Desalination and Water Treatment
www.deswater.com

1944-3994/1944-3986 © 2012 Desalination Publications. All rights reserved
doi: 10/5004/dwt.2012.2974

Taylor & Francis
Taylor & Francis Group

44 (2012) 142–150
June

Application of using surface constructed wetland for removal of chemical oxygen demand and ammonium in polluted river water

Haiming Wu[a], Weijiang Li[b], Jian Zhang[a,*], Cong Li[a], Jinyong Zhang[a], Huijun Xie[c]

[a]*Shandong Provincial Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Shandong University, Jinan 250100, P.R. China*
Tel./Fax: +86 531 88363015; email: zhangjian00@sdu.edu.cn
[b]*School of Environmental and Municipal Engineering, Qingdao Technological University, Qingdao 266033, P.R. China*
[c]*Environment Research Institute, Shandong University, Jinan 250100, P.R. China*

Received 20 May 2011; Accepted 5 December 2011

ABSTRACT

River water was mostly polluted in northern China in the past decades and the major contaminants were organic matter and ammonia. In this study the performance of the pilot-scale and full-scale surface constructed wetlands for removing COD (chemical oxygen demand) and ammonium from polluted river water was evaluated. Results showed that the effluent COD and NH_4^+-N concentrations in the pilot scale wetland systems were 10.72~19.34 mg l^{-1} and 0.18~0.90 mg l^{-1}, respectively, which met Grade-III (COD 20 mg l^{-1}, NH_4^+-N 1 mg l^{-1}) of national surface water standards in China. The maximal COD and NH_4^+-N removal efficiency was 96.18% and 99.78%. COD and NH_4^+-N removal in spring and summer were better than that in fall and winter based on the k–C* model. Combined with research results of the two-year full-scale study, it indicated that the surface wetland system was a promising technology for treating polluted river water to meet the requirement of Grade-III water quality in northern China.

Keywords: Constructed wetland; Polluted river treatment; COD; Ammonium; First-order removal; Vegetation

---

1. Introduction

At present there are severe environmental problems especially water crisis including water shortages, water pollution and deterioration in China. The water crisis is becoming more serious because of low water use efficiency and worsening man-made pollution or natural contamination [1]. Faced with above challenges, the Chinese government has adopted a series of policies to improve water resources management. South to North Water Transfer Project is designed to solve the water shortage problem in northern China by diverting water from the south of the country up to the dry north. The eastern route of the project is based on the existing river channel, lakes and the Jiang-Hang Grand Canal [1]. However, the water quality of these rivers and lakes can not reach the Grade-III (mainly COD 20 mg l^{-1}, NH_4^+-N 1 mg l^{-1}) national surface water standards in China, especially Nansi Lake in Shandong Province. The major contaminants of the Nansi Lake are ammonia nitrogen and COD from point source and non-point source along the main route. Thus the water pollution of Nansi Lake Basin has affected water quality and the viability of this project [2].

---

*Corresponding author.

In order to secure water quality to meet Grade-III standards, it is obvious that the cost-effective, natural and ecologically-friendly constructed wetland system should be an alternative for purifying polluted water and can be a supplement to the existing pollution control strategies [3–6]. Constructed wetland system is based on biological, chemical and physical removal of pollutants from wastewater, mainly including microbial degradation, plant uptake, sorption, sedimentation, filtration and precipitation. Constructed wetlands are generally divided into two categories, that is, free water surface (FWS) and subsurface flow (SSF) wetlands. The FWS wetland can simulate natural systems as the water flows over the bed surface and is filtered through a dense stand of aquatic plants. And SSF wetlands have better removal ability in organic matter and suspended solids than FWS wetlands [7,8].

There are currently thousands of constructed wetlands worldwide receiving and treating domestic and municipal sewage, storm water, agricultural and urban runoff wastewaters, which are mainly used for nutrient and organic matter removal [9–16]. Such artificial ecological systems have also been found useful in improving the quality of river water [5,17]. However, its successful application in river water quality improvement remains a challenge in northern China.

The main objectives of this study are (1) to evaluate the performance of COD and ammonium removal from polluted river water by FWS constructed wetland system in northern China; (2) to estimate parameters of the modified first-order k–C* model for COD and Ammonium removal in constructed wetlands and to quantify the influence of temperature and plant species; (3) to evaluate effect of design factors, for example, hydraulic retention time (HRT), on the efficiency of constructed wetland system. Useful suggestion for the design of constructed wetlands will be brought forward.

2. Materials and methods

2.1. Pilot-scale study

2.1.1. Experimental setup and design

The experimental site was located in the Baihua Park in Jinan, Northern China (36°40′36″N, 117°03″42″E) with the sub-humid continental monsoon climate, characterized by annual precipitation of 670.7 mm and annual temperature of 14.3°C.

The pilot-scale surface flow wetland systems were designed and established under the transparent rain shelter on March 20, 2009. The 15 experimental wetland units were constituted by polyethylene tubs. The treatment units were 50 cm deep and 40 cm in diameter, with an outlet on the bottom, filled with washed river sand (particle size < 2 mm, mainly Si_2O_3, Al_2O_3, Fe_2O_3) as the substrate with a depth of 25 cm. A perforated pipe (30 mm in diameter) was placed in the center of the system. Water depth was kept 15 cm above the sand surface. Each wetland tub contained 20 l water when filled up. Fig. 1(a) shows the profile of the pilot-scale constructed wetland unit.

