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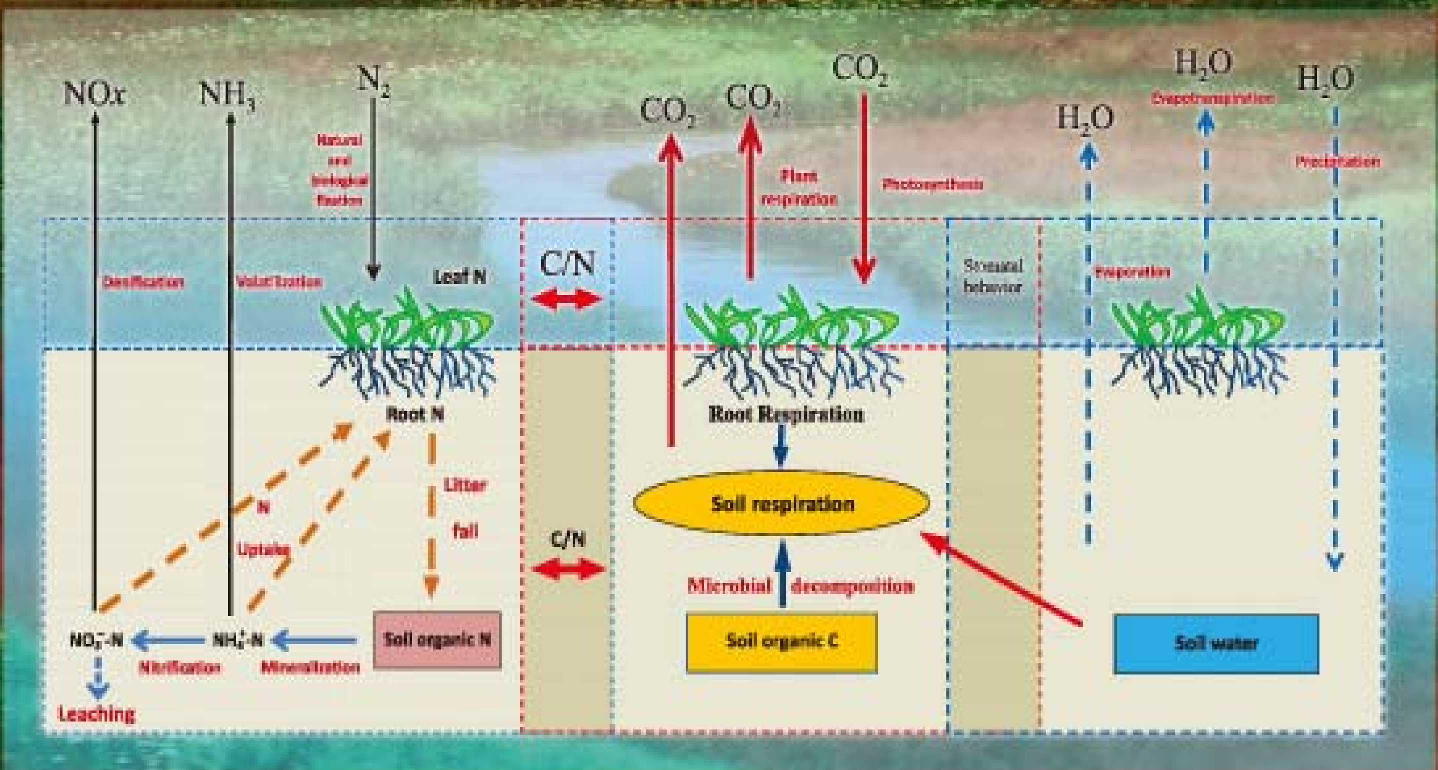

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Hybrid constructed wetlands for highly polluted river water treatment and comparison of surface- and subsurface-flow cells

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ABSTRACT

A series of large pilot constructed wetland (CW) systems were constructed near the confluence of an urban stream to a larger river in Xi'an, a northwestern megacity in China, for treating polluted stream water before it entered the receiving water body. Each CW system is a combination of surface- and subsurface-flow cells with local gravel, sand or slag as substrates and *Phragmites australis* and *Typha orientalis* as plants. During a one-year operation with an average surface loading of 0.053 $m^3/(m^2 \cdot day)$, the overall COD, BOD, NH_3-N, total nitrogen (TN) and total phosphorus (TP) removals were 72.7% ± 4.5%, 93.4% ± 2.1%, 54.0% ± 6.3%, 53.9% ± 6.0% and 69.4% ± 4.6%, respectively, which brought about an effective improvement of the river water quality. Surface-flow cells showed better NH_3-N removal than their TN removal while subsurface-flow cells showed better TN removal than their NH_3-N removal. Using local slag as the substrate, the organic and phosphorus removal could be much improved. Seasonal variation was also found in the removal of all the pollutants and autumn seemed to be the best season for pollutant removal due to the moderate water temperature and well grown plants in the CWs.

