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Feasibility Study on Using Constructed Wetlands for Remediation of A Highly Polluted Urban River in A Semi-Arid Region of China

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ABSTRACT

In semi-arid regions, dry climate and insufficient rainfall brings about limited base flow in river channels. For some urban rivers, treated and untreated domestic wastewater and industrial effluent may become the main flow. In order to improve the urban water environment, a large pilot constructed wetland (CW) system was constructed on the bank of an urban river in Xi'an. With a total area about 8000 m^2, the pilot CW system was put into operation for two years at an average flow rate of 362 m^3/d. The influent water from the urban river contained high concentrations of COD (350.9 ± 29.4 mg/L), BOD_5 (125.6 ± 11.4 mg/L), NH_3-N (27.2 ± 1.8 mg/L), TN (38.5 ± 1.7 mg/L), and TP (3.9 ± 0.3 mg/L). In the two years of operation, the overall COD, BOD_5, NH_3-N, TN and TP removals were 74.5%, 94.4%, 57.5%, 56.3% and 69.2%, respectively. Moreover, the removal rates of SS, COD, BOD_5 and TP showed linear positive correlations with the inflow loading. Finally, higher removal was achieved as T >15˚C for each of the pollutants, but the influence of water temperature was different for different substances pollutants. The high efficiency of the CW system for the improvement of the inflow water quality from such a highly polluted urban river provided practical evidence of the applicability of the CW technology for protecting urban water environment.

Keywords: Constructed wetland; urban river; pollutant removal; water quality

1. INTRODUCTION

Since the 1990s, China has experienced booming economy and rapid urbanization, along with the growing quantity and expanding distribution of wastewater (Upadhyay et al., 2016). As one of the main functions of urban river is to serve as drainage channel, most of treated and untreated domestic sewage, industry effluents and agriculture runoff were finally discharged into urban rivers, which lead to the pollution of the ultimate receiving water body (Zheng et al., 2016). This phenomenon is much more severe in the regions where wastewater treatment systems were insufficient and/or with arid and semi-arid climate. Therefore, in order to improve the urban water environment, the improvement on urban river water quality is currently an urgent task in

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China. Such measures as increased coverage of urban sewage/drainage systems, construction of new urban wastewater treatment facilities and upgrading of existing treatment facilities were taken lately. However, these methods either result in huge costs, or insufficiently treated water.

Constructed wetlands (CWs) are engineered systems that have been designed and constructed for treating wastewater by simulating the processes of natural wetlands (Cooper, 2009; Kadlec and Wallace, 2008). CWs can be typically constructed as free water surface (FWS), horizontal subsurface flow (HSSF) and vertical flow (VF) systems (IWA, 2000; Kadlec and Wallace, 2008). Nevertheless, there has been a growing interest in the development of hybrid systems in which different types of CWs are combined to complement each other to achieve more efficient pollutants removal from wastewater. A number of biological, physical and chemical processes integrating in wetland vegetation ecology, substrate, and associated microbial communities assist pollutants removal (Song et al., 2006; Zhang et al., 2009). CWs have been used to treat a variety of wastewater successfully worldwide (Baddam et al., 2016; Kadlec and Wallace, 2008; Lu et al., 2016; Wu et al., 2015). However, there are quite few studies that focus on the use CWs for on-site river water improvement especially in large scale. Experience seems lacking in adopting the system configuration, loading and seasonal change of performance, in particular, in the polluted urban rivers in arid and semi-arid regions.

Xi'an is located in the northwest of China, a typical semi-arid city. Dry climate and insufficient rainfall brings about limited base flow in river channels. The flood lands along the urban rivers can be developed into CWs to treat the polluted river water, stabilize riverbank and maintain stability of river ecological system integrity. However, the design and operation of CWs are based mainly on rules of thumb approaches and various types of CWs have their own characters. Zaohe River is a river in Xi'an that currently mainly function as an urban drainage channel to receive treated and/or untreated domestic effluent and industrial wastewater (Jin et al., 2008). In order to improve the water quality of Zaohe River, a large pilot-scale CW on-site experimental system with different combinations of surface- and subsurface-flow stages were constructed and operated. The objectives of the study were 1) to examine the efficiency and capacity of the pilot CW system to improving the water quality of highly polluted urban river; 2) to evaluation the effect of water temperature on the removal efficiency of the CW system; 3) to provide practical evidence of the applicability of the CW technology for protecting urban water environment in a semi-arid region.

