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Comparison of semi-natural and constructed wetlands for agricultural wastewater treatment

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ABSTRACT

An experiment was carried out to assess the effectiveness of two different wetland systems in the treatment of agricultural wastewater. East River wetland is a semi-natural riparian wetland system, with three functional units, grit chamber, organic oxidation pond, and surface flow wetland unit. The functional units were planted with umbrella plant (*Cyperus alternifolius* L.), canna (*Canna indica* L.), calamus (*Acrorus calamus* L.), etc. Yaonigou wetland is a kind of constructed wetland, with different wetland plants. The wetland removed the significant amount and the degree of total suspended solids and biochemical oxygen demand (BOD), respectively, from agricultural wastewater. The results demonstrated that the effluent concentration of ammonia, nitrite, nitrate, and total nitrogen of East River riparian wetland increased in spring and summer, decreased in autumn and winter. On average removal rates for nitrogen compounds ranged from 70.45 to 97.59% for ammonia, 7.87 to 96.25% for nitrite, and 12.5 to 77.8% for nitrate, while the phosphorus removal rate was 56.0–89.90% for soluble phosphorus and 11.11–67.86% for total phosphorus. Comparatively, the purification efficiency of pollutants of Yaonigou wetland was better than East River riparian wetland. Most of the phosphorus concentrations in East River riparian wetland were very low due to the low concentration of influent agricultural wastewater. However, the phosphorus concentration of influent and effluent was high in Yaonigou wetland system. Significant difference was observed between the two wetland systems in relation to agricultural wastewater treatment. Based on these results, it may be concluded that the combined action of microbes and the plants residing in the constructive wetland was the effective for agricultural wastewater treatment.

Keywords: Wetlands; Water pollution; Nitrogen; Phosphorus

1. Introduction

Constructed wetlands are artificial wetlands designed to intercept wastewater and remove a wide range of pollutants before discharge into natural water bodies [1]. A wide range of pollutants such as biochemical oxygen demand (BOD), total suspended solids (TSS), nitrogen (ammonia, nitrite, nitrate, and total nitrogen (TN)), and phosphorus (total phosphorus

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(TP), phosphate) from wastewater can be removed with these natural technologies via microbial degradation, plant uptake, substrate adsorption, filtration by the packed media, and biological predation [2]. Constructed wetlands are widely used as low-cost alternatives to conventional tertiary municipal wastewater treatment worldwide [3]. Application of the wetlands to treat municipal wastewaters has been encouraged over the last few years [4]. The use of constructed wetlands also represents a relatively new approach for stormwater treatment [5]. Depuration of waters with wetlands is also attracting some interest for its potential application to agricultural wastewaters [6]. The effectiveness of constructed wetlands for tertiary treatment of effluent from a petroleum refinery, agricultural runoff, high salinity tannery wastewater, dairy wastewater, and landfill leachate was always evaluated [7–9].

The situation of most of the rivers in the north shore of Fuxian Lake deteriorated in the last decades due to long-term negligence because of population growth, agricultural emissions, and lack of adequate treatment and uncontrolled disposal of wastewater to the rivers [10]. Eutrophication can cause environmental degradation and also has significant economic impacts on lake creatures and municipal drinking water supplies [11,12]. Treatment wetlands can be designed to be semi-natural wetlands or constructed wetlands. Natural wetlands are at the most natural, low-energy end of the scale, and gravity-fed. Vegetation may be allowed to proceed by natural recruitment [13]. Constructed wetlands are higher energy wetlands and more highly engineered systems than natural wetlands.

With the aid of an engineered system that was constructed on north shore of Fuxian Lake, the treatment efficiency of non-point source wastewater was examined. The system was designed in a continuous flow configuration. In this study, two types of wetlands, East River riparian wetland and Yaonigou integrated wetland system, were monitored intensively to assess their performance in removing key pollutants of concern, and thus reducing the total pollutant load being delivered to Fuxian Lake. Besides an evaluation of the treatment performance of both wetland types, emphasis was put on some operational improvements proposed for the possible problems of wetlands functions.

2. Material and methods

2.1. The riparian wetlands

2.1.1. East River riparian wetland

East River riparian wetland was constructed and operated on the north shore of Fuxian Lake for sewage purification and natural landscape of riparian zone restoration. The wetland area is 26,000 m^2. The sewage treatment capacity of this wetland system is 15,000 $m^3 d^{-1}$ in dry period and 25,000 $m^3 d^{-1}$ in wet period, respectively. Hydraulic retention time of the wetland is 41 h in dry period and 22 h in wet period. The process flow diagram of the wetland treatment system is inflow → grit chamber → organic oxidation pond → surface flow wetland unit → gravel beach → outflow (Fig. 1). The effective purification area of grit chamber is 994 m^2. Its depth is 1.8–2.0 m. Mixed plantation is better than monoculture for effective pollutants treatment. The area of organic oxidation pond is 7,780 m^2, where the cress (*Oenanthe javanica* Bl. & DC.) and waterlily (*Nymphaea tetragona*) were cultured. The depth of organic oxidation pond is also 1.8–2.0 m. The area of surface flow wetland unit is 10,641 m^2. Its depth is 0.2–0.4 m, where the cress (*O. javanica* Bl. & DC.) and arrowhead (*Sagittaria sagittifolia*) were cultured and harvested. The area of gravel beach is 4,720 m^2, where umbrella plant (*Cyperus alternifolius* L.), canna (*Canna indica* L.) and calamus (*Acrorus calamus* L.) were cultured. The hydraulic loading ranged from 0.488 to 0.81 $m^3 m^{-2} d^{-1}$.

