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RESEARCH ARTICLE

Performance of a pilot demonstration-scale hybrid constructed wetland system for on-site treatment of polluted urban river water in Northwestern China

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Abstract Hybrid constructed wetland (HCW) systems have been used to treat various wastewaters across the world. However, large-scale applications of HCWs are scarce, particularly for on-site improvement of the water quality of highly polluted urban rivers in semi-arid regions. In this study, a large pilot-scale HCW system was constructed to improve the water quality of the Zaohe River in Xi'an, China. With a total area of about 8000 m^2, the pilot HCW system, composed of different configurations of surface and subsurface flow wetlands, was operated for 2 years at an average inflow volume rate of 362 m^3/day. Local *Phragmites australis* and *Typha orientalis* from the riverbank were planted in the HCW system. Findings indicate a higher treatment efficiency for organics and suspended solids than nutrients. The inflow concentrations of 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN), NH_3-N, and total phosphorus (TP) were 125.6, 350.9, 334.2, 38.5, 27.2, and 3.9 mg/L, respectively. Average removal efficiencies of 94.4, 74.5, 92.0, 56.3, 57.5, and 69.2 %, respectively, were recorded. However, the pollutant removal rates were highly seasonal especially for nitrogen. Higher removals were recorded for all pollutants in the autumn while significantly lower removals were recorded in the winter. Plant uptake and assimilation accounted for circa 19–29 and 16–23 % of the TN and TP removal, respectively. Moreover, *P. australis* demonstrated a higher nutrient uptake ability and competitive potential. Overall, the high efficiency of the pilot HCW for improving the water quality of such a highly polluted urban river provided practical evidence of the applicability of the HCW technology for protecting urban water environments.

Keywords Constructed wetland · Pollution · Urban river restoration · Seasonal performance

Introduction

Rapid population growth, urbanization, and economic development have caused increases in the production and discharge of wastewater in many countries, particularly developing countries (Gobel et al. 2007; Zhang et al. 2012). The pollutants from domestic sewage (Babatunde et al. 2008), industrial (Arroyo et al. 2013), and agricultural effluents (Diaz et al. 2009) often find their way into urban rivers, deteriorating the water quality. This phenomenon is much more severe in arid and semi-arid regions where annual rainfall is insufficient. Thus, many wastewater treatment systems have been developed to mitigate the problems of urban river pollution. Nevertheless, additional measures, to improve the water quality in situ, may be required for safekeeping the urban rivers.

As a cost-effective and eco-friendly wastewater treatment technology, the application of constructed wetlands (CWs) has been increasing rapidly over the last few decades (Kadlec and Wallace 2009; Borin and Malagoli 2015). A number of abiotic and biotic processes integrating in wetland vegetation ecology, soil, and associated microbial assemblages assist

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contaminant removal when the wastewater flows through the CWs, which results in an efficient pollutant removal (Mander et al. 2014; Zhi and Ji 2012). The pollutant removal can be further improved by combining several CW types into so-called hybrid systems (Vymazal 2013). However, the use of hybrid constructed wetlands (HCWs) has largely been focused on treating domestic and municipal wastewater, although various industrial wastewater treatments have been successfully achieved worldwide (Ávila et al. 2013; Vymazal 2013; Comino et al. 2011). In fact, relatively little has been reported on the use HCWs for on-site river water improvement especially in large scale (Cui et al. 2011). Experience is lacking in adopting optimal system configurations, operation parameters, and seasonal changes of performance, in particular for the polluted urban rivers in the loess plateau of China, a semi-arid region.

Macrophytes are considered to be the main biological component of CWs and play a major role in nutrient removal (Březinová and Vymazal 2014). They not only contribute directly to pollution reduction through uptake and assimilation but also by facilitating the growth of the microbes in the rhizosphere and promoting a variety of chemical and physical purification process in CWs (Jenssen et al. 1993). However, several studies have demonstrated that the growth characteristics and nutrient uptake ability of different wetland plants varied greatly and are affected by the climatic condition and temperature (Cheng et al. 2009). Furthermore, the most appropriate plant species used in CWs in different regions vary widely, and the plants exhibit different competition ability under long-term operation and in mix culture situations (Borin and Salvato 2012; Březinová and Vymazal 2014).