2.1.2. Composition of polluted river water

In order to minimize variability in the experiment, simulated polluted river water was used in the experiment, which was based on a systematic analysis of the on-line data of water quality monitoring sections from the local environmental protection authorities. The major pollutants of the polluted river water were organic matter, ammonia nitrogen and total phosphorus, total nitrogen, so the simulated polluted river water was used and prepared from tap water, composed of sucrose, $(NH_4)_2SO_4$, KH_2PO_4 and KNO_3. The influent qualities of the pilot-scale wetland units were as follows: COD 65.70 ± 3.0 mg l^{-1}, TN 18.84 ± 1.10 mg l^{-1}, NH_4^+-N 8.41 ± 0.41 mg l^{-1}, TP 1.56 ± 0.12 mg l^{-1}. All other micronutrients for the normal growth and development of the plant (mg l^{-1}): 21 Ca, 10 Mg, 14 S, 0.8 P, 0.3 Fe, 0.03 Zn, 0.01 Cu, 0.03 Mn, 0.03 B, 0.002 Mo were kept at the same level in all the treatments by adding $CaCl_2$, $MgSO_4$, Fe-EDTA, $ZnSO_4$, $CuSO_4$, H_3BO_3, H_2MoO_4, $MnCl_2$ [18].

2.1.3. Macrophyte selection and culture

Four native macrophyte species (*T. orientalis, P. australis, S. validus and I. pseudacorus*) were transplanted from Nansi Lake in Shandong Province. The transplanted plants were then put into a container filled with 10% modified Hoagland's solution [19] to cultivate for use after their roots were washed with tap water to remove soil and dead plant tissue.

After one week's cultivation, healthy plants of similar size (approximately 0.3–0.5 m in height) were transplanted into each unit (U1: *T. orientalis*, U2: *P. australis*, U3: *S. validuswas*, U4: *I. pseudacorus*, U5: control). The vegetation was planted by hand, and the plants were placed in the sand at a roughly equal depth. Each species consisted of three units, just three replicates. The planting density of *P. australis* was eight plants per unit, *T. orientalis* four plants per unit, *S. validus* 10 plants per unit and *I. pseudacorus* four plants per unit. Three unplanted units were used as control units.

Immediately after the transplantation, plants were watered every 2 d with simulated polluted river water to maintain the water level just up to the sand surface. The water level gradually increased until it was up to 0.15 m. After acclimated for two-weeks, the experiments were started.

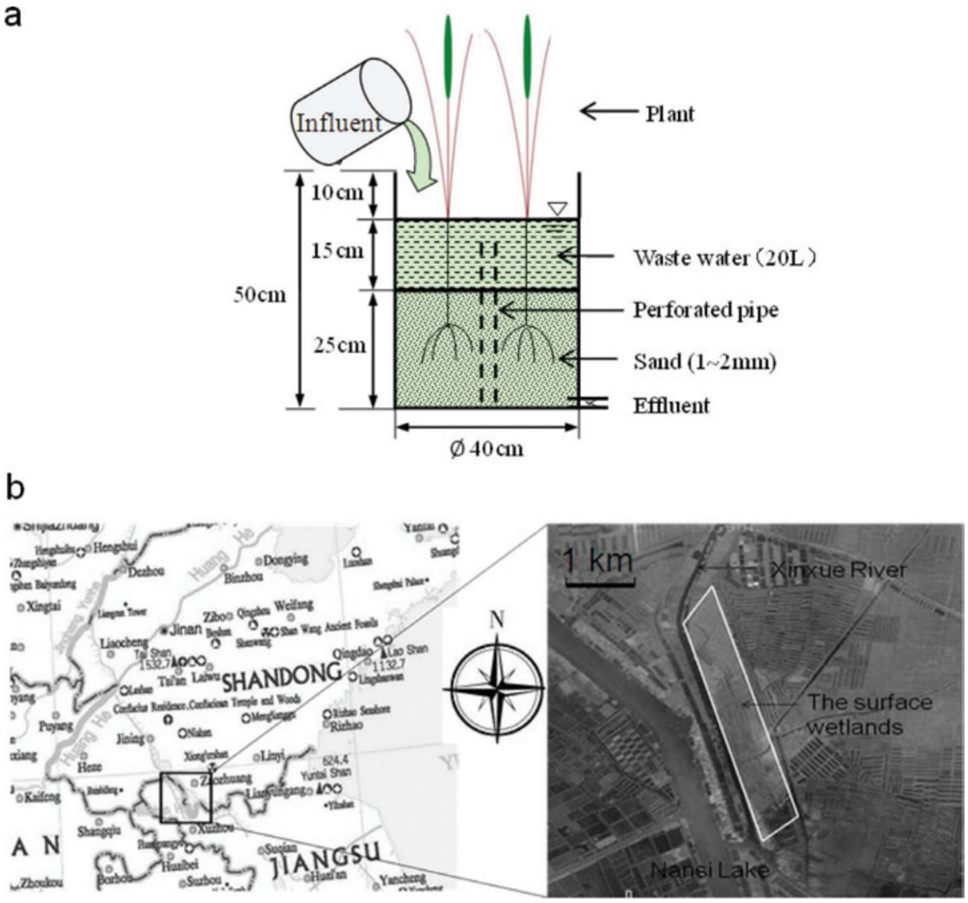

Fig. 1. Profile of the pilot-scale constructed wetland unit (a) and location of full-scale constructed wetland (b).

2.1.4. Operation of the wetland systems

Sequencing fill-and-draw batch mode was applied. From April 2009 to October 2009, each unit had a HRT of 10 d; when temperature was low from November 2009 to March 2010, HRT was 15 d or 30 d. The units were manually filled with the simulated polluted river water, and the water depth above the sand surface was 15 cm with 20 l simulated water in the total volume. Each unit was manually drained through a valve on the bottom after a cycle. Units were re-filled with simulated water immediately after drainage. Evapotranspiration loss was also estimated and compensated with distilled water for each wetland unit during the experiment.