2.1.2. Yaonigou integrated wetland

The area of Yaonigou wetland is 15,000 m^2. The sewage treatment capacity of the wetland system is 3,520 $m^3 d^{-1}$ and hydraulic retention time is 72 h. The process flow diagram of the wetland treatment system is inflow → grille → biological purification tank →

Fig. 1. East River riparian wetland.

organic oxidation pond → subsurface flow wetland unit → surface flow wetland unit → outflow (Fig. 2). The treatment system received agricultural wastewater into a biological purification tank. The effective purification area of the biological purification tank area is 900 m^2 with the depth of 1.0–1.5 m, which reduced the organic and solids load on the receiving system. Then, the sewage flowed into an organic oxidation pond of a 4,660 m^2 areas and water depth of 1.5–1.8 m. The heart of the treatment system was subsurface flow wetland unit and surface flow wetland unit. The subsurface flow wetland unit was composed of four 15 × 15 m ponds, set in a row and continuous flow configuration, operating in parallel with a depth of 0.6 m filled with gravel or cinder and surface area of 900 m^2, where umbrella plant (*C. alternifolius*), reed (*P*hragmites australis), and cattail (*T*ypha latifolia) were cultured.

2.2. Sampling and analysis of agricultural wastewater

The experiments were carried out from April to November 2009 and November 2009 to January 2010. Influent and effluent samples were collected once a month for one year and thereafter on a monthly basis. There were no influent and effluent data in both wetlands from September to October 2009 and therefore no load reduction data. The results were related only two sampling points along the system: influent and effluent. Measurements at the East River riparian and Yaonigou integrated wetlands included the taking of samples for laboratory analyses of nitrogen and phosphorus compounds in agricultural wastewater. Parameters were measured including BOD, TSS, nitrogen (ammonia, nitrite, nitrate, and TN), and phosphorus (TP and soluble phosphate). BOD, TSS, nitrogen, and phosphorus were estimated by hydraulic load. The average hydraulic load was determined by volumetric method under per square meter per day. Water quality parameters were analyzed using conventional methods described in APHA-AWWAWPCF [14].

3. Results and discussion

3.1. Removal of organic matter (BOD)

Monthly concentrations (in mg L^{-1}) of BOD to the wetland system from the East River and Yaonigou Ditch are plotted in Fig. 3 (W1: East River wetland; W2: Yaonigou wetland). The influent and effluent concentration of BOD in East River wetland had 1.43–8.96 mg L^{-1} and 8–15 mg L^{-1}, respectively. The influent and effluent concentration of BOD_5 in Yaonigou wetland had 1.43–8.96 mg L^{-1} and 3.61–27.67 mg L^{-1}, respectively. Further removal of organic matter by these two wetlands was not efficient for eutrophication water body of low organic pollution and there was no significant difference between the two wetlands. A high removal capacity of BOD had mainly occurred in East River wetland system. Other researchers also reported that significant amount of BOD_5 removed by wetland systems [15].

Fig. 2. Yaonigou integrated wetland.

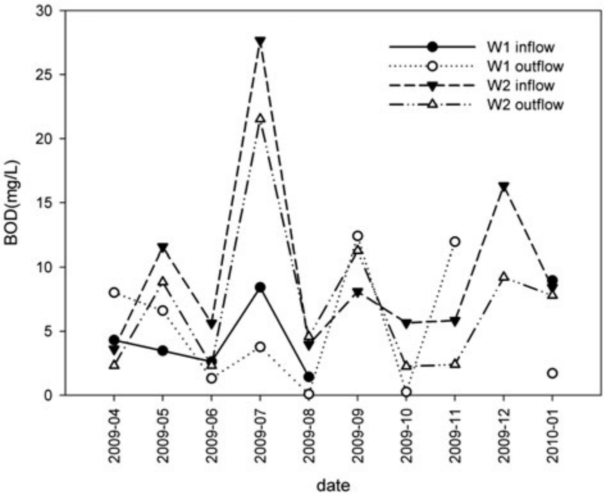

Fig. 3. Influent and effluent of BOD in these two wetland. (W1: East River wetland; W2: Yaonigou wetland).

3.2. Removal of SS

Fig. 4 shows much reduction of SS during the flow through the two wetlands. Influent SS mass loading to the East River wetland system was 15.0–96.0 kg d^{-1}. The wetland consistently reduced the SS concentration by 25.0–95.5% to 1.0–30 kg d^{-1}. Main mechanisms are filtration and settling, which would be expected to operate more effectively as retention time increase. The input loads of 7.0–181 kg d^{-1} to Yaonigou wetland gave an average loading of 55.5 kg d^{-1}, which was reduced to an average of 19.8 kg d^{-1}, equivalent to a removal of 7.1–99.9% of load.

These two kinds of wetland systems are composed of three or more functional units. SS removal is caused by multiple filtering, interception, and sedimentation. The influent SS loading was much higher in Yaonigou wetland than in East River wetland. There was no plants and filters units for the removal SS in the oxidation pond of Yaonigou wetland. On the contrary, the phytoplankton in the pond would increase SS effluent loading. A large number of agricultural wastes carried by the rivers were salvaged and cleaned up in biological purification tank before entering into the wetland unit. The amount of garbage salvage in these two wetlands is shown in Fig. 5. Monthly salvage quantity of floating garbage was 9,600–63,200 kg m^{-1} in the organic oxidation pond of East River riparian wetland. Average daily salvage quantity was the highest in June, exceeding 500 kg d^{-1}. Salvage quantity was significantly reduced from December 2009 to April 2010, which presented difference between dry season and rainy season.