The research aim addressed by this article was to evaluate the performance of a large pilot-scale HCW on-site demonstration system in the loess plateau of China. The HCW consists of different configurations of surface and subsurface flow CWs. They were operated over a 2-year period to improve the water quality of a highly polluted urban river in the semi-arid region. The specific objectives were (1) to assess the treatment performance of the pilot HCW system in improving the water quality of the highly polluted urban river, (2) to evaluate the seasonal variation of performance in the HCW system, and (3) to investigate the aboveground biomass and nutrient uptake ability of local *Phragmites australis* and *Typha orientalis* during the 2-year operation in the prevailing northern latitude conditions.

Materials and methods

Characteristics of the urban river

Xi'an is the most famous and a typical semi-arid city in the loess plateau. It has a subhumid continental monsoon climate. The monthly mean air temperature reaches a maximum of 26.3 °C in July and a minimum of −1.3 °C in January, with an average annual precipitation of 500–750 mm. Zaohe River, the polluted urban river investigated in this study, is located in the west suburb of Xi'an. It is 22.3 km long and has a drainage area of 135 km^2. The natural base flow of the river is very limited due to the dry climate and deteriorated environment. Currently, the main function of the Zaohe River is an urban drainage channel to receive effluents from several domestic wastewater treatment plants and untreated industrial wastewater (Ma et al. 2012). According to our long-term monitoring between November 2010 and October 2012, the average quality characteristics of the river water are as follows: dissolved oxygen (DO), 0.54 mg/L; suspended solids (SS), 334.2 mg/L; chemical oxygen demand (COD), 350.9 mg/L; biochemical oxygen demand (BOD), 125.6 mg/L; total nitrogen (TN), 38.5 mg/L; NH_3-N, 27.2 mg/L; and total phosphorus (TP), 3.9 mg/L. The temperature of the river water varied with the seasons, ranging from 6.8 to 30.3 °C, with an average of 19.4 °C.

Description of the pilot HCW system

The pilot HCW system was constructed on the eastern bank of the end of the Zaohe River (34° 22′ 54″ N, 108° 51′ 05″ E). The total surface area of the system is about 7000 m^2, within a curtilage area of about 8000 m^2. It comprises of five CW series, which were composed of five free water surface (FWS) and four horizontal subsurface flow (HSSF) wetlands (Fig. 1a). The rationale for having five different wetland series was to determine the optimal configuration for achieving the highest treatment efficiency. The wetland cells were lined with high-density polyethylene to prevent the seepage of polluted water to the underlying groundwater. Water from the Zaohe River is pumped into an elevated feeding tank for sedimentation and subsequent distribution to the HCW system. The total influent volume flow rate to the pilot HCW system was 362 m^3/day, which correspond to an average HRT of 3.6 days and an average surface loading of 5.3 cm/day. Treated water from the HCW system flowed into a 300-m^3 effluent trench before being discharged back into the Zoahe River downstream. The hydraulic loading for series A–D was 68 and 90 m^3/day for series E (Fig. 1a). The land area for each series is presented in Table 1. The analyses considered in this article focused on the whole system.

The main wetland media substrates were local gravel, slag, and sand. The particle sizes of both the gravel and slag substrates ranged from 1 to 70 mm, and average initial porosities were about 50 %. For the sand, the particle size ranged from 0.06 to 10 mm, with average initial porosity of about 30 %. The chemical characteristics of the substrates are shown in Table 2. The detailed description of the design was described by Zheng et al. (2014). Two most common plant species at the bank of the Zaohe River, *P. australis* and *T. orientalis* were planted in equal proportions in the CWs with a density of nine