Introduction

With intensive urbanization and rapid industrialization in recent decades, surface water pollution has become a serious issue in China (Bu et al., 2010; Guo, 2007). Because of the insufficient wastewater treatment systems, large quantities of treated and untreated domestic wastewater and industrial effluent were discharged directly or indirectly into urban streams which lead to the pollution of the ultimate receiving water body. According to the latest statistical data (MEP, 2011), 39% of the rivers in China are polluted and unsuitable as source water for drinking water production. River water pollution is much more serious in the urban area where many streams appear black and malodorous (Qu and Fan, 2010). In northwestern China, due to dry climate and insufficient rainfall, treated and/or untreated wastewater may become the main flow in the dry season or even throughout a dry year. Therefore, finding appropriate ways for improving urban river water quality is highly desirable in many cities.

It has long been recognized that wetlands can remove pollutants in natural and/or engineered systems. The constructed wetlands (CWs), as artificial units to simulate the processes of the natural wetlands in an enhanced manner, have been well developed since later 1980s (Vymazal, 2009). Due to their low cost, simple operation and maintenance, and favorable appearance, CWs are considered to be a very promising technology for various wastewater treatments as long as the land is available for construction (Shutes, 2001). According to the local condition and treatment requirement, the CWs can be constructed in different types such as free water surface (FWS) and subsurface flow (SSF) wetlands (IWA, 2000). In fact, each type of the CWs

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has its own advantage and disadvantage. Therefore, 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 effective removal of pollutants for treating various wastewaters (Vymazal, 2008; Tuszyńska and Obarska-Pempkowiak, 2008; Bulc, 2006; Comino et al., 2011) and for treating polluted river and lake waters (Jing et al., 2001; Wu et al., 2011; Cui et al., 2011; Dong et al., 2012).

The treatment of polluted river water by CWs is usually for a reduction of the pollutant loading from a smaller tributary to a larger stream. The most possibility to build the CWs for polluted river water quality improvement is to make use of the flood lands near the confluence of the tributary to the main stream for CWs construction. Due to the uncertainties in the polluted river water quality, the design and operation of the CWs in such a case have to deal with circumstances much different from the CWs for wastewater treatment. This is the case of the present study which was conducted for investigating the feasibility of using CWs to treat the water from a polluted urban stream for reducing its pollutant loading to a river that receives the stream flow. For this purpose, pilot CWs combining FWS and SSF cells were constructed and operated. The objective of the study was to gain knowledge and experiences for the design and construction of the full scale CWs to be constructed for practical operation.

1 Materials and methods

1.1 Polluted condition of the urban stream

Zaohe River, the urban stream investigated in this study is located in the west suburb of Xi'an, a megacity in northwestern China where insufficient rainfall and dry climate result in serious problem of water shortage. With a basin area of 135 km^2 and a total length of 22.3 km, the natural base flow in the Zaohe River is very limited and its main function at present time is an urban drainage channel to receive effluents from several domestic wastewater treatment plants all the time and storm water in the rainy days. Similar to many cities nowadays in China, the provision of urban infrastructure including sewerage works can not always meet the needs of urban development in Xi'an. For this reason, untreated domestic wastewater and even industrial wastewater from small industries are also discharged into Zaohe River. **Figure 1** shows the water quality monitoring results in the one-year study period from November 2010 to October 2011 at the entrance of