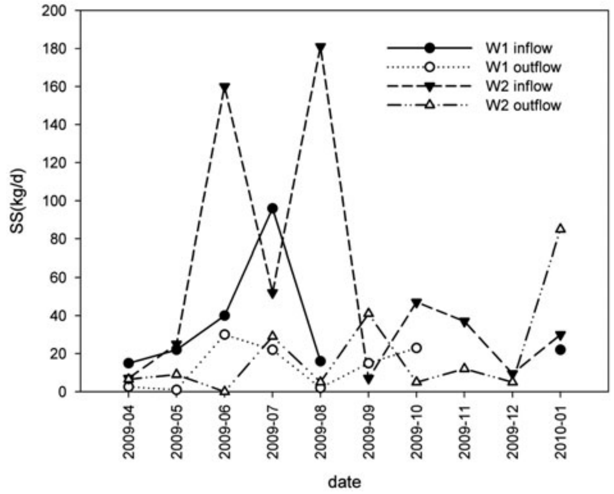

Fig. 4. Influent and effluent of SS in these two wetland. (W1: East River wetland; W2: Yaonigou wetland).

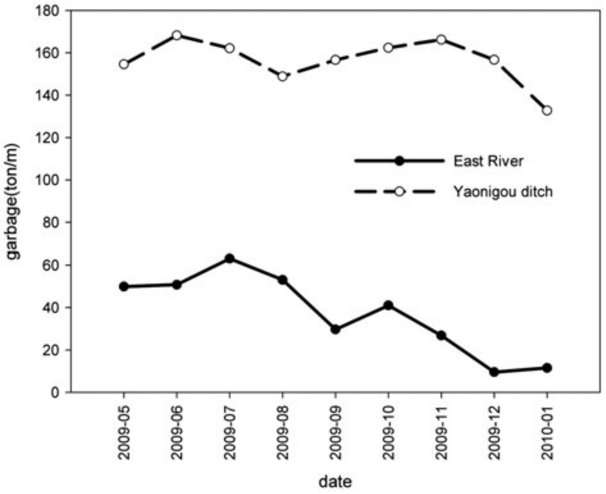

Fig. 5. Garbage in these two wetland.

There is the largest floating garbage carried by Yaonigou ditch among all the rivers on the north shore of Fuxian Lake. Monthly salvage quantity of floating garbage was 132,800–168,200 kg m^{-1} in biological purification tank of Yaonigou wetland, which joined from Yaonigou ditch to the wetland. Average daily salvage quantity was more than 2,500 kg d^{-1} in February and March 2010, which actually exceeded 4,000 kg d^{-1} during other studied months. Average daily salvage quantity of floating garbage was the largest in November 2009, which was close to 5,500 kg d^{-1}. The present results demonstrated that planted gravel filter dam with horizontal subsurface flow unit is a possibility to continuously reduce SS in the inlet of wetlands and to polish the effluent. The retention of phytoplankton was related to enhanced treatment of TN and TP during the whole year. Removal capacity of SS was higher in Yaonigou wetland system than Eastern River riparian wetland system. The characteristics of constructed wetlands are impacting resistance, stabilizing the effluent quality, simplifying operation and maintenance, and low operating cost. However, their floor spaces are larger and the wetlands exhibit higher pollutant removal rates under greater loading condition [16]. Previous literature results also indicated that the differences in the efficiency of wetland functioning which can be ascribed to a great number of variables. These are natural conditions (geographic, climatic, and hydrological) of the region, amount and quality of treated water, characteristics of substrate, hydrological system, type, characteristics of the aquatic plants, etc. [17].

3.3. Nitrogen removal

Several forms of nitrogen interact with wetland's environment. The principal species are ammonia, organic, and oxidized nitrogen. The Fuxian lakeside wetland system received water which dominated by ammonia, nitrite, and nitrate.

3.3.1. Ammonia (NH_3-N)

The influent and effluent of ammonia concentrations in two wetlands are shown in Fig. 6. The average ammonia concentration was less than 5 mg L^{-1} in East River wetland. Wetland consistently reduced the ammonia concentration by 0.13–1.18 mg L^{-1} to 0.02–1.04 mg L^{-1}. The removal efficiency of ammonia was 70.45–97.59%. In East River wetland, there was a positive correlation between effluent and influent concentrations of ammonia. Fig. 6 shows a little reduction of ammonia during the flow through the Yaonigou wetland. The influent and effluent concentrations ranged from 1.87 to 10.80 mg L^{-1} and 0.57 to 10.85 mg L^{-1}, respectively. The effluent ammonia concentrations were higher than influent from April to July, 2009. The monitoring concentrations of ammonia of the Yaonigou wetland were higher than those of influent in spring and summer. The removal efficiency of ammonia was favorable in autumn and winter. There is much less water, even no water in autumn and winter. Water flow is very slow. And hydraulic retention time of sewage in the wetlands is large. The removal efficiency of ammonia in autumn and winter is better than in summer and spring.

3.3.2. Nitrite/Nitrate (NO_2-N/NO_3^--N)

Figs. 7 and 8 show that the two wetlands reduced the nitrate and nitrite concentrations in wastewater. Nitrite and nitrate concentrations were reduced from influent of agricultural wastewater. The nitrate and nitrite removal were effective, also during winter periods. In the Yaonigou wetland, the influent concentrations of nitrite and nitrate had been below 0.2 and 6 mg L^{-1}, expect for individual concentration values. The influent and effluent of nitrite concentrations in the Yaonigou wetland were 0.023–0.544 mg L^{-1}, 0.028–0.443 mg L^{-1}; those of nitrate concentrations were 0.52–8.96 mg L^{-1}, 0.54–2.13 mg L^{-1}, respectively. The removal efficiencies of nitrite and nitrate were 63.33–87.90%, 81.7–93.3%, respectively.