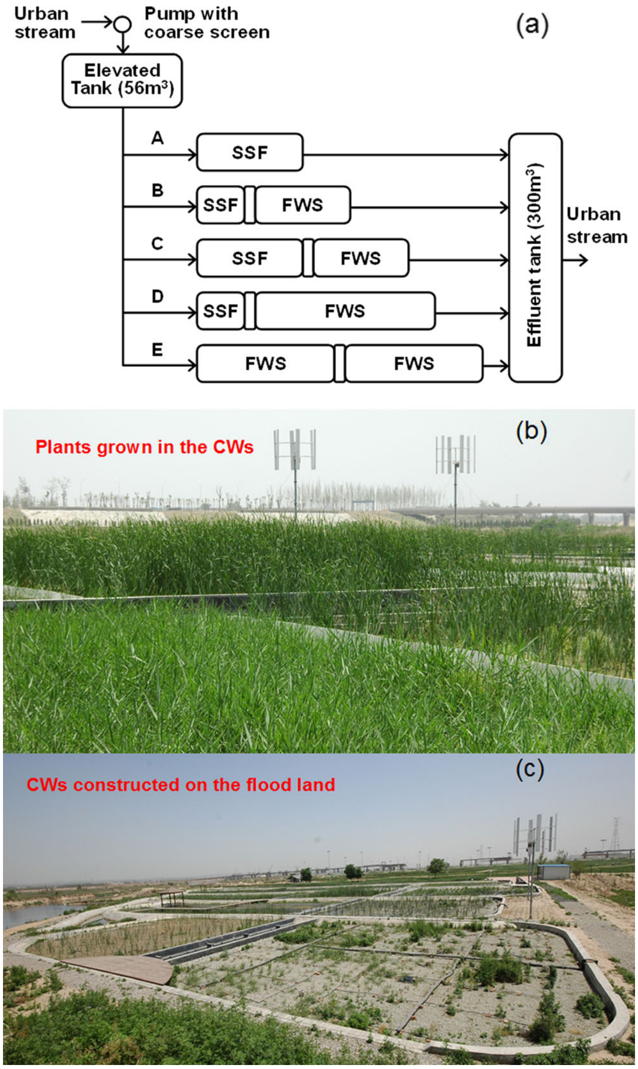

Fig. 1 Schematic diagram (**a**) and photos (**b**, **c**) of the pilot HCW system at Xi'an, China

plants per m^2 and a height of about 20 cm. The pilot HCW system was commissioned in November 2010.

Water sampling and chemical analysis

In the period from November 2010 to November 2012, weekly water samples were collected from the influent and effluent of the pilot HCW system. All of the water samples were sent to the laboratory for chemical analyses within 24 h regarding suspended SS, COD, BOD_5, NH_3-N, TN, and TP. Standard methods were referred for the chemical analyses (MEPC 2002). However, due to logistical constraints, BOD_5 could not be measured in the first several months. Water temperature, pH, and DO were measured on site with a portable meter (HQ30d53LED^{TM}, HACH, USA). The seasonal variation of the treatment performance of the HCW system was analyzed by one-way ANOVA (α=0.05). All statistical analyses were performed with the SPSS Statistics 20.0 (SPSS Inc., Chicago, USA).

Plant biomass quantification and analysis

During the experimental period, the aboveground plant biomass was harvested and analyzed in every November by cutting at about 20 cm above the wetland bed surface. Because the initial height of plants was 20 cm when they were planted, the harvested biomass can be considered as the net increased. In order to obtain the total weight of each plant species, three random sample quadrats (0.5 × 0.5 m) were set in each wetland for both *P. australis* and *T. orientalis*. The stems and leaves of whole aboveground plants harvested from these quadrats were milled together and analyzed for total N and P according to the routine analysis method for soil agrochemistry (Bao 2000). The dry biomass produced per unit area and the nutrient concentrations in the plant were determined as an average of all

Table 1 Specifications of the pilot HCW system

CWs	Cells	Length (m)	Width (m)	Depth (m)	Average flow rate (m^3/day)	Average surface loading (m^3/m^2 day)	Substrate
A	HSSF[a]	34	20	0.8	68	0.100	Gravel
B	HSSF[a]	17	20	0.8	68	0.060	Slag
	FWS[b]	40	20	0.6			Sand
C	HSSF[a]	34	20	0.8	68	0.046	Gravel
	FWS[b]	40	20	0.6			Sand
D	HSSF[a]	17	20	0.8	68	0.040	Gravel
	FWS[b]	69	20	0.6			Sand
E	FWS[b]	45	20	0.6	90	0.050	Sand
	FWS[b]	45	20	0.6			Sand
Total					362	0.053	