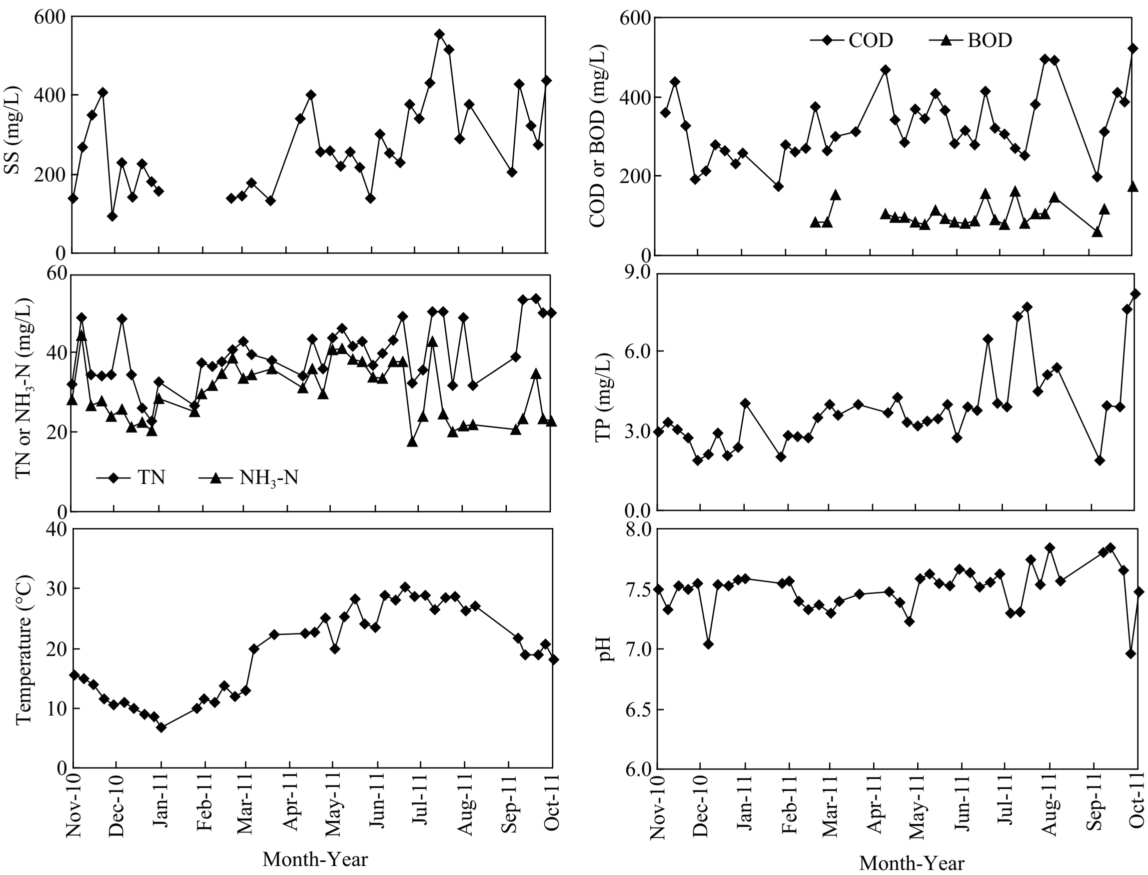

Fig. 1 Water quality of the Zaohe River during the one-year study period from Nov 2010 to Oct 2011.

the receiving tank for the pilot CWs. The annual average concentrations of suspeded solid (SS), organic contants (COD, BOD), ammonia nitrogen (NH_3-N), total nitrogen (TN) and total phosphorus (TP) with 95% confidence intervals were 359.4 ± 77.7 mg/L, 333.3 ± 34.6 mg/L, 105.7 ± 13.7 mg/L, 29.9 ± 2.3 mg/L, 39.6 ± 2.4 mg/L and 3.9 ± 0.5 mg/L, respectively, indicating a very seriously polluted condition of the Zaohe River. As the river finally enters the main channel of the Weihe River, the largest tributary of the Yellow River, which flows through the northern suburb of Xi'an, it becomes a concentrated pollutant source to deteriorate the urban water environment.

1.2 Pilot CW systems

The pilot CWs were constructed in the flood land near the confluence of the Zaohe River to the Weihe River with a layout as shown in **Fig. 2**. Each of the pilot CWs was designed as a hybrid system with combination of FWS and SSF cells with specifications as shown in **Table 1**.

A pump with coarse screen was placed in the stream of the Zaohe River to pump water to the elevated tank where water level was controlled by an overflow weir and the water was distributed to the five CW systems by gravity and with valves and flow meters for adjusting and monitoring the flow. With a hydraulic retention time for 4 hr, the elevated tank also performed the function of a pre-settler for the removal of solid substances. Local gravel, slag and sand were used as substrates for the CWs. For the SSF cells, the total thickness of the substrates was 60 cm with particle size ranging from 1 to 70 mm and average initial porosity about 50%. The water depth in these CWs was controlled as 55 cm (5 cm beneath the top of the substrates). For the FWS cells, the total thickness of the substrates was 35 cm with particle size ranging from 0.06 to 10 mm and average initial porosity about 30%. The water depth in these CWs was controlled as 40 cm (5 cm above the substrates). The bottom slope of all the CWs was 0.5%.

