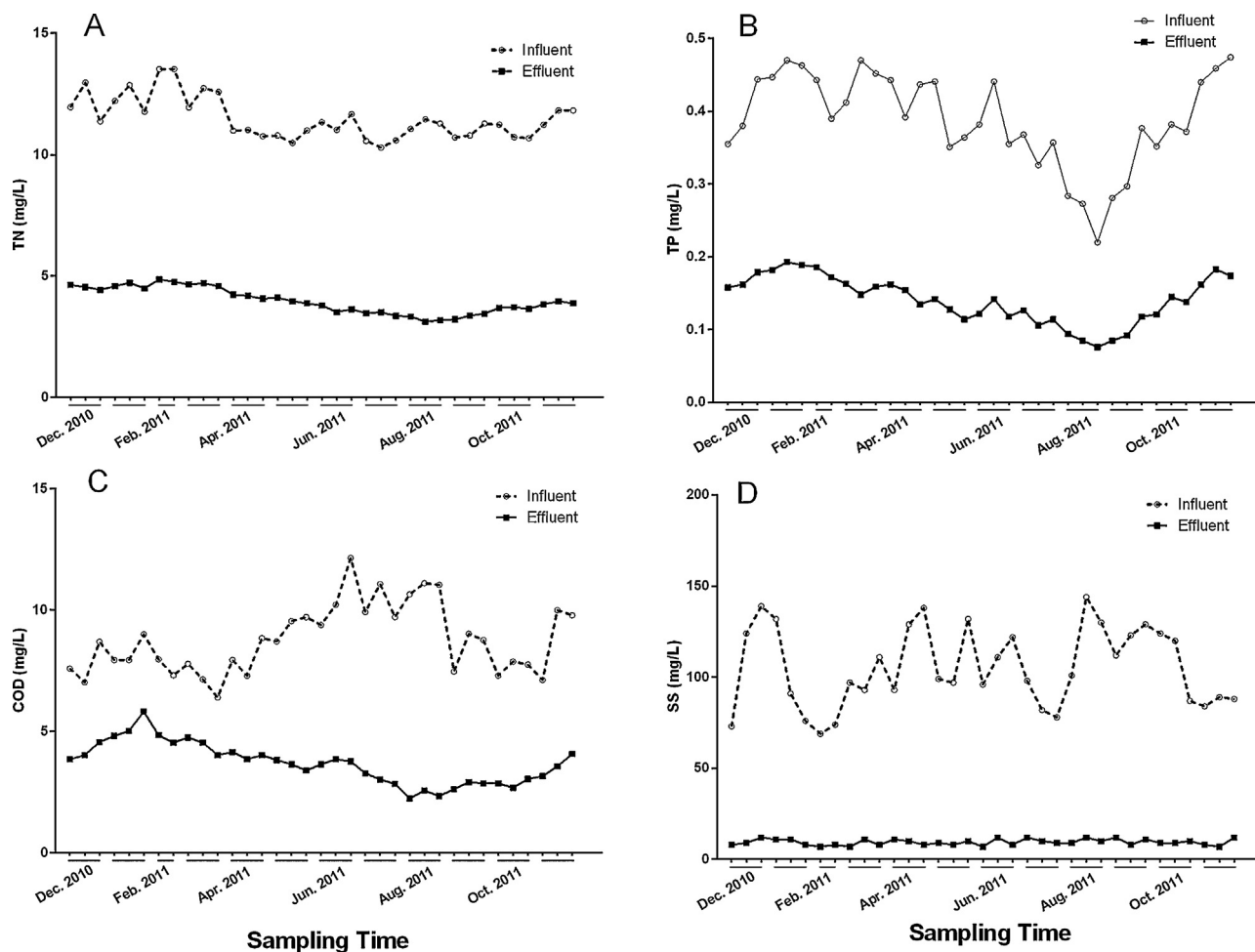
higher than those of other plants. In a growth cycle, the AFI removed 0.14 tons of nitrogen and 0.06 tons of phosphorus from the water.