Organic nitrogen in wastewater was transformed into ammonia by oxidative decomposition under the action of micro-organisms and then the ammonia was further removed through nitrification and denitrification processes. In spite of this, the nitrate concentration was increased. In East River wetland most of influent nitrate concentrations were less than 0.2 mg L^{-1}. The nitrite concentrations were slightly higher in Yaonigou wetland than in East River wetland. Nitrite was unstable in water. It was easily transformed into nitrate under certain conditions. The influent of nitrite and nitrate concentrations in East River wetland was 0.027–0.57 mg L^{-1} and 0.34–6.34 mg L^{-1}, respectively. The effluent of nitrite and nitrate concentrations was 0.001–0.121 mg L^{-1} and 0.091–4.75 mg L^{-1}, respectively. The removal efficiencies of nitrite and nitrate were 7.87–96.25% and 12.5–77.8%, respectively. In East River

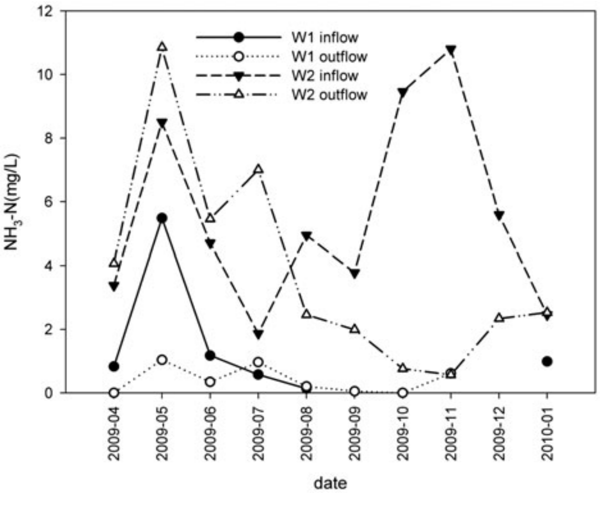

Fig. 6. Influent and effluent of NH_3-N in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

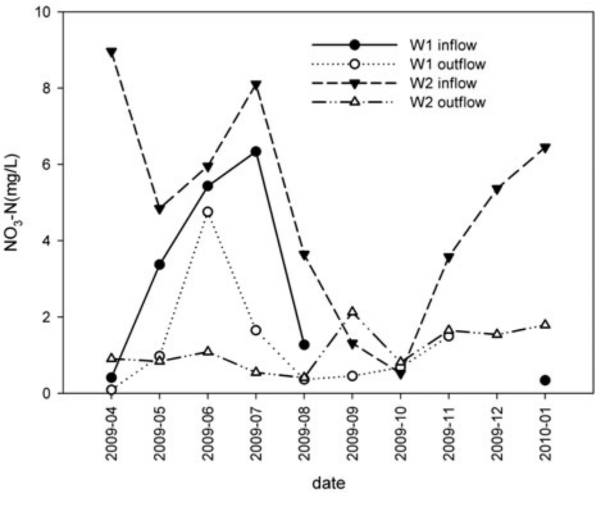

Fig. 7. Influent and effluent of NO_3-N in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

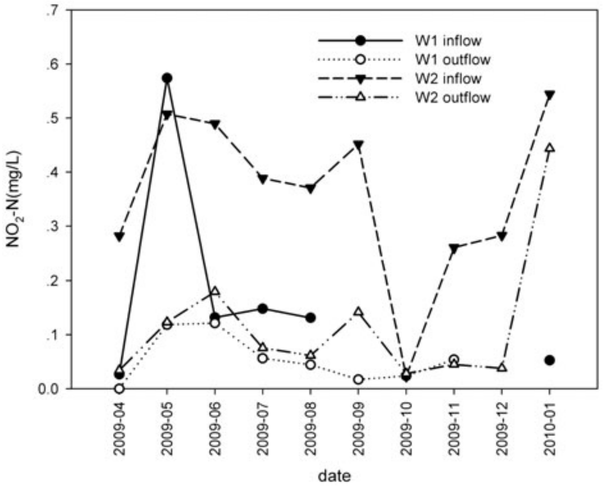

Fig. 8. Influent and effluent of NO_2-N in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

wetland most of influent nitrate concentrations were less than 4 mg L^{-1}. Nitrogen removal capacity was effective, especially for nitrate and ammonia.

3.3.3. Total nitrogen

Fig. 9 describes removal concentrations of TN from the wastewater. In East River wetland, the influent TN concentrations were 1.72–11.48 mg L^{-1}; the effluents were 0.23–4.17 mg L^{-1}. To compare the monitoring values in May, the effluent TN concentrations were only 0–3 mg L^{-1}. The average TN removal in the wetland system had been nearly 50%. In East River wetland, the TN removal efficiency in spring and summer was better than in autumn and winter. TN removal was carried by nitrification and denitrification process under the action of micro-organisms. In winter and autumn, the temperature was low, which affected microbial activity. The influent TN concentrations in Yaonigou wetland were 9.81–16.12 mg L^{-1}, relatively high. The effluent TN concentrations were 3.43–12.81 mg L^{-1}. TN removal in Yaonigou wetland was good.

