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Research Paper

Effects of clogging on hydraulic behavior in a vertical-flow constructed wetland system: A modelling approach

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ABSTRACT

The hydrological behavior of subsurface flow constructed wetlands changes with the operation time due to the gradual clogging of the matrix pores. However, studies on changes in hydraulics associated with the clogging process in constructed wetlands are still inadequate, with the variations of internal flow field that cause changes of hydraulic behavior still unknown. Conservative tracer tests and Computational Fluid Dynamics (CFD) software Fluent 6.3 were combined in this study to analyze the effect of clogging on hydraulic behavior in a vertical-flow constructed wetland experimental system. As the porosity of the experimental system decreased from 0.3669 to 0.316 caused by clogging, both the nominal hydraulic retention time and the actual average retention time decreased sharply, with the latter dropping even faster, indicating that the reduction of the pore volume caused by clogging is not the only reason for the decrease in the actual hydraulic retention time. During the experimental period, the system had a serious short-circuiting and mixing phenomenon, and the dead zone area was rather large. The overall hydraulic efficiency was poor. According to the CFD simulation results, which were verified by Nash-Sutcliffe efficiency factor (NSE), the flow rate in the experimental system increased with the operation time. Correspondingly, the time required to pass through the matrix pores decreased, which contributed to an additional drop in hydraulic retention time, along with the decrease of porosity.

1. Introduction

Subsurface flow constructed wetlands (SSF CWs) have been used worldwide for sanitation, especially in small communities, because of their natural design and low cost of operation and maintenance (Cooper et al., 1990; Vymazal, 2010; Wang et al., 2015). Based on the flow direction, the SSF CWs can be categorized as vertical flow or horizontal flow. Pollutants are removed through physical, chemical, and biological responses, which are time-dependent processes in CWs (Haberl et al., 2003; Paulo et al., 2009). With pollutants remaining for a longer time, the amount of removed pollutants increases (Postila et al., 2015; Kusin et al., 2014). Hydraulic retention time of pollutants in CWs is influenced by the flow regime. In all flow regimes, plug flow is the most efficient flow pattern, because it leads to maximum residence time with every parcel of pollutants in the inflow reaching the outlet over the same time (Rengers et al., 2016). However, it is impossible to achieve plug flow in practice, due to complicated hydrodynamics in CWs such as short-circuiting or mixing (Thackston et al., 1987; Persson et al., 1999; Rash and Liehr, 1999). Therefore, understanding hydraulic behavior is of great importance in evaluating constructed wetland performance.

Tracer tests are widely used traditional tools for the analysis of hydraulic behavior in CWs (Headley and Kadlec, 2007; Wang et al., 2014; Postila et al., 2015). Tracer breakthrough curves indicate residence time distribution (RTD), through which hydraulic efficiency can be evaluated (Werner and Kadlec, 2000). Hydraulic efficiency is used to measure the extent to which the hydraulic behavior deviates from the ideal state (Persson et al., 1999). Some hydraulic efficiency indicators for evaluating short-circuiting, mixing and effective volume in CWs have already been determined (Rengers et al., 2016; Thackston et al., 1987; Persson et al., 1999). With these indicators, hydraulic behavior in CWs can be evaluated quantitatively. Through tracer tests, Wang et al. (2014) compared the short-circuiting, effective volume, distribution of dead zones, and dispersion situation of experimental constructed wetlands with different configurations of filter size, inflow rate, and inlet-outlet design. Likewise, Liu et al. (2016) studied the

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impacts of water level on effective volume in a surface-flow constructed wetland.

With the operation of SSF CWs, the matrix will gradually accumulate material, which leads to clogging (Blazejewski and Murat-Blazejewska, 1997; Knowles et al., 2011; Nivala et al., 2012; Caselles-Osorio et al., 2007; Pedescoll et al., 2013). The internal channel of the subsurface flow constructed wetland changes due to the gradual clogging of the matrix pores through the wetland operation, and therefore the hydrological behavior in wetlands changes correspondingly (Ranieri et al., 2013). However, current research on hydraulic behavior of CWs is focused mainly on the influence of different design and operation configurations on hydraulic characteristics (Chazarenc et al., 2003; Jenkins and Greenway, 2005; Suliman et al., 2006b; Wang et al., 2014; Liu et al., 2016).

Studies of changes in hydraulics associated with the clogging process in CWs are still inadequate. Aiello et al. (2016) studied three full-scale horizontal SSF CWs that were operated for eight years, two years, and two years, respectively; tracer tests indicated that there were some dead zones and short-circuiting phenomena in the eight-year constructed wetland. Dittrich and Kincsik (2015) conducted tracing experiments at a horizontal subsurface flow constructed wetland over four different operating periods, and the Frechet distribution function was found to fit more accurately with the tracer results than with other conventional distribution functions and the hydraulic retention time and other hydraulic efficiency parameters could be calculated more accurately by this distribution function. However, these studies analyzed the overall changes in hydraulic efficiency in CWs, which cannot reveal the variations of internal flow field accompanied by pore clogging in SSF CWs that cause these changes in hydraulic behavior.