[a] Horizontal subsurface flow constructed wetland

[b] Free water surface flow constructed wetland

Table 2 Chemical properties of the substrates

Substrate	pH	Chemical composition mass percentage %									
		C	O	Na	Mg	Al	Si	K	Ca	Ti	Fe
Slag	10.55	4.38	48.29	–	2.39	6.40	12.00	–	19.45	0.49	6.60
Gravel	8.76	–	51.61	1.11	1.01	8.79	27.58	4.05	0.73	–	5.12
Sand	7.14	–	56.82	2.99	0.23	7.67	26.25	3.55	0.87	–	1.62

the samples. Plants uptake of N and P was estimated by multiplying the total dry biomass of the system by the specific ratio of nutrients per dry biomass. Because the focus of the current analyses was on the standing stock of plant biomass, the belowground plant biomass was not harvested, and only the data relating to the aboveground plants will be discussed here.

Results and discussion

Overall performance of the pilot HCW system

The influent and effluent pollutant concentrations of the HCW system during the experimental period are shown in Fig. 2. The results indicate that the river water was highly polluted and fluctuated widely. Nevertheless, the performance of the pilot HCW system was still highly efficient. The HCW system performance further increased considerably after the first half year, due to the maturing and rapidly expanding microbial and plant biomass (Mitsch et al. 2012; Stefanakis and Tsihrintzis 2012).

Figure 2a–c indicates highly efficient and stable organic matter and suspended solid treatment capacities during the operation period. The average effluent concentrations of BOD_5, COD, and SS were 6.7, 74.5, and 22.4 mg/L, respectively. The corresponding average removal efficiencies were 94.4, 74.5, and 92.0 %, respectively. The slightly lower COD removal was caused by the low BOD_5/COD ratio (0.36), which indicated that the biodegradable organic matter made up a small proportion of the COD. Some of the wetland cells were replanted in the first spring period, which would account for the sharp increase in SS (Fig. 2c).

The removal of nutrients was moderate compared with organic matter and SS (Fig. 2d–f). The average effluent TP concentration was 1.1 mg/L, and an average removal efficiency of 69.2 % was recorded. The results showed a higher removal efficiency compared with the results reported by other researchers, despite the influent concentration being higher (Calheiros et al. 2009). The average effluent TN and NH_3-N concentrations were 16.4 and 11.4 mg/L, and average removal efficiencies of 56.3 and 57.5 %, respectively, were recorded. Despite the removal efficiencies being similar to those reported by Wang et al. (2012), the effluent TN and NH_3-N concentrations were still high. Additionally, the concentrations of NO_3^- and NO_2^- in the effluent were 0.5 and 0.1 mg/L, respectively. Many studies have reported that the major nitrogen removal mechanism in wetlands is microbial nitrification-denitrification processes (Vymazal 2007). Thus, the above results indicated that nitrification was limited in this pilot HCW system and that a better TN removal performance can be achieved by improving the nitrification potential. Furthermore, the lower nitrogen removal efficiencies in the first year compared with the other pollutants indicated that the optimal conditions for nitrogen removal were slower to develop in the wetlands.

Table 3 summarizes the SS, COD, BOD_5, NH_3-N, TN, and TP removals by each CW series based on the 2-year water quality analysis results. Overall, the five CW series did not show significant differences ($P>0.05$) in the removals of SS (about 95 %), COD (about 75 %), and BOD_5 (about 92 %). Regarding nitrogen and phosphorus removal, series A, with a higher surface loading (0.1 m^3/m^2 day) was apparently inferior to the other systems ($P<0.05$). Furthermore, series B, C, and D, which had similar configurations of HF + FWS, recorded higher nitrogen and phosphorus removal rates when the surface loading was lower. Finally, series E (FWS) achieved the highest nitrogen removal, due to the provision of more aerobic conditions, which improved nitrification to convert ammonia into nitrates and/or nitrites, which can further be denitrified.

