A high-flux constructed wetland for tertiary treatment of brackish wastewater treatment plant effluent: Process performance and influence factors

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Abstract. With the scarcity of water resources and environmental degradation of water bodies, tertiary treatment of wastewater and brackish water have become necessary in countries like China. Operational data from a constructed wetland (CW), treating an average flow of 27 thousand m³/d of secondarily-treated brackish wastewater, is analyzed in this study. At a salinity level of 2-8g/L (as Cl⁻), and an average hydraulic loading rate (HLR) of 1.08 m/d, the high-flux CW system had an average removal rate of 20.43% and 65.16% for NH₄⁺-N and COD respectively, while tertiary treatment of total phosphorus (TP) and total nitrogen (TN) was less successful, indicating a background concentration in the system. Correlation analysis was done to investigate the influences of HLR, rainfall, temperature and chloride concentration on the treatment performance. Kinetic model fitting was done to determine reaction coefficients.

1. Introduction

China’s freshwater resources per capita is one third of the world’s average [1]. Decades of rapid economic growth and urbanization had resulted in increased discharge of wastewater from households, agriculture, and industry, bringing China into the rim of water crisis [2]. In 2006, the Ministry of Environmental Protection reported that an average about 52% of the water in the seven main rivers in China is rated Grade V or worse, i.e. slightly to heavily polluted [3]. Correspondingly, a countrywide shift in water regime has taken action, with management and technological measures, resulted in a turning point of water quality degradation trend. In 2016, the percentage of Grade V of worse waters in the seven main rivers had decreased to 15.5%, and percentage of high quality waters (Grade I to Ⅲ) increased from 46% as of 2016 to 67.8% [4]. Promotion of municipal wastewater treatment facilities is a key contributor in this process. At the same time, more rigid effluent regulations have been published for wastewater treatment plants, with some regions requiring effluent from wastewater treatment plants to reach national Grade V standard or better.

Brackish water, with a salinity of 2-5 g/L, is an important water source for China, especially for arid and semi-arid areas [5]. Brackish water is widely used for agricultural and industrial activities in Northern and Northwestern China [6], and discharged into the municipal sewer system thereafter. Therefore, under the scenario of stringent discharge standard, development of viable technology to purify brackish wastewater to tertiary level has become necessary. This is also the case for areas worldwide in coastal areas, regions with soil salinization problems, and industries involving use of salt. Conventional water treatment technologies, such as activated sludge reactor and membrane...
systems have been widely applied in the purification of brackish and saline wastewater [7]. Disadvantages of these systems lie mainly in the complexity in construction and operation, which greatly increase investment and requirement for chemicals and educated labor.

Constructed wetlands (CWs), as ecological and alternative solutions for wastewater treatment have been proven effective worldwide [8]. In particular, constructed wetlands have been shown to outperform conventional biological techniques in nutrient removal at tertiary level [9]. In China, the application of constructed wetland started in 1980s, and over three decades of development, the total treatment capacity has reached 84 M tons/d, with 43.8% of constructed wetlands used for treatment of slightly polluted water, i.e. wastewater plant effluent and river water [10].

Constructed wetlands have also been proven effective in purification of brackish wastewater from tannery industry, metallurgic industry, pulp and paper industry, and aquaculture industry [7]. Lab studies on the nutrient removal performance of constructed wetlands have been conducted, and influence of plant species and salinity levels have been evaluated [7]. However, no field applications with long data series in tertiary treatment of municipal wastewater has been reported.

In this current study, a large scale constructed wetland receiving 40,000 m$^3$/d of secondary-treated brackish wastewater is monitored and analyzed. The study objectives are as follows: (1) evaluate the overall removal efficiencies of organics and nutrients of the system; (2) evaluate the consistency of treatment performance over 22 months of operation; (3) examine the influence of water temperature and salinity on the treatment efficiencies; and (4) explore the kinetic coefficient suitable for the constructed wetland studied. The information obtained from this study will provide realistic reference for developing field scale constructed wetland systems for similar applications.

2. Materials and methods

2.1. The constructed wetland system studied

The wetland system (Shandong CW) studied in this paper is a horizontal subsurface flow constructed wetland, located in Shandong, China. The total footprint is about 27500 m$^2$, and the effective treatment area is 25300 m$^2$. The designed hydraulic loading rate (HLR) is 1.58 m/d, which is higher than recommended values by technical manuals in US, Europe and China (typically at 0.1-0.5 m/d). Therefore the system is considered a high-flux system.

