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PRIMARY RESEARCH PAPER

Nitrogen removal from agricultural runoff by full-scale constructed wetland in China

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Abstract We aimed at indicating some regularities of a constructed wetland treating agricultural runoff in China. The regularities, including the nitrogen removal capacity all year round, the nitrogen distribution pathways, and the nitrogen species removal kinetics, of a free water surface constructed wetland (2,800 m^2) in the Dianchi Valley, which has been in operation for 27 months, were studied. The planted *Phragmites australis* and *Zizania caduciflora* were harvested biannually. The average inflow rate was recorded by an ultrasonic flow instrument, and then the hydraulic loading rate (HLR) and hydraulic retention time (HRT) were calculated. The average inflow and outflow concentrations of total nitrogen (TN), ammonia, and nitrate were measured, while the corresponding removal rates were calculated, showing better results than other constructed wetlands. Then the distribution pathways of nitrogen were analyzed, which indicated that plant harvesting was more important in wetland-treated agricultural runoff than in domestic wastewater. The reason for a good nitrogen removal capability and the obvious function of plants in the present wetland is the sound climate and intermittent inflow in the wetland. Results showed that inflow load had significant correction with both TN and ammonia removal efficiency. HLR, inflow rate, inflow nitrogen concentration, and temperature had significant and positive correction with both TN and ammonia removal. However, HRT had negative correction with both TN and ammonia removal, and the nitrate removal efficiency and parameters mentioned earlier were not significantly correlated. The rate constant values for nitrate and ammonia in summer were obviously larger than in winter. It is possible that bacterial and microbial activities were more active in summer than winter, and more conducive to bacterial and vegetative growth in summer than winter. Since this study was a pioneer for the implementation of constructed wetlands in China treating agricultural runoff, it has proved that this eco-technology could be used effectively for water quality enhancement in China and other areas with a similar climate.

Keywords Nitrogen removal · Free water surface · Constructed wetland · Agricultural runoff · Plant harvesting · Correlation · Rate constant

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Introduction

Nitrogenous compounds (N) in agricultural runoff are an important factor in causing eutrophication of recipient water bodies; thus, it is important to control N levels from such sources. Constructed wetlands have usually been used for domestic wastewater and industry wastewater treatment. According to Vymazal (1998), the first constructed wetland for agricultural runoff treatment was studied in 1982, whereas the first full-scale constructed wetland for agricultural runoff treatment dates back to 1993. Four restored wetlands, with areas of 9,313, 10,328, 10,351, and 5,456 m^2, respectively, dominated by *Phragmites australis*, *Typha latifolia*, and *Scirpus lacustris*, were used to improve the quality of agricultural runoff in the delta of the Ebro River (NE Spain) in 1993 (Romero et al., 1999). In four small surface-flow constructed wetlands, N retention was investigated from 3 to 7 year's operation in the cold climate of Norway (Braskerud, 2002).

Borin and Tocchetto (2007) reported the 5-year performance of a constructed surface-flow wetland in reducing diffuse N pollution coming from croplands, begun in 1998 in NE Italy. The 0.32-ha wetland is vegetated with *Phragmites australis* (Cav.) Trin. and *Typha latifolia* (L.). It receives drainage water from 6 ha of land managed for an experiment on drainage systems, where maize, sugar beet, winter wheat, and soybean are cultivated. The Dianchi Lake of China has shown high sensitivity to pollutants, and it is one of the key water bodies to be protected in China. Constructed wetlands are a relatively economical alternative to conventional wastewater treatment technologies, especially in small rural communities with low populations (USEPA, 1993; Li and Jiang, 1995; Vymazal, 1998; Healy and Cawley, 2001; Luederitz et al., 2001). A constructed wetland with an area of 1,257 m^2 used for agricultural runoff treatment in China was reported in a previous study (Liu, 1997); this wetland was dominated with the helophytes Lemnaceae and *Phragmites australis*. The removal rates of total nitrogen (TN) and total dissolved nitrogen (TDN) were 35.5 and 41.2%, respectively. Jiang et al. (2007) reported the removal capacity of agricultural non-point source pollutants of ditches grown with nature reed (*Phragmites communis* Trin) and wild rice (*Zizania latifolia* Turcz) so as to find a way to alleviate eutrophication in Lake Taihu. They illustrated that reeds and wild rice have a high nitrogen uptake ability. Iamchaturapatr et al. (2007) investigated the removal of high nutrient contents from polluted water, focused on the comparisons between nitrogen phosphorus removal rates by area-based calculation and biomass-based calculation using various kinds of aquatic plants (18 emergent and 3 floating plants). Results showed that all floating plants performed maximum nutrient removal rates based on plant weight calculation, while most emergent plants performed maximum nutrient removal rates based on planted area calculation.

