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Review

Relationship between design parameters and removal efficiency for constructed wetlands in China

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ABSTRACT

Constructed wetlands (CWs), as an important ecological engineering technology, are designed and built to utilize the natural functions of wetlands for wastewater treatment within a more controlled environment. CWs have been widely used across the world. This review specifically aims at analyzing design parameters, pollutant removal efficiencies and their relationships for CWs built in China. The ANOVA analysis indicated that the design parameters and pollutant removal efficiencies were significantly different in different types of CWs and in different wastewater sources, and that wastewater sources should be considered as important factors for design of CWs operating parameters. Regression analysis of design parameters and pollutant removal efficiencies showed that regression equations were Logarithmic for total suspended solids (TSS), Power for ammonium (NH_3-N), Compound for total nitrogen (TN) and Linear for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD_{cr}) and total phosphorous (TP). However, the correlation index (R^2) was quite low because of poor correlativity between design parameters and removal efficiencies, probably because of the diverse nature of the data analyzed. The application of CWs is most appropriate and beneficial in decentralized wastewater treatment in small town and rural areas as well as for low polluted water of rivers and lakes due to low costs for construction, operation and maintenance.

1. Introduction

The concept of ecological engineering was initially formulated in the 1960s in China, and was first independently proposed by Professor Ma Shijun, who was known as “the father of ecological engineering in China” (Ma, 1998). As one of the fundamental ecological engineering technologies, constructed wetlands (CWs) are constructed as artificial wetlands to utilize the natural functions of wetlands for wastewater treatment within a more controlled environment (Kadlec and Knight, 1996). The three main components of CWs are pollution-resistant wetland vegetation, filled media typically consisting of sand, gravel and other materials and microorganisms within the system (Zhang et al., 2012). According to the water flow regime, CWs can be divided into free water surface (FWS) and subsurface flow CWs. Subsurface flow CWs can be further classified into horizontal subsurface flow (HF) and vertical flow (VF) CWs (Vamzal and Kropfelova, 2008). For optimal use of the different mechanisms and efficiencies of pollutant removal within HF and VF CWs, the combined/hybrid-type CWs of HF and VF have recently appeared to improve the effluent water quality.

The first experiments on treating wastewater by CWs were carried out by Kathe Seidel in the 1950s in Germany (Seidel, 1961). In 1974, the first HF CW was put into operation for treatment of municipal sewage in Liebenburg-Othfresen, Germany, based on the “Root-zone theory” researched by Kiehuth (Kickuth, 1980). As a new kind of wastewater treatment technology, CWs were formally accepted in the water pollution control area during the Fourth International Seminar in Austria, Vienna in 1996. At present, CWs have been constructed worldwidely and utilized to treat a variety of wastewaters including industrial wastewater, domestic sewage, storm water runoff, agricultural polluted water, surface water and effluent of wastewater treatment plants (WWTPs) (IWA, 2001; Zhang et al., 2012).

In China, the first CW was established in 1987 by the Tianjin Academy of Environmental Sciences, with an area of 60,000 m^2 and capacity of 1400 m^3 per day for domestic wastewater treatment (Peng et al., 2000). Another CW, the Bainikeng CW, was put into operation in July 1990 in the Shenzhen Special Economic Zone, which covered 2 ha

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area and treated domestic wastewater at a rate of 500 m^3 per day. Other early CWs established in the 1990s include: the FWS system of 20,000 m^2 area constructed in Changping District, Beijing for municipal sewage treatment at 500 m^3 per day; the Yantian CW built for 1000 m^3 wastewater per day with about 6667 m^2 area in the Shenzhen Industry Development Zone; and the HF system for treating 350 m^3 domestic wastewater per day in Guangzhou (Chen, 1994; Chen and Ye, 1996). Since the 1990s, China has undergone rapid economic development, increasing urbanization and industrialization, and along with the significant increases in wastewater quantity, CWs have been applied in more than 80% of the province-level administrative regions in South China and along the coastal areas (Zhang et al., 2012).

Based on literature survey, this research investigated the data of CWs performance and operation published from 1988 to 2016 in China, including 790 CWs cases. These CWs were designed mainly by following the Technical Specification of Constructed Wetlands for Wastewater Treatment (HJ 2005–2010) (MEPC, 2010). Since the design parameters vary quite widely, it may be that the pollutant removal efficiencies also vary. Therefore, this research analyzed the type of CWs, their design parameters and pollutant removal efficiencies, operation costs and the relationship between design parameters and pollutant removal efficiencies from 168 CWs cases, and made recommendations for better CWs design and application in the future.