##### 3.1.3. Multi-pond constructed wetlands

Influent and effluent of the multi-pond CWs were sampled and analyzed three times a month from Dec. 2010 to Nov. 2011. The results are shown in Fig. 3. Concentrations of TN in the influent fluctuated warmly, which were higher in winter and spring (12 mg/L approximately) and lower in summer and autumn (11 mg/L approximately). Similarly, concentrations of TP in influent changed a lot, ranging from 0.47 to 0.22 mg/L, and reached the minimum in summer. Concentrations of COD in influent changed significantly as well, ranging from 6.4 to 12.2 mg/L, but reached the maximum in summer. For SS, the concentrations in influent ranged from 70 to 140 mg/L. After the multi-pond CWs running, concentrations of pollutants in the effluent reduced remarkably ( $p < 0.05$ ). Concentrations of TN and TP in the effluent were 3.12–4.76 mg/L and 0.075–0.193 mg/L respectively, and the variation patterns were the same as those of the influent, suggesting the influence imposed by influent. Concentrations of COD in the effluent were 2.2–5.8 mg/L but changed in contrast with that of the influent, and the concentrations in summer and autumn were lower than those in winter and spring. Concentrations of SS in the effluent were stable and irrelevant with the influent and remained around 10 mg/L all year round, suggesting the system worked well in removing SS. According to Table S3, the annual removal of TP, TN and COD by this project was 0.37, 10.94 and 7.36 tons, respectively.

**Table 1**  
Biomass and absorption of nitrogen and phosphorus of the AFI plants.

Plants	Net increase biomass (dry weight) (kg)	Content (dry weight)(mg/g)		Total content (kg)	
		TN	TP	TN	TP
<i>Canna indica</i> L.	767.5	8.9	5.1	6.8	3.9
<i>Hydrocotyle Verticillata</i>	3545.4	19.1	7.3	67.7	25.8
<i>Myriophyllum aquaticum</i> (Vell.) Verdc.	5007.6	12.5	6.1	62.6	30.5
Total				137.1	60.2



**Fig. 3.** Variations of TN, TP, COD and SS of the influent and effluent of the multi-pond CWs.

### 3.2. Purification performance of the integrated eco-engineering system

Fig. 4 indicates that the concentrations of TP, TN and COD in the water sampled from upstream changed a little before and after the project, but their monthly changes followed a similar pattern. Hence, within two years of monitoring, the amounts of pollutions in the West Floodwater Drainage Ditch remained almost the same. Prior to the project, concentrations of the pollutants in downstream and upstream kept a similar trend of change, that was, the concentrations of pollutants in the outgoing water varied with the concentrations of pollutants in the incoming water. And occasionally, it was even as same as that of the incoming water. This result suggested that apart from the influence of the loading of pollutants from the North Bank, the self-purification ability of the river was rather weak. After the implementation of the project, however, though concentrations of pollutants in downstream changed similarly with that

of the upstream, the former was distinctly lower than the latter, indicating a significant water quality improvement ability of the integrated eco-engineering.

After the project, the concentrations of TP, TN and COD decreased by 10.5%, 11.8% and 8.2%, respectively (implied by Tables S2 and S3). Actually, this project, with restricted conditions such as investment and municipal planning, was carried out merely on an 800 m section of the 1.45 km SQ River and the 3.33 km upstream was not harnessed. Nevertheless, the present program obtained an ideal result of river water purification. Based on the presented engineering effects, should the residual section and the upstream be administered similarly, the water quality would be improved substantially.

### 3.3. The contribution of single engineering units

In one year before the engineering (Table S2), the annual removal amounts of TP, TN and COD by the river's self-purification

