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Original Research Article

Assessing the effects of flow distribution on the internal hydraulic behavior of a constructed horizontal subsurface flow wetland using a numerical model and a tracer study

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ABSTRACT

This study was aimed at investigating the effects of flow distribution on a constructed subsurface horizontal flow wetland of 26 m length, 4 m width and one percent bed dip. Inlet configurations were selected as a variable parameter. Three different inlet flow configurations including midpoint–midpoint (A), corner–midpoint (B) and uniform–midpoint (C), with the same fixed outlet configurations, were studied. The combined use of tracer and numerical modeling for the evaluation of hydraulic characteristics of constructed wetlands in the horizontal sub surface flow system was presented. The mean retention time for each configuration was found to be 4.53, 3.24 and 4.65 days, respectively. According to tracer breakthrough curve, the effective volumes for configurations A and C were 87.5%, as compared to 62.1% for the configuration B. Retention distribution curves were useful in assessing the internal dispersion and hydraulic parameters to interpret the short-circuiting flow for each configuration setup. Finally, the best configuration of inlet–outlet layout to improve the performance of effluent treatment based on both numerical simulations and physical experiments was found to be the uniform–midpoint by all performance criteria and this was followed by midpoint–midpoint as the second best one.

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1. Introduction

Constructed wetlands (CWs) are engineered systems that are low-cost in construction, operation and maintenance, use eco-technological biological wastewater treatment technology, have an excellent pollutant removal performance, and enjoy lower energy consumption. These systems are designed to mimic processes found in natural wetland ecosystems for the treatment of wastewater.

Horizontal subsurface flow constructed wetlands (HSSF CW) have long been applied to improve water or wastewater quality (Vymazal, 2011). A HSSF CW is a shallow basin filled with some sort of filter material (substrate), usually sand or gravel, and planted with some vegetation tolerant of saturated conditions.

Constructed wetlands can diminish the contaminant concentrations through complex physical, chemical, and biological mechanisms that may take place by water, substrate, plants, and microorganisms interactions. Removal mechanisms of constructed wetlands are extremely relevant to wastewater constituents. Physical procedures are mainly filtration by the substrate layer, plant–root zone, and sedimentation. The main chemical reactions

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consist of chemical precipitation, adsorption, cation exchange, and oxidation/reduction reactions. It is widely acknowledged that biochemical reactions attributed to bacterial communities (biofilms) play the most important role in pollutant transformation in aerobic and anaerobic conditions (Kadlec, 2000; Ramond et al., 2012; Chang et al., 2011; Samsó and García, 2013). The performance of constructed wetlands, in terms of removal efficiency and hydraulic performance, depends on many factors among which the most significant ones are basin volume, hydraulic loading rate (HLR), and hydraulic retention time (HRT).

The hydraulic retention time (HRT), which is considered as a critical parameter in designing constructed wetlands, is the average time for water moving from the inlet to the outlet. In fact, HRT is the needed time for treating pollutants. Jafet Rodríguez Alcocer et al. (2012) stated the aspect ratio (length to width ratio), the size of the porous media and the loading rate of HSSF CWs could influence HRT. The effect of medium particle size on hydraulic behavior was not as clear as it was for the aspect ratio. This was because there was no clear relationship between the medium particle size and the normalized delay time. They, therefore, have argued that a constructed subsurface flow wetland design should incorporate a combination of higher aspect ratios, higher loading rate and finer porous media to induce a hydraulic behavior closer to an ideal plug flow system. Some researchers have illustrated that the effective volume is strongly influenced by the aspect ratio and in- and outlet configurations (Persson and Wittgren, 2004; Stowell et al., 1986; Reed et al., 1995; USEPA, 2000). Su et al. (2009) have stated that in free water surface constructed wetlands, when the aspect ratio is greater than 5, the hydraulic efficiency will reach 0.9, or even higher. If the project site or field area cannot meet the theoretical standard, the recommended aspect ratio is higher than 1.88 to ensure some hydraulic efficiency greater than 0.7.

A tracer study is the most applicable approach to obtain valuable information about internal hydraulic parameters in a constructed wetland which is the interaction of hydraulic behavior and removal efficiency. A tracer test is a method to measure the residence time distribution (RTD) directly. Hydrodynamics of constructed wetlands and streamlines could be investigated by the tracer to determine the direction and velocity of water movement (Suliman et al., 2005). It is also useful for the calculation of other hydraulic parameters such as porosity ($\emptyset$), hydraulic conductivity (k), dispersivity, short-circuiting and effective volume indirectly through further analyses.

The three most popular choices for tracers are ionic compounds such as bromide or chloride, isotopes, and dyes. In comparison, dyes have the advantages of low detection limits, high accuracy, zero natural background, and relatively low cost. There are some common dyes to select as a tracer, such as Rhodamine, Uranine and Eosine, with a given concentration within a short time. These tracers can return more than 95% of the injected amount in submerged aquatic vegetation-dominated mesocosms (Dierberg and DeBusk, 2005). Chang et al. (2011) used Rhodamine in subsurface up-flow wetland to explore the interface between hydraulic and environmental performance in concert with a transport model to collectively provide hydraulic retention time (7.1 days) and compelling evidence of pollutant fate and transport processes. Research findings indicated that pollution-control media demonstrate smooth nutrient removal efficiencies across different sampling port locations. One of the most applicable dyes is Na-fluorescein (Uranine). Because of its conservative behavior, low detection limits and low costs against Rhodamine, Na-fluorescein is a widely applied dye for tracer experiments. Naurath et al. (2011) used Uranine in mine water as tracer tests with extremely low concentrations detection limit (3 ppt).

Previous studies on wetland systems have focused on trying to comprehend the processes leading to the removal of pollutants. Research on flow hydraulics through the porous media of constructed wetlands has concentrated primarily on the assessment of relationships and interactions between microbial communities, plants and the reduction of pollutants in the system (Caselles-Osorio et al., 2007; García et al., 2005; Steer et al., 2002). However, there are still some areas of its internal functioning that are not yet well understood. Comparatively, there have been fewer studies dedicated to the assessment of flow distribution on hydraulic behavior through the wetland. To help understand the internal behavior of these systems, several numerical models of diverse complexity have been developed (Langergraber, 2008).

Research has shown that hydraulic performance can be enhanced by appropriately managing flow distribution at the inlet and the outlet. Hence, the objective of this study was to provide information about the internal hydraulic behavior of HSSF CWs by imparting a different hydraulic flow distribution with the aid of 3D numerical simulation and tracer study. This study evaluated the impact of the configuration of inlet and outlet on the hydrodynamic behavior in HSSF CWs. The experiment was conducted using tracer tests which provided the retention time distribution (RTD) employed to compute integral parameters such as the plug flow ratio, dead volume and hydraulic efficiency. The aim of present study was to analyze wetland internal processes depicting how flow distribution affected hydraulic behavior by using 3 different input flow layouts.

2. Materials and methods

2.1. Site description

The wetland system studied in current research was located in the suburb of Isfahan city, central Iran. The treatment system consisted of a horizontal subsurface flow in a constructed wetland having an aspect ratio of 6.5 and the bed slope of one percent. The flow in the wetland was isolated with a synthetic polyethylene liner laid on bed and border walls. The geometry of this system, which was 4 m wide × 26 m long × 1 m deep, was planted with *Phragmites australis* (Fig. 1).

This system was fed with secondary effluent from the Isfahan North Wastewater Treatment Plant. Despite its dependence on local conditions, the average influent rate

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