However, most of the previous studies on treatment of agricultural runoff by constructed wetlands were focused on agricultural regions without plastic shed mulch or farmland without a plastic cover to maintain good conditions for crop growth. The monitoring frequencies were usually one to two times per month in previous wetland studies. This study focused on a wetland in the subtropic zone treating agricultural runoff in a region with high plastic shed coverage (85%), and the monitoring frequency was five to six times per month. The local farmers are able to plant flowers and vegetables nearly year round due to the suitable climate and plastic shed mulch, so it was obvious that the rate of fertilizer applied was large and the N discharge regularity was different from that of farmland without plastic shed mulch. Moreover, the accumulative inflow rate of this wetland was accurately recorded by an ultrasonic flow instrument. The N discharge regularity of this farmland was summarized in detail in a previous paper (Gui et al., 2003).

Another purpose of this study was to investigate the effect of hydraulic loading rate (HLR), hydraulic retention time (HRT), and temperature on N retention, as well as on the kinetic parameters (K_t) of ammonia and nitrate removal. K_t is a temperature-dependent removal rate coefficient and can act as an indicator of wetland nitrogen removal performance. With the increase of biochemical activity in the constructed wetland, the K_t value increased. These results demonstrate a successful case study and provide useful data for the effective treatment of agricultural runoff in arable watersheds.

Materials and methods

Site description

The free water surface constructed wetland (FWS) was built in the eastern side of Dianchi Lake, which is located to the east of Kunming City, China. This area is in the north subtropical zone, with a high average annual rainfall (797–1,007 mm).

The area of the constructed wetland was approximately 2,800 m^2, and the inflow consisted of agricultural runoff coming from the upstream farmland with a watershed area of 0.23 km^2. The water level of Dianchi Lake was kept lower than that of the constructed wetland effluent during the rainy season (from May to September), because storm water was allowed to discharge into Dianchi Lake in order to protect the surrounding villages from flood; thus, during this period the effluent of the constructed wetland was discharged into Dianchi Lake directly. However, the water level of Dianchi Lake was kept higher than that of the constructed wetland effluent during the dry season, because the water in Dianchi Lake is stored during this season in order to provide water for irrigation. Thus, the constructed wetland effluent was discharged into the surface drain before being pumped into Dianchi Lake.

Sample analysis

The monitoring and surveying of the constructed wetland was performed from May 2002 to June 2004. Water and plant samples were analyzed periodically.

The daily water inflow rate of the wetland was recorded by an ultrasonic flow instrument (HBML-3, Beijing Huanke Environmental Protection Technology Co.) in the inflow ditch. Temperature and pH were measured on site when water samples were taken. Water was collected for the analyses of ammonia (NH_3–N), nitrate (NO_3–N), and TN five to six times per month. Since the concentrations of nitrite are usually very low in the water, it is sometimes neglected (Andersen & Olsen, 1994). Organic nitrogen (ON) was calculated by the following equation:

$$\mathrm{ON} = \mathrm{TN} - (\mathrm{NH_3{-}N}) - (\mathrm{NO_3}^{-}{-}\mathrm{N}) \tag{1}$$

The water samples were analyzed using protocols found in *Standard Methods* (SEPA, 2002). TN and nitrate were analyzed using the ultraviolet spectrophotometric method, while NH_3–N was measured using the Nash-reagent photometry method. The concentrations of nitrogenous compounds were reported as N concentration.

The biomass (dry and wet), height, water content (WC), and nutrient content of plants were also measured in this study. In November 2002 and July 2003, plants were harvested. Plant tissues were sampled within 2 m^2 of the sampling plot. Plant materials were chopped and dried at 65°C for 30 min and 105°C for 24 h before analysis of nitrogen content (Lu, 2000).

N distribution pathways in constructed wetland

The major N distribution pathways in the constructed wetland were nitrification, denitrification, plant harvest and seed transport, ammonia volatilization and discharge into the wetland itself (Vymazal, 1998; Reinhardt et al., 2006). Ammonia volatilization was ignored here because the pH value was lower than 7.5. The corresponding N loads of input, discharge, plant uptake, and removal by harvesting and seed transport can be calculated from the data obtained during the study. Thus, the N load due to nitrification, denitrification, exchange with groundwater/ammonia adsorption/bacteria, algae, and animal assimilation can be calculated as the following equation:

$$L_{\mathrm{ndea}} = L_{\mathrm{i}} - L_{\mathrm{d}} - L_{\mathrm{ht}} \tag{2}$$

L_{ndea}: N load due to nitrification, denitrification, exchange with groundwater/ammonia adsorption/bacteria, algae, and animal assimilation; L_{i}: input N load; L_{d}: discharged N load; L_{ht}: plant uptake and removal by harvesting and seed transport N load.

N removal

N removal can be calculated using the following equation (Jing & Lin, 2004):

$$K_t = \frac{\ln \frac{C_{AN-\mathrm{inf}}}{C_{AN-\mathrm{eff}}}}{\mathrm{HRT}} \tag{3}$$

where C_{inf} is influent ammonia concentration (mg l^{-1}), C_{eff} is effluent ammonia concentration (mg l^{-1}), and HRT is hydraulic residence time (d). K_t is a temperature-dependent rate constant for surface flow wetlands (d^{-1}), which can be calculated with the following equation:

$$K_t = K_{t20} \times \theta^{(T-20)} \tag{4}$$

where K_{t20} is the volumetric removal efficiency constant at 20°C (d^{-1}); θ is the temperature coefficient, and T is the water temperature (°C).