2.2. Full-scale study

The surface constructed wetland (Fig. 1(b)) was built on the southern side of the mouth of Xinxue River at the eastern shore of Nansi Lake, which is located in Weishan County, Shandong province, north China (34°44′30″N, 117°08′32″E). Topographical information in this area was high in the north and low in the south, and gently topography, with an average attitude of 35 m. The constructed wetland was divided into platform fields and shallow water zones according to differences in elevations. The constructed wetland (3700 m × 270 m, approximately 1.33 km^2) consisted of a natural soil layer and had 50 cm depth of water above the substrate. The constructed wetland was planted with the dominant native wetland plants such as *T. orientalis, P. australis, S. validus* and *Z. latifolia.* Hydraulic loading rate applied was about 1.6 cm d^{-1}, and the theoretical HRT was about 16 d. The wetland has been operating since the year 2008. The inflow of the constructed wetland was Xinxue River water which originated from Shanting mountain areas, flowed about 84 km and mainly consisted of treated water from the urban sewage. The effluent was discharged into Nansi Lake directly.

2.3. Sampling and chemical analyses

In pilot-scale study, water samples were collected using a syringe tube at 10 cm depth below the water surface of each unit every 2 d (corresponding to nominal HRTs of 10, 8, 6, 4 and 2 d, respectively) in 10-d operating period from April 2009 to October 2009, and when the HRT was 15 or 30 d from November 2009 to March 2010, the time intervals for sampling was 3 d. In full-scale study, the influent and effluent were collected using a sampling bottle every 2 mo from 2008 to 2010.

Laboratory analyses were performed on the water samples for COD, ammonium (NH_4^+-N), total nitrogen (TN), nitrate (NO_3-N) and nitrite (NO_2-N). Water temperature, pH, and dissolved oxygen (DO) above/below the surface of the substrate were measured by a DO Meter (HQ30d 53LED™, HACH, USA) in situ. All the parameters mentioned above were determined, based on standard methods [20].

2.4. First-order modeling

It is generally recognized that the removal of pollutants in constructed wetlands can mostly be described using first-order plug-flow kinetic model [8,23]. This model is given as follows:

$$\frac{(C - C^*)}{(Co - C^*)} = \exp(-K_v T)$$

where, C is the COD (or NH_4^+-N) concentration (mg l^{-1}), C_0 is the influent COD (or NH_4^+-N) concentration (mg l^{-1}), C^* is the background COD (or NH_4^+-N) concentration (mg l^{-1}), T is the retention time (d) and K_v is the the first-order volumetric rate constant (d^{-1}).

The model was employed in this study to evaluate the behavior of COD (or NH_4^+-N) reduction in constructed wetlands. Background concentrations used in the model were 10.0 mg l^{-1} for COD and 0 mg l^{-1} for NH_4^+-N which are typical for CWs [21].

2.5. Statistics

All statistical analyses were performed through the statistical program SPSS 11.0 (SPSS Inc., Chicago, USA), including analysis of variance(ANOVA), Bartlett's and Levine's test for homogeneity of variance and normality, and Duncan's multiple range test for differences between means. In all tests, differences were considered statistically significant when $P < 0.05$.

3. Results and discussion

3.1. Temperature, evapotranspiration, DO and pH

In the pilot-scale study, air temperature from April 2009 to March 2010 (Fig. 2) ranged from –7.0°C in January to 31.0°C in July; water temperature during the experimental period was similar in different wetland units ($P > 0.05$), ranging from 0.5°C in December to 28.1°C in July. The water was frozen in January and February. It was observed that evapotranspiration from wetland units was approximately 7 mm d^{-1} in summer, and evaporation values for planted units were higher than those in unplanted units. As shown in Table 1, DO in planted wetland units, generally ranging between 5.62 and 6.12 mg l^{-1}, was higher than that in the unplanted units. This was beneficial to the aerobic biodegradation around the root zone area. Higher DO in U1 and U4 might be due to their higher capacity of oxygen release owing to oxygen transportation mechanism of plant vascular systems. Higher DO was also observed above the surface of the substrate compared to the results obtained below the surface of the substrate, which indicated that natural reaeration at the water surface caused the significant DO variations above and below the surface of the substrate. Some differences were detected in pH among the units ($P < 0.05$), ranging from 7.75 to 7.88.

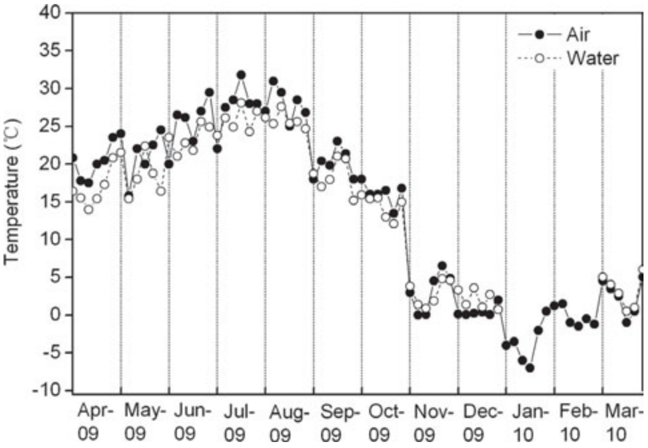

Fig. 2. Variations of air and water temperature in the pilot-scale study from April 2009 to March 2010.