Seasonal performance of the pilot HCW system

During the experimental period, weekly average water temperature in the HCW system ranged from 3 to 25 °C. The water temperature was lowest in winter (1.0 °C), highest in summer (28.9 °C), and moderate in both spring and autumn. In addition, almost all the influent pollutant concentrations were lowest in winter and highest in spring (Fig. 3). Nevertheless, the removal efficiencies for all pollutants were lowest in winter while the highest occurred in autumn (Fig. 3). A slightly different pattern has often been reported, whereby removal efficiencies of pollutants were highest in the spring and summer (Dong et al. 2011; Dzakpasu et al. 2011). This difference could be explained by the fact that the water loss through evapotranspiration that occurred in the hot months of

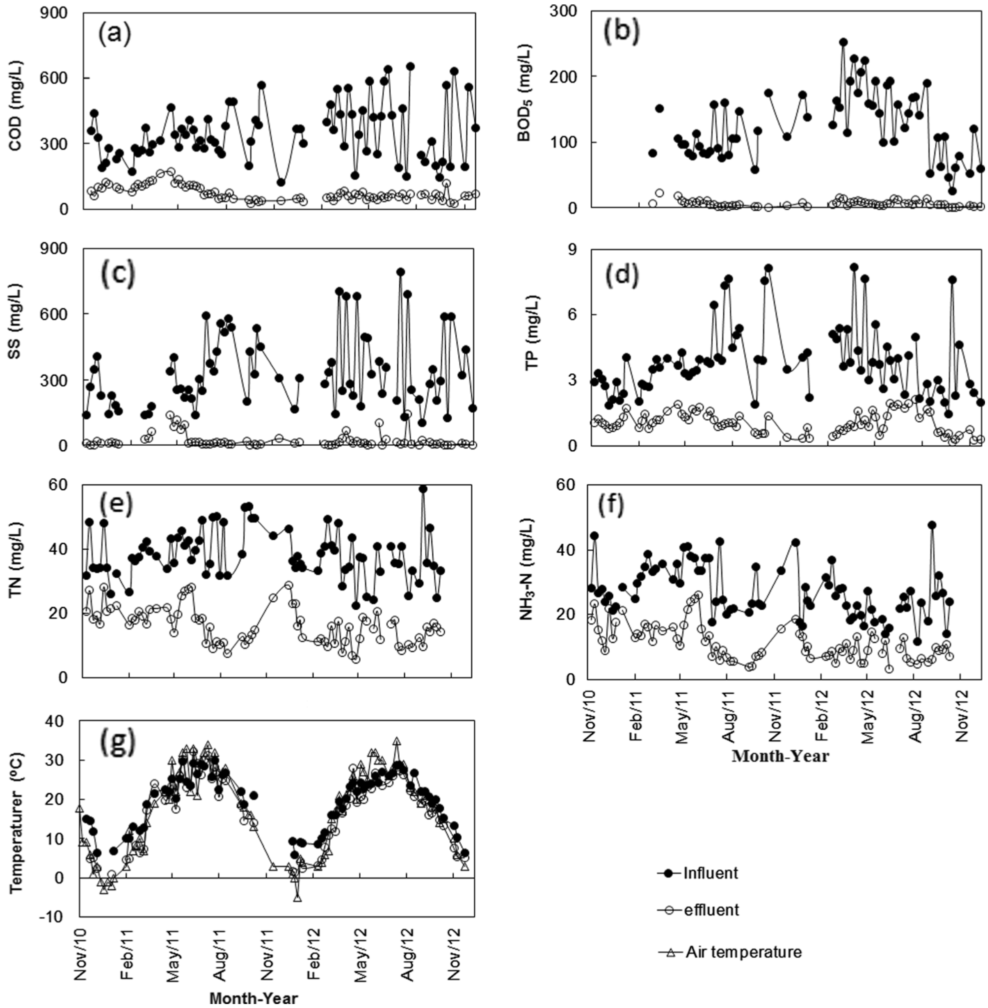

Fig. 2 Variations in **a** COD, **b** BOD_5, **c** SS, **d** TP, **e** TN, **f** NH_3-N concentrations, and **g** temperature in the pilot HCW system during the operation period (n=77; for BOD_5, n=62)

summer altered the pollutant concentrations (Gagnon et al. 2012). The pollutant removal rates in this HCW system were highly seasonal, but for different pollutants was quite different. For organic matter, although the water temperatures were similar in spring and autumn, the removal rates were significantly different ($P<0.05$) (Fig. 3b, c). On the other hand, despite the significantly different temperature ($P<0.05$), the growth state of plants was similar, and the removal efficiencies in spring and summer were not statistically different ($P>0.05$). This finding indicated that the effects of temperature on the organic removal were limited and that the growth state of plants could be an important factor influencing the

