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Effects of solids accumulation and plant root on water flow characteristics in horizontal subsurface flow constructed wetland

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ABSTRACT

Void space clogging of horizontal subsurface flow constructed wetlands (HSSF CWs) can result in hydraulic malfunction and reduced service life. In this study, the effect of solids accumulation and root growth on the hydrodynamics of the HSSF CWs was evaluated by tracer tests. The experimental HSSF CWs were designed to be unplanted, uniformly planted and linearly planted to investigate the role of Iris (*I. pseudacorus*) root and the effects of different planting patterns. Results showed that the traditional design of HSSF CW was easy to develop the preferential bottom flow, and the solids accumulation near inlet zone aggravated the fast bottom flow throughout the whole systems. Plant root impeded the upper layer flow at the initial stage and promoted the uniform flow in the severe clogging situation. Consequently, the water flow was more uniform in the linearly planted (dispersion number (d) = 0.16) and uniformly planted (d = 0.13) systems than the unplanted system (d = 0.10) at the final stage. The opening of new void spaces by root growth and the upward water drag induced by plant transpiration was responsible for such phenomenon.

1. Introduction

Subsurface flow constructed wetlands (SSF CWs) have a widespread application in the treatment of a wide range of wastewaters due to its prominent advantages of good purifying capacity, and low construction and operation cost (Wu et al., 2017; Zhang et al., 2017). Since the 1990s, wetland systems were extensively studied worldwide, and high per-unit purification efficiency was pursued by researchers to reduce the required land of the systems. Nevertheless, the pervasive problem of void space clogging has attracted increasing attention in the last 10 years (Corbella et al., 2016; Nivala et al., 2012). The long-term stable operation of the systems is challenged by void space clogging, which seriously hampered the extensive application of SSF CWs.

With the running of SSF CWs, the void space of the substrate was prone to be clogged by suspended solid accumulation, biofilm growth and root filling. Clogging could lead to hydraulic malfunction, and even overland flow in severe cases (Hua et al., 2017; Knowles et al., 2011). Furthermore, the longevities of the systems were reduced from the expected 50–100 years to the actual 10–15 years, or even less (Knowles et al., 2011). The common approaches to remedy the clogged SSF CWs were to clean or change the substrate, which were limited and expensive. Thus, strategies to prevent void space clogging should be emphasized. Optimized methods in designs (e.g., pretreatment process, graded substrate) and operations (e.g., reduced loading, intermittent feeding) have been proposed to alleviate the clogging progress (Nivala et al., 2012; Uggetti et al., 2010). It was concluded that hydraulic conductivity of substrate was negatively correlated to the cumulative load, and the purposes of these optimization methods were to reduce the rate of clog matter accumulation and maintain the hydraulic conductivity of wetland bed (Nivala et al., 2012). However, even for the clogged substrate, the conductivity values (usually more than 100 m/d) were generally much higher than the actual flow rates (about 10 m/d), which confirmed that high hydraulic conductivity was not equal to the uniform flow (Knowles et al., 2010). Hence, the exploration of flow behavior in SSF CWs, other than hydraulic conductivity, is essential to evaluate the performance of the systems (Yang et al., 2017). However, the change of flow characteristics on amount of solids accumulation was rarely studied.

Aquatic plants usually had well developed root system in SSF CWs. The role of plant root on void space clogging and hydraulic performance was debatable. On the one hand, according to IWA (2001) the subsurface root and rhizome occupied large void space (usually 1/4 to

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1/3) in the root zone, and the additional surface area brought by the root could enhance the solids accumulation. The internal hydraulic features of horizontal SSF CWs (HSSF CWs) were studied by many researchers, and similar results of preferential flow in the bottom layer of the planted bed were obtained (Breen and Chick, 1995; García et al., 2003). These kinds of hydraulic malfunction were attributed to the vertical gradient of void ratios with plant establishment. On the other hand, some reports claimed that the root swelling could provide macropores for water flow and counteract the void space clogging (Carvalho et al., 2013; Knowles et al., 2011). Due to the prevalent of aquatic plants in HSSF CWs, it was significant to study the role of plant root on solids accumulation and flow behavior.

Due to the limited knowledge in previous literatures, the main objectives of present work were to (1) study the effect of solids accumulation on flow behavior of HSSF CWs; (2) investigate the role of plant root and the design of different planting patterns (uniform & linear) on water flow distribution in different layers; (3) explore the mechanisms of flow characteristics influenced by solids accumulation and root growth.

2. Materials and methods

2.1. Characterization of microcosm wetlands

The experiment was carried out in the central campus of Shandong University, northern China (36°40′32″N, 117°03′14″E). Three parallel laboratory-scale HSSF CWs (A, B and C) were designed with traditional methods, each with length of 150 cm, width of 30 cm and depth of 40 cm. The water level was maintained 35 cm above the bottom of the equipment. Clean gravel was used as the main substrate with the diameter of about 1.0 cm. Gravel with a relatively larger diameter of about 2.5 cm was arranged at inlet zone (30 cm in the length direction) to facilitate the water distribution uniformly. The inlet and outlet pipes were located at the above-surface of the wetland bed. Four perforated PVC pipes were buried vertically in the middle of each system with an equal spacing distance of 50 cm to take the water sample from the internal of the system. In this study, system A, B and C were unplanted, planted with Iris (*I. pseudacorus*) in uniform style (the space between the neighboring plants was 8 cm) and planted with Iris (*I. pseudacorus*) in linear style (in a line at the middle position), respectively. The density of Iris in both system B and C was 130 plants m^{-2}.

