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Determination of hydraulic flow patterns in constructed wetlands using hydrogen and oxygen isotopes

Haimeng Sun [a], Zhen Hu [a], Jian Zhang [a,*], Weizhong Wu [b], Shuang Liang [a], Shaoyong Lu [c], Huaqing Liu [a]

[a] Shandong Key Laboratory of Water Pollution Control and Resource Reuse, School of Environmental Science & Engineering, Shandong University, Jinan 250100, PR China
[b] Department of Environmental Science, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, PR China
[c] Research Centre of Lake Environment, Chinese Research Academy of Environmental Sciences, Beijing 100012, PR China

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ABSTRACT

The treatment efficiency of constructed wetlands (CWs) is highly dependent on the stability of the hydraulic flow patterns. To date, general technologies used to study hydraulic flow patterns of CWs mainly include tracer method, model simulation and velocity measurement, which are either expensive, empirical, or having secondary pollution. In this study, a new technology, which was based on the isotopic composition variation in CWs, was applied to detect the hydraulic flow patterns of two different CWs. Results showed that the hydraulic flow patterns of the two studied wetlands could be detected effectively by using hydrogen and oxygen isotopes. Furthermore, the locations of stagnant areas (SAs) and preferential flow areas (PFAs) were also determined. Significant regional difference in isotopic composition existed inside each CW, and two wetland design suggestions are proposed after hydraulic analysis. One is that the influent of CWs is supposed to be distributed uniformly, and another piece of advice is that the vegetation in the direction perpendicular to water flow should be maintained at the same types and density.

1. Introduction

Constructed wetlands (CWs), which are designed on the basis of all kinds of reaction process in natural wetlands but make the process occur in more controlled systems, have a rapid momentum of development especially in last three decades [1]. These systems, which are robust, low power consumption, easy to maintain and operate, are suitable for advanced treatment of municipal sewage plants' effluent or decentralized wastewater [2,3].

The pollutants such as suspended material, nitrogen, phosphorus, organic matters, and metals are removed by the complex and abundant reactions relying on physical, chemical and biological processes [4]. Pollutants removal mechanisms are mainly organic matters decomposition by microorganism, nitrogen removal through nitrification – denitrification, and nutrient elements absorption by the plants and substrate. The implementation of these reactions depends on the joint function of plants, matrix, and microorganisms. To a certain extent, nutrients removal efficiencies are dependent on the time that waste water touched with vegetation, matrix, and microorganisms in the CWs. As a result, hydraulic retention time (HRT) has significant effect on water pollutants removal efficiency [5–7]. Furthermore, CWs' water flow is rather complex because of its large areas of plants and artificial matrix. Hydraulic performance of CWs is influenced by several factors, such as plant species richness and density, the CW's aspect ratio, the inlet and outlet's form [8,9]. A combination of these factors leads to different hydraulic conditions inside the CWs, and the hydraulic flow patterns are the comprehensive performance of all hydraulic conditions which also are the external presentation of the residence time distribution (RTD) [10]. Since RTD is a value of process quantity, it can't reflect the hydraulic conditions inside the CWs in situ. It is important to investigate the hydraulic variation inside CWs, which can help us find the unfavorable hydraulic phenomenon such as stagnant areas (SAs) or preferential flow areas (PFAs).

At present, many researchers focus on the application of tracer, hydraulic models and velocity measurement to simulate hydraulic flow patterns in CWs [11–15]. However, in large-scale CWs, adding tracers is not a good choice because of the high cost, potential of secondary pollution caused by adding external material into the CWs, and the intensive continuous monitoring time [16]. As to hydraulic model, its results can not reflect the hydraulic flow patterns synchronously as the parameter is always empirical [17]. Finally direct velocity measurement inside the CWs needs expensive apparatus, not to mention that field measurement is considered a labor-consuming job [18,19].

Stable isotopes of oxygen and hydrogen are a novel technology which has been used in hydrology for investigating water composition and circulation in rivers, lakes, oceans, ground water and atmosphere [20–22]. In liquid water, isotopes molecules' vapor pressure is inversely proportional with its molecular weight. Compared to ^{18}O and ^{2}H, ^{16}O and ^{1}H have higher vapor pressure, indicating that they could separate

* Corresponding author.
E-mail address: zhangjian00@sdu.edu.cn (J. Zhang).

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from the liquid phase more easily, which lead to the enrichment of the heavy water isotopes ^{18}O and ^{2}H [23]. In CWs, the cumulative amount of evaporation in different regions has strong relationship with regional water residence time [24]. Moreover, regional water residence time determined the flow patterns. If an accurate survey was done on the distribution of water isotopic composition, the hydraulic flow patterns would be known inside CWs. The isotopes technology utilizes the internal elements in CWs to detect the hydraulic flow patterns real-timely and has a low cost without secondary pollution.

The aims of the present study were to characterize hydraulic flow patterns using isotope technology, further, to determine the locations of the SAs and PFAs in CWs. After hydraulic analysis, some engineering suggestions are proposed. The ammonia nitrogen's distribution characteristics in different hydraulic conditions were studied as well.

2. Materials and methods

2.1. Sites description

Two sites were identified based on differences in shapes, plants species and inlet patterns: Wu river constructed wetland (W-CW) (N: 34° 52′6.9″; E: 118°20′42.7″) and Qihe ecological constructed wetland (Q-CW) (N: 36°56′26.9″; E: 116°47′24.7″). Both sites belong to monsoon climate of medium latitudes, with four distinctive seasons. Both the CWs accept treated sewage water from local sewage treatment plants, and the water quality met Chinese National Class I (Grade A) Sewage Discharge Standard. Detailed information of the two CWs are given in Table 1. The surface flow constructed wetlands (SFCWs) in the two CWs were selected as our experimental subjects to study the hydraulic flow patterns using isotopic technology and velocity distribution. In W-CW, the experimental subject was the SFCW between second and third over flow weir, which was about 16.1 ha and straight type without bend, a single culvert set as the inlet pattern (Fig. 1a). In Q-CW, the experimental subject was the five surface flow treated units, which was about 3.5 ha and with two bends in shape. Inlet pattern was several culverts distributing in the bank, an overflow weir set between every two unit for oxygen supplement (Fig. 1b).