It is difficult for the conservative tracer test to expose the flow field inside the wetland system. Therefore, in order to analyze the effect of clogging on the internal flow field in CWs and the consequent changes in hydraulic efficiency, a conservative tracer experiment and Computational Fluid Dynamics (CFD) were combined in this study. CFD was developed to solve fluid flow problems accompanied by the rapid development of computer technology (Karpinska and Bridgeman, 2016). With this tool, new insight into the flow field change caused by clogging can be acquired. Therefore, the objectives of this research were: (a) to discuss the change of hydraulic efficiency in the experimental vertical flow CW system by tracer test, and (b) to reveal the change of flow field with the decrease of porosity in the experimental system through the simulation based on CFD, which was to be validated according to tracer test results.

2. Material and methods

2.1. Experimental system

This study was conducted in an experimental laboratory-based system, with operation in effect for 180 days. The effects of microbial growth and plant root growth on the hydrological behavior of CWs are complex (Suliman et al., 2006a; Zhao et al., 2009; Brix 1997) and it is difficult to identify whether changes in hydraulic behavior caused by clogging of microorganisms and plant roots are induced only by reduced porosity. Therefore, physical clogging caused by suspended solids in the inflow was selected as the focus of this research. To exclude contributions from biofilms or macrophytes, organic matter and nutrients were not added into the inflow in the experimental systems. Furthermore, macrophytes were not planted.

Fig. 1 shows the configuration of the experimental vertical flow constructed wetland system. The suspensions were prepared by zeolite powder, with particle size ranging from 2 μm to 124 μm, then uniformly mixed with tap water by a magnetic stirrer in the upstream tank. The mixture was pumped up through the influent pipe to the experimental column filled with the uniform gravel, which was sieved to 3 mm − 4 mm in diameter and carefully cleaned by ultrasonic waves in water.

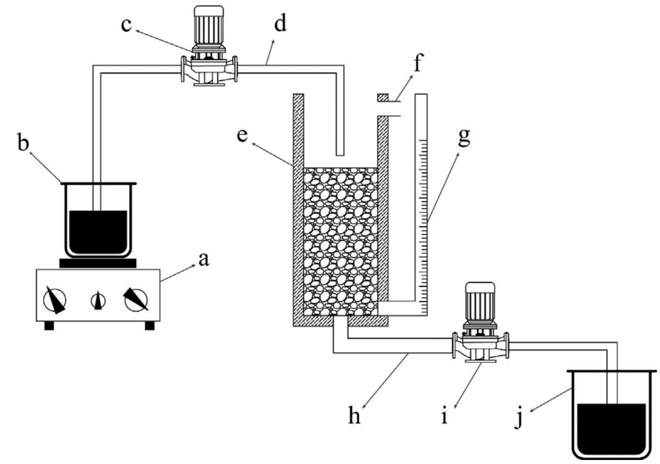

Fig. 1. Configuration of the experimental system. Each part of the system is listed bellow: a. magnetic stirrer; b. upstream tank; c. water pump-1; d. influent pipe; e. experimental column filled up with gravels; f. outfall for excess water; g. manometer; h. effluent pipe; i. water pump-2; j. dowstream tank. The diameter and height of the experimental column are 5 cm and 15 cm, respectively, and the gravels are filled with a height of 10 cm.

The diameter and height of the experimental column were 5 cm and 15 cm, respectively, and the gravel was filled to a height of 10 cm. The column was equipped with a manometer connected near the bottom to monitor the water head. The outflow was sent to the downstream tank through the effluent pipe at the same rate as the inflow under the control of pump-2.

The steady inflow condition was maintained throughout the whole experimental period. The concentration of total suspended solids (TSS) was about 500 mg/L, and the rate of inflow to the experimental column was 37 mm/day in height, resulting in the value of 36.5 mg/day for the load of TSS. Air temperature in the laboratory where the apparatuses were installed was kept at 20 °C throughout the experiment.

The initial effective porosity of the substrates was 0.372. Effective porosity was measured every 3 days, while a tracer test was conducted every 15 days. The tracer test failed on the 60th day and the 150th day, and therefore those experimental results were not taken into account.

2.2. Tracer test

NaCl is widely chosen as a tracer because of its stable nature, cheap cost, and not being adsorbed by the matrix (Aiello et al., 2016; De Matos et al., 2015). The tracing test was carried out using NaCl as the tracer to estimate the actual hydraulic retention time of the experimental system as well as other hydraulic parameters. The NaCl solution was instantaneously dosed at the inlet of the experimental system and the effluent sample was collected every 5 min at the system outlet by means of an automatic sampling device. The electronic conductivity of the collected water samples was measured by conductivity meter, and the electronic conductivity values of the effluent samples were converted to the NaCl concentration values according to the linear relationship between conductivity and concentration of NaCl solution measured at 20 °C (R^2 = 0.9999).

2.3. Calculation of hydraulic parameters

The residence time distribution (RTD) of the tracer test was calculated as follows (Kusin et al., 2014):

$$\mathrm{E(t)} = \frac{Q(t)C(t)}{M_0} \tag{1}$$

$$M_0 = \int_0^\infty Q(t)C(t)dt \tag{2}$$

Where E(t) is the residence time distribution, min^{-1}; Q(t) is the flow