All of the plants in wetland units grew well without obvious symptoms of toxicity or nutrient deficiency during the whole experimental period, and they all reached their maximum height in summer due to the proper temperature and humidity. Particularly, *I. pseudacorus* produced a vegetation cover with flowers that had a nice appearance.

Table 1
Average DO and pH in the wetland microcosm units during the experiment

Treatment unit	Parameter		
	DO_1 (mg l^{-1})	DO_2 (mg l^{-1})	pH
U1	5.74 ± 1.18	2.90 ± 1.91	7.82 ± 0.21
U2	5.44 ± 0.75	4.13 ± 2.16	7.86 ± 0.26
U3	5.54 ± 1.22	2.42 ± 1.31	7.75 ± 0.25
U4	5.88 ± 0.56	4.44 ± 2.05	7.75 ± 0.30
U5	5.91 ± 1.01	4.51 ± 1.91	7.88 ± 0.30

DO_1: dissolved oxygen above the surface of the substrate;
DO_2: dissolved oxygen below the surface of the substrate.

3.2. Removal performance in each unit

3.2.1. Removal of COD

The COD removal efficiency in the pilot-scale wetland units from April 2009 to March 2010 is shown in Fig. 3(a). No significant difference were observed among for COD removal rates of different wetland units ($P < 0.05$) and the average COD removal efficiency was high (above 70.0%) during the study period. As shown in Fig. 3(a), the COD removal efficiency was in the range of 68.87~79.07%, relatively lower at the beginning (i.e., April 2009). It may be because the plants in newly-built wetlands were not flourishing and microbial population beneficial to biodegradation of pollutants around the root zone area was not well developed in the start-up period. From May to October 2009, COD removals for the wetland units were higher than and also more stable, with the maximum of removal (96.18%) occurring in May 2009. The results indicated that the increasing temperature and suitable humidity as well as luxuriant plants, to a certain extent, benefit the improvement of effluent quality in summer. Furthermore, the presence of plants provided a more effective distribution of the roots and a more propitious habitat which encouraged the development of a great diversity of microbial communities. In November 2009, COD removal efficiency in the wetland units decreased to some extent due to lower temperature and withered plants, although the HRT was increased to 15 d. Specifically, COD removal efficiency in the wetland units with plants was observed to range from 58.7% to 74.85%, while COD removal in unplanted unit was significantly reduced to 30.08%. In December when the HRT was 30 d, COD removal in wetlands units was higher than in November. In addition, planted units were significantly better than unplanted unit. Because of temperatures dropped below zero, the experiment was stopped in winter (January 2009 and February 2010) due to freezing weather. Two months later, the lower efficiency of COD removal was observed in March when HRT was 15 d, and COD removal in unplanted unit (66.85%) was significantly better than planted units (25.93~43.08%). This was most probably due to that residual dead leaves and withered plants in planted units decayed and released some organic matter as the weather warmed up in March 2010. The average COD removal in wetlands of spring, summer, fall, and winter were 83.2%, 92.39%, 60.0% and 69.0%, respectively. The air temperatures varied from season to season, ranging from 0.5°C (in winter) to 28.10°C (in summer). The results indicated that the COD removal decreased with the decrease of the air temperature and the low COD removal in fall and winter may be due to low temperature.

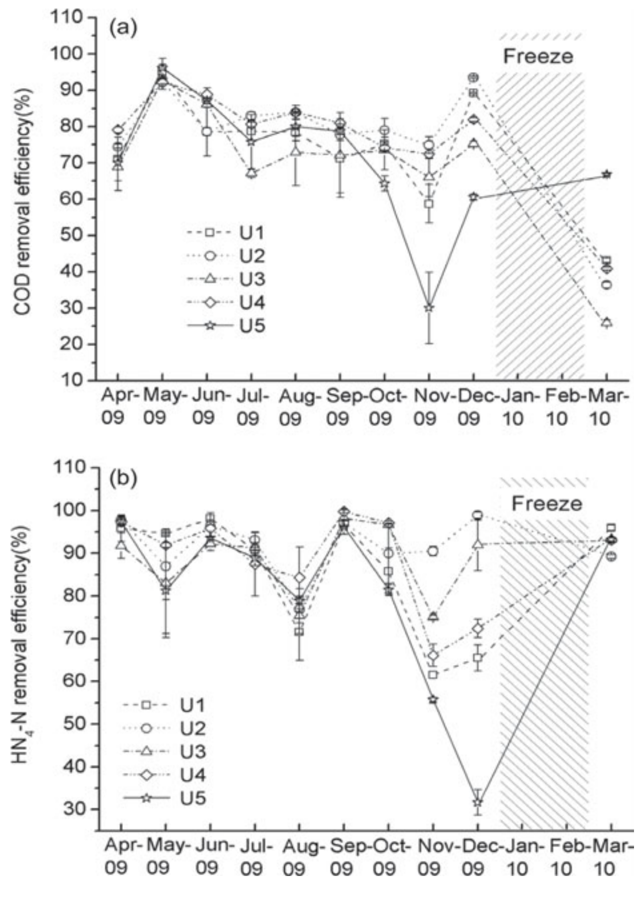

Fig. 3. (a) COD and (b) NH_4^+-N removal efficiency of the pilot-scale wetland units from April 2009 to March 2010.

The COD removal efficiency is similar to the results (77.1%) obtained by Zurita et al. [22] and (79%) by Ansola et al. [11], and higher than the results (37~69%) achieved by Chen et al. [23]. However the COD removal efficiency obtained is slightly lower than that (93.6%) achieved by Radoux et al. [24]. It may be attributed to a variety of factors including type and size of substrate, size of system, HRT, influent concentration, and climate.