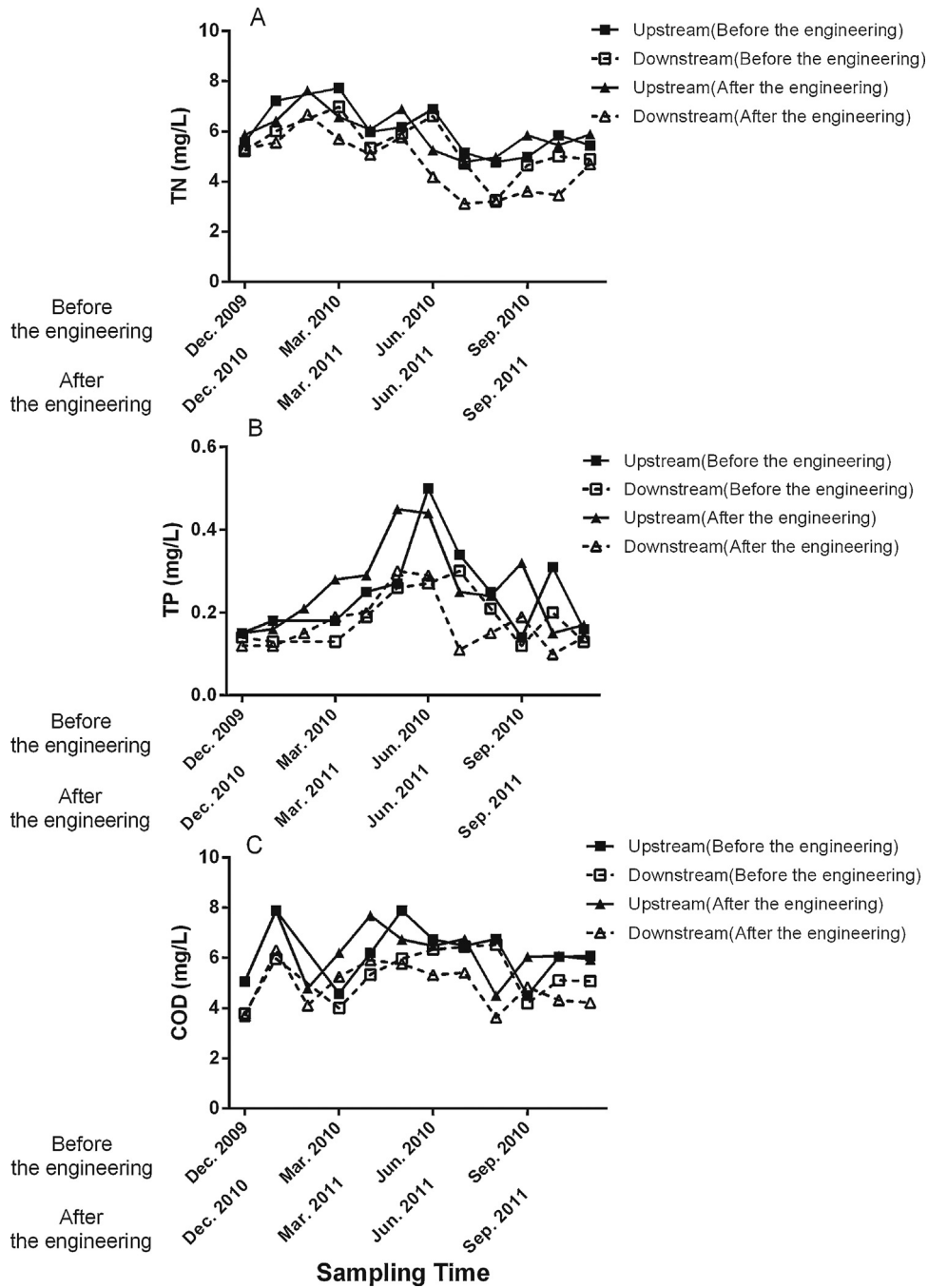


Fig. 4. Variations of TP, TN and COD of the River waters before and after the engineering.

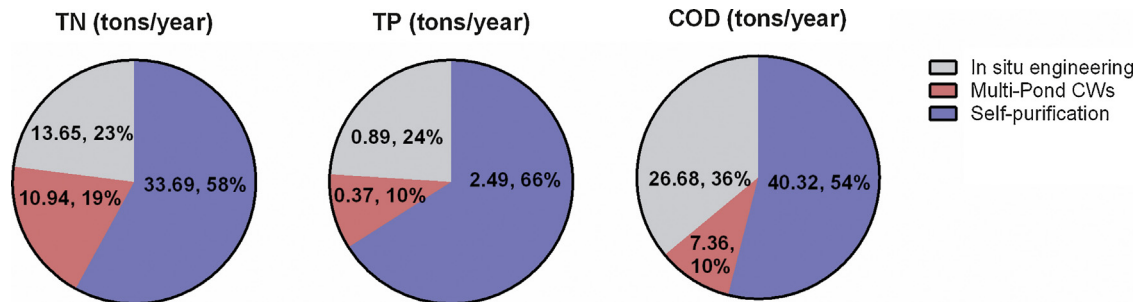


Fig. 5. Contributions of single engineering unit to the integrated engineering on the removal rates of TP, TN and COD.

were 2.49, 33.69 and 40.32 tons, respectively. As compared, in one year after the engineering implementation (Table S3), the annual removal amounts of TP, TN and COD of the whole engineering area were 3.75, 58.28 and 74.36 tons. Namely, the removal rate of this area was dramatically increased by 50.6%, 72.9% and 84.4% for TP, TN and COD, respectively. As indicated by Table S3 and Fig. 5, the removal amounts of TP, TN and COD of the multi-pond wetlands and the in situ purification system accounted for 10%, 19%, 10% and 24%, 23%, 36% respectively of the total removal amounts.