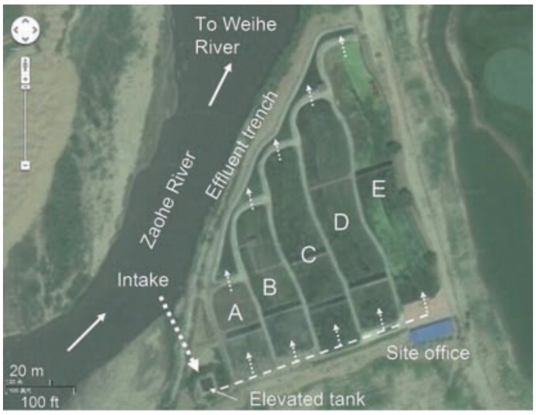

Fig. 2 Satellite view of the pilot constucted wetlands (CWs) and the flow diagram.

Two kinds of local plants, *Phragmites australis* and *Typha orientalis* were obtained from the field near the river bank so that they could easily grow in the wetlands because of the similar environment. Plants of similar size (20–30 cm in height) were selected and washed with tap water in order to remove soils and dead tissues from their roots. They were then planted in the CWs with a density of 9 plants per m^2. In the first two weeks after planting, river water was intermittently led into the bed for the plants to acclimate. After this acclimation period, river water was led to the bed at the prescribed flow rate. The grown plants were harvested in November before the cold winter came by cutting their upper parts about 20–30 cm above the ground while leaving their roots in the bed so that the plants could grow again in the next spring.

The total flow of the five CW systems was 362 m^3/day on average which corresponded to an average HRT of 3.6 day and an average surface loading of 0.053 $m^3/(m^2·day)$. The treated water from these CW systems flowed into the effluent trench. The construction of the pilot CWs was completed in August 2010. After 3 months trial operation, they were turned to continuous operation from November

Table 1 Specifications of the pilot CW systems

CWs	Flow type	Average flow rate (m^3/day)	Average surface loading ($m^3/(m^2·day)$)	HRT (day)	Cells	Length × width × height (m × m × m)	Substrate
A	SSF	68	0.100	2.8	SSF	34 × 20 × 0.8	Gravel
B	SSF + FWS	68	0.060	3.2	B1 (SSF)	17 × 20 × 0.8	Slag
					B2 (FWS)	40 × 20 × 0.6	Sand
C	SSF + FWS	68	0.046	4.6	C1 (SSF)	34 × 20 × 0.8	Gravel
					C2 (FWS)	40 × 20 × 0.6	Sand
D	SSF + FWS	68	0.040	4.5	D1 (SSF)	17 × 20 × 0.8	Gravel
					D2 (FWS)	69 × 20 × 0.6	Sand
E	FWS + FWS	90	0.050	3.1	E1 (FWS)	45 × 20 × 0.6	Sand
					E2 (FWS)	45 × 20 × 0.6	Sand
Total		362	0.053	3.6			

SSF: subsurface flow; FWS: free water surface; HRT: practical hydraulic retention time by taking into account the average void ratio of the wetland bed.

2010.

1.3 Sampling and chemical analyses

In the period from November 2010 to October 2011, water samples were collected weekly from the influent, effluent, and water at the outlet of each cell of the CWs. After sampling, the samples were sent to the laboratory for chemical analyses within 24 hr regarding SS, COD and BOD, NH_3-N, TN and TP. Standard methods were referred for the chemical analyses (MEPC and WWMAA, 2002). Water temperature, pH were measured *in-situ* using a potable meter (HQ30d53LED^{TM}, HACH, USA). In order to fractionate suspended and dissolved substances, 0.45 μm membrane filters were utilized for sample pretreatment (those penetrated the filter were considered to be 'dissolved' while those retained by the filter to be 'suspended'). For all the tests, differences were taken as statistically significant when $p < 0.05$.

2 Results and discussion

2.1 Overall removal of pollutants by the pilot CWs

Table 2 summarizes the SS, COD, BOD, NH_3-N, TN and TP removals by each of the CW systems based on the one-year water quality analysis results. Generally speaking, the five CW systems did not show much difference ($p > 0.05$) in the removals of SS (90%), COD (70%) and BOD (93%). Comparing with literatures on wetland systems for wastewater treatment (Klomjek and Nitisoravut, 2005; Vymazal, 2005), the BOD removal in this study was at a high level but the COD removal was relatively low. This might be due to the intrusion of industrial wastewater into the Zaohe River, which brought about an increase of the non-biodegradable organic substances in the inflow to the CWs. Regarding nitrogen and phosphorus removal, System A with a higher surface loading (0.100 $m^3/(m^2 \cdot day)$) was apparently inferior to other systems ($p < 0.05$). The nitrogen removal (NH_3-N and TN) was only about 30% and TP removal was about 50%. System B, with a surface loading (0.060 $m^3/(m^2 \cdot day)$) lower than System A but higher than the total average surface loading (0.053 $m^3/(m^2 \cdot day)$), also could not achieve high nitrogen and phosphorus removal. For Systems C, D and E with surface loading lower than 0.05 $m^3/(m^2 \cdot day)$, the NH_3-N and TN removal was about 60% or higher and the TP removal was more than 70%.