3.2.2. Removal of NH_4^+-N

The NH_4^+-N removal efficiency in the pilot-scale wetland units during the study period is shown in Fig. 3(b). Like COD removal, a similar variation trend for NH_4^+-N removal was seen in Fig. 3(b), but there were some differences at the beginning and the end of the experiment. A possible reason for this is that ammonia may be mainly adsorbed from solution through a cation exchange reaction with the substrate in the start-up period. Furthermore, the plants were animated in March 2010, so NH_4^+-N removal was still high because of nitrogen assimilation of growing plants. It is well accepted that nitrification occurs when oxygen is present in a concentration (DO > 2 mg l^{-1} in this study) high enough to support the growth of strictly aerobic nitrifying bacteria, which will effectively improve ammonia nitrogen removal from wastewater in constructed wetlands. Particularly, the average NH_4^+-N removal efficiency in planted and unplanted units was high (about 90.0%) during the study period except November and December 2009 when NH_4^+-N removal decreased sharply due to low temperature and dead plants, and NH_4^+-N removal efficiency in planted units was relatively higher than in unplanted unit ($P < 0.05$).

As shown in Fig. 3(b), from April to October 2009, the NH_4^+-N removal efficiency was in the range of 71.49~99.78% with the maximum of removal occurring in September 2009. A possible explanation was that the temperature in wetlands in summer met required temperatures of plants and microorganism, and vegetating plants also improved NH_4^+-N removal in wetlands by plant uptake, added surfaces for microbial colonization and released plant exudates and oxygen for microbial activity. Although HRT was raised to 15 d in November 2009, NH_4^+-N removal became inefficient in all units (the minimum 55.73%). In November 2009, likewise, HRT was even increased to 30 d but NH_4^+-N removal efficiency ranged from 31.65% to 91.85%. The results indicated in one aspect that suitable temperature and growing wetland plants were beneficial for improving the NH_4^+-N effluent quality because of the increasing microbial nitrification–denitrification activities in the systems. When the weather warmed up in March 2010, NH_4^+-N removal efficiency in all units was observed ranging between 83.22 and 95.97%. The removal efficiency of NH_4^+-N recorded in this study is similar to the result 95% [25] but higher than other studies, such as, North America, 24.6% [21]; Mexico, 48.6% [22] and Taiwan, 34~75% [23]. This may be caused by the difference of HRT and HLR as well as the climate.

3.3. Effect of vegetation and HRT on removal of COD and NH_4^+-N

The removal efficiencies of COD and NH_4^+-N from the wetland units with different HRT (2, 4, 6, 8 and 10 d) during the period of April to October 2009 were examined and compared to evaluate the effectiveness of HRT on COD and NH_4^+-N removal (Table 2). As shown in Table 2, the COD and NH_4^+-N removal efficiencies in the wetland units with a 2-d HRT were 62.12~64.00% and 29.11~40.71%, respectively. When HRT was raised to 4 d the removal efficiency was observed to achieve a significant increase, with the removal of 79.40~83.92% for COD and 45.36~66.69% for NH_4^+-N. However, the HRT had no correlation with COD removal efficiency when the HRT ranged from 4 to 10 d. The possible reason may be that the amount of COD is limited in water because the mass loading of COD in this study was not high. In contrast, when HRT ranged from 4 to 10 d, the removal efficiency of NH_4^+-N increased continuously with rising HRT. Especially, it was observed that when HRT ranged from 4 to 10 d the removal efficiencies of COD and NH_4^+-N ranged from 79.40~83.92% (HRT = 4 d) to 75.24~82.24% (HRT = 10 d) and from 45.36~66.69% to 88.78~94.87%, respectively. As a whole, the HRT had a slight effect on the removal of COD from the wetland units but HRT played a significant role in the removal of NH_4^+-N. The results in this study were in agreement with those obtained by Akratos and Tsihrintzis [26] and Chen et al. [23].

From Table 2 it can be seen that the removal efficiency of COD was generally no significant interaction between wetland units (including the unplanted units). In contrast, NH_4^+-N removal in planted units were better that unplanted unit. This was consistent with the results obtained by He and Mankin [27] as

Table 2
Average COD and NH_4^+-N removal efficiencies from the wetland microcosm units with different HRT during the experiment from April 2009 to October 2009

Parameter	HRT	Removal efficiency in treatment unit (%)				
	(d)	U1	U2	U3	U4	U5
COD	2	63.09 ± 16.19	62.12 ± 18.84	62.35 ± 15.55	62.76 ± 13.92	64.00 ± 13.97
	4	79.40 ± 7.10	82.84 ± 8.12	81.62 ± 7.64	83.92 ± 5.93	80.83 ± 7.14
	6	78.16 ± 6.85	78.94 ± 13.98	78.60 ± 7.33	78.92 ± 8.93	78.30 ± 6.34
	8	81.64 ± 9.00	83.13 ± 7.98	81.29 ± 7.88	85.41 ± 5.11	75.60 ± 13.43
	10	77.40 ± 8.06	80.72 ± 5.91	75.24 ± 10.65	82.84 ± 5.75	77.56 ± 10.06
NH_4^+-N	2	31.81 ± 12.32	29.11 ± 13.41	39.09 ± 14.60	40.71 ± 18.16	32.39 ± 11.23
	4	52.59 ± 18.04	54.10 ± 18.85	66.69 ± 17.86	60.90 ± 12.04	45.36 ± 9.32
	6	76.83 ± 13.51	77.65 ± 15.55	84.58 ± 14.86	85.79 ± 10.21	67.88 ± 12.80
	8	88.56 ± 9.19	87.93 ± 8.95	90.59 ± 5.71	92.17 ± 4.02	85.19 ± 10.49
	10	92.08 ± 5.64	94.87 ± 2.27	92.51 ± 3.39	93.95 ± 5.29	88.78 ± 7.79