The location of Shandong CW is affected by soil salinization, and the influent comes from a WWTP whose incoming wastewater sources include domestic and industrial, featuring average salinity of 5 g/L (as Cl$^{-}$). The system was built and ramped up in 2016 and was commissioned in full capacity in 2017. The current study covers the operational data of January 2017 to October 2018, and the operational parameter is listed in table 1.

| Parameters                     | Unit | Mean      | Range          | n  |
|-------------------------------|------|-----------|----------------|----|
| Flow rate                     | m$^3$/d | 27527.3  | 757-46421      | 240|
| Hydraulic Loading Rate        | m/d  | 1.09      | 0.03-1.83      | 240|
| Hydraulic Retention Time (Estimated) | d     | 0.34      | -              | -  |

Shandong CW consists of 42 parallel wetland units (figure 1). The units are rectangular with an area of 28m×20m×0.9m each. Figure 2 shows the longitudinal section of the wetland unit. The system operates continuously with horizontal subsurface flow. The wetland substrate consists of three parts, from top to bottom being: 40 cm of volcanic rocks with a diameter of 30-50 mm, 40 cm of gravels with a diameter of 50-80 mm, and 10 cm of fine sand. A inflow distribution zone filled with 80-120 mm gravels is set at the front of each unit. And a catchment zone with similar media is set at the end.
Figure 1. The plan view of wetland unit (Green: intake canal. Blue: outlet canal.).

Figure 2. Longitudinal section of the Shandong CW unit.

2.2. Sampling and analytical method
Sampling and analyses of water quality indices were performed in accordance with “Technical Specifications Requirements for Monitoring of Surface Water and Wastewater (HJ/T91-2002)”. COD and NH$_4^+$-N were tested daily, with analytical methods of oxidized method with potassium dichromate and t Nessler’s Reagent Spectrophotometry respectively. The silver nitrate titration method was used to analyze chloride. The analyses of T-P and T-N were made daily in February, March and May 2018, with alkaline potassium persulfate digestion-ultraviolet spectrophotometry and ammonium molybdate spectrophotometry respectively. The water temperature is measured daily by thermometer. The flow of Shandong CW was measured daily with a Parshall flume.

2.3. Kinetic model
First order k-C$^*$ model is a well-recognized model for constructed wetlands [8]. By assuming an exponential removal rate to reflect a non-zero background wetland concentration (C$^*$), the model is expressed as follows:

$$\ln\left(\frac{C_e - C^*}{C_i - C^*}\right) = -\frac{k}{q}$$  \hspace{1cm} (1)

In which,

$$k = k_{20}e^{(T-20)}$$  \hspace{1cm} (2)
Where: \( C_e \) = outlet concentration, mg/L; \( C_i \) = inlet concentration, mg/L; \( C^* \) = background concentration, mg/L; \( k \) = first-order rate coefficient, m/d; \( k_{20} \) = first-order rate coefficient when T is 20℃, m/d; T = temperature, ℃; \( \theta \) = temperature coefficient, dimensionless; \( q \) = hydraulic load, m³/(m² · d).

2.4. Regression and statistical analyses
In order to verify whether there is a significant difference between the water quality of influent and effluent, statistical data and independent sample T test with 95% confidence interval was performed with the statistics software Statistical Product and Service Solutions (SPSS).

Considering the influence of temperature and salinity on the removal rate of wetland pollutants, SPSS is mainly used to carry out correlation analysis of binary variables.

3. Results and discussion

3.1. Wetland plants
The Shandong CW was planted with iris (Iris sibirica L.) and cattail (Typha orientalis) during construction in 2016, but both species did not survive the saline condition. The CW system was then taken over by phragmites (Phragmites australis) and Chinese silvergrass (Miscanthus sacchariflorus), both of which are indigenous species.

