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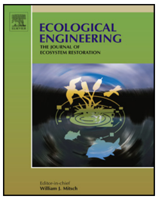

Variations of effective volume and removal rate under different water levels of constructed wetland

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ABSTRACT

Water depth is a key parameter in the design and operation of constructed wetlands. In this study, the effect of water depth on the effective volume and the removal rate was explored through dye tracer experiments in water depths of 20 cm, 40 cm, and 60 cm at a constructed wetland located at the Center Station of Irrigation Experiment, Nanchang City, China. The One-dimensional Transport with Inflow and Storage (OTIS) model and a so-called CSTRs + PFD (continuously stirred tank reactors + plug flow with dispersion) model were calibrated for analysis of the hydraulic parameters. The results are summarized as