2. MATERIALS AND METHODS

2.1 Pilot CW system construction

The pilot CW system was constructed at the eastern bank of the Zaohe River (34˚22'54"N, 108˚51'05"E). The climate condition of the CW system site is cold and lack of rain in winter, contrary to summer, the yearly mean temperature is about 13.1-14.3˚C, with an average precipitation of 500~750 mm. The total area of the CW system is about 8000 m^2, which included five free water surface (FWS) CWs and four subsurface flow (SSF) CWs (Fig. 1), the detailed description of the composition was described by Zheng et al. (2016). Local gravel, slag and sand were used as substrates for the pilot CW system, because these media are abundant in the basin area of the Zaohe River. For the SSF cells, gravel and slag were filled with a depth of 60 cm while the water depth was 55 cm. The particle size ranging from 1-70 mm and the initial porosity was 50%. For the FWS cells, sand was filled with a depth of 35 cm while the water depth was 40 cm. The particle size ranging from 0.06-10 mm and the initial porosity was 30%. Two species plants: *Phragmite saustralis* and *Typha orientalis* which collected from the bank of the Zaohe River were planted equally in the CW system with a density of 9 plants/m^2. The construction of the pilot CWs was completed in August 2010.

2.2 Operation and management

Prescreened wastewater pumped from the Zaohe River was sediment and store at an elevated feeding tank (56 m^3) at the beginning of the pilot CW system. This wastewater was then distributed to the pilot CW system by gravity; the constant inflow rate of the system was 362 m^3/d which corresponded to an average hydraulic retention time (HRT) of 3.6 days and an average surface loading of 0.053 m/day. The treated water from this system flowed into the effluent trench (300 m^3) before being discharged back into the downstream (Fig. 1). After three months' stabilization period, the system was turned to continuous operation from November 2010. Furthermore, during the experimental period, the plants grown in the wetland system were harvested in every November by cutting at about 20 cm above the wetland bed surface.

2.3 Description of the polluted urban river

Zaohe River, flows through Xi'an City, its entire length is 22.3 km and the average drainage area is 135 km^2. Due to climate change and the current main function of the Zaohe River, wastewater has become to the major part of the river flow. According to our long-term monitor from November 2010 to November 2012 on the quality of the river water (Table 1), it indicated the Zaohe River was seriously polluted. Moreover, during the two years' monitor, the pH value and the DO concentration of the river water were less fluctuation, which was with an average of 7.6 and 0.54 mg/L, respectively. The temperature of the river water was ranging from 6.8 to 30.3˚C, with an average of 19.4˚C.

2.4 Sampling and chemical analysis

During the experimental period from November 2010 to November 2012, water samples were collected weekly from the influent and effluent of the pilot CW system. The water samples were sent to the laboratory for chemical analyses within 24 h regarding suspended solids (SS), organic contents (COD and BOD_5), ammonia nitrogen (NH_3-N), total nitrogen (TN), nitrite (NO_3^-), nitrate (NO_2^-) and total phosphorus (TP). Standard methods were referred for the chemical analyses (MEPC and WWMAA, 2002). Water temperature, pH and dissolved oxygen (DO) were measured by a DO Meter (HQ30d53LED™, HACH, USA).

2.5 Statistical analysis

The removal efficiency of the pilot CW system was calculated from the difference in concentration between the influent and effluent of the system. All statistical analysis were performed with the SPSS 20.0 (SPSS Inc., Chicago, USA), statistical tests were considered as significant when $p < 0.05$.

Figure 1 Satellite view of the pilot constructed wetland (CWs) system

Table 1 Pollutants concentrations and the overall removals by the pilot CW system during the experimental period. Mean ± S.D.