3.2. Overall system performance on water quality improvement
Over 22 months of operation, the influent water quality did not exceed the designed concentration, while the salinity level, measured as Cl⁻, averaged 5188 mg/L, which is approximately 27% of sea water. Due to the input of industrial cooling water in the original waste stream, the temperature variance of the wetland influent is mild. Considering COD and NH₄⁺-N, the two parameters required by the discharge regulations, treated effluent from the Shandong CW had reached the design target, conforming to Class V of the national surface water quality standard. In table 2, the statistical data of water quality indicators for inlet and outlet water are listed, and they are compared with the water quality standards.

| Parameters | Units | Water Quality Standard | Influent Mean | Range | n | Effluent Mean | Range | n |
|------------|-------|------------------------|---------------|-------|---|----------------|-------|---|
| Temperature | ℃     | -                      | 20.7          | 14.2-23.1 | 358 |                  |       |   |
| Cl⁻        | mg/L  |                        | 5188          | 225-9976 | 65 |                  |       |   |
| COD        | mg/L  | 50                     | 40            | 29.35-50.0 | 599 | 23.36          | 3.4-40 | 599 |
| NH₄⁺-N    | mg/L  | 5.0                    | 2.0           | 1.33-4.85 | 599 | 0.46           | 0.01-3.20 | 599 |
| T-P        | mg/L  | 0.5                    | 0.4           | 0.26-0.58 | 76 | 0.30           | 0.08-4.16 | 76 |
| T-N        | mg/L  | 15                     | N/A           | 9.11-14.60 | 76 | 8.85           | 0.27-14.70 | 76 |

Table 3. Independent sample T test of influent and effluent concentrations.

| T-test for Equality of Means | t | Degree of freedom | Sig. (two-sided) | Difference of Means |
|-----------------------------|---|------------------|------------------|---------------------|
| COD                         | 12 | 1236             | 0.00             | 6.14                |
| NH₄⁺-N                     | 20.21 | 867              | 0.00             | 0.94                |
| T-P                         | -0.758 | 83.7             | 0.45             | -0.04               |
| T-P>0.25mg/L               | 3.033 | 68                | 0.003            | 0.056               |
| T-N                         | 0.458 | 148.6            | 0.648            | 0.26                |

To further compare influent and effluent concentrations, independent sample t-test was performed, and results are exhibited in table 3. The results implied that over 2 years, the treatment of COD and NH₄⁺-N is evident in the Shandong CW, but TP and TN concentrations were not significantly reduced.
However, when influent TP concentration was higher than 0.25 mg/L (25 out of 76 samples), the treatment of TP is evident, with an average removal rate of 15.6%. As displayed in figure 3, when influent TP concentration was higher than 0.25 mg/L, effluent TP concentrations were significantly lower (data points within green box to the right).

![Figure 3. Influent and effluent TP concentrations.](image)

![Figure 4. Monthly-averaged concentration removal rate.](image)

The average concentration removal rates of COD and NH$_4^+$-N are 20.43% and 65.16% respectively, during the 22-month operation. The overall mass removal rates of COD and NH$_4^+$-N are 16.29% and 66.90% respectively. The reductions of pollution load per unit area of COD and NH$_4^+$-N are 4.45 g/(m$^2$∙d) and 0.89 g/(m$^2$∙d) respectively.

Comparing the monthly concentration removal rates of 2018 and 2017 (figure 4), the purification capacity of NH$_4^+$-N of Shandong CW in the second year of operation was comparable with its first year. The seasonal variation of areal mass removal rate did not exhibit consistent trend.

### 3.3. Comparison with CWs receiving brackish water

The capacity of CWs to remove nutrient, especially nitrogen, has been well demonstrated [8]. However, it was also recognized that at low incoming concentration, the further treatment efficiency could be inhibited by available carbon sources and background concentration. Therefore, tertiary treatment CWs could require more land area than secondary treatment systems, depending on the expecting results. High salinity in the influent could bring more uncertainty to the issue.

Several researchers have reported the performance of CWs in treating wastewater with salinity levels, pollution strengths and hydraulic parameters to the present study (table 4). Shi et al [11] built a 221.0 m$^2$ VF-HF hybrid CW system to purify recirculating water from shrimp culturing tank. During the 113-day study period, average removal rates of Total-ammonia-nitrogen (TAN) and COD were respectively 70.8% and 26.7%, which are also comparable to the result of the present study (67.3% and 20.8%). However, Shi et al reported that the total nitrogen in the hybrid CW system was reduced by 66.8% on average, whereas the present study shown no significant total nitrogen removal. This could be a result of the low biodegradability of the influent carbon and the aerobic conditions in the CWs.