2. Methods

2.1. Data survey

In the past several decades, the number of CWs has been growing so rapidly that it makes it difficult to estimate an accurate number of such installations in China. This survey uses the literature investigation method to gain the relevant data of engineering cases of CWs in China. The first step was to survey cases of CWs published from 1988 to 2016, and then to analyze the correlation between design parameters and removal data of those published cases, including hydraulic load (HL), hydraulic retention time (HRT), pollutant loading, presence of pretreatment, influent and effluent concentration for conventional wastewater contaminants, and removal rate of pollutants according to the Technical Specification of Constructed Wetlands for Wastewater Treatment (HJ 2005-2010).

The main literature sources were: (1) consultant reports related to CWs obtained through the Beijing Normal University library and online book stores; (2) Wanfang database, China National Knowledge Infrastructure database (CNKI), CQVIP information system, SpringerLink, Elsevier ScienceDirect, Web of Science and other main databases; and (3) project information from the websites of environmental companies in China. We collected 790 CWs engineering cases up to 2017 March 30 of which 168 have design parameters and removal efficiencies available for the statistical analysis. The analyzed data were within three years after CWs operation. The FWS, HF, VF and hybrid systems are 31, 61, 48 and 28, respectively.

2.2. Statistical methods

The relationships in design parameters and removal efficiencies among four types of CWs and different wastewater sources treated were evaluated using the least-significant difference (LSD) test of the one-way ANOVA at 5% level of significance with SPSS® v. 13.0.

Analysis of the Pearson Correlation and Regression between design parameters and removal efficiencies was also performed using SPSS® v. 13.0.

3. Design parameters for the engineering of CWs

3.1. Design parameters for different types of all CWs

Table 1 summarizes the statistics for 168 wetland systems in China, and shows that design parameters have a variation for different types of CWs. The HL and HRT are the most important parameters for CWs design and removal efficiency. However, the actual engineering design parameters are not only higher than those specified in the technical specification in China but also much higher than those in western countries. The average HL of 0.2 m/d for FWS and 0.5 m/d for HF was larger than < 0.1 m/d and < 0.5 m/d in the technical specification, respectively. In addition, the average HRT of 11.1 d for FWS was out of the range of between 4 and 8 d in the technical specification. Although the average HL and HRT of VF systems were in the range of 0.2–0.8 m/d and 1–3 d in China, they were much higher than 0.2–0.3 m/d in western countries. The organic loading from 10.6 to 55.3 g BOD_5/m^2.d in China were also overloaded in comparison with loading varying from 6 to 10 g BOD_5/m^2.d in western countries. In China, the rapid growth of urban areas and the population explosion lead to higher land price and less available land space. As a result, the overloading is a common feature for Chinese CWs due to this land barrier.

3.2. Design parameters for different wastewater sources

3.2.1. Design parameters of different types of CWs for specific wastewaters

Considering different wastewater sources, the different types of CWs treating industrial wastewater, domestic sewage, polluted river water and effluent of WWTPs were analyzed by the ANOVA method. The statistical results in Fig. 1 show that the design parameters of CWs treating heavily polluted water, including industrial wastewater and domestic sewage, are in accordance with the Chinese technical specification requirement, but they are not for micro-polluted water, including polluted river water, polluted lake water and effluent of WWTPs.

For the CWs treating industrial wastewater, the HL of CW systems was 0.10 m/d for FWS, 0.57 m/d for VF and 0.59 m/d for hybrid systems. The HRT of FWS systems (2.4 d) was very different from that of VF (2.11 d, P = 0.002) and hybrid (1.13 d, P = 0.003) systems (Fig. 1).

The design parameters of domestic sewage treatment in different types of CWs showed similar trends with industrial wastewater CWs and both of them met the requirement for technical specification. The HL was 0.10 m/d for FWS, 0.36 m/d for HF, 0.46 m/d for VF and

Table 1
The mean value of design parameters for CWs (n = 168).