	SS	COD	BOD_5	NH_3-N	TN	NO_3^-	NO_2^-	TP
Influent (mg/L)	334.2±43.6	350.9±29.4	125.6±11.4	27.2±1.8	38.5±1.7	0.5±0.1	0.1±0.04	3.9±0.3
Effluent (mg/L)	22.4±7.6	74.5±7.3	6.7±1.0	11.4±1.2	16.4±1.3	1.4±0.3	0.2±0.04	1.1±0.1
Removal (%)	92.0	74.5	94.4	57.5	56.3	-	-	69.2

3 RESULTS AND DISCUSSION

3.1 Pilot CW system efficiency for pollutants removal

Table 1 presents influent and effluent concentrations, respective removal efficiencies for organic, nitrogen, phosphorus and SS for the entire operation period. Fig. 2 presents influent and effluent concentration charts during the entire operation period. The results indicated that the river water was highly polluted and the pollutants concentrations were fluctuated widely during the experimental period, however, the performance of the pilot CW system was still highly efficient.

3.1.1 Organic matter

Excellent BOD_5 treatment capacity was observed at the effluent of the CW system, with removal efficiency about 94.4% (Fig. 2b). Moreover, the BOD_5 removal rate increased linearly with the inflow loading in the range of 0-34 $g/m^2 \cdot d$ (Fig. 3b). This is mostly due to the intensified biological metabolism at greater loading (Saeed and Sun, 2011). According to Fig. 2a, the COD concentration of the effluent was decreased after the first 6 months, as the plants in the wetland required several months to get stable. The COD removal rate also showed linear positive correlation with the inflow loading in the range of 0-14 $g/m^2 \cdot d$ (Fig. 3a), and some similar removal tendencies were found with quite different inflow loading rates (Doherty et al., 2015; Xu et al., 2014). However, comparing with the literature on wetland systems for wastewater treatment (Vymazal, 2005), the BOD_5 removal in this study was at a high level but the COD removal was relatively ordinary. This could be explained by the low BOD_5/COD ration (0.36), which lead to a poor biodegradability of the organic substances in the influent.

3.1.2 Suspended solids

Similar to the organic matter, high removal efficiency was also observed for SS with mean value of 92% (Table 1). The removal efficiency was similar to those reported by other authors (Rozema et al., 2016). Replanting would be the reason for the fluctuation of the SS during the first spring (Fig. 2c). Moreover, the SS removal rate significantly increased with the loading rate in the range of 0-42 $g/m^2 \cdot d$ (Fig. 3c). A similar relationship was also reported by Xu et al. (2014) with a similar inflow loading range. The explanation of this phenomenon may be that the sedimentation, filtration and microbial degradation processes responsible for SS removal were achieved well in this pilot CW system (Kadlec and Wallace, 2009).