well as Akratos and Tsihrintzis [26]. The explanation of the above phenomenon may be that the main mechanism responsible for COD removal was the aerobic and anaerobic microbial process [28,29]. However, for NH_4^+-N removal there could be some more important mechanisms, such as microbial nitrification, plant uptake, sedimentation and ammonia volatilization [30,31]. Assimilation into biomass and sediment and removal through microorganism nitrification and denitrification were main nitrogen removal and transformation mechanisms. In this study plants in the units grew well. Plants can not only assimilate nitrogen directly, but also increase the environmental diversity in the rhizosphere and enhance a variety of chemical and microbial processes for nitrogen removal.

3.4. First-order removal kinetics

A summary of the computed first-order removal rate constants (*k*) for COD removal in the pilot-scale constructed wetlands based on the k–C* model of each season is presented in Table 3. As shown, the calculated *k* values for COD in planted wetland units were slightly higher than that in the unplanted units. Specifically, the calculated k values for COD in planted and unplanted units were 0.07 ~ 0.90 d^{-1} and 0.04 ~ 0.76 d^{-1}, respectively. And the k values for COD in all units in spring and summer (high temperature) were significantly higher than in fall and winter (low temperature) since higher temperature favored the biodegradation rate [32]. The calculated *k* values in this study were close to those reported in literature [21,33–35], but slightly lower than the values obtained by Stein et al. [32].

A summary of the computed first-order removal rate constants (*k*) for NH_4^+-N removal in the pilot-scale constructed wetlands based on the k–C* model of each season was also shown in Table 3. The calculated *k* values for NH_4^+-N in planted wetland units were significantly higher than that in the unplanted units. Specifically, the calculated k values for NH_4^+-N and were 0~0.20 d^{-1} in the planted units and 0.03 ~ 0.29 d^{-1} in the unplanted units. And the k values for NH_4^+-N in spring and summer were significantly higher than in fall and winter. The calculated k values for NH_4^+-N were similar to those reported in literature [21,36], but lower than the results obtained by Jing and Lin [17] and Jing et al. [33]. This variation of removal rate constants (*k*) may be because *k* value was generally affected by the influent

Table 3
First-order removal rate constants (*k*) and coefficients of determination (R^2) for COD removal in the pilot-scale constructed wetlands based on the k–C* model

	Unit	Season	*k* (d^{-1})	R^2		Unit	Season	k (d^{-1})	R^2
COD	U1	Spring	0.66 ± 0.14	0.9858	NH_4^+-N	U1	Spring	0.29 ± 0.04	0.9675
		Summer	0.78 ± 0.28	0.9778			Summer	0.22 ± 0.02	0.9954
		Fall	0.11 ± 0.01	0.9883			Fall	0.09 ± 0.02	0.7321
		Winter	0.19 ± 0.09	0.9293			Winter	0.03 ± 0.00	0.8862
	U2	Spring	0.59 ± 0.08	0.9959		U2	Spring	0.17 ± 0.04	0.9181
		Summer	0.90 ± 0.47	0.9829			Summer	0.25 ± 0.02	0.9973
		Fall	0.13 ± 0.00	0.9891			Fall	0.13 ± 0.02	0.8779
		Winter	0.16 ± 0.03	0.9730			Winter	0.08 ± 0.02	0.8757
	U3	Spring	0.66 ± 0.11	0.9924		U3	Spring	0.22 ± 0.04	0.9628
		Summer	0.80 ± 0.35	0.9742			Summer	0.30 ± 0.01	0.9989
		Fall	0.14 ± 0.00	0.9933			Fall	0.10 ± 0.00	0.9620
		Winter	0.07 ± 0.00	0.9906			Winter	0.08 ± 0.01	0.9831
	U4	Spring	0.64 ± 0.10	0.9974		U4	Spring	0.27 ± 0.03	0.9819
		Summer	0.76 ± 0.24	0.9778			Summer	0.29 ± 0.01	0.9994
		Fall	0.17 ± 0.01	0.9914			Fall	0.07 ± 0.00	0.9810
		Winter	0.10 ± 0.00	0.9975			Winter	0.04 ± 0.01	0.8742
	U5	Spring	0.54 ± 0.10	0.9920		U5	Spring	0.16 ± 0.02	0.9705
		Summer	0.76 ± 0.28	0.9752			Summer	0.20 + 0.01	0.9950
		Fall	0.04 ± 0.00	0.9435			Fall	0.06 + 0.00	0.8527
		Winter	0.13 ± 0.01	0.8611			Winter	0	0.0000

Spring: April and May, summer: from June to October, fall: November, winter: December.