Types of CWs	HL (m/d)	HRT (d)	Inflow Loading (g/m^2.d)					
			TSS	BOD_5	CODcr	NH_3-N	TN	TP
FWS	0.2 ± 0.1*	11.1 ± 4.7	19.8 ± 8.8	10.6 ± 4.0	19.6 ± 5.6	1.8 ± 0.6	1.7 ± 0.8	0.2 ± 0.1
HF	0.5 ± 0.1	2.4 ± 0.3	80.3 ± 27.3	34.0 ± 8.8	82.6 ± 22.2	8.4 ± 2.1	6.5 ± 1.2	0.8 ± 0.1
VF	0.6 ± 0.1	1.4 ± 0.2	56.2 ± 9.8	55.3 ± 13.7	109.0 ± 29.3	10.9 ± 2.0	20.1 ± 5.0	1.6 ± 0.3
Hybrid	0.5 ± 0.1	1.8 ± 0.3	59.9 ± 26.6	16.1 ± 3.2	42.4 ± 6.3	4.0 ± 0.8	5.5 ± 1.3	0.8 ± 0.1

* The number means Mean ± S.E.

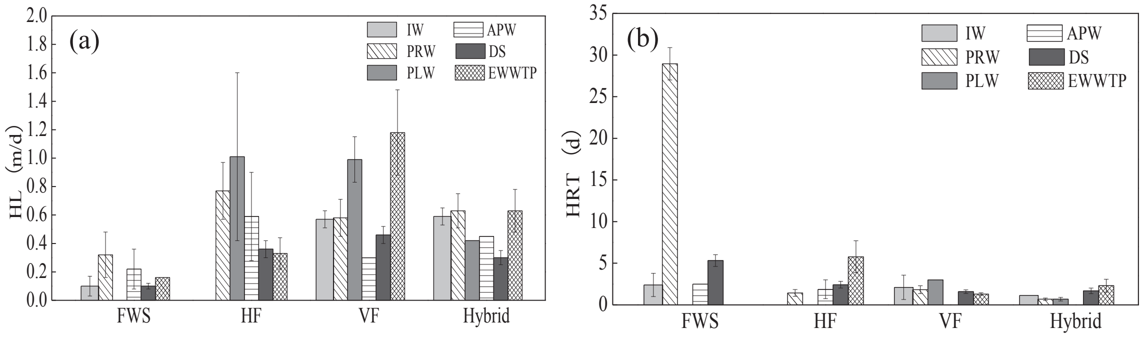

Fig. 1. (a) The mean value of hydraulic loading (HL) for different wastewater sources in FWS, HF, VF and hybrid CWs; (b) The mean value of hydraulic retention time (HRT) for different wastewater sources in FWS, HF, VF and hybrid CWs. IW means industrial water; PRW means polluted river water; PLW means polluted lake water; APW means agricultural polluted water; DS means domestic sewage; EWWTP means effluent of WWTPs.

0.30 m/d for hybrid systems, respectively ($P > 0.05$). The difference of HRT was significant between FWS (5.32 d) and HF (2.42 d), VF (1.59 d) and hybrid (1.69 d) systems ($P < 0.05$) (Fig. 1).

The design parameters of polluted river water, polluted lake water and effluent of WWTPs were mostly beyond the scope of technical specification. For the polluted river water, the average HL of 0.32 m/d for FWS and 0.77 m/d for HF were larger than 0.1 m/d and 0.5 m/d, and the HRT up to 28.95 d for FWS was more than the 8 d in Chinese technical specification. The HL for the effluent of WWTPs for VF (1.18 m/d) was out of range 0.2–0.8 m/d (Fig. 1).

3.2.2. Design parameters of different wastewaters for specific type of CWs

Some of the design parameters for wastewater sources made a significant difference only in FWS for HRT and VF systems for HL ($P < 0.05$), and not for HF and Hybrid systems ($P > 0.05$). In VF CWs, the average HL for the effluent of WWTPs (1.18 m/d) was significantly larger than for polluted river water systems (0.58 m/d, $P = 0.007$), and the average HL was significantly different between 0.99 m/d for polluted lake water and 0.46 m/d for domestic sewage ($P = 0.009$).

In conclusion, the statistical results indicate that wastewater sources are important for designing CWs since the pollutant loads are different in different influents. In reality, wastewater sources were not considered as a main parameter of design, which was in accordance with Technical Specification of Constructed Wetlands for Wastewater Treatment (HJ 2005–2010). Importantly, however, some of the design parameters for wastewater sources are different in specific types of CWs, especially HL and HRT for heavily polluted water and micro-polluted water.