Table 3 Overall removals of pollutants by the five CW systems over the 2-year study period (expressed as mean ± 95 % confidence interval, n=77; for BOD_5, n=62)

CW	Units	SS	COD	BOD_5	TN	NH_3-N	TP
Influent	mg/L	334.2±43.6	350.9±29.4	125.6±11.4	38.5±1.7	27.2±1.8	3.9±0.3
Series A effluent	mg/L	13.5±3.4	67.8±4.8	10.2±1.7	27.3±1.6	22.5±1.6	1.9±0.2
	%	96.0	80.7	91.9	29.1	17.3	51.3
Series B effluent	mg/L	12.5±3.4	70.2±8.1	5.8±1.3	16.7±1.6	11.4±1.5	1.1±0.1
	%	96.3	80.0	95.4	56.6	58.1	71.8
Series C effluent	mg/L	13.8±5.2	71.3±8.2	4.2±1.4	13.4±1.6	8.1±1.6	0.8±0.1
	%	95.9	79.7	96.7	65.2	70.2	79.5
Series D effluent	mg/L	11.1±3.9	70.9±9.1	4.8±1.1	12.0±1.5	7.6±1.4	0.8±0.1
	%	96.7	79.8	96.2	68.8	72.1	79.5
Series E effluent	mg/L	12.8±4.8	83.8±9.5	7.6±2.5	10.3±1.5	5.8±1.3	0.9±0.1
	%	96.2	76.1	93.9	73.2	78.7	76.9