Vegetation coverage area was another obviously different factor between the two studied wetlands. According to the method proposed by Jiang et al. [25], vegetation coverage ratios were 26% and 83% for W-CW and Q-CW, respectively. W-CW's flow channel was constructed on the river watercourse (named watercourse channel type), mainly water areas. Yet the Q-CW was built artificially (named man-made channel type), which had abundant vegetation species and high density.

Vegetation types were mainly emergent plants and submerged plants. The emergent plants were mainly *Typha orientalis* and *Phragmites australis* while the submerged plants were mainly *Vallisneria natans* and *Nymphaea tetragona*. It would be specially mentioned that a middle inlet was set in the second level wetland, through which a small part of outflow of sub-surface CWs flew into the SFCW directly when high water inflow rate occur. Coincidentally, the middle inlet was open when the measurement was conducted, which increased hydraulic changes.

Sampling points in this study were set in the areas that had different hydraulic conditions such as open water areas, various vegetation species coverage areas, inlet and outlet regions (Fig. 1). Isotopes were all collected at about 10 cm below the water surface. The sampling job was conducted after consecutive ten more days without rain. The collected water was put into 250 mL plastic bottles then preserved into insulation box with ice bags in it. A GPS (72H) was used to determine the sampling points' location. Water sampling job was conducted in August 2013 for W-CW, and June 2015 for Q-CW. There were 21 and 33 sampling points designed in W-CW and Q-CW, respectively (Fig. 1).

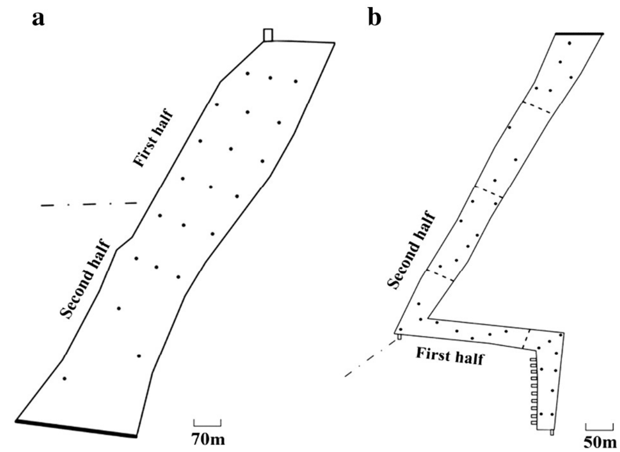

Fig. 1. The schematic diagrams of the W-CW (a) and Q-CW (b). Circles represent sampling points (21 points in W-CW while 31 points in Q-CW), and squares stand for the inlets. The bold lines instead for the outlet and the dashed lines instead for the overflow weir.

2.2. Water isotopes analysis

Isotopic composition is expressed δ in ‰ as:

$$\delta^{X}E = \left(\frac{R_{sample}}{R_{standard}} - 1\right) * 1000 \quad (1)$$

where X is the atomic mass of the heavy isotope of element E and R is the ratio of the heavy to light isotope ($^{18}O/^{16}O$). R_{sample} is the ratio of heavy (e.g. ^{2}H and ^{18}O) to light (e.g., ^{1}H and ^{16}O) isotope of water samples; $R_{standard}$ is the ratio of heavy (e.g., ^{2}H and ^{18}O) to light (e.g., ^{1}H and ^{16}O) isotope related to VSMOW standard.

The isotopic composition of oxygen and hydrogen was analyzed by wavelength-scanned cavityring-downs pectroscopy (WS-CRDS) [26], using Picarro L2140-i $\delta^{18}O/\delta^{17}O/\delta D/^{17}O$-excess high-precision isotopic water analyzer in Beikerui Detection Technology Co., Ltd. The relationship between surface water signatures of δD and $\delta^{18}O$ relative to the local meteoric water line (LMWL) showed the degree of evaporation intuitively [27]. Since the experimental subjects located in eastern China, the eastern China meteoric water line (ECMWL) proposed by Yu et al. [28] was selected as LMWL. In order to show the distribution of the isotopes clearly, Surfer 10.0 was used to give a $\delta^{18}O$ distribution contour map of the wetland using an ordinary kriging interpolation [29].

If a statistically significant difference in the isotopic distribution was found inside two studied wetlands, it indicated that the hydraulic conditions heterogeneity existed. In the areas of contour values were high, indicating that high evaporation leading to heavy isotopes enrichment, where a long HRT and SAs might exist. On the contrary, in the PFA, the short HRT lead to relative low evaporation enrichment, so small numerical isotopic values line would be distributed in these areas. In the $\delta^{18}O$ distribution maps, the range of measured $\delta^{18}O$ values would be

Table 1
Properties of the studied wetlands.

	Parameters						
Wetlands	Area (ha)	Influent type	Flow rate (m^3/d)	Experimental subject (ES)	ES's area (ha)	ES's shape	Plant coverage ratio
W-CW	533.33	Treated sewage water	3.0×10^5	Second surface flow treated unit	16.1	Straight type	26%
Q-CW	68.53	Treated sewage water	4.0×10^4	5 surface flow treated units	3.5	Turning type	83%