4. Analysis of pollutant removal efficiency

4.1. Removal efficiency for different types of all CWs

A summary of removal efficiency for the CWs is shown in Table 2. The removal efficiencies were different between FWS and subsurface flow wetlands (HF, VF and Hybrid). The average removal efficiencies of FWS were lower than other types of CWs for all pollutants. Although removal of TSS, BOD_5, COD_{cr} and TN was shown to be not significantly different based on types of CWs ($P > 0.05$), FWS systems appeared less efficient in the removal of NH_3-N (49.4%) as compared to HF (70.1%), VF (70.8%) and Hybrid (71.9%) ($F = 4.590$, $P < 0.05$), and FWS also removed TP (50.4%) less efficiently than other types of CWs ($F = 4.916$, $P < 0.05$).

The removal efficiencies of pollutants were quite variable, which showed that the CW design parameters made a great difference in the actual systems performance and indicated that those design parameters were very important to consider for anyone looking at designing a system. However, the average removal efficiencies of pollutants were in accordance with the technical specification due to wide specified range for 40–90% BOD_5, 50–80% COD_{cr} and SS, 20–75% NH_3-N and 35–80% TP.

4.2. Removal efficiency for different wastewaters

4.2.1. Removal efficiency of different types of CWs for specific wastewaters

The ANOVA analysis was conducted among different types of CWs for specific wastewater sources and the results was similar to Section 4.1 that showed removal efficiency differences between FWS and subsurface flow wetlands. For polluted river water, FWS showed much lower removal efficiencies for NH_3-N of 41.88% compared to HF (71.60%, $P = 0.008$)

Table 2
The mean value of inflow, outflow and removal efficiency for CWs (n = 168).

Pollutants	Types of CWs	Inflow (mg/L)	Outflow (mg/L)	Removal efficiency (%)	Pollutants	Types of CWs	Inflow (mg/L)	Outflow (mg/L)	Removal efficiency (%)
TSS	FWS	157.0 ± 43.3	22.0 ± 3.5	74.9 ± 10.2	BOD_5	FWS	97.5 ± 46.1	7.3 ± 1.8	71.2 ± 9.2
	HF	169.5 ± 38.0	17.3 ± 3.2	84.7 ± 1.9		HF	67.3 ± 12.2	12.2 ± 2.0	71.6 ± 4.2
	VF	104.4 ± 13.7	12.1 ± 2.0	82.1 ± 3.2		VF	90.6 ± 19.7	8.4 ± 1.5	81.8 ± 2.3
	Hybrid	161.6 ± 56.9	13.1 ± 4.3	84.2 ± 4.7		Hybrid	47.1 ± 12.7	5.9 ± 1.1	71.1 ± 5.2
COD_{cr}	FWS	134.9 ± 39.2	34.6 ± 6.1	58.1 ± 6.2	NH_3-N	FWS	6.4 ± 2.0	2.6 ± 0.7	49.4 ± 6.5
	HF	166.4 ± 19.0	37.3 ± 3.3	70.7 ± 2.6		HF	18.7 ± 2.4	4.7 ± 0.8	70.1 ± 3.0
	VF	181.6 ± 41.6	27.0 ± 2.6	72.6 ± 3.1		VF	19.4 ± 3.0	3.9 ± 0.7	70.8 ± 3.6
	Hybrid	113.6 ± 18.0	24.6 ± 2.7	71.7 ± 3.4		Hybrid	13.6 ± 2.8	2.2 ± 0.5	71.9 ± 4.0
TN	FWS	12.8 ± 5.4	3.7 ± 1.5	56.0 ± 8.1	TP	FWS	1.1 ± 0.4	0.3 ± 0.1	50.4 ± 5.5
	HF	19.4 ± 3.2	6.2 ± 1.1	61.9 ± 4.3		HF	1.9 ± 0.2	0.5 ± 0.1	70.9 ± 3.0
	VF	29.1 ± 6.0	8.8 ± 1.6	63.7 ± 5.1		VF	3.0 ± 0.6	0.4 ± 0.1	75.6 ± 3.3
	Hybrid	18.1 ± 3.8	7.0 ± 1.5	59.9 ± 5.1		Hybrid	2.3 ± 0.6	0.5 ± 0.1	68.4 ± 4.2

*The number means Mean ± S.E.