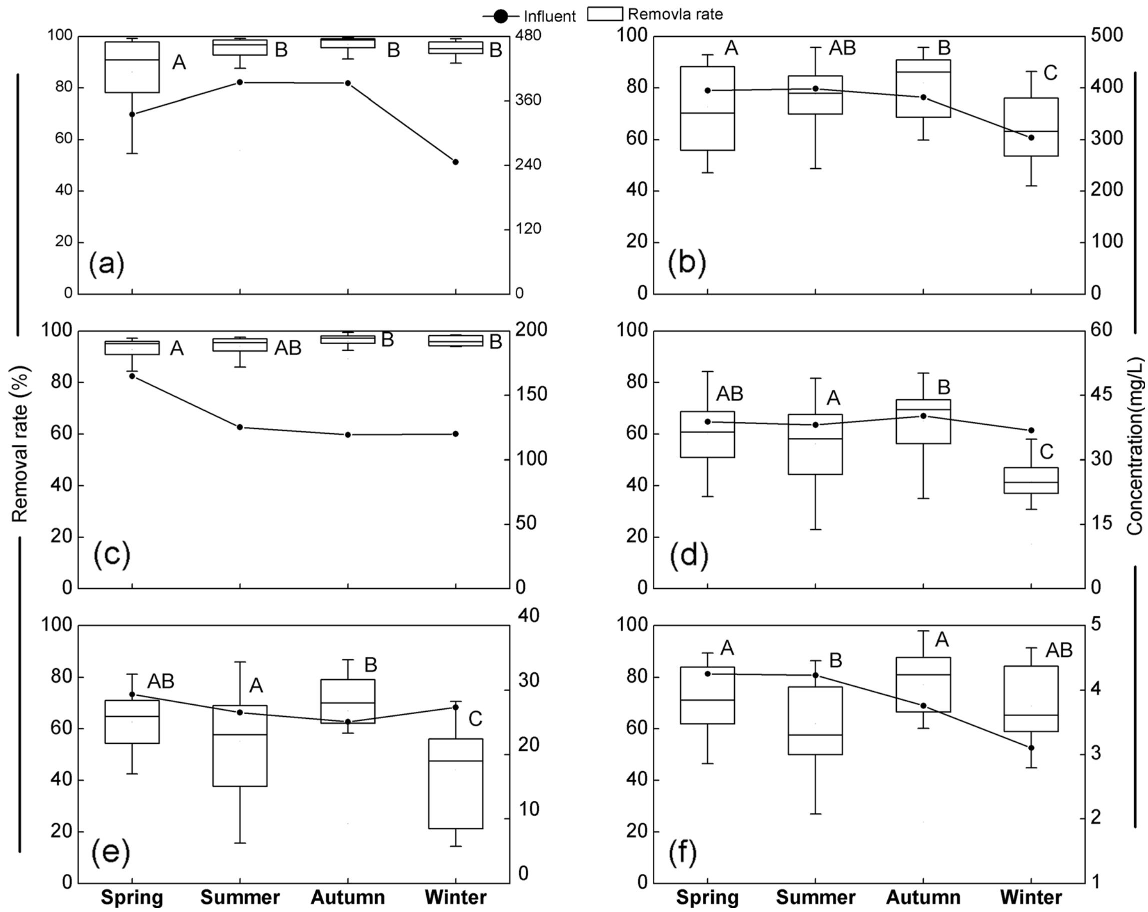

Fig. 3 Seasonal variations of **a** SS, **b** COD, **c** BOD_5, **d** TN, **e** NH_3-N, and **f** TP concentrations (*right vertical axis*) and removal efficiencies (*left vertical axis*) in the pilot HCW system during the experimental period. *Different letters on the top of the bars* indicate significant differences among the four seasons according to one-way ANOVA at α=0.05 (n=77; for BOD_5, n=62)

removal of organics. The effect of temperature on the nitrogen removal was very different from that of the organic matter removal. The significantly different temperature in summer and winter resulted in significantly different removal efficiencies ($P<0.05$), whereby higher removal rates were recorded in the summer than winter. The low removal efficiencies recorded in the winter were partly a result of the adverse influence of low ambient temperature within the wetland system (Fig. 2g), reducing the activities of plants and microorganisms responsible for the nitrogen removal and oxygen diffusion rates (Phipps and Cumpton 1994; Spieles and Mitsch 2000; Kuschk et al. 2003). This shortcoming probably caused reductions in nitrification and denitrification rates at the lower temperatures. More specifically, in the winter of the study period, the ambient temperature was below 0 °C, and although the pond water surface was not actually frozen, this may have increased anaerobic conditions, leading to low ammonia degradation. Previous research shows that the biological removal of nitrogen is most efficient at temperatures ranging from 25 to 30 °C (Dong et al. 2011). The similar temperatures in spring and autumn resulted in removal efficiencies that were not statistically different ($P>0.05$) (Fig. 3d, e). Finally, the seasonal variations in the removal efficiencies of SS and TP were not as pronounced as those for nitrogen and organic matter (Fig. 3a, f). The minimal seasonal variation in SS and TP removal efficiencies is because they are removed mainly by processes such as sedimentation and sorption of phosphate by Fe and Al in the substrate. Nonetheless, during colder periods, there is little plant uptake of phosphorus, which led to a slight decline in the TP removal efficiency during the winter of 2012. However, the system is still relatively immature, and high nutrient adsorption and storage capacities are, therefore, to be expected.

Nutrient uptake and competition between the different plant species

Both *P. australis* and *T. orientalis* in this HCW system grew well during the experimental period. Their densities at the end of the second year were increased to about 20 times higher than that at the beginning of the experiment. As shown in Table 4, the nutrient removals were increased from 407.9 g N/m^2 and 50.7 g P/m^2 in the first year to 425.9 g N/m^2 and 54.6 g P/m^2 in the second year. Furthermore, the nutrient

Table 4 Contribution of plant uptake to nutrient removal in the pilot HCW system during the experimental period

	Parameter (g/m^2)	Influent (g/m^2)	Effluent (g/m^2)	*P. australis*			*T. orientalis*			Others[d] (g/m^2)	Plant uptake (%)
				DM[a] (kg/m^2)	C[b] (mg/g)	N[c] (g/m2)	DM[a] (kg/m^2)	C[b] (mg/g)	N[c] (g/m^2)		
2011	TN	744.39	336.50	1.58	29.50	46.61	1.12	27.88	31.23	330.05	19.08
	TP	72.20	21.46	1.58	2.73	4.31	1.12	3.52	3.94	42.48	16.27
2012	TN	693.75	267.82	2.31	34.43	79.53	1.51	30.51	46.07	300.33	29.49
	TP	73.42	18.82	2.31	3.05	7.05	1.51	3.56	5.38	42.18	22.75