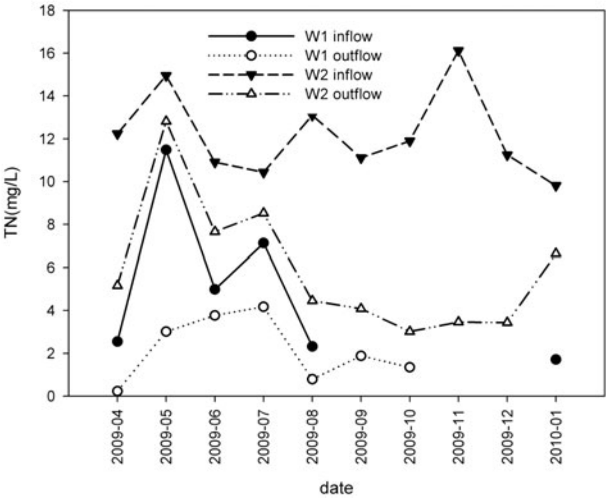

Fig. 9. Influent and effluent of TN in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

The results obtained during the one year of operation showed that Yaonigou wetland and East River wetland treatment systems had an excellent performance with respect to nitrogen removal from agricultural wastewater. High nitrogen (ammonia, nitrite, nitrate, and TN) removal had occurred in Yaonigou wetland systems. As a constructed wetland, its functional pools were made of concrete construction. Correspondingly, East River wetland is a kind of semi-natural riparian wetland. The treatment pond was built by using existing nature slopes and ridge. Therefore, the whole treatment system did not negatively affect the local ecosystem [18,19]. Significant amount of ammonia (84.02%) removal was observed in effluent of agricultural wastewater. In constructed wetland, nitrogen is removal via several pathways (plant uptake, nitrification, denitrification, and volatilization) that may start with the decomposition of organic nitrogen present in wastewater by heterotrophic bacteria and fungi to ammonia through ammonification process. This process may occur both in aerobic and aerobic environments, but is much faster under the former condition. Part of the produced (NH_4^+-N) uptake by cultured plants. Also, ammonia may be temporarily removed from the water column by binding to negatively charged sites on soil particles in the constructed wetland sediment through adsorption [20]. Ammonia is oxidized to nitrite (NO_2^-) and further to nitrate by bacteria nitrification bacteria. The transformation is generally completed within 5–6 d. Nitrate is not easily absorbed by the soil and it is easy to migrate through denitrification process. Denitrification is favored by anoxic conditions, high availability of organic carbon, high temperatures (optimum 60–75℃), and pH ranges of 6–8.5 [21]. The denitrification process means a one-way loss of nitrogen from a constructed wetland system. Ammonia nitrogen may also be lost to the atmosphere as ammonia gas (NH_3) through volatilization process from agricultural wastewater. Our results indicated that maximum influent NO_3^--N concentration was obtained from April to July 2009 but the effluent NO_3^--N concentration was very low during the entire experimentation periods side by side organic carbon content was very high due to vigorous growth of cultured plants. In this period, nitrate is transformed by bacteria through a denitrification process to nitrogen gas (N_2), which diffuses from the constructed wetland water surface and thus returns to the atmosphere [22–24]. Results also revealed that NH_4^+-N concentration in effluent was higher than influent from April to July 2009. Different reasons are involved for the enrichment of NH_4^+-N in constructed wetland systems which are as follows: organic nitrogen in agricultural wastewater is transformed into ammonia through ammonification. This process may occur both in aerobic and anaerobic environments. Ammonification took place through anaerobic condition in wetland system during this period. On the other hand, nitrification process is determined by an aerobic condition. The nitrification rates in a wetland are favored by oxic conditions, the availability of inorganic carbon, and NH_4^+-N as well as temperature and pH ranges of 30–40℃ and 7.5–8.0, respectively. Temperature was favorable for the vigorous growth of cultured plants. As a result, nitrogen transformation from NH_4^+-N to NO_3^--N was completely inhibited due to lack of nitrification process. Some researchers claimed that nitrification may still occur at dissolved oxygen (DO) levels down to about 0.3 mg L^{-1} [21]. However, more recent studies have indicated that oxygen levels of 1–2 mg L^{-1} in wetland water columns can decrease NH_4^+-N removal through lower nitrification rates because all nitrifying bacteria are aerobic nature [25]. Most plants are dormant and wilting during cold weather and have no capacity for absorbing nitrogen, which lead to reduce the nitrogen mitigation (NH_4^+-N uptake by plant) capacity of constructed wetlands in autumn and winter. The soil in the wetland has clogged severely after years of operation, especially in the subsurface wetland unit. Porous media provides attachment surface for plant and microbial communities and in gradients for bio-reactions as well as removing nitrogen by sedimentation, filtration and sorption of media. However, porous media cannot provide long-term stable the capacity of nitrogen removal due to their saturated adsorption, resulting in removing nitrogen from the media. On the other hand, soil porosity was so low that only topsoil was used to provide support for the microbial growth as carrier for biofilm. The water flowed through wetland surface and the capacity of oxygen exchange in the wetland was poor. The space for biofilm decreased significantly. The rate of nitrification processes is lower and unnoticed because of the low concentrations of nitrite and nitrate measured in the effluents and low DO (Fig. 10). The reduction of TN is the primary aim of nitrogen migration and transformation in the fields of this wetland system. Therefore, removal of nitrogen in the system is mainly due to plant uptake and sedimentation of organic matter [26].