Nitrate removal kinetic equation

The following first-order plug flow concentration profile equation (Craig & Michael, 1999) was used to describe the removal of nitrate.

$$K_t = \frac{\ln \frac{C_{NN-\mathrm{inf}}}{C_{NN-\mathrm{eff}}}}{\mathrm{HRT}} \qquad (5)$$

where C_{inf} is the influent nitrate concentration (mg l^{-1}), and C_{eff} is the effluent nitrate concentration (mg l^{-1}). HRT, K_t, K_{t20}, θ, and T are the same as in Eq. 3.

Table 5 shows the calculated kinetic parameters.

Results

Water temperature and inflow rate variations

The average water temperature in winter, spring, autumn and summer was 12.7, 18.9, 19.8, and 23.1°C, respectively.

The seasonal variation of water inflow rate is illustrated in Fig. 1. The average annual inflow rate was measured to be 242 m^3 d^{-1}.

Nitrogen removal rate

The average HRT, HLR, seasonal water quality, and contaminant removal efficiency, as well as a comparison of the influent load and removal efficiency of TN with the average North American surface flow wetland system ($\mathrm{FWS}_{\mathrm{aNA}}$) (Kadlec & Knight, 1996; Nelson et al., 2003), are shown in Table 1. The average pH values of the influent and effluent were 7.0 and 7.4, respectively. The TN load rate of this wetland was 3.7-fold higher than that of the $\mathrm{FWS}_{\mathrm{aNA}}$; the present wetland and $\mathrm{FWS}_{\mathrm{aNA}}$ had TN removal rates of 61.4 and 53.0%. The nitrate concentration of the inflow was lower than the ammonia concentration. The constructed wetland had lower HRT and average water temperature (Fig. 1), and higher HLR and inflow load (Table 1) in spring than in autumn. The wetland had TN removal rates in spring and autumn of 61.9 ± 16.2 and 54.7 ± 19.7, respectively.

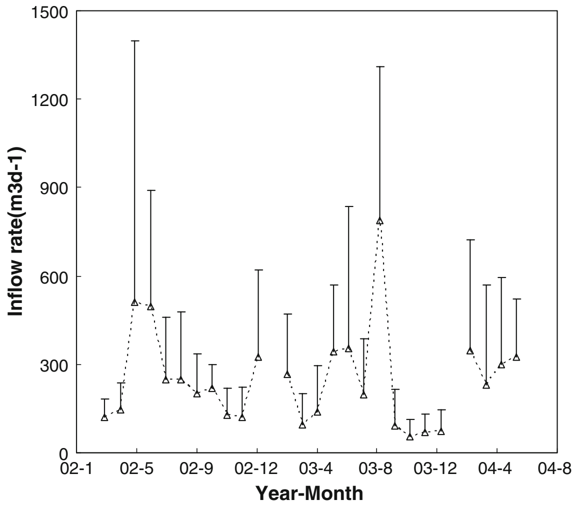

Fig. 1 Seasonal variation of average water inflow rate

The constructed wetland had NH_3–N removal rates in spring and autumn of 69.7 ± 21.2 and 67.9 ± 28.8, respectively. The constructed wetland had NO_3^-–N removal rates in spring and autumn of 43.3 ± 1,126 and 42.3 ± 214, respectively. The constructed wetland had TN removal rates in summer and winter of 65.4 ± 20.2 and 55.8 ± 13.6, respectively. The constructed wetland had NH_3–N removal rates in summer and winter of 63.6 ± 49.5 and 47.9 ± 21.1, respectively. The constructed wetland had NO_3^-–N removal rates in summer and winter of 60.9 ± 132.7 and 58.4 ± 574, respectively.

The effluent nitrate concentration was occasionally higher than the influent nitrate concentration; during these times, the daily nitrate removal efficiency was negative. However, the average effluent nitrate concentration was lower than the average influent nitrate concentration (Table 1).

The removal efficiency of ON in autumn was only 28.6%, which was significantly lower than in other seasons.

To better understand the performance of the constructed wetland in different seasons and conditions, we compared the constructed wetland performance in spring and autumn (Fig. 2a), as well as in summer and winter (Fig. 2b), because spring and autumn each have 1 month belonging to the rainy season, and summer and winter have temperature variations that may affect helophyte growth rates.

The N removal rates of this wetland were compared with other wetlands (Table 2).