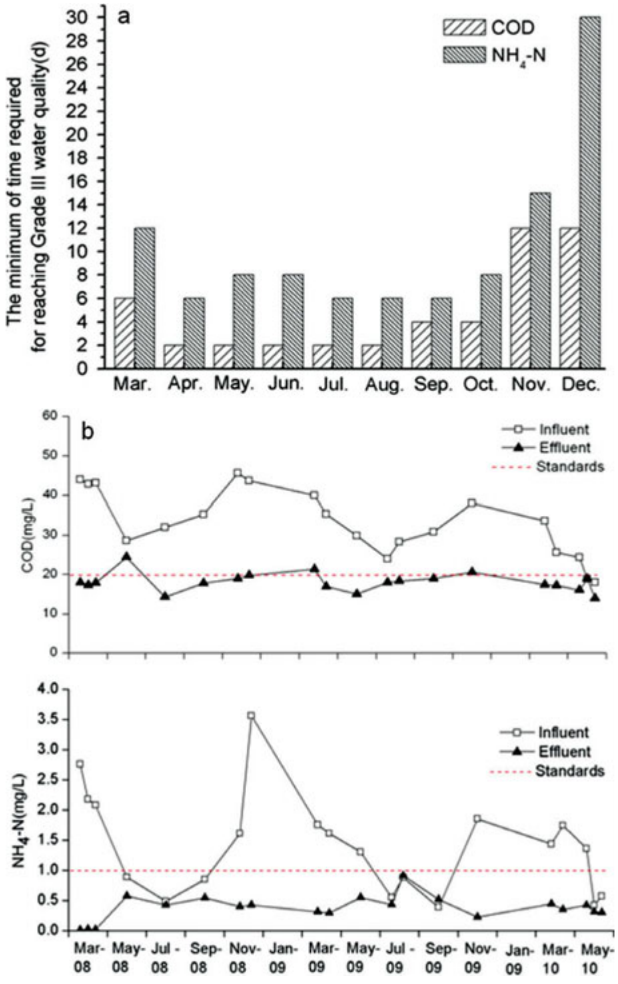

Fig. 4. The minimum of time required for reaching Grade-III water quality in China in different month throughout the year (a) and average COD and NH_4^+-N influent and effluent concentration from the full-scale constructed wetland from March 2008 to April 2010 (b).

concentrations, the hydraulic load rate and the water depth as well as climatic conditions in the area.

3.5. Design suggestions and full-scale study

The high COD and NH_4^+-N removal of surface constructed wetland systems (Fig. 3) indicated that it is a promising alternative treatment scheme for the polluted river water. The present research results allowed us to estimate the required HRT for a surface constructed wetlands located in this area of China. It was estimated that a HRT above 6 d is adequate for relatively high removal of COD and NH_4^+-N. Fig. 4(a) showed the minimum time required for reaching Grade-III water quality in China in different month throughout the year based on the result of this study. It was seen that for COD removal the required HRT was about 2~12 d from March to December and for NH_4^+-N removal the required HRT was about 6 ~ 30 d. On the whole, time required for reaching Grade-III water quality in spring and summer was shorter than in fall and winter. Furthermore, we recommend that plant be harvested in winter, the decaying vegetation be gathered and pest control be implemented.

Fig. 4(b) showed average COD and NH_4^+-N influent and effluent concentrations in the full-scale constructed wetland from March 2008 to April 2010. The result indicated that the treated river water mostly met Grade-III water quality in China and could be directly discharged into Nansi Lake which is an important drinking water source in northern China. In addition, the surface constructed wetland partially rehabilitated the degenerated lakeshore wetland. An improvement in the diversity of species was observed in and around the system.

4. Conclusions

Surface flow constructed wetland was found to be suitable for removal of COD and ammonium in polluted river water in northern China and the treated river water met Grade-III water quality of China. The wetland systems with different plants showed no significant difference in COD removal. In contrast, planted units were better than unplanted units in terms of NH_4^+-N removal. The HRT had a slight effect on the removal of COD but a more significant effect on the removal of NH_4^+-N. And the calculated k values for COD and NH_4^+-N in spring and summer were significantly higher than that in fall and winter. It was estimated that the required HRT to reach Grade-III water quality for COD removal was shorter than that for NH_4^+-N removal. Through full-scale study, the surface constructed wetland not only improved the quality of the river water but also partially rehabilitated the degenerated lakeshore wetland.

Acknowledgements

This work was supported by the National Water Special Project (No. 2009ZX07210-009-04) and Independent Innovation Foundation of Shandong University (No. 2009JQ009).

References

[1] China EPA, Bulletin of China environment status (in Chinese), (2010).

[2] C. Wang, Y.Y. Wang and P.F. Wang, Water quality modeling and pollution control for the eastern route of south to north water transfer project in China, J. Hydrodyn. Ser. B., 18 (2006) 253–261.

[3] H. Brix, T. Koottatep and C.H. Laugesen, Wastewater treatment in tsunami affected areas of Thailand by constructed wetlands, Water Sci. Technol., 56 (2007) 69–74.

[4] A. Wood, Constructed wetlands in water pollution control: fundamentals to their understanding, Water Sci. Technol., 32 (1995) 21–29.

[5] R.H. Kadlec and D.L. Hey, Constructed wetlands for river water quality improvement, Water Sci. Technol., 29 (1994) 159–168.

[6] S.R. Jing, Y.F. Lin, D.Y. Lee and T.W. Wang, Nutrient removal from polluted river water by using constructed wetlands, Bioresour. Technol., 76 (2001) 131–135.

[7] D.A. Hammer, Constructed Wetlands for Wastewater Treatment, Lewis Publishers Inc., Chelsea, MI, (1989).

[8] G.A. Moshiri, Constructed Wetlands for Water Quality Improvement, CRC Press, Boca Raton, FL, (1993).

[9] J. Vymazal, H. Brix, P.F. Cooper, M.B. Green and R. Haberl, Constructed Wetlands for Wastewater Treatment in Europe, Backhuys Publishers, Leiden, (1998) pp. 366.

[10] R.H. Kadlec, R.L. Knight, J. Vymazal, H. Brix, P. Cooper and R. Haberl, Constructed wetlands for pollution control: processes, performance, design and operation, IWA Specialist Group on use of Macrophytes in Water Pollution Control, IWA Publishing, London (2000) p. 156.