Liang et al [12] reported a mesocosm study with several EC levels and influent loads to CWs. At the EC value of 7 mS/cm, HRT of 1 day, and plant species of Phragmites australis, the system exhibited a removal rate of NH$_4^+$-N at 53%, and insignificant TN removal. It was explained that TN was not removed from the Liang system probably because the influent synthetized water did not contain organics.

Comparing the results from the present study with the reports from Shi et al [11] and Liang et al [12], it could be concluded that Shandong CW, as a large scale constructed wetland operating at its second year, has comparable results to the lab scale and small scale CWs with similar configuration.
Table 4. CWs treating brackish wastewater in literature.

| References | Wastewater Types of CWs | Operation parameters | Salinity | Wastewater Strength | Removal efficiency |
|------------|-------------------------|----------------------|----------|---------------------|--------------------|
| Liang et al [12] | Synthetic water Mesocosm HSSFs and VF s | Batch Flow with HRT of 7 days | EC at 7, 10, 15 and 30 mS/cm | NH₄⁺-N: 1.5-6.0 mg/L; NO₃⁻-N: 2.5-5.0 mg/L; PO₄³⁻: 2.0-4.0 mg/L | NH₄⁺-N: 53% |
| Shi et al [11] | Aquaculture tank Medium-scale VF s+HSSF s | HLR: 0.56-1.3 m/d | Salinity 8.25-8.26‰ | NH₄⁺-N: 70.8% | COD: 26.7% |
| Wang et al [13] | Seawater mixed with domestic sewage Mesocosm HSSF s | HLR: 0.1 m/d | EC 4.5-18.17 | COD: 109-193 mg/L; TN: 3.15-7.23 mg/L; TP: 0.68-1.30 mg/L | COD: 69.6-82.3% |

The performance of CWs with different plants were investigated in several studies. Liang et al [12] reported that Canna indica exhibited superior nutrient removal comparing to Phragmites australis, Thypa orientalis and Vetiveria zizanioides. Klomjek and Nitisoravut [13] demonstrated that T. angustifolia possessed the most satisfactory performance for growth and nutrient assimilation, when treating simulated saline water in CWs. It should be noticed though, that plants with outstanding pollutant removal potential might not be the most feasible species in large-scale engineering systems. At the Shandong CW, not all the emergent plants selected in the engineering design survived the 2-year operation, and the CW has been taken over by phragmites and China silvergrass eversince.

Although there are many successful studies showing that CWs vegetated with halophytes can improve saline wastewater treatment, their removal efficiency for highly saline wastewater is weak and labile compared with non-saline or low saline wastewater. Wang et al [13] investigated CWs fed with mixture containing increasing ratios of seawater and domestic sewage and found that when EC is between 4.5-13.5 mS/cm (between 10-30% ratio of seawater to sewage), CW performance on COD removal did not vary significantly. Liang et al [12] reported that NH₄⁺-N removal dropped significantly when EC value is increased to 30 mS/cm, while salinity difference did not influence the NH₄⁺-N removal significantly when EC is at and below 15 mS/cm. In the present study, level of Cl- also didn’t affect the COD removal, and is significantly and positively related to NH₄⁺-N removal rate. It might be therefore concluded that salinity level of lower than 15 mS/cm does not inhibit the CW performance on COD and NH₄⁺-N treatment, when suitable halophyte species are grown.

3.4. Fluctuation of concentrations and analysis of relevant factors
Analyzing the monitoring data of 599 days, the daily fluctuation of influent and effluent concentrations is evident.

Influent flowrate, rainfall, temperature and salinity are three important factors affecting treatment efficiencies of CWs, among others. For Shandong CW, these factors are taken into account to explore their influences on the concentration removal rates of COD and NH₄⁺-N. The values of the independent and response variables are presented in Table 5.