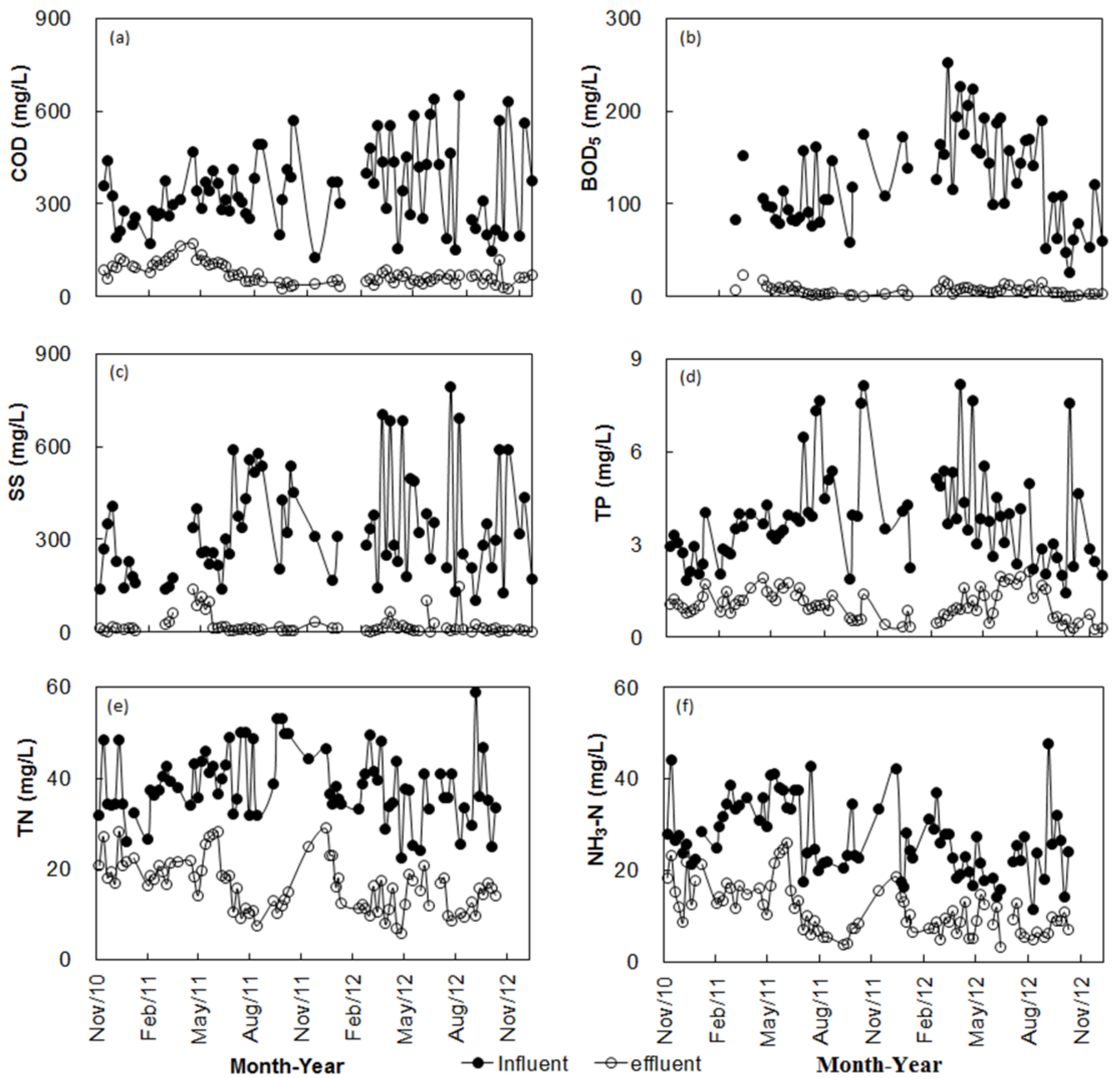

Figure 2 Concentrations of: (a) COD; (b) BOD_5; (c) SS; (d) TP; (e) TN; (f) NH_3-N in the pilot CW system during the experimental period

3.1.3 Phosphorus

Compared with organic matter and SS, the removal efficiency of the TP was moderate. However, it was still at a high level compared to that reported in other previous studies (Calherios et al., 2009; Vymazal, 2005) (Table 1). The TP concentration increased slightly during the second summer period (Fig. 2d). Furthermore, the TP removal rate increased with the inflow loading as well (Fig. 3). This could be explanation by the presence of high sorption sites for P precipitation and adsorption into the substrates, which are the main removal mechanism of TP in CWs (Blanco et al., 2016), and the pilot CW system is young and not clogged.