Table 1 N concentration, load, and removal rate of constructed wetland treating agricultural runoff in various seasons

	Spring	Summer	Autumn	Winter	All seasons	Reference[a]
HLR (cm d^{-1})	12.6	16.0	11.3	6.3	12.7	–
HRT (d)	2.0	1.7	2.2	3.8	2.0	–
L-TNinf (kg ha^{-1} d^{-1})	7.17	9.61	5.55	3.70	7.26	1.94
TNin (mg l^{-1})	8.80 ± 5.69	8.60 ± 7.68	7.00 ± 4.12	8.35 ± 6.63	8.40 ± 6.30	9.03
TNeff (mg l^{-1})	3.35 ± 2.24	2.98 ± 2.34	3.17 ± 1.60	3.69 ± 2.12	3.24 ± 2.18	4.27
TNre (%)	61.9 ± 16.2	65.4 ± 20.2	54.7 ± 19.7	55.8 ± 13.6	61.4 ± 17.8	53
NITin-$_{L}$ (kg ha^{-1} d^{-1})	1.64	2.74	0.86	0.44	1.63	
NITin (mg l^{-1})	2.01 ± 3.31	2.45 ± 3.32	1.08 ± 0.97	0.99 ± 1.13	1.89 ± 2.89	–
NITeff (mg l^{-1})	1.14 ± 1.49	0.96 ± 1.19	0.62 ± 0.46	0.41 ± 0.41	0.93 ± 1.21	–
NITre (%)	43.3 ± 1,126	60.9 ± 132.7	42.3 ± 214	58.4 ± 574	50.7 ± 798	–
AMMin-$_{L}$ (kg ha^{-1} d^{-1})	3.56	2.91	3.39	1.19	3.09	
AMMin(mg l^{-1})	4.37 ± 2.65	2.60 ± 1.87	4.28 ± 2.55	2.69 ± 1.07	3.58 ± 2.39	–
AMMeff (mg l^{-1})	1.32 ± 1.04	0.95 ± 0.59	1.38 ± 1.04	1.40 ± 0.50	1.22 ± 0.88	–
AMMre (%)	69.7 ± 21.2	63.6 ± 49.5	67.9 ± 28.8	47.9 ± 21.1	66.0 ± 34.6	–
CODin (mg l^{-1})	119.01 ± 64.24	103.00 ± 83.27	114.00 ± 41.74	132.22 ± 80.42	116.34 ± 73.40	
TPin (mg l^{-1})	0.91 ± 0.77	0.82 ± 0.59	1.00 ± 0.87	0.76 ± 0.24	0.87 ± 0.68	
n	53	47	20	18	138	

[a] Data from average North American surface wetlands (summarized in Kadlec & Knight, 1996) (Nelson et al., 2003)

This calculation was based on 138 water samples taken during the 27 months of operation

HLR, Hydraulic loading rate (cm d^{-1}); *HRT*, hydraulic retention time (d); *TNin*, influent concentration of total nitrogen (mg l^{-1}); *TNeff*, effluent concentration of total nitrogen (mg l^{-1}); *TNre*, removal rate of total nitrogen (%); *NITin-$_{L}$*, influent load of nitrate (kg ha^{-1} d^{-1}); *NITin*, influent concentration of nitrate (mg l^{-1}); *NITeff*, effluent concentration of nitrate (mg l^{-1}); *NITre*, removal rate of nitrate (%); *AMMin-$_{L}$*, influent load of ammonia (kg ha^{-1} d^{-1}); *AMMin*, influent concentration of ammonia (mg l^{-1}); *AMMeff*, effluent concentration of ammonia (mg l^{-1}); *AMMre*, removal rate of ammonia (%); *CODin*, influent concentration of COD (mg l^{-1}); *TPin*, influent concentration of total phosphorus (mg l^{-1})

Correlation between characteristics of inflow and operation

The correlation analysis between inflow characteristics and operation characteristics is shown in Table 3.

N distribution pathways

To understand the contaminant removal mechanism of the constructed wetland, the N distribution pathway was studied. The biomass, water content, and nutrient content of the helophytes sampled are shown in Table 4.

Discussion

Variations of water inflow rate and temperature

The lowest monthly average water temperature during the 27 months was above 10°C. This was beneficial for the application of constructed wetland for wastewater treatment because the plants and microbes in the wetland were able to maintain growth activity year round. The varying inflow rate in different seasons had an impact on contaminant reduction in the wetland.

Analysis of nitrogen removal

Although the TN load rate of this wetland was 3.7-fold higher than that of the FWS$_{aNA}$, the present constructed wetland had a higher TN removal rate than that of the FWS$_{aNA}$. This can be attributed to the following three reasons. First, for an SF (surface flow wetland) system, there was a good relationship between the load applied and the removal rate. As the load increased, so did the removal rate (Tanner et al., 1995; Headley et al., 2001); removal rate usually depends on influent concentrations and not effluent. Secondly, while the FWS$_{aNA}$ was located in