[11] G. Ansola, J.M. González, R. Cortijo and E. Luis, Experimental and full–scale pilot plant constructed wetlands for municipal wastewaters treatment, Ecol. Eng., 21 (2003) 43–52.

[12] M. Solano, P. Soriano and M. Ciria, Constructed wetlands as a sustainable solution for wastewater treatment in small villages, Biosyst. Eng., 87 (2004) 109–118.

[13] M.A. Maine, N. Sune, H. Hadad, G. Sanchez and C. Bonetto, Influence of vegetation on the removal of heavy metals and nutrients in a constructed wetland, J. Environ. Manage., 90 (2009) 355–363.

[14] J. Vymazal, Constructed wetlands with horizontal subsurface flow in the Czech Republic: two long-term case studies, Desalin. Water Treat., 4 (2009) 40–44.

[15] H. Sellami, S. Benabdallah and A. Charef, Performance of a vertical flow constructed wetland treating domestic wastewater for a small community in Rural Tunisia, Desalin. Water Treat., 12 (2009) 262–269.

[16] H. Kuroda, T. Kato, Y. Koshigoe, D. Yaegashi, S. Horaguti, K. Inubushi, T. Yamagishi and Y. Suwa, The improvement of the nitrogen removal capacity in wetlands, Desalin. Water Treat., 19 (2010) 46–148.

[17] S.R. Jing and Y.F. Lin, Seasonal effect on ammonia nitrogen removal by constructed wetlands treating polluted river water in southern Taiwan, Environ. Pollut., 127 (2004) 291–301.

[18] D.O. Huetta, S.G. Morrisb, G. Smitha and N. Hunt, Nitrogen and phosphorus removal from plant nursery runoff in vegetated and unvegetated subsurface flow wetlands, Water Res., 39 (2005) 3259–3272.

[19] D.R. Hoagland and D.I. Arnon, The water-culture method for growing plants without soil, Calif. Agr. Exp. Sta. Circ., 347 (1950) 1–39.

[20] APHA, Standard Methods for the Examination of Water and Waste Water, American Public Health Association, Washington, DC (1998).

[21] R.H. Kadlec and R.L. Knight, Treatment Wetlands, CRC Press, Boca Raton, FL (1996).

[22] F. Zurita, J. De Anda and M.A. Belmont, Treatment of domestic wastewater and production of commercial flowers in vertical and horizontal subsurface-flow constructed wetlands, Ecol. Eng., 35 (2009) 861–869.

[23] T.Y. Chen, C.M. Kao, T.Y. Yeh, H.Y. Chien and A.C. Chao, Application of a constructed wetland for industrial wastewater treatment: a pilot-scale study, Chemosphere, 64 (2006) 497–502.

[24] M. Radoux, D. Cadelli, M. Nemcova, A. Ennabili, J. Ezzahri and M. Ater, Optimization of natural wastewater treatment technologies in the MHEA® experimental centre in M'Diq, Mediterranean coast of Morocco. In: Proceedings of the Seventh International Conference on Wetland Systems for Water Pollution Control, Lake Buena Vista, FL (2000) pp. 1145–1152.

[25] A.K.C. Chung, Y. Wu, N.F.Y. Tam and M.H. Wong, Nitrogen and phosphate mass balance in a sub-surface flow constructed wetland for treating municipal wastewater, Ecol. Eng., 32 (2008) 81–89.

[26] C.S. Akratos and V.A. Tsihrintzis, Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands, Ecol. Eng., 29 (2007) 173–191.

[27] Q. He and K. Mankin, Performance variations of COD and nitrogen removal by vegetated submerged bed wetlands, J. Am. Water Resour. Assoc., 38 (2002) 1679–1689.

[28] M. Greenway and A. Woolley, Constructed wetlands in Queensland: performance efficiency and nutrient bioaccumulation, Ecol. Eng., 12 (1999) 39–55.

[29] J. Vymazal, The use of sub-surface constructed wetlands for wastewater treatment in the Czech Republic: 10 y experience, Ecol. Eng., 18 (2002) 633–646.

[30] J. Vymazal, Removal of nutrients in various types of constructed wetlands, Sci. Total Environ., 380 (2007) 48–65.

[31] L. Yang, H.T. Chang and M.N.L. Huang, Nutrient removal in gravel and soil based wetland microcosms with and without vegetation, Ecol. Eng., 18 (2001) 91–105.

[32] O.R. Stein, J.A. Biederman, P.B. Hookc and W.C. Allen, Plant species and temperature effects on the k–C* first-order model for COD removal in batch-loaded SSF wetlands, Ecol. Eng., 26 (2006) 100–112.

[33] S.R. Jing, Y.F. Lin, T.W. Wang and D.Y. Lee, Microcosm wetlands for wastewater treatment with different hydraulic loading rates and macrophytes, J. Environ. Qual., 31(2002) 690–696.

[34] R.H. Kadlec and K.R. Reddy, Temperature effects in treatment wetlands. Water Environ. Res., 735 (2001) 543–557.

[35] M.A. Belmont and C.D. Metcalfe, Feasibility of using ornamental plants (Zantedeschia aethiopica) in subsurfaceflow treatment wetlands to remove nitrogen, chemical oxygen demand and nonylphenol ethoxylate surfactants—a laboratoryscale study, Ecol. Eng., 21(2003) 233–247.

[36] J. Huang, R.B. Reneau Jr and C. Hagedorn, Nitrogen removal in constructed wetlands employed to treat domestic wastewater, Water Res., 34 (2000) 2582–2588.