The multi pond-wetlands system, covering an area of 8000 m<sup>2</sup>, was adopted to treat the external pollution of 4 wastewaters from the North Bank. As to the internal pollutants of the river, in situ purification technology covering an area of 88,000 m<sup>2</sup> was employed. Indeed, the constructed wetlands system's capacity of removing TP, TN and COD was 41.8%, 80.1% and 27.6% of that of the in situ treatment system while its area was merely 9% of the latter. Should their areas be as same as the latter, the efficiency of pollutants removing of the former would be 3.1–8.9 times higher.

In this project, the AFI covered an area of 3000 m<sup>2</sup>. The amounts of TN and TP absorbed by the AFI plants were merely 1% and 6.7% of that of the whole in situ purification system, respectively. In the in situ purification system, the area of hydrophytes restoration was 40,000 m<sup>2</sup>, which included approximately 9000 m<sup>2</sup> of submerged plants. Suppose all of the plants should have the same capacity of adsorbing nitrogen and phosphorus as the AFI plants, they would account for 13.3% nitrogen and 89.3% phosphorus of the whole removal amount of the in situ purification system.

Actually, the hydrophytes on the river slope adsorb nitrogen and phosphorus from the soil instead of the water, and the submerged plants in water adsorb nitrogen and phosphorus directly from the sediment rather than the water (Mi et al., 2014; Zhao et al., 2012). Therefore, besides direct absorption, the synergistic effect produced by aquatic plants also plays an important role in the removal of pollutants (e.g. through photosynthesis and provide microorganisms a favorable environment).

Besides the process of biotransformation, physical and chemical processes also play an important role in the removal of pollutants. Watercourse at the inlet of the project was 80 m in width and became wider after that, with the maximum being 190 m. With the increase of width, the water flowed slowly and pollutants in the water coming from the upstream settled down in the river. This conclusion could also be proved by Fig. 2. Upon the completion of the dredging, the content of pollutants in the surface sediments dropped significantly. Two years later, however, wastewater from the upstream brought the TP, TN and COD back to a high level and even higher than those before the dredging. Therefore, dredging alone showed no obvious effect on the improvement of water quality. Despite the dredging project was began in Apr. 2010, the improvement of water quality in 2010 was much less satisfying than 2011 (Fig. 4). As the dredging was carried out in spring, the habitat for aquatic plants and microorganisms in the watercourse was damaged and the aquatic plants missed the best time for sprouting and growing. As a result, the growth of aquatic plants throughout 2010 was very poor (data not shown). Until 2011 when the project of hydrophytes restoration was implemented, the aquatic plants started to recover. Meanwhile, aquatic plants promoted the sedimentation of pollutants and improved water quality significantly (Fig. 4).

In light of the above discussion, the measures of pollutant interception, dredging, CWs, AFI or aquatic plants restoration alone seldom obtain satisfying achievement in pollutant removal. Only by taking biological, physical and chemical processes comprehensively into consideration and adopting integrated engineering actions can the water quality be improved effectively.