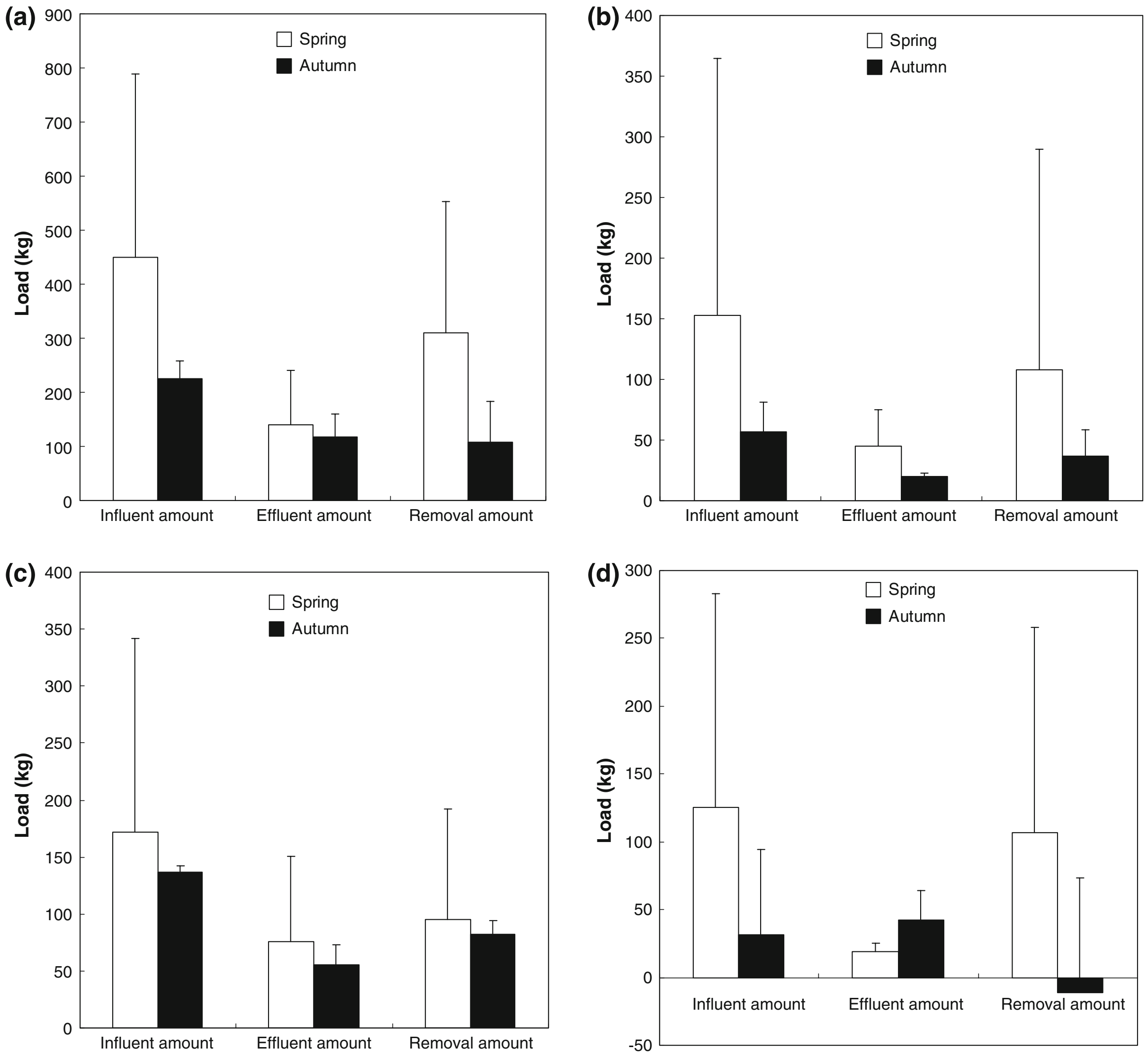

Fig. 2 Inflow, outflow and removal load (kg) of different forms of nitrogen in spring and autumn; (**a**) total nitrogen; (**b**) nitrate; (**c**) ammonium; (**d**) organic nitrogen

a temperate region, the present wetland was located in a subtropical region, so the latter had a climate more conducive to constructed wetland success (Vymazal, 1998). Thirdly, the intermittent inflow of the present wetland caused by having agricultural runoff all year round was beneficial to the N removal (Brix, 1994; Verhoeven & Meuleman, 1999; Sun et al., 2005).

Borin and Tocchetto (2007) reported that a wetland treating agricultural runoff in Italy discharged 206 kg ha^{-1} of N over the 5-year period, with an apparent removal efficiency of about 90%. Though the influent loads of this SF is lower than that of Borin and Tocchetto (2007), the removal rate of the latter is higher than the former. The variance of ratio of wetland area to catchment area of these wetlands is one important reason. The size of this SF, about 1.2% of the catchment area, is lower than 5% of the wetland reported by Borin and Tocchetto (2007). If the ratio of wetland area to catchment area is increased, then the nitrogen removal rate increases.

