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Short Communication

Secondary effluent purification by a large-scale multi-stage surface-flow constructed wetland: A case study in northern China

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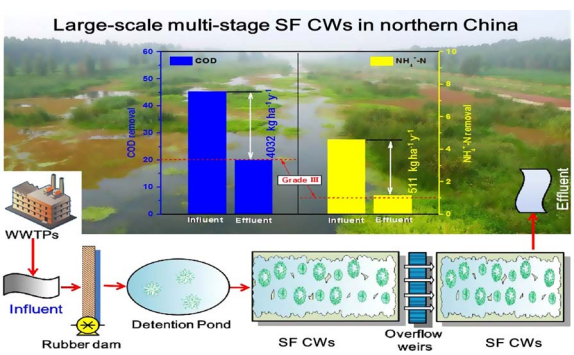
GRAPHICAL ABSTRACT



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ABSTRACT

Assessment of treatment performance in the large-scale constructed wetland (CW) for secondary effluent purification remains limited. The aim of this case study was to therefore to investigate the long-term treatment capacity of organics and ammonium pollutants in a large-scale multi-stage surface-flow (SF) CW fed with secondary effluents from the wastewater treatment plants (WWTPs) in northern China. The results for two-and-half-year study period indicated that the water quality parameters including chemical oxygen demand (COD) and ammonium (NH_4^+-N) met the Chinese Grade III of Environmental Quality Standards. The mass reductions of COD and NH_4^+-N were 53% (4032 kg ha^{-1} y^{-1}) and 72% (511 kg ha^{-1} y^{-1}), respectively. However, there was a significant positive correlation between influent loads and treatment performance. The optimal loading of 2.5 g m^{-2} d^{-1} for COD and 0.3 g m^{-2} d^{-1} for NH_4^+-N could be recommended for designing the sustainable large-scale multi-stage SF CW wastewater treatments.

1. Introduction

Nowadays, when facing the rising demand for clean water, the treatment capacity and effluent quality is still relatively low even though the majority of existing WWTPs including various centralized and decentralized systems have been developed in developing countries (Wu et al., 2016a,b). Moreover, the standard limits for effluent quality and surface water quality are becoming much stricter in order to satisfy

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the growing environmental legislation (He and Xue, 2010; Rai et al., 2013; Wu et al., 2016a; Zhang et al., 2017). Therefore, some eco-sustainable treatment technologies after sewage treatment would be an alternative and economical option for secondary effluent purification.

Constructed wetlands (CWs), as a typical ecologically based wastewater treatment system with less constructing and operating costs, have been attracted more attention especially in rural and remote regions in developing countries (Wu et al., 2015a,b; Vivant et al., 2016). Numerous previous studies have shown that CWs, depending on their configurations and characteristics, can deal with a wide range of wastewaters including domestic sewage, agricultural wastewater, industrial effluent, mine drainage, landfill leachate, urban runoff and polluted river water (Matamoros et al., 2008; Saeed and Sun, 2012; Verlicchi and Zambello, 2014; Wu et al., 2016a; Li et al., 2017). Currently, given their low cost and broad adaptability, CWs have been also used to treat WWTP effluents which might be discharged directly into natural aquatic environments (rivers, lakes, oceans, wetlands). Several studies reported that CWs can efficiently reduce organic and inorganic pollutants as well as harmful pathogens from WWTP effluents, and could effectively improve the water quality and restore river ecological environment (Wang et al., 2012; Chen et al., 2014; Wu et al., 2016c; Vivant et al., 2016). However, most of those studies were performed in microcosm-scale or pilot-scale CW systems with a small area, and few studies exist on purifying secondary effluent by using a full-scale or large-scale CW system. Matamoros et al. (2008) studied the removal of a variety of organic pollutants in a full-scale surface flow (SF) CW treating conventional WWTP secondary effluent discharged into the River Besos of northeastern Spain, and indicated that CW was efficient for removing 12 organic micropollutants from WWTP effluent. Avila et al. (2015) studied the treatment capacity of a multi-stage CW system as a supplementary to conventional WWTP. Their results demonstrated an excellent elimination of conventional water quality parameters, and proved that the final effluent could comply with existing Spanish regulations for various reuse applications (Avila et al., 2015). Moreover, a recent study of using SF CWs for treating effluent from a WWTP by Vivant et al. (2016) reported that SF CWs could be an efficient system to limit the dissemination of fecal contamination to the aquatic environment, but vegetated areas of the CW during the warmer months reduced the efficiency of the SF CW. So far, not enough data are currently available on the long-term treatment efficiency of the large-scale CWs for removing organic and nitrogen pollutants from secondary effluent of WWTPs.