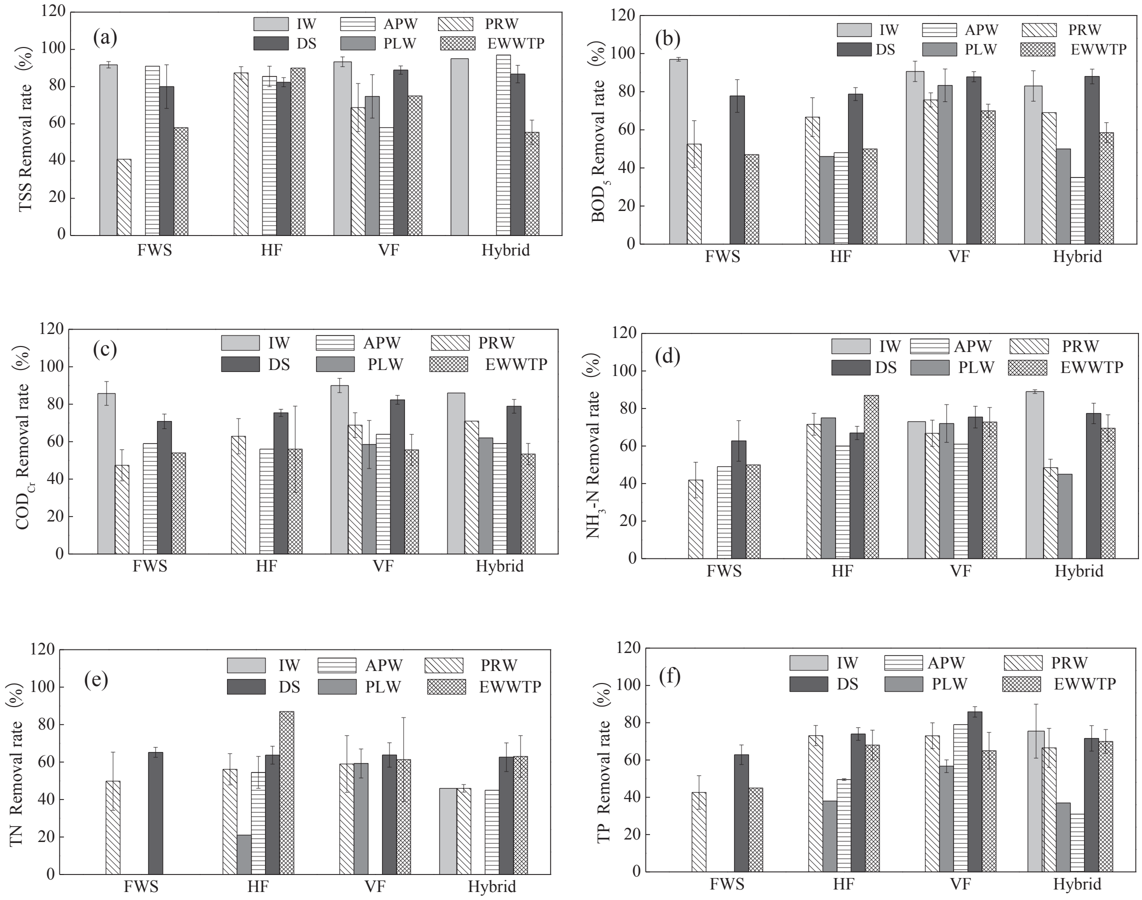

Fig. 2. (a)–(f) represent TSS, BOD_5, COD_{cr}, NH_3-N, TN and TP removal efficiency for different wastewater sources in FWS, HF, VF and hybrid CWs, respectively; IW means industrial water; PRW means polluted river water; PLW means polluted lake water; APW means agricultural polluted water; DS means domestic sewage; EWWTP means effluent of WWTPs.

and VF (66.78%, P = 0.026). The removal of TP for HF (73.09%, P = 0.006) and VF (73.00%, P = 0.009) appeared more efficient than for FWS (42.60%) (Fig. 2d and f). For domestic sewage treatment, the TP removal between FWS (62.83%) and VF (85.83%) was quite different in performance (F = 3.765, P = 0.005) (Fig. 2f). Although the differences among CW types were not significant for industrial wastewater and effluent of WWTPs ($P > 0.05$), the average removal efficiency of FWS was also lower than for the other types of CWs (Fig. 2a–f).