Considering the different structure and loading characteristics of natural and artificial systems treating point- and non-point-source pollution, it is not

Table 2 Total nitrogen, nitrate, and ammonia removal rates

	Removal rates (mg N m^{-2} d^{-1})			References
	Total nitrogen	Nitrate	Ammonia	
Spring	443.8	71.0	248.1	This study
Summer	628.5	166.9	185.1	
Autumn	303.6	36.4	230.2	
Winter	206.5	25.7	57.0	
Average values	445.8	82.6	203.9	
Average values	513 ($n = 37$)	125 ($n = 51$)	250 ($n = 63$)	Bachand & Horne (2000)[a]

n means the calculated wetland numbers

[a] NATWD (North American Treatment Wetland Database) currently lists 115 wetlands being used for nitrogen removal. A large portion of these wetlands are used for treating secondary treated or lower quality (e.g., primary, agricultural runoff, and storm water) wastewater

Table 3 Correlation analyses between influent characteristics and operation parameters (the entries in the table are correlation coefficients)

	Inflow (m^3 d^{-1})	N forms * concentration (mg l^{-1})	Water temperature (°C)	Hydraulic load rate (cm d^{-1})	Hydraulic retention time (d)	N forms[a] load (kg ha^{-1} d^{-1})
Removal rate of total nitrogen (%)	0.61	0.54	0.42	0.66	−0.44	0.84
Removal rate of nitrate (%)	0.00	0.06	0.01	0.00	0.09	0.09
Removal rate of ammonia (%)	0.48	0.54	0.58	0.55	−0.82	1.00[b]

[a] N forms mean the corresponding N (total nitrogen or nitrate or ammonia) to the removal rate

[b] Significant level $\alpha = 0.01$, $n = 5$

Table 4 Biomass, water content and nutrient content of *Zizania caduciflora* and *Phragmites australis*

Time	Plant	Water content (%)	Biomass (kg dry wt m^{-2})	N (% dw)	Dry weight ratio of leave to stem
November 2002	*Zizania caduciflora*	64.0	2.45	0.70	1.82
	Phragmites australis	54.3	1.64	1.11	0.36
July 2003	*Zizania caduciflora*	74.8	1.05	1.43	2.23
	Phragmites australis	58.2	1.27	0.90	0.49

surprising that reported retention rates vary widely (Reinhardt et al., 2006).

Jordan et al. (2003) reported an initial annual retention of 59%. However, in the 2nd year of their study, the annual retention was markedly decreased.

Although the average inflow water temperature was 18.7°C, lower than the optimum nitrification temperature (Kuschk et al., 2003), the removal of ammonia and TN was significant, with an average value higher than 50% (Gerke et al., 2001). The major reason for this was that the drying-wetting cycle in the wetland caused by the intermittent inflow was beneficial to the processes of nitrification and denitrification (Verhoeven & Meuleman, 1999) (Table 3).

The constructed wetland had lower HRT, lower average water temperature (Fig. 1), higher HLR, and higher inflow load (Table 1) in spring than in autumn. However, in spring the constructed wetland had better TN, NH_3–N, and NO_3^-–N removal rates. The major reason was that in spring helophytes grow and assimilate N rapidly, while from mid- to late-autumn they wither away and release N to the wetland. This is in agreement with the results of Kroger et al. (2007).

In summer, the N removal rates of the constructed wetland were higher than in winter (Fig. 2b), because summer had higher temperatures and helophyte growth rates than winter. This result indicates that temperature has an important effect on the removal of N. This is in agreement with the results obtained by Reddy et al. (2001) and Poach et al. (2004).

The removal rate of ON in autumn was only 28.6%, which was significantly lower than in other seasons. This was because the release of N from decaying organic material caused an increase of ON in the effluent (Fig. 3).

The removal rate of N in winter was not far lower than in other seasons (Table 1). A similar result was also obtained by Maehlum and Stalnacke (1999), in which they found that the contaminant removal rate of the constructed wetland had less than 10% difference between the warm and cold periods. Furthermore, the removal rate of a reed bed treating domestic and agricultural wastewater in a previous study did not show any seasonal pattern (Kern & Idler, 1999). In the present study, the good performance of the constructed wetland during winter was mainly caused by the following three reasons. Firstly,