The aim of this study was therefore to investigate the long-term treatment capacity of a large-scale multi-stage SF CW system for purifying secondary effluents from the conventional WWTPs in northern China. The specific objectives were to: (i) evaluate the removal performance of organics and ammonium pollutants in the large-scale multi-stage SF CW operated for more than two years; (ii) determine the sustainability of the CW system in water quality improvement to meet the environmental quality standards in China; (iii) explore the effect of input loading on the removal efficiency in the large-scale CW system.

2. Material and methods

2.1. Site description

This study was carried out in a large-scale CW system (namely Wu River CW) situated in Linyi, Shandong province, northern China (34°52′14″ N, 118°20′53″ E). The large-scale CW system was designed as a purification system to treat the secondary effluent from the municipal WWTPs (400,000 equivalent inhabitants). The climate condition of this area is a warm temperate continental monsoon climate with a mean annual temperature and an average annual precipitation of 13.4 °C and 840.1 mm, respectively. Average seasonal air temperatures during the experimental period are spring (from March to May) 7.5 °C, summer (from June to September) 24.5 °C and fall (from October to November) 19.1 °C, winter (from December to February) 2.7 °C.

2.2. Constructed wetland design

The Wu River large-scale CW was designed in a multi-stage SF CW style and it was mainly composed of a rubber dam, a distribution ditch, a detention pond, seven stages of SF CWs, and several overflow weirs. The schematic diagram of the Wu River large-scale CW is given in the Supporting Information. The large-scale system was constructed in 2010 to polish on average $3.8 \times 10^5\,m^3\,day^{-1}$ of secondary effluent from municipal WWTPs, and the total available land area of the system was about $86.6 \times 10^5\,m^2$. The substrate of CW system was the natural soil of the Wu River and held a 0.3–0.5 m depth of water. Theoretical hydraulic retention time (HRT) was 7 day with an average hydraulic loading rate (HLR) of $0.035\,m\,day^{-1}$. In the SF CWs, several native wetland plant species were planted, including *Phragmites australis* (*P. australis*), *Typha orientalis* (*T. orientalis*), *Zizania latifolia* (*Z. latifolia*), *Nelumbo nucifera* (*N. nucifera*), *Nymphaea tetragona* (*N. tetragona*), *Potamogeton crispus* (*P. crispus*), *Lemna minor* (*L. minor*) and *water hyacinth.* During the long-term experiment from July 2011 to December 2013, average influent concentrations of chemical oxygen demand (COD) and ammonium (NH_4^+-N) were $45.3\,mg\,L^{-1}$ and $4.5\,mg\,L^{-1}$. The effluent from the Wu River large-scale CW, which was discharged into a river named Yi River, was designed to meet the Grade III of Chinese Environmental Quality Standards for Surface Water (GB3838-2002). That is, the purified effluent should not exceed the permitted limits of COD $20\,mg\,L^{-1}$ and NH_4^+-N $1\,mg\,L^{-1}$, respectively. The water quality and removal performance of the Wu River large-scale CW are described in the Supporting Information.

2.3. Water sampling and monitoring

During the whole experimental period, water samples were collected at the inlet and the outlet of the Wu River large-scale CW once or twice a day (a total of 1000 times between July 2011 and December 2013. All the collected samples were kept refrigerated and transferred immediately to the laboratory. Then they were stored at 4 °C until chemical analysis. The parameters analyzed mainly included COD and NH_4^+-N. Unfiltered water samples were used directly in COD analysis, while water samples for NH_4^+-N were filtered through glass microfiber filters. All of these analyses were performed according to standard laboratory procedures and methods (APHA, 2005).

2.4. Calculations and statistics

In order to evaluate the removal performance of COD and NH_4^+-N in the Wu River large-scale CW, removal efficiency (rate) was calculated as follows:

$$\text{Removal efficiency}(\%) = \frac{(C_i Q_i - C_e Q_e)}{C_i Q_i} \times 100$$

$$\text{Removal rate}(g\,m^{-2}d^{-1}) = q \times (C_i - C_e)$$

where C_i Influent pollutant concentration ($mg\,L^{-1}$); C_e Effluent pollutant concentration ($mg\,L^{-1}$); Q_i Daily volumetric water influent flow rate ($m^3\,day^{-1}$); Q_e Daily volumetric water effluent flow rate ($m^3\,day^{-1}$); q Hydraulic loading rate ($m\,day^{-1}$).

All statistical analyses were performed by using the statistical program SPSS 11.0 (SPSS Inc., Chicago, USA). Two-sample *t*-test and one-factor analysis of variance were used for the compare the differences between means. In all tests, differences and correlations were considered statistically significant when $P < .05$.

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