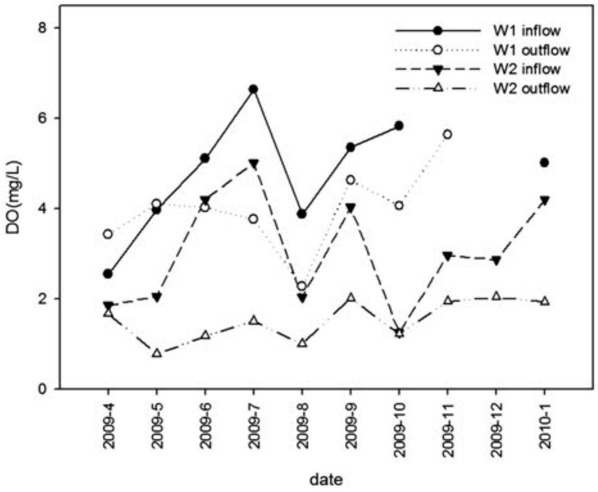

Fig. 10. Influent and effluent of DO in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

3.4. Phosphorus removal

Phosphorus removal mechanism in the wetlands includes fillers adsorption, plant uptake, and microbial assimilation. Bacteria and algae containing biological oxidation pond is another factor for excess phosphorus removed from the effluent. Sedimentation of organic matter and incorporation into biomass by the macrophytes might cause this effect. TP and phosphate removal in these two wetland treatment systems is presented in Figs. 11 and 12. The two wetland systems had performed excellent with respect to TP removal throughout the experimentation. The influent concentration of TP and phosphate in East River wetland was 0.10–0.51 mg L^{-1} and 0.065–0.23 mg L^{-1}, respectively. The effluent concentration of TP and phosphate was 0.06–0.23 mg L^{-1} and 0.047–0.26 mg L^{-1}, respectively. The removal efficiencies of TP and phosphate were 11.11–67.86% and 56.0–89.90%, respectively. Phosphorus did not consider as the major pollutant in the wetland systems due to low concentration in influent. But the amount of outflow phosphorus was more than the inflow phosphorus (negative elimination efficiency) which is caused by the release of phosphates. In some other studies, the release of phosphorus was reported under anaerobic conditions or during the reduction of incoming phosphorus. Another reason behind the increase in the outlet phosphorus in the main reactor in this study could be the death of cultured plants and the release of

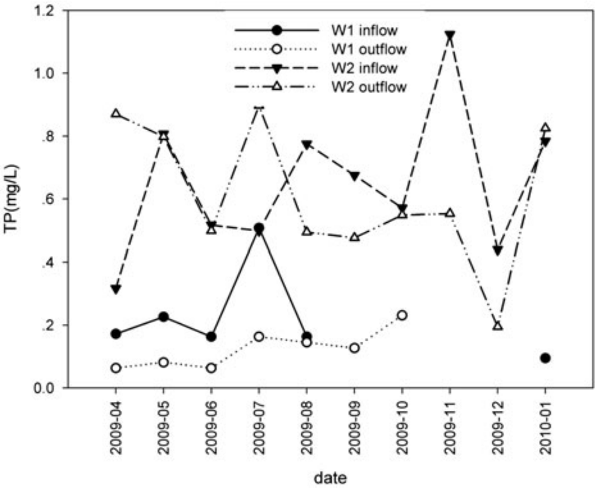

Fig. 11. Influent and effluent of TP in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

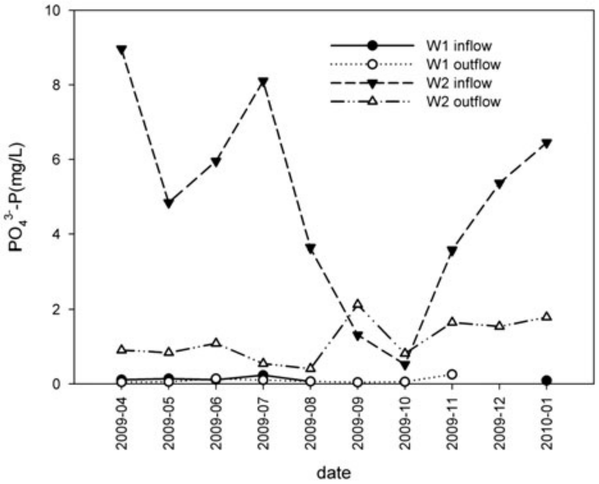

Fig. 12. Influent and effluent of PO_4-P in these two wetland (W1: East River wetland; W2: Yaonigou wetland).

phosphorus for the pieces of plants [27]. Under certain conditions, the phosphorus adsorbed on the surface of the soil was backed to the water in various ways, resulting in phosphorus loading increased. The reduction of effluent phosphorus and their compounds was not the primary target of the wetlands for the influent phosphorus concentration. However, results revealed that phosphorus concentrations (TP and phosphate) were removal from East river wetlands influent to the effluent. The reduction was stable throughout the period of one year. The influent and effluent concentrations of TP were slightly higher in the Yaonigou wetland than in the East River wetland. The influent concentrations of TP and phosphate in Yaonigou wetland were 0.32–1.12 $mg\,L^{-1}$ and 0.52–8.96 $mg\,L^{-1}$, respectively. The effluent concentrations of TP and phosphate were 0.19–0.90 $mg\,L^{-1}$ and 0.41–2.13 $mg\,L^{-1}$, respectively. Part of the data presented the phosphorus release in the wetland. An increase in effluent TP concentration up to 0.9 $mg\,L^{-1}$ in Yaonigou wetland was observed during the studied period, in January and July 2009, but the average effluent concentration was still lower than the local wastewater discharge limit of 0.5 $mg\,L^{-1}$. The soil was clogged and filter porosity decreased in the Yaonigou wetland after several years, operation, especially in the subsurface wetland unit. Sewage partly did not enter the filter layer of the wetland and flowed directly through the wetland surface. Soil adsorption is an important way for phosphorus removal, followed by plants and microorganisms. The soil and plant were both similar for the phosphorus purification capacity in these two types of wetlands. The wetland soil has already saturated adsorption after a long run.