4.2.2. Removal efficiency of different wastewaters for specific types of CWs

The ANOVA statistical analysis of different wastewater sources was conducted for each type of CWs and showed large differences of removal efficiency among different wastewaters.

In FWS CWs, the analysis showed very low removal efficiencies of BOD_5 (52.50%) in polluted river water, compared to industrial wastewater (97.00%, P = 0.013) (Fig. 2b). Similarly, the removal of COD_{cr} for polluted river water (47.38%) was quite different from industrial wastewater (85.75%, P = 0.003) and domestic sewage (70.83%, P = 0.023) (Fig. 2c).

In VF CWs, statistically significant differences were observed for all the pollutants, with BOD_5 (F = 3.165, P = 0.029), COD_{cr} (F = 4.950, P = 0.003), and TP (F = 4.931, P = 0.007) showing significant removal from different types of wastewater, but not for NH_3-N and TN. The BOD_5 removal from domestic sewage (87.82%) was significantly higher than polluted river water (75.71%, P = 0.017) and effluent of WWTPs (70.00%, P = 0.013). The removal of BOD_5 in industrial wastewater (90.67%) also performed very well as compared to effluent of WWTPs (P = 0.025). The removal of COD_{cr} in polluted river water and effluent of WWTPs was 68.80% (P = 0.014) and 55.60% (P = 0.006) respectively, and was significantly lower than industrial wastewater (90.00%). Domestic sewage showed very efficient removal performance for COD_{cr} (82.35%) as compared to polluted river water (68.80%, P = 0.035), polluted lake water (58.50%, P = 0.010) and effluent of WWTPs (55.60%, P = 0.002). Removal efficiencies of TP in VF CWs ranged from 56.67% to 85.83%, and the removal level depended on the type of wastewater. The removal efficiencies from domestic sewage were better than polluted lake water (P = 0.005) and effluent of WWTPs (P = 0.012) (Fig. 2a–f).

The results for Hybrid systems were similar to FWS CWs. The removal of BOD_5 (F = 10.816, P = 0.005) and COD_{cr} (F = 9.742, P = 0.002) were significantly different among different types of wastewater. Both pollutant removals were significantly lower in effluent WWTPs than in industrial wastewater and in domestic sewage; 58.50% for BOD_5, 53.40% for COD_{cr} in effluent WWTPs, as compared to 83.00% for BOD_5, 86.00% for CODcr in industrial wastewater and 88.00% for BOD_5, and 78.90% for COD_{cr} in domestic sewage (Fig. 2b and c).

In conclusion, FWS showed lower removal efficiencies than other types of CW systems. Only the removal of NH_3-N and TP proceeded differently in different types of CWs, and other pollutants removal efficiencies were not largely different for CW types. The removal efficiencies of pollutants showed large variation among wastewater sources and this may be that the different pollutant levels influence the CW performance as a function of the wastewater sources.

In addition, different CW types had different efficiencies for the same pollutant, and even the same CW type had different efficiencies for the same pollutant in China. It is obvious that design parameters clearly played a significant role in the removal of pollutants, and that design parameters were mainly selected on experience due to somewhat

Table 3
Pearson Correlation between design parameters and removal efficiency.

Pollutants	Temperature	HL	HRT	Pre-treatment	TSS Loading	BOD_5 Loading	COD_{cr} Loading	NH_3-N Loading	TN Loading	TP Loading
	(°C)	(m/d)	(d)	/	(g/(m²·d))					
TSS	0.054	−0.005	−0.012	0.111	0.264*	0.134	0.165	0.267	0.232	0.194
BOD_5	0.253*	−0.246*	0.238	−0.102	−0.225	0.349**	0.261	0.215	0.260	0.312
COD_{cr}	0.203*	−0.184*	−0.255*	−0.025	0.065	0.333	0.259**	0.324	0.251	0.211
NH_3-N	0.305**	−0.166	−0.161	0.096	−0.061	−0.001	−0.008	0.101	0.016	0.147
TN	0.162	−0.193	−0.303*	−0.129	−0.020	0.041	0.159	0.262	0.164	0.161
TP	0.252**	−0.256**	−0.198	0.103	−0.221	0.173	0.122	0.265	0.152	0.277**

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

ineffective CW design specification in China. This also verifies that uniform specification might not be possible for the entire country, due to the significant influence of local climate, geography, etc. on CW function and performance. Therefore, it is suggested that an important next step is to build the relationships between CWs design parameters and pollutant removal efficiencies.