From the influent concentrations of all these pollutants shown in **Table 2**, it was understood that the Zaohe River was really under a seriously polluted condition and its quality was almost at a level similar to that of the municipal wastewater. According to Chinese Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18919-2002), the mixed effluent from the CWs was with a quality between Class I-B (permissible for discharging into protected surface waters other than source waters for potable supply) and Class II (permissible for discharging into normal surface waters), which meets the requirement for effluent discharge into the Weihe River.

2.2 Comparison of SSF and FWS for pollutants removal

Figure 3 compares the pollutants removals by C1 (SSF) and E1 (FWS) which were the first cells for System C and System E, respectively. The surface loadings of both cells were about 0.1 $m^3/(m^2 \cdot day)$. While the SS removal was the same for the two cells ($p > 0.05$), C1 apparently achieved higher COD, BOD and TP removals than E1 ($p < 0.05$), showing the privilege of SSF over FWS due to the more active biological functions for organic decomposition (Greenway and Woolley, 1999; Vymazal, 2005) and stronger adsorption, microbial activity and/or precipitation for phosphorus removal (Kadlec and Wallace, 2009; Vymazal, 2005) in the subsurface bed layer. However, for nitrogen removal E1 acted much better than C1 ($p < 0.05$) due to the provision of more aerobic condition for nitrification for turning ammonia into nitrates and/or nitrites which can further be denitrified (Green, 1997;

Table 2 Overall removals of pollutants by the five CW systems in the one-year study period (expressed as mean ± 95% confidence interval)

	CWs	SS	COD	BOD	NH_3-N	TN	TP
Removal (%)	A	91.4 ± 4.8	74.1 ± 4.1	92.8 ± 2.6	28.5 ± 6.4	33.6 ± 6.1	50.6 ± 6.5
	B	88.6 ± 6.2	71.1 ± 4.5	92.5 ± 2.8	47.5 ± 8.1	47.2 ± 7.3	66.9 ± 5.5
	C	88.6 ± 6.0	70.2 ± 4.5	93.2 ± 3.4	60.6 ± 8.0	55.6 ± 7.0	72.5 ± 5.4
	D	92.6 ± 3.5	72.0 ± 5.9	94.7 ± 2.3	66.5 ± 7.0	61.9 ± 6.6	70.6 ± 5.1
	E	89.9 ± 6.7	67.3 ± 6.0	91.7 ± 3.1	69.9 ± 6.7	62.3 ± 6.7	70.1 ± 5.2
	Overall	92.9 ± 4.6	72.7 ± 4.5	93.4 ± 2.1	54.0 ± 6.3	53.9 ± 6.0	69.4± 4.6
Concentration (mg/L)	Influent	359.4 ± 77.7	333.3 ± 34.6	105.7 ± 13.7	29.9 ± 2.3	39.6 ± 2.4	3.9 ± 0.5
	Mixed effluent	25.6 ± 12.0	90.9 ± 11.4	6.9 ± 2.4	13.7 ± 1.9	18.3 ± 1.8	1.2 ± 0.1
	Class I-B*	20	60	20	8 (> 12°C) 15 (< 12°C)	20	1
	Class II*	30	100	30	25 (> 12°C) 30 (< 12°C)	–	3

* Chinese discharge standard of pollutants for municipal wastewater treatment plant (GB18918-2002)