Table 5. Values of independent and response variables.

| Parameters | Unit | Minimum | Maximum | Average±SD |
|------------|------|---------|---------|------------|
| Salinity (Chloride inlet concentration) | mg/L | 225.23 | 9975.63 | 4873.56±2538.26 |
| T (temperature) | °C | 14.2 | 23.1 | 20.7±2.03 |
| Q (inlet flux) | m³/d | 757.0 | 46421.0 | 27527.3±7018.59 |
Tables 6 and 7 show the Pearson correlation coefficients (r) of the variables studied. NH₄⁺-N removal rate had a relatively high correlation with COD removal rate (r=0.411). Chloride and temperature did not show significant correlation with removal rates. The mild variances of temperature could possibly explain the neglectable impact on system function. The wastewater treatment plant whose effluent the Shandong CW had been receiving, had a substantial amount of industrial cooling water as its waste stream, which significantly raised the wastewater temperature in winter. The range of 14.2 to 23.1°C is favorable for microbiological activities. Therefore, although the above-ground tissues of emergent plants have withered in winter, the overall system performance did not decrease.

At 4873.56± 2538.26 mg/L of Cl⁻, the variance of influent salinity is noticeable. However, the changing of salinity did not cause significant change of pollutant removal rate either. This is in agreement with what Liang et al [12] and Wang et al [13] found in their experiments, an indication that the salinity of under 15 mS/cm or approximately 10000 mg/L as Cl⁻ would not inhibit biochemical removal of NH₄⁺-N and COD, as long as the CW system is well established with halophyte vegetation.

3.5. Model fitting and kinetic constant
Although influent flowrate did not show a strong correlation to the removal rates, model-fitting using averaged flowrate could lead to kinetic constants that reflect average treatment efficiency of the system. Since temperature is not relevant to removal rates, neglecting the temperature coefficient, the first order k-C* model has a simple form as in equation (1), which can be transformed into equation (3).

\[ C_e = e^{-k_i q} C_i + (1-e^{-k_i q}) C^* \]  

The reaction constant k and the background concentration C* were then determined using linear fitting formula (figure 5). The regression R-squares is 0.47 for NH₄⁺-N, with C*(NH₄⁺-N) of 0.11 mg/L and k(NH₄⁺-N) of 1.38 m/d. The regression R-squares is 0.23 for COD, with C*(COD) of 18.7 mg/L and k(COD) of 0.89 m/d. The results of first-order k values are compared with the data reported by Kadlec and Wallace [8], which were the statistics results of multiple wetland sites around the world.
The k(NH$_4^+$-N) value derived from Shandong CW is higher than the recommended value, representing high nitrification performance. Although the k(COD) value is also higher than the k(BOD) values recommended, the regression was unsuccessful, indicating no significant linear relevance between the inlet and outlet COD concentration.

![Figure 5. Linear fitting map of Shandong CW influent and effluent of NH$_4^+$-N (a) and COD (b).](image)

**Table 8.** Comparison of k values of NH$_4^+$-N/ COD.

| k values (m/d) | Shandong CW | Kadlec and Wallace 2009 (Median) |
|---------------|-------------|----------------------------------|
| NH$_4^+$-N    | 1.38        | 0.031                            |
| COD/BOD*     | 0.89        | 0.236                            |

* k values for BOD were referenced in Kadlec and Wallace (2009) [8] while k values for COD for Shandong CW are listed.

4. Conclusions

The results obtained from Shangdong CW indicate that constructed wetlands can serve as an efficient method of tertiary treatment of brackish wastewater, and high hydraulic loading could be possible. At a salinity level of 2-8g/L (as Cl$^-$), and an average HLR of 1.08 m/d, both of which exceed the regular operation parameters for CWs, Shangdong CW exhibited satisfactory treatment performance for NH$_4^+$-N and COD. Purification of TP was significant only when the influent TP is above 0.25 mg/L, indicating a background concentration in the system. To further improve the TP removal efficiency, wetland substrates with higher absorption capacity could be incorporated. Removal of TN is not evident. The low carbon availability, nitrogen input from plant residues and atmospheric precipitation were considered possible causes.

Under chloride concentration of 4873.56±2538.26 mg/L (as Cl$^-$), the variance of salinity did not show significant impact on the system’s treatment efficiencies. Salinity did inhibit the growth of plants including iris and cattail, but Phragmites and Chinese silvergrass were well adapted.

It is commonly accepted that HLR had a dominant impact on the treatment efficiencies of CW. However, the present study did not exhibit significant correlation in this regard, indicating a resilience of performance under the mild fluctuation of HLR (1.09 ±0.28 m/d). Similarly, a resilience towards temperature change was exhibited.

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