[a] Dry matter per unit area

[b] Average nutrient concentration of the aboveground plant parts

[c] Amount of nutrient uptake by the plants

[d] Represents the nutrient removal by microbial processes and adsorption by substrates, which were obtained by subtracting the amount of nutrients removed by plants from the total amount removed in the system

uptake by the plants were increased from 77.8 g N/m^2 and 8.3 g P/m^2 in the first year to 125.6 g N/m^2 and 12.4 g P/m^2 in the second year. Therefore, the purification ability of the system, which increased considerably in the second year, can be partly attributed to the development of plants. Furthermore, the amount and proportion of nutrient uptake by plants increased significantly along with the operation of the system. However, the two species of plants showed different competitive abilities during the period. The dry matter of *P. australis* and *T. orientalis* were 1.58 and 1.12 kg/m^2 in the first year, which increased to 2.31 and 1.51 kg/m^2 in the second year, respectively (Table 4). Additionally, the *P. australis* started to encroach the *T. orientalis* zones in the second year. This could be explained by the fact that *P. australis* has much higher gas space (Březinová and Vymazal 2014) in rhizomes, much stronger growing capability, and competitive potential (Fu et al. 2011). It is well known that the amount of nutrient removal by harvesting mainly depend on the biomass rather than nutrient concentrations in the plant tissues (Březinová and Vymazal 2014; Carvalho et al. 2014). Thus, the nutrient uptake by *P. australis* was higher than *T. orientalis*, despite the phosphorus content in *T. orientalis* tissues being higher than that of *P. australis* (Table 4). The N and P uptake by plant accounted for 29.5 % of the N removal and 22.8 % of the P removal, respectively, at the end of the second year of the experimental period.

Implications for practice

There were no obvious trend/differences in the treatment performance of the five different CW configurations, except for some seasonal variability during the 2 years of operation. More specifically, the different combinations of FWS and HSSF CWs did not show significant differences in the removal of SS and organic substances. However, we generally found lower TN and NH_3-N removal during winter and spring periods relative to summer and autumn periods. Most previous studies have reported that increased contaminant loads and reduced retention time contribute to reducing removal efficiency. We recommend using the seasonal data in a dynamic operational context to increase the effectiveness for nutrient removal by reducing the loading rate and increasing retention time during the winter. Furthermore, increasing hydraulic loadings during periods when the system removes highest rates of nitrogen and phosphorus, for example, those of warmer periods, may also contribute to increasing pollutant removal from the polluted river water. From the results of this pilot study, it is found that the surface loading of the CWs needs be controlled for any CW flow type or hybrid scheme. Thus, the overall hydraulic loading based on a system mass balance should be considered during the planning and early design stage.

Conclusions

Findings from the 2-year on-site demonstration study of a pilot HCW system for improving the water quality of a highly polluted urban river in a semi-arid region indicate a higher treatment performance capability for organics and suspended solids than nutrients. Average removal efficiencies of 94.4 74.5, 92.0, 56.3, 57.5, and 69.2 % were recorded respectively for BOD_5, COD, SS, TN, NH_3-N, and TP at inflow concentrations of 125.6, 350.9, 334.2, 38.5, 27.2, and 3.9 mg/L, respectively. The variations in pollutant removal efficiency were highly seasonal especially for nitrogen. Higher removals were achieved for all pollutants in the autumn whereas significantly lower removals were recorded in the winter. The nutrient uptake by plants accounted for 19–29 % of N removal and 16–22 % of P removal. Local *P. australis* demonstrated a higher nutrient uptake ability and competitive potential. As the pilot HCW system was constructed on the flood land of the river and operated under practical conditions, the results could be useful for the construction of full-scale CWs for improving the water quality of the polluted river.

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Conflict of interests The authors declare that they have no conflict of interests.

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