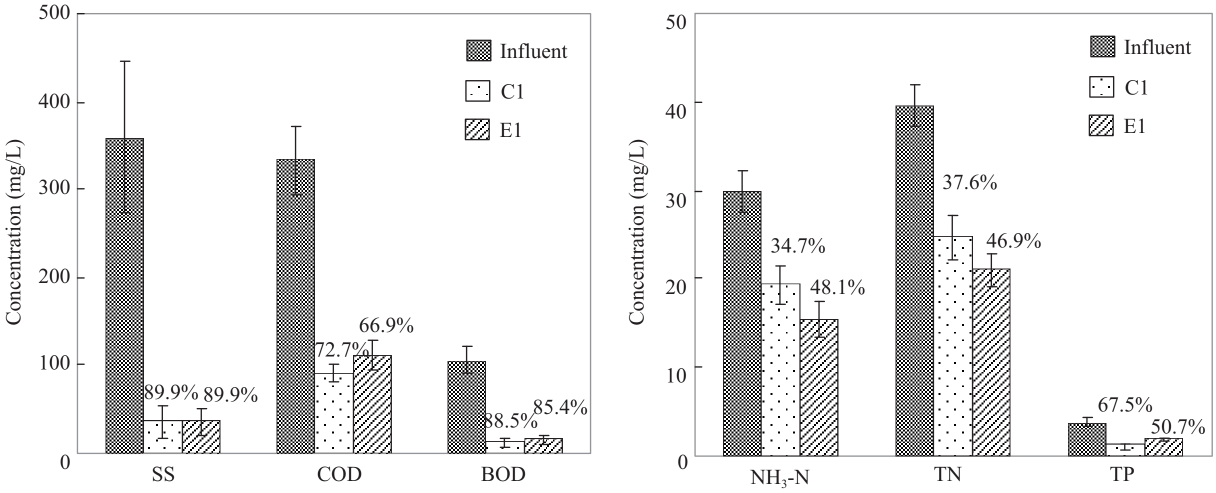

Fig. 3 Comparison of pollutants removal by SSF (C1) and FWS (E1) cells under similar operational conditions.

Chapentier et al., 1998). Nevertheless, if we compare the NH_3-N removal with TN removal for the same cell, it can be seen that for C1 its NH_3-N removal (34.7%) was lower than TN removal (37.6%), while for E1 its NH_3-N removal (48.1%) was higher than TN removal (46.9%), indicating that SSF could provide a more favorable condition for denitrification than nitrification. Such a phenomenon can be seen clearer in **Fig. 4** when we compare the NH_3-N removal with TN removal for all the SSF cells and all the FWS cells. Because less oxygen could diffuse into the subsurface flow, there would be exist anoxic and/or anaerobic zones in the SSF cells where denitrification proceeded (Kadlec and Wallace, 2009).

2.3 Influence of substrates on pollutants removal

Figure 5 compares the pollutants removals by the SSF cells B1 and D1 as the first stages of System B and System D, respectively. The surface loadings of both cells were about 0.2 $m^3/(m^2 \cdot day)$ but the substrate for B1 was slag and that for D1 was gravel. It can be seen that for nitrogen removal (NH_3-N and TN) there was almost no difference ($p > 0.05$) between the two cells because the most important nitrogen removal process in wetland would be nitrification and denitrification, and the identical subsurface flow conditions might have provided similar anaerobic circumstance (Kadlec and Wallace, 2009). However, B1 with slag as the substrate apparently achieved better SS, COD, BOD and TP removals ($p < 0.05$), probably due to the aggregation of microbes on the coarser surface of the slag which assisted the removal of particulate and colloidal substances, such as SS and part of the COD and BOD, by aerobic and/or anaerobic heterotrophic bacteria in the wetlands (Vymazal, 2005). The existence of active metal ions such as aluminum, iron, calcium etc., could also bring about effective removal of phosphorus by physicochemical actions (Vymazal, 2005).

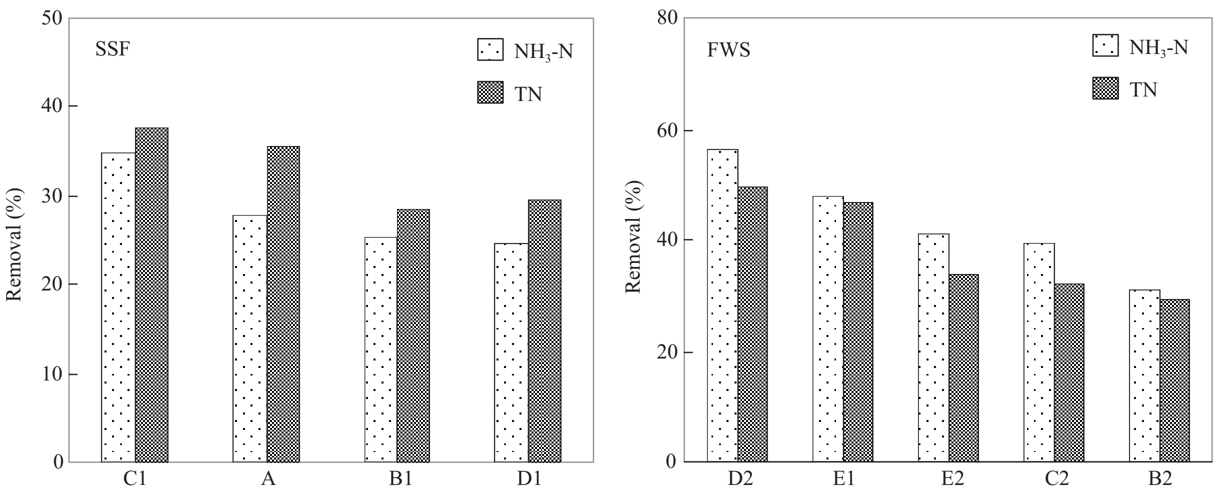

Fig. 4 Comparison of NH_3-N and TN removals by SSF and FWS cells.