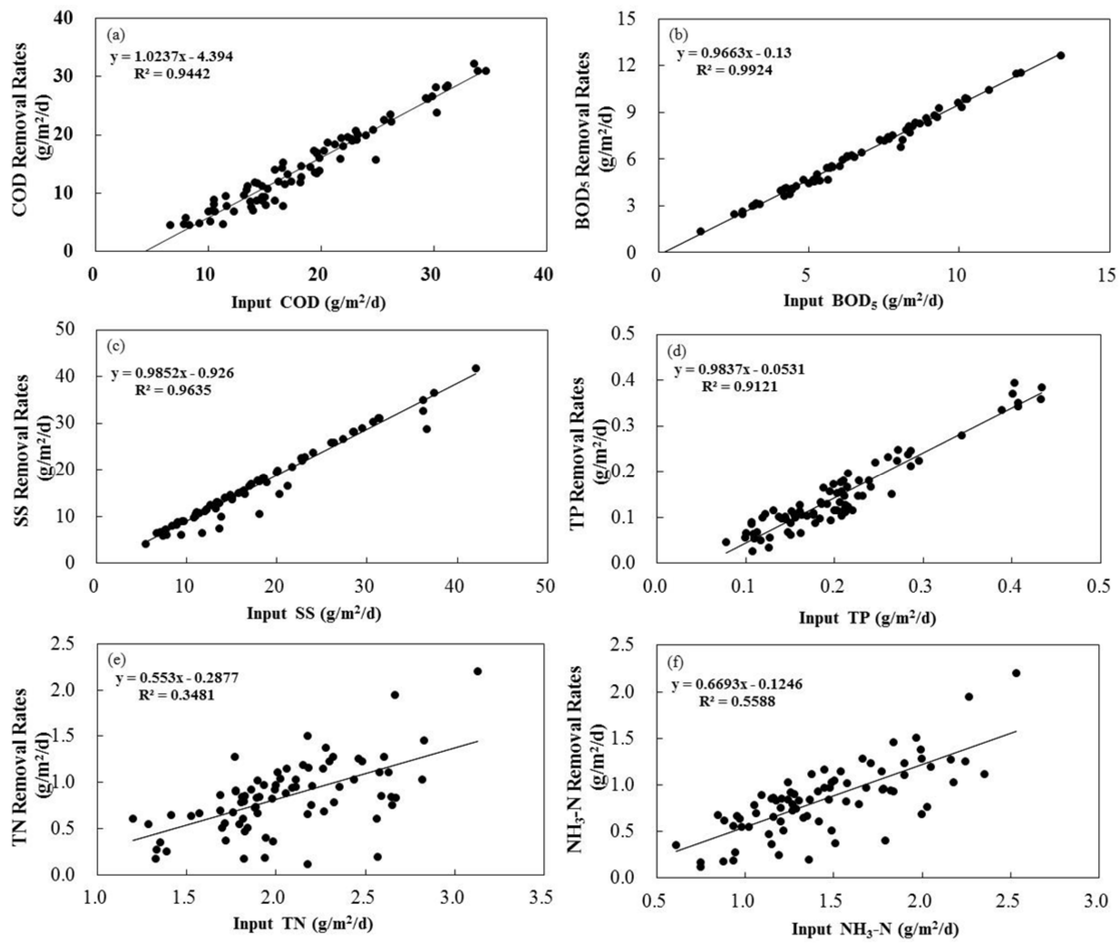

Figure 3 Correlation charts between input loading and removal rates for: (a) COD; (b) BOD_5; (c) SS; (d) TP; (e) TN; (f) NH_3-N

3.1.4 Nitrogen

During the experimental period, in both of influent and effluent, NH_3-N always took about 70% of TN and the concentrations of NO_3^--N and NO_2^--N were quite low (Table 1). Moreover, the pilot CW system removed 57.5% of NH_3-N and 56.3% of TN, indicated that this pilot CW system could be achieved nitrification and denitrification at the same time and the nitrification was the restrict step for nitrogen removal. The removal efficiency of the nitrogen fluctuated obvious (Fig. 2e, f), also, the removal rate was slightly positive with the inflow loading (Fig. 3e, f), indicated that the inferior performance of nitrogen removal in this pilot CW system and the growth rate of the nitrification microorganism was lower than the heterotrophic microorganism. As the biological nitrification-denitrification is the main mechanism responsible for the nitrogen removal in CWs (Fan et al., 2016).

3.2 Influence of water temperature

In order to evaluate how water temperature influences the removal of various pollutants, 15˚C was chosen as a critical temperature to differentiate high water temperature (T >15˚C) and low water temperature (T <15˚C) periods. This temperature value has been selected as a limit above which the bacteria responsible for nitrogen transformation, as well as the vegetation, function properly (Kuschk et al., 2003). Fig. 4 compares the removals of pollutants in the two periods. Generally, higher removal was achieved as T >15˚C for each of the pollutants but the influence of water temperature was different for different substances pollutants. The SS removal tended to be much less temperature dependent than the other pollutants while the influence of water temperature was very strong for the removal of NH_3-N (62.8% as T >15˚C vs. 43.4% as T <15˚C) and followed by the removals of COD (76.7% vs. 61.6%), TN (57.3% vs. 45.8%), and TP (70.2% vs. 61.1%). The influence of water temperature on the removal of BOD_5 (93.6% vs. 87.8%) was not as strong as the former parameters, possibly due to the high proportion of biodegradable organic matter in the stream water. The influence of water temperature on pollutants removal would be mainly caused by the variation in the activities of microorganisms and plants in the CW beds (Kuschk et al., 2003; Zheng et al., 2015).