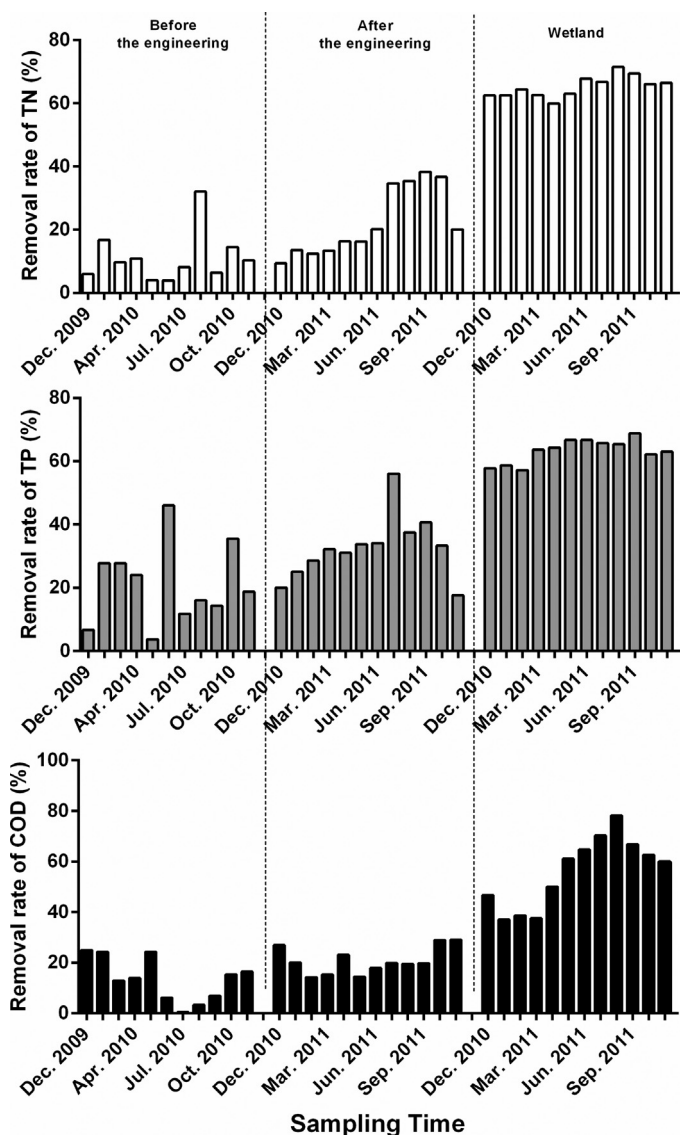


Fig. 6. Seasonal dynamics of removal rates of TP, TN and COD before and after the engineering.

#### 3.4. The seasonal variations of pollutants removal

Fig. 6 shows the seasonal dynamics of the pollutant removal rate in the whole area under the project in one year before and after its implementation, as well as in one year upon the operation of the CWs. Prior to the implementation, the area's removal rate of COD reached the maximum in winter and the minimum in summer, and the removal rate of TP and TN fluctuated largely on a monthly basis but varied uncorrelated to the season. After the implementation, the area's removal rate changed obviously with the season. It was minimal in winter and increased gradually to the maximum in summer for TP and TN. And the removal rate of COD grew obviously but changed in an identical way with that prior to the implementation.

As mentioned above, the eco-engineering increased the pollutant removal rate by 50.6–84.4%. Prior to the implementation, the amount of TP, TN and COD from the four flows of wastewater of the North Bank accounted for 5.6%, 6.9% and 6.1% respectively of the total nutrients input (Table S2). Therefore, the changes in pollutant removal rate after the implementation should be mostly caused by the in situ purification project rather than mainly influenced by CWs.

By virtue of the synergistic effects of physical, chemical and biological processes in the natural system, ecological treatment purify wastewater mainly through filtration, adsorption, coprecipitation, ion exchange, plant absorption and microorganisms decomposition (Kadlec, 2009; Tang et al., 2009). The biological processes are easily affected by season (or by temperature) for the change of season greatly influences plants' growth and microorganisms' activities. For example, the activity of this kind of process increases from spring to summer but decreases from autumn to winter, resulting higher pollutant removal rate in summer and autumn. Though showing the best effect of removing pollutants in summer and the worst in winter (Fig. 6), the multi-pond CWs kept a high efficiency in removing pollutants. Thus it could be deduced that besides the biological process, the physical and chemical processes, hardly affected by the temperature, played an important role as well in the CWs. In comparison, the effect of the in situ purification system for nitrogen and phosphorus removal in summer was obviously better than other seasons, which implied biological processes played a leading role (Bu and Xu, 2013). As for COD, impurities rich in organic matters were easily formed and released to the water column in summer when the temperature was high and aquatic organisms acted more intensively. As a result, COD in the water increased in summer and its removal rate fell down.

Therefore, those in situ treatment techniques, mainly exploiting the potential of aquatic plants and microorganisms, are easily influenced by season and can hardly remove nitrogen and phosphorus from water when temperature falls down. Contrastively, CWs are under less influence of temperature. When the plants and microorganisms work less effectively in removing pollutants due to the drop of temperature, the physical and chemical processes would function in the substrate and make compensation (Coleman et al., 2001; Hunter et al., 2001). Hence, to some extent, a combination of hydrophytes restoration and CWs is more suitable to reduce the impact of season change on water purification.

#### 4. Conclusion

This research illuminated the applicability of an integrated ecological technique to remediate a heavily polluted river. An ideal result of eutrophic river waters purification was obtained, which was closely related to the complex function of the engineering units of this project. The combined CWs technique is capable of disposing heavily polluted wastewater and its effect varies moderate to the change of season and remains relatively high all year round. Dredging is capable of removing the pollutants in sediments rapidly in a short term and reducing the potential risks of pollutants releasing to the water column, but such effect can be hardly kept if the external nutrient loading was not well dealt with. The in situ treatment technology relying on aquatic plants is capable of enhancing the self-purification capacity of the river as well as the stability of the ecosystem. However, it is easily affected by the season and its efficiency is lower than that of the CWs technique. Therefore, one single technique is insufficient to remediate the river. In order to enhancing water quality effectively and diminishing the influence posed by the change of season and environment conditions, combined techniques should be adopted based on the actual situation of the pollution of river and the features of each technique.

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#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecoleng.2016.06.003>.

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