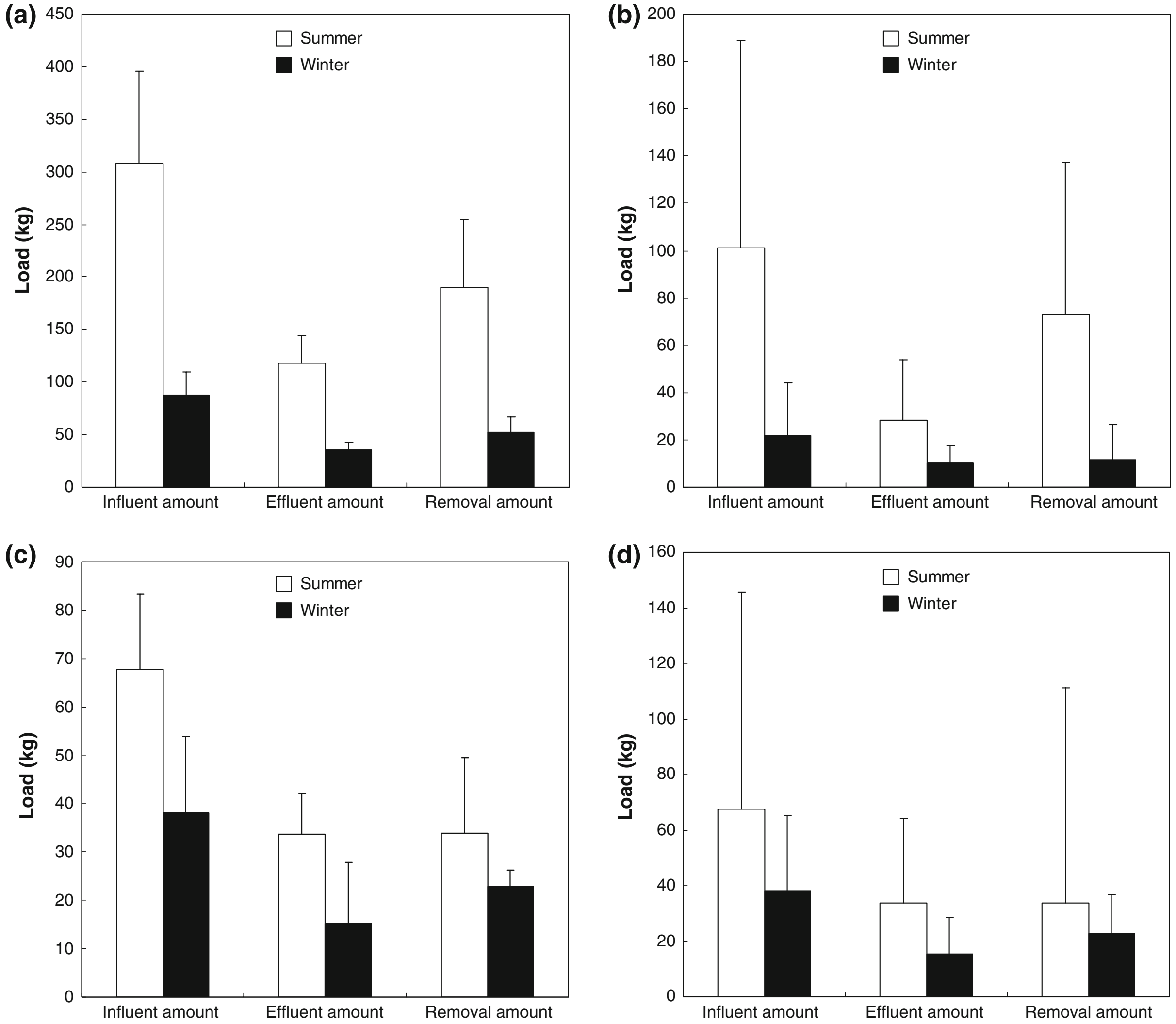

Fig. 3 Inflow, outflow and removal load (kg) of different forms of nitrogen in summer and winter; (**a**) total nitrogen; (**b**) nitrate; (**c**) ammonium; (**d**) organic nitrogen

the initial harvest in November 2002 prevented N release caused by the decomposition of plant matter (Lu et al., 2005) and strengthened oxygen diffusion from the atmosphere. Secondly, the average water temperature in winter was higher than the minimum required temperatures for nitrification and denitrification (5°C) (Vymazal et al., 1998). Thirdly, the intermittent inflow of this wetland caused by having agricultural runoff all year round was beneficial to the processes of nitrification and denitrification (Verhoeven & Meuleman, 1999; Sun et al., 2005).

The yearly average N removal rate in this constructed wetland was lower than the average value in the North American Treatment Wetland Database (NATWD) (Bachand & Horne, 2000). The inflow type was one important reason for this difference (Table 2). Among the 115 wetlands of NATWD, 25% of them were for treating storm water or agricultural runoff, and only 7 were for advanced treatment. Thus, the average N concentration in the inflow of this study was lower than that in NATWD.

Correlation analysis between inflow characteristics and operation characteristics

With respect to the TN removal rate (Table 3), TN inflow load was found to show a positive correlation ($R^2 = 0.8373$). Additionally, HLR, inflow, inflow concentration, and temperature all exhibited positive correlation with TN removal rate, while the HRT presented a negative correlation when HRT spanned from 1.7 to 3.8 d (Table 3).

Such ranges of HRT were not long enough to provide an appropriate condition for denitrification. Thus, the TN removal rate was decreased with increased HRT.

Nitrate removal rate did not have any significant correlation with inflow nitrate load, HRT, inflow concentration, temperature, or inflow rate (Table 3), possibly due to the complicated relationship between inflow nitrate load, HRT, inflow concentration, temperature, and inflow rate.