3.3 Implications for management

This study was used to investigate the feasibility of using CW system for on-site polluted urban river water improvement. Based on the findings from the two-year operation of the pilot CW system, some initial recommendations for full-scale CWs in semi-arid region for highly polluted urban river water are presented here. From the discussions in the former sections, it is understood that the pilot CW system could provide an improvement of the polluted river, and the removal of SS and organic substances in the CW system were quite high and stable. However, as an effective nitrogen removal depends on a good nitrification-denitrification condition, the provision of aerobic zones with oxidized condition for nitrification and anoxic and / or anaerobic zones with reductive condition for denitrification becomes necessary (Green, 1996). Furthermore, since the polluted urban river water always contains large quantities of suspended substances (SS and suspended COD and BOD), there is always a fear of clogging of the substrate bed. Comparing with SSF CWs, the FWS CWs, which are not prone to bed clogging are and are more suitable to be placed in the first stage in CW system. Thus, a combination of surface- and subsurface-flow CWs to form a CW system may be a good solution especially from the viewpoint of effective nitrogen removal. However, it would be more plausible that the surface-flow stage be placed prior to the subsurface-flow stage to provide a condition for sequential nitrification and denitrification. Finally, for the removal of phosphorous, the selection of a suitable substrate type is important (Vymazal, 2007).

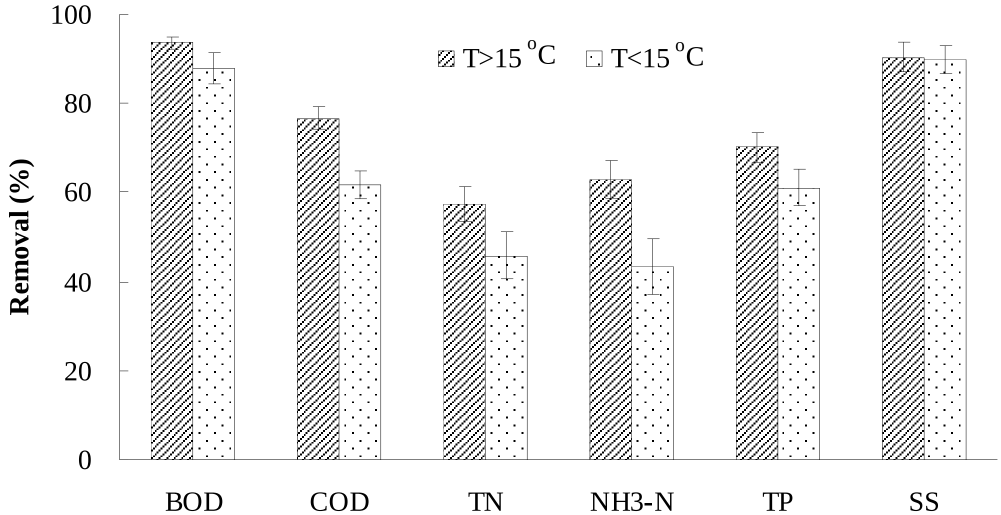

Figure 4 Comparison of pollutants removals by CW system in high water temperature and low water temperature periods

CONCLUSIONS

Over the two-year operation, the large pilot CW system significantly improved the water quality in the highly polluted urban river. The influent water from the urban river contained high concentrations of COD (350.9±29.4 mg/L), BOD_5 (125.6 ± 11.4 mg/L), NH_3-N (27.2 ± 1.8 mg/L), TN (38.5 ± 1.7 mg/L), and TP (3.9 ± 0.3 mg/L). The overall COD, BOD_5, NH_3-N, TN and TP removals achieved about 74.5%, 94.4%, 57.5%, 56.3% and 69.2%, respectively. Moreover, the removal rates of SS, COD, BOD_5 and TP showed linear positive correlation with the inflow loading. Finally, higher removal was achieved as T >15˚C for each of the pollutants, but the influence of water temperature was different for different substances pollutants. Thus, the high efficiency of CW system for the improvement of the inflow water quality from such a highly polluted urban river provided practical evidence of the applicability of the CW technology for protecting urban water environment.

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