3.5. Yearly pollutants reductions

The empirical design data used in wetlands for nitrogen, phosphorus, and COD are generally 10, 1, and 60 $g\,m^{-2}\,d^{-1}$ in China, respectively, when the hydraulic loading is 0.2 $m^{-2}\,d^{-1}$. Pollutants loadings in these two wetlands are shown in Table 1. East River wetland COD loading reduction was 37,140 $kg\,a^{-1}$ (3.91 $g\,m^{-2}\,d^{-1}$). The removal rate was 52.06%; TN loading reduction was 17,283 $kg\,a^{-1}$ (1.82 $g\,m^{-2}\,d^{-1}$). The removal rate was 52.09%; TP loading reduction was 515 $kg\,a^{-1}$ (0.05 $g\,m^{-2}\,d^{-1}$). The removal rate was 31.77%. Correspondingly, in Yaonigou wetland COD loading reduction was 24,402 $kg\,a^{-1}$ (46.48 $g\,m^{-2}\,d^{-1}$). The removal rate was 48.02%; TN loading reduction was 12,439 $kg\,a^{-1}$ (2.27 $g\,m^{-2}\,d^{-1}$). The removal rate was 48.30%; TP loading reduction was 450 $kg\,a^{-1}$ (0.08 $g\,m^{-2}\,d^{-1}$). The removal rate was 28.09%. Compared to the empirical values, TN went increasingly beyond the range. It showed that TN was the main important pollutant in the two wetlands.

4. Problems and improvements during wetlands operation

Wetland vegetation plays a major role in wetlands. Lush vegetation, huge biomass, timely harvest management, and vegetation renewal are the fundamental guarantees for water purification in the wetland systems. However, vegetation degradation is relatively common in the wetland treatment systems. Wetland vegetation was good in the early running, which was

Table 1
Pollutants loading in these two wetland

Wetland	COD_{Cr} ($kg\,a^{-1}$)		TN ($kg\,a^{-1}$)		TP ($kg\,a^{-1}$)	
	Loading	Loading reduction	Loading	Loading reduction	Loading	Loading reduction
East River wetland	71,339	37,140	33,181	17,284	1,621	515
Yaonigou wetland	50,816	24,403	25,753	12,439	1,601	450

severely degraded or absent in the operation and maintenance process for various reasons. For example, the plant is not timely replanted after death in winter; the dominant species is replaced by others naturally during plant growth process, seasonal plants growth, mismanagement, etc. Vegetation with high purification performance in the biological oxidation pond of East River wetland did not consider carefully during the construction of wetlands. In addition, East River wetland is a riparian wetland of high-water level. The effluent discharged directly to Fuxian Lake. Several drainage ditches were covered up by the sand and gravel blown up by the wind and waves of the lake beach. Wetland effluent is not easy to discharge into the lake, for the reason that wetland flow is not uniform. In addition, flood discharge gate on the entrance to the wetlands resulted in solid contaminants into the lake and reduced the removal efficiency of SS. Some improvements are needed to make on sedimentation tank in the East River estuary.

Arch dam is selected to replace the river sluice. Diversion tank should be increased for all sewage precipitation treatment and improvement of solid pollutant removal. In addition, dredge and transformation of the wetland drainage system should also be carried on. Drainage ditches in the bottom of wetland outlet should be dug as cross-section of 2,000 × 500 mm (effluent weir to the bottom as datum), using natural slope. Narrow leaf cattail should be planted in the gullies. Operation and management of Yaonigou wetland will be in good condition through these improvements.

5. Conclusion

The results obtained during this one year of operation showed that Yaonigou wetland and East River wetland treatment systems had an excellent performance with respect to all constituents of pollutants besides individual water quality parameters. A high removal capacity of BOD and SS had mainly occurred in East River wetland system. However, high nitrogen removal has occurred in Yaonigou wetland. As a constructed wetland, its functional pools were made of concrete construction. Correspondingly, East River wetland is a kind of semi-natural riparian wetland. The treatment pond was built by using existing nature slopes and ridge. Therefore, the whole treatment system did not negatively affect the local ecosystem. During summer and winter, the consumed oxygen is mainly used for the heterotrophic metabolism of organic compounds. This resulted in ammonia elimination by the wetland of nearly 20% in summer and half of this in winter. Also, a continuous reduction of TN and TP was measured during the whole year, mostly higher in fall. This might be an effect of the phytoplankton's death and sedimentation in the wetland during fall. Another factor at which both wetlands may differ was the release of components during degradation of dead plant material. In the Yaonigou wetland, the standing biomass was removed timely in the past and as such no decaying plant build-up was present.

Microbial removal of pollutants is a very important pathway for several contaminants. Because of the difference in age and process units between both wetland types, a difference in biofilm development may be present. At the start of the experiments, both wetland types had an actual age of five years (Yaonigou wetland) and three years (East River wetland). Although East River wetland was much younger, it can be expected that in both used wetland types, a stable microbial community was present and that gravel, submerged plant parts, soil surface and the water column were completely colonized by biofilms. Subsurface flow wetland unit and surface flow wetland unit were involved in Yaonigou wetland. Correspondingly, there was only surface flow wetland unit in East River wetland. The gravel in the subsurface flow wetland unit was more important in removal of P than the soil substrate in the surface flow wetland unit. The gravel in the subsurface flow wetland unit has a higher adsorption capacity than the soil and provides a larger contact area as water flows within the gravel substrate rather than on top of the soil surface.