Ammonia removal rate had significant correlation with inflow ammonia load ($\alpha = 0.01$). Temperature, inflow ammonia load, and inflow had a positive correlation with ammonia removal rate (Table 3). However, the HRT had a negative correlation with the ammonia removal rate when the HRT ranged from 1.7 to 3.8 d (Table 3). In time periods with large inflow, such as stormy periods, the HRT was lower than in other periods, but the temperature was usually higher during these times than during higher HRT periods, such as winter. The ammonia removal rate was usually found to be higher in high temperature periods than during other periods.

N distribution pathways

Zizania caduciflora had higher water content than *Phragmites australis* (Table 4), which was mainly because the former had a higher leaf-to-stem ratio (in weight) than the latter (Table 4). *Zizania caduciflora* had a larger biomass (in wet weight) than *Phragmites australis*, which was mainly because the former had larger growth density than the latter (Table 4).

From August 2002 to July 2003, there were two harvests in November 2002 and July 2003, respectively. Only 14% of L_i was incorporated into the plant biomass; 39% of L_i was discharged. We know from this that 47% of L_i was removed by nitrification/denitrification/exchange with groundwater/ammonia adsorption/bacteria, algae, and animal assimilation and that this was the major N distribution pathway in this wetland. This was in agreement with the results of Vymazal (1998) and USEPA (1988). Reinhardt et al. (2006) reported that the wetland removed 45 g m^{-2} $year^{-1}$ N during the studied 2.5 years, corresponding to a removal rate of 27%. In this wetland, denitrification contributed 94% to the N removal, while only 6% of the removed N accumulated in the sediments. This does not mean that plants were unimportant for the wetland, as the plants provided good growth conditions for microbes, which removed the majority of the N from the constructed wetland. Borin and Tocchetto (2007) reported that during the period 1998–2002, the wetland received from 4,698 to 8,412 mm of water per year (on average, about nine times the environmental rainfall); its water regimen was discontinuous, and flooding occurred on a variable number of days per year (from 13 to 126). Nitric nitrogen was the most important form of element load. Its concentration in the inflow water over time was rather discontinuous, with median values ranging from 0.2 (in 2001) to 4.5 (in 2000) mg l^{-1}. Inflow nitric N concentrations were occasionally in the 5–15 mg l^{-1} range. Concentrations reduced passing through the wetland, with a more evident effect in the last year. Over 5 years, the

Table 5 Kinetic parameters (K_t) of constructed wetland in various seasons

	Spring	Summer	Autumn	Winter	Year round	Winter	Year round
K_t-nitrate (d^{-1})	0.28	0.55	0.25	0.23	0.36	0.12–0.25[a]	–
K_t-ammonia (d^{-1})	0.59	0.60	0.51	0.17	0.54	0.20–0.25[a]	0.219–2.88[b, c]
T (°C)	15.5	21.9	18.4	10.0	16.4	5–10[a]	–

[a] Craig (1999); [b] Reed et al. (1995); [c] Jing & Lin (2004)

wetland received slightly more than 2,000 kg ha^{-1} of nitrogen, 87% in nitric form, mostly from farmland drainage. Field drainage loads had a discontinuous time pattern and occurred mostly during autumn–winter, with the exception of the 2001–2002 season, which was very dry. The nitrogen removal was mostly due to plant uptake (1,110 kg ha^{-1}) and soil accumulation (570 kg ha^{-1}), with the contribution of denitrification being estimated at around 7%.

The important role played by helophytes in N removal from this wetland was due to the following three reasons. Firstly, the sound season provided good conditions for the growth of *Zizania caduciflora* and *Phragmites australis*. These two kinds of plants had large biomass and then had good N and P absorption capability. Secondly, plant harvesting conducted in December 2002 and July 2003 not only prevented N release from the helophytes, but also moved some quantity of N out of the wetland. Thirdly, the influent TN load was at a low level (119 g m^{-2}), lower than that of municipal wastewater treatment wetland. Thus, the amount of N removed by this wetland was lower than it would have been when the same wetland was used for municipal wastewater treatment.

Kinetic parameters (K_t) of ammonia and nitrate removal

K_t were affected by various factors, such as contaminant concentration, HLR, particle size, and species and growth rates of the aquatic plants present.

Ammonia removal kinetic equation

N removal is temperature-dependent and is sensitive to low temperatures. When water temperature is below 5°C, the N removal rate becomes very low. The N form also has an important effect on N removal in wetland; nitrate can be removed more easily than ammonia.

Nitrate removal kinetic analysis

It was found that in winter the K_t value of nitrate was in the typical range recommended by Craig and Michael (1999) (Table 5). K_t values of ammonia were in the typical value ranges recommend by Jing and Lin (2004) and Reed et al. (1995). However, in winter the K_t value of ammonia was only 0.17 d^{-1}, which was lower than the typical range of 0.20–0.25 recommended by Craig and Michael (1999).

During the course of the year, the maximum K_t values for nitrate and ammonia occurred in summer, and the minimum K_t values for nitrate occurred in winter. The reason for this was that during the summer it was warmer, and bacteria and vegetation were more active (more denitrification and N-uptake) than in the colder winter when the bacteria were less active and the vegetation was dormant.

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