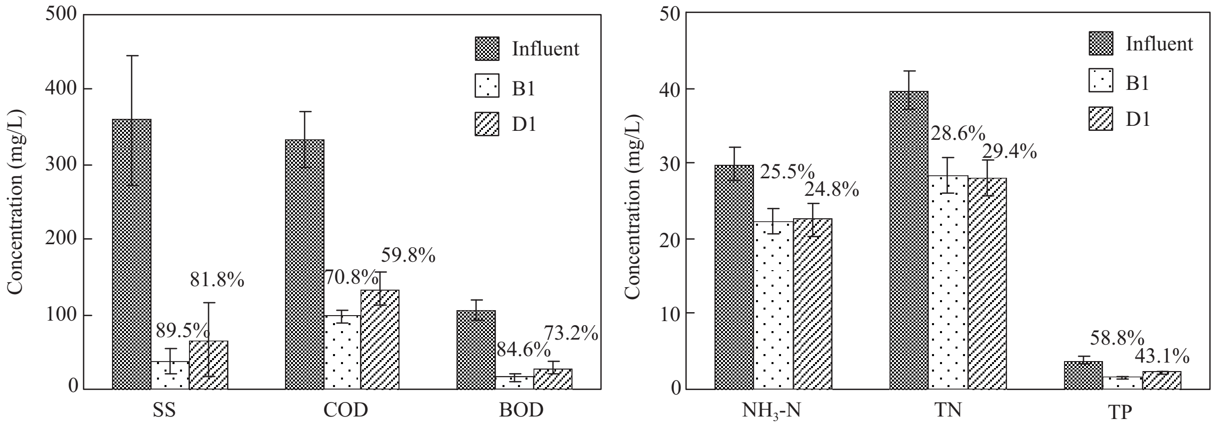

Fig. 5 Comparison of pollutants removal by SSF cells with slag (B1) and gravel (D1) as substrates under similar operational conditions.

2.4 Suspended and dissolved organic removal by the CWs

By fractionating COD and BOD into suspended and dissolved fractions using 0.45 μm membrane filter, **Fig. 6** was obtained to show the organic components in the influent and the mixed effluent. If BOD/COD ratio was taken as a parameter to reflect the biodegradability of organic substances in water, after the treatment by the CWs, the BOD/COD ratio was reduced from 0.32 to 0.08, indicating that almost all the biodegradable organic substances were removed by the CWs and those residual in the treated water were mostly non-biodegradable substances which took about 27% of the total COD in the influent. From **Fig. 6** it can be seen that for either COD or BOD, the suspended fraction (57% and 59%, respectively) was higher than the dissolved fraction (43% and 41%, respectively) and after treatment by the CWs, the suspended fractions were effectively removed by 95% and 98% for COD and BOD, respectively, and those residual in the treated water were mostly the dissolved organic substances. The effects of CWs for retaining suspended pollutants were also reported by other studies (Nguyen, 2000; Tuszyńska and Obarska-Pempkowiak, 2008).

2.5 Seasonal variation of pollutants removal

In order to know how pollutants removal was influenced by climate, we took System E which was operated as a two-stage FWS wetland as an example for a seasonal comparison. As shown in **Fig. 7**, both air and water temperatures varied in the similar tendency during the experimental period. In the winter and early spring seasons both the temperatures were lower than 15°C and the lowest temperatures between –3°C and 0°C occurred in January (**Fig. 7**). 15°C was often taken as a critical water temperature below which the CWs would perform poorly for pollutants removal (Kuschk et al., 2003; Kadlec and Reddy, 2001). The low water temperature period almost coincided with the low pollutants removal especially for TN. A quick rise of water temperature could be seen after March. The high temperature period was in the whole summer and early autumn (**Fig. 7**). However, the highest removal of all the pollutants was achieved in the autumn, probably due to the moderate temperature for the active actions of microorganisms as well as the action of the well grown plants in the CWs (Kuschk et al., 2003; Verhoeven and Meuleman, 1999).