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References

[1] A.B. Pérez-Marín, M. Lloréns, M.L. Aguilar, J. Sáez, J.F. Ortuño, V.F. Meseguer, A. López-Cabanes, An innovative technology for treating wastewater generated at the University of Murcia, Desalin. Water Treat. 4 (2009) 69–75.

[2] T. Saeed, G.Z. Sun, A comparative study on the removal of nutrients and organic matter in wetland reactors employing organic media, Chem. Eng. J. 171 (2011) 439–447.

[3] A.K. Kivaisi, The potential for constructed wetlands for wastewater treatment and reuse in developing countries: A review, Ecol. Eng. 16 (2002) 545–560.

[4] A.O. Abbas, F. Manar, Treatment of domestic wastewater by subsurface flow constructed wetlands in Jordan, Desalination 155 (2003) 27–39.

[5] D.P. Mungasavalli, T. Viraraghavan, Constructed wetlands for stormwater management: A review, Fresen. Environ. Bull. 15 (2006) 1363–1372.

[6] P. Mantovi, M. Marmiroli, E. Maestri, S. Tagliavini, S. Piccinini, N. Marmiroli, Application of a horizontal subsurface flow constructed wetland on treatment of dairy parlor wastewater, Bioresour. Technol. 88 (2003) 85–94.

[7] S.L. Lansing, J.F. Martin, Use of an ecological treatment system (ETS) for removal of nutrients from dairy wastewater, Ecol. Eng. 28 (2006) 235–245.

[8] C.S.C. Calheiros, P.V.B. Quitério, G. Silva, L.F.C. Crispim, H. Brix, S.C. Moura, P.M.L. Castro, Use of constructed wetland systems with Arundo and Sarcocornia for polishing high salinity tannery wastewater, J. Environ. Manage. 95 (2012) 66–71.

[9] Y.C. Chen, S.L. Lo, Y.C. Lee, Distribution and fate of perfluorinated compounds (PFCs) in a pilot constructed wetland, Desalin. Water Treat. 37 (2012) 178–184.

[10] N. Ran, M. Agami, G. Oron, A pilot study of constructed wetlands using duckweed (*Lemna gibba* L.) for treatment of domestic primary effluent in Israel, Water Res. 38 (2004) 2241–2248.

[11] J.A. Camargo, A Alonso, Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment, Environ. Int. 32 (2006) 831–849.

[12] S.E. Rosenquist, W.C. Hession, M.J. Eick, D.H. Vaughan, Variability in adsorptive phosphorus removal by structural stormwater best management practices, Ecol. Eng. 36 (2010) 664–671.

[13] R.H. Kadlec, Comparison of free water and horizontal subsurface treatment wetlands, Ecol. Eng. 35 (2009) 159–174.

[14] APHA-AWWA-WPCF, Standard Methods for the Examination of Water and Wastewater, 19th ed., American Public Health Association, Washington, DC, 1995.

[15] M.H. George, W.B. Gillespie, J.H. Rodgers, Using constructed wetlands to treat biochemical oxygen demand and ammonia associated with a refinery effluent, Ecotoxicol. Environ. Safe 45 (2000) 188–193.

[16] X. Song, Q. Li, D. Yan, Nutrient removal by hybrid subsurface flow constructed wetlands for high concentration ammonia nitrogen wastewater, Procedia Environ. Sci. 2 (2010) 1461–1468.

[17] R.H. Kadlec, S.D. Wallace, Treatment Wetlands, 2nd ed., CRC Press, Boca Raton, FL, 2009.

[18] L.J. Nokolic, S. Stojanovic, D. Lazic, Role of reed (*Phragmites australis* (Cav.) Trin. ex Steud.) in the process of treatment of municipal wastewaters using constructed wetland systems, Contemp. Agric. 51 (2007) 230–235.

[19] M. Greenway, The role of macrophytes in nutrient removal using constructed wetlands, Environ. Biorem. Technol. (2007) 331–351.

[20] W.J. Mitsch, J.G. Gosselink, Wetlands, 3rd ed., Wiley, New York, NY, 2000.

[21] K.R. Reddy, W.H. Patrick, Nitrogen transformations and loss in flooded soils and sediments, Crit. Rev. Environ. Control 13 (1984) 273–309.

[22] M.A. Mallin, J.A. McAuliffe, M.R. McIver, D. Mayes, M.A. Hanson, High pollutant removal efficacy of a large constructed wetland leads to receiving stream improvements, J. Environ. Qual. 41 (2012) 2046–2055.

[23] G. Sun, Y. Zhu, T. Saeed, G. Zhang, X. Lu, Nitrogen removal and microbial community profiles in six wetland columns receiving high ammonia load, Chem. Eng. J. 203 (2012) 326–332.

[24] J. García, D.P.L. Rousseau, J. Morató, E. Lesage, V. Matamoros, Contaminant removal processes in subsurface-flow constructed wetlands: A review, Crit. Rev. Environ. Sci. Technol. 40 (2010) 561–661.

[25] T.O. Okurut, G.B.J. Rijs, J.J.A. Vanbruggen, Design and performance of experimental constructed wetlands in Uganda, planted with and, Water Sci. Technol. 40 (1999) 265–271.

[26] N. Ran, M. Agami, G. Oron, A pilot study of constructed wetlands using duckweed (*Lemna gibba* L.) for treatment of domestic primary effluent in Israel, Water Res. 38 (2004) 2241–2248.

[27] E. Asghar, T. Ensiyeh, H.E. Mohammad, N Sara, J. Fatemeh, S. Rahele, F. Ali, Efficiency of constructed wetland vegetated with *Cyperus alternifolius* applied for municipal wastewater treatment, J. Environ. Public Health 2013 (2013) 1–5. doi: 10.1155/2013/815962