2.2. Experimental procedure

Wastewater was continuously fed through the distribute-holes of the launder under the hydraulic retention time (HRT) of 12 h. Synthetic domestic wastewater was used in this study according to Bracklow et al. (2007). The concentrations of all ingredients were diluted to meet the Technical Specification of Constructed Wetlands for Wastewater Treatment Engineering (HJ 2005–2010). The wastewater composition was 38.7 mg L^{-1} milk powder, 5.8 mg L^{-1} peptone, 40.7 mg L^{-1} starch, 17.4 mg L^{-1} yeast, 9.7 mg L^{-1} soy oil, 26.5 mg L^{-1} sodium acetate, 30.6 mg L^{-1} urea, 4.27 mg L^{-1} NH_4Cl, 7.8 mg L^{-1} KH_2PO_4, 9.7 mg L^{-1} $MgHPO_4{\cdot}3H_2O$, 1.9 mg L^{-1} $FeSO_4{\cdot}7H_2O$ and 0.1% (v/v) of trace elements solution. In particular, the clogging process in real scale CWs would take several years (Knowles et al., 2011). For fast simulation of the clogging process in the laboratory, 100 mg L^{-1} kaolin was added to simulate the suspended solid (SS), as applied by Niu et al. (2016). The COD and SS concentration of the synthetic wastewater were 40 g m^{-2} d^{-1} and 27 g m^{-2} d^{-1}, respectively. After the transplantation of Iris seedling, the systems were supplied with half-strength Hoagland nutrient solution for two months until the plants were well established. Then, the systems were fed with synthetic wastewater and operated formally until the severe solids accumulation occurred at the inlet zone.

Table 1
Characteristics of system operation and tracer experiment.

Index	System A	System B	System C
V_{sys} (L)	63.9	62.0	61.3
Q_{in} (L d^{-1})	120.0	120.0	122.0
Q_{out} (L d^{-1})	118.3	112.1	110.7
τ_n (h)	12.9	12.8	12.6
C_{tracer} (mg L^{-1})	400.0	400.0	400.0
Δt [min]	40.0	40.0	40.0
M_{in} (g)	1.3	1.3	1.3

Value V_{sys} equals pore volume of the system; Q_{in} equals influent rate; Q_{out} equals effluent rate; τ_n equals theoretical hydraulic retention time, $\tau_n = 2V_{sys}/(Q_{in} + Q_{out})$; C_{tracer} equals the concentration of fluorescein sodium; Δt equals the time interval of tracer injection; M_{in} equals the mass of tracer injected.

2.3. Tracer study

Tracer study was conducted at the initial stage and final stage of the experiment, respectively. Except for analyzing the outlet breakthrough curves (BTCs), local tracer BTCs were monitored by taking water samples at different flow distances (50 cm, 100 cm) and substrate depths (7 cm, 18 cm, 29 cm). Fluorescein sodium ($C_{20}H_{10}O_5Na_2$) tracer was chosen as the tracer, and the water samples were pretreated and analyzed according to Seeger et al. (2013). Specifics of the tracer experiment were shown in Table 1.

In the tanks-in-series model, the flow characteristics of HSSF CWs were between plug-flow and stirred-flow. Based on the tracer response curve at the outlet, hydraulic parameters could be obtained. Briefly, the recovery rate represented the quality of the tracer study and the reliability of the hydraulic parameters, and its value was calculated from Eq. (1). The actual HRT was the average retention time of wastewater in the system, and its value could be obtained by integrating Eqs. (2) and (3). The dispersion number was used as an indicator of dispersion tendency of hydraulic behavior in the system, and its value could be obtained by integrating Eqs. (4) and (5):

$$R = \frac{Q_{out}\int_0^\infty C(t)dt}{M_{in}} \times 100 \quad (1)$$

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \quad (2)$$

$$\tau = \int_0^\infty tE(t)dt \quad (3)$$

$$\sigma_\theta^2 = \frac{\int_0^\infty (t-\tau)^2E(t)dt}{\tau^2} \quad (4)$$

$$\sigma_\theta^2 = 2d - 2d^2\left[1-\exp\left(\frac{-1}{d}\right)\right] \quad (5)$$

where R is tracer recovery rate (%); C(t) is tracer concentration at time t (mg/L); E(t) is the retention time distribution (RTD) function (1/h); τ is the actual HRT (h). $\sigma_\theta{}^2$ is the dimensionless variance (dimensionless); d is the dispersion number (dimensionless).

2.4. Composition of accumulated solids

At the end of the experiment, all systems were drained for two hours. After that, two liters of substrate samples were taken at different flow distances (10 cm, 50 cm, 100 cm and 140 cm) and substrate depths (7 cm, 18 cm, 29 cm). Clog matter was sufficiently separated from the gravel substrate by wash and air pump filtration. The substrate samples were weighted before and after the washing process, and the weight loss was obtained as the wet weight of the clog matter. Then total solids (TS) and volatile solids (VS) were determined by drying the separated clog matter at 105 °C to a constant weight and burning the residue at 550 °C for 40 min, respectively (Marin et al., 2010). Water holding