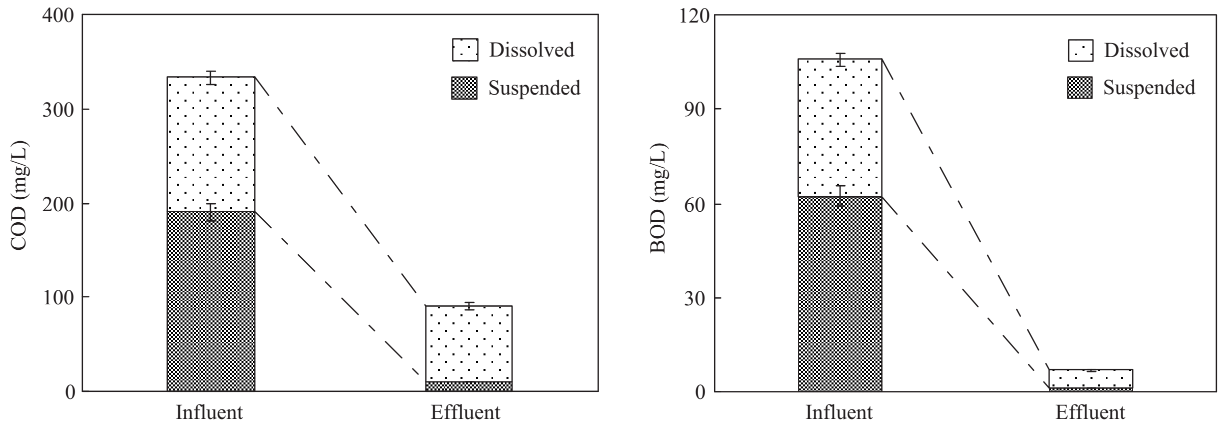

Fig. 6 Distribution and removal of dissolved and suspended COD and BOD by the CWs.

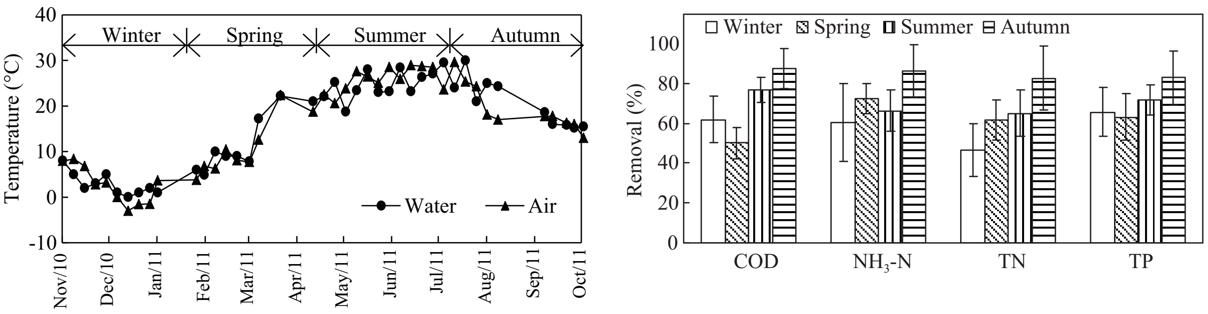

Fig. 7 Seasonal variation of air and water temperature and pollutants removal by System E throughout the experimental period.

3 Conclusions

Through one-year study of the pilot CWs for the treatment of the polluted Zaohe River water, it was verified that SS, organic substances, nitrogen and phosphorus could be effectively removed. The main advantages of the CWs were found to be their high removal efficiencies, low construction, operation and maintenance costs, and easy manipulation of the system in the experimental period for treating the highly polluted urban river water. From the pilot study result, it could be estimated that under the current condition of water pollution in the Zaohe River, if the effluent quality is taken as the target of treatment, the surface loading of the CWs should be controlled at 0.05 $m^3/(m^2 \cdot day)$ for any flow type or hybrid scheme. For SS and organic removal, different CWs did not show much difference, but the flow type did influence nitrogen removal to certain extent. A FWS cell could perform NH_3-N removal well because of the sufficient supply of dissolved oxygen while the TN removal tended to be lower due to lack of denitrification environment. In contrast to this, high NH_3-N removal could not be achieved in a SSF cell but the denitrification effect was attractive so that higher TN removal could be expected. For SSF cells the substrate material also influenced the pollutants removal. Comparing with gravel, by using slag as the substrate the organic and phosphorus removal could be much improved. All these can provide useful information for the design and optimization of the CWs for the full scale system to be constructed. However, as the flood land may experience flooding during periods of high discharge in the rainy season, the CWs should be able to cope with both the conditions of normal treatment and flooding. Even in the winter time when the temperature dropped down to a level that might not be suitable for good biodegradation of pollutants, the CWs could still achieve 50%–60% of COD, NH_3-N and TN removals and a higher TP removal. The most important maintenance of the CWs would be harvesting the plants before the winter time in order to prevent them from decaying in the CWs that may result in secondary pollution.

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