5. Relationship between design parameters and removal efficiency

5.1. Correlation analysis between design parameters and removal efficiency

In order to explain the relationship between design parameters and pollutant removal efficiency, Pearson Correlation was conducted and the results are shown in Table 3. The statistical analysis indicated that the removal of TSS was only correlated with TSS loading ($P < 0.05$), while BOD_5, COD_{cr} and TP removal efficiencies were related to temperature ($P < 0.05$), HL ($P < 0.05$) and pollutant loading ($P < 0.01$). The removal of NH_3-N and TN was only significantly correlated with temperature ($P < 0.01$) and HRT ($P < 0.05$), respectively.

5.2. Regression analysis between design parameters and removal efficiency

Through comparing various types of regression model parameters, the best regression fitting the degree of relationship was chosen as the model. The results of regression analysis showed that the regression equation of TSS removal efficiency was $Y = 0.616 + 0.061 \ln X$ ($R^2 = 0.244$), and X represents for TSS loading. The regression equations of BOD_5, COD_{cr} and TP removal were linear models, $Y = 0.703–0.238X_1 + 0.001X_2 + 0.01X_3$ ($R^2 = 0.386$) for BOD_5, $Y = 0.604–0.242X_1 + 0.001X_2 + 0.011X_3$ ($R^2 = 0.319$) for COD_{cr} and $Y = 0.640–0.209X_1 + 0.031X_2 + 0.009X_3$ ($R^2 = 0.345$) for TP. The independent variables X_1, X_2 and X_3 represent HL, pollutant loading and temperature, respectively. The nonlinear regression equations of NH_3-N and TN removal were $Y = 0.137\ (X^{0.543})$ ($R^2 = 0.126$) for power model and $Y = 0.619 \cdot (0.943)X$ ($R^2 = 0.284$) for compound model, and X represents the temperature and HRT, respectively (Table 4).

These regression analyses results indicated that the fitting degree of a curvilinear regression equation did not perform very well due to the value of the correlation index (R^2) being very low. At the same time, the results showed that the correlation between design parameters and removal efficiency was poor. The design parameters were selected more on experience due to lack of regional design specification for different types of CWs in China, and this will pose new challenges and research topics for CWs design parameters and removal efficiencies in different types of CWs and different wastewater sources in future, with the aim of more uniform and reliable technical specifications of CWs based on different regions in China.

6. Cost and land requirement

6.1. Cost

In China, traditional wastewater treatment plants (WWTPs) are efficient and cost-effective for wastewater treatment in densely populated urban areas. Wastewater in small towns and rural areas has not been treated by WWTPs because of non-economical investment and lack of funds to support the operation cost. The use of CWs for polluted water treatment has been increasing since the 1990s because of its low costs for construction, operation and maintenance. The application of CWs is more appropriate in small town and rural areas.

The investment and operation cost for a WWTP and CWs in China is compared in Table 5. The unit capital cost of CWs ranged from 32.19 to 369.86 US$/m^3, compared to 154.67–174.00 US$/m^3 for a conventional WWTP, so it appears that some CWs don't present an advantage in construction cost. In contrast, the operation and maintenance cost of CWs (0.007–0.0116 US$/m^3) was much lower than that of conventional WWTPs (0.073–0.075 US$/m^3) (Table 5).

6.2. Land requirement

CWs for wastewater treatment usually require more space and land than conventional WWTPs for wastewater (Kivaisi, 2001). The land requirement of CWs for wastewater treatment ranged from 0.41 to 50 m^2 to treat 1 m^3 of polluted water. In addition to different CWs types, the diversity of geography, climate, land, and water resource distribution is considerable between northern and southern China, and the availability of land use for CWs varies correspondingly (Dong et al., 2009). The land requirement for CWs may be a barrier for its wider application especially in the rural/underdeveloped areas of the country in China because of high land price and dense population, but the

Table 4
Regression analysis of pollutant removal efficiency with design parameters.

Y	X	Equation	Model	R^2	F	P
TSS	X—TSS loading	$Y = 0.616 + 0.061\ \ln X$	Logarithmic	0.244	24.176	0.000
BOD_5	X_1—HL; X_2—BOD_5 Loading; X_3—T	$Y = 0.703–0.238X_1 + 0.001X_2 + 0.01X_3$	Linear	0.386	11.307	0.000
COD_{cr}	X_1—HL; X_2—COD_{cr} Loading; X_3—T	$Y = 0.604–0.242X_1 + 0.001X_2 + 0.011X_3$	Linear	0.319	12.661	0.000
NH_3-N	X—T	$Y = 0.137\ (X^{0.543})$	Power	0.126	16.265	0.000
TN	X—HRT	$Y = 0.619 \cdot (0.943)^X$	Compound	0.284	17.886	0.000
TP	X_1—HL; X_2—TP Loading; X_3—T	$Y = 0.640–0.209X_1 + 0.031X_2 + 0.009X_3$	Linear	0.345	12.134	0.000

Table 5
Comparisons of construction and operation costs of WWTPs and CWs.

	Type of wastewater	Design capacity (m^3/d)	Total capital cost (US$)	Unit capital cost (US$/$m^3$)	Operation cost (US$/$m^3$)
Conventional activated sludge process in Guangdong province (Me, 2004)	–	–	–	174.00	0.075
SBR in Guangdong province (Me, 2004)	–	–	–	154.67	0.073
CWs in Guangdong Province (Yi, 2006)	Polluted river water	14000.00	580000.00	58.00	0.010
CWs in Wuhan city, Hubei Province (Zhang, 2007)	Polluted lake water	1500.00	48285.00	32.19	0.007
Yuehu CWs in Wuhan City, Hubei Province (Xu and Cheng, 2006)	Polluted lake water	2000.00	145000.00	72.50	0.017
Shiyan CWs in Shenzhen, Guangdong Province (Peng, 2004)	domestic sewage	15000.00	1160000.00	77.33	0.026
Gankeng CWs in Shenzhen, Guangdong Province (Me, 2004)	domestic sewage	16000.00	942500.00	58.91	
Mantanghe CWs in Shenyang City, Liaoning Province (Yuan and Chang, 2011)	domestic sewage	20000.00	1595000.00	79.75	0.036
CWs in Guangdong (Chen, 1994)	domestic sewage	350.00	34510.00	98.60	
CWs in Jiaonan city, Shandong province (Chi and Chen, 2003)	domestic sewage	60000.00	4350000.00	72.50	
CWs in Sichuan Province (Wu and Ou, 2008)	domestic sewage	3000.00	424560.00	141.52	0.051
CWs in Chongqing (He and Li, 2009)	domestic sewage	500.00	108750.00	217.50	0.013
CWs in Chengdu city, Sichuan Province (Chen et al., 2012)	domestic sewage	2000.00	558250.00	279.13	0.116
CWs in Fujian Province (Li and Lin, 2012)	domestic sewage	130.00	48082.00	369.86	0.017
Longhua CWs in Shenzhen, Guangdong Province (Yang, 2009)	Effluent of WTPs	20000.00	5367856.50	268.39	0.029
CWs in Changzhou city, Jiangsu province (Wang and Zhang, 2013)	Effluent of WTPs	100.00	35960.00	359.60	0.015

potential of CWs application is substantial based on the progress of water pollution control policy in China, which encourages ecologically friendly technology for water pollution control. At the same time, CWs are an optimal method for polluted river and lake restoration.

7. Conclusions

From the study of CWs in China, it can be concluded that design parameters and pollutant removal efficiencies of CWs have a wide variation. Due to land barriers, the actual engineering design parameters for different types of CWs are higher than those specified in the technical specification in China and that recommended in western countries, especially for CWs treating micro-polluted water. The average removal efficiencies of FWS were lower than HF, VF and Hybrid CWs for all pollutants, and the removal efficiencies of pollutants showed large variation among wastewater sources. The ANOVA analysis verified that the type of CWs was one of the main factors considered for a wetland application while wastewater sources were usually ignored in designing a CW in these cases.

Regression equations for different pollutant removal efficiencies were Logarithmic for TSS, Power for NH_3-N, Compound for TN and Linear for BOD_5, COD_{cr} and TP, but correlation indices (R^2) ware very low, which can explained by the poor correlativity between design parameters and removal efficiency.

The application of CWs has great potential for decentralized wastewater treatment in small towns and rural areas and for low polluted water and river and lake pollution control given the low costs for construction, operation and maintenance. However, the nature of wastewater and the various contaminants will determine the best type of CW to be applied, as opposed to simply using the technical guidance to select this. In addition, the importance of HL and HRT must be understood by designers in order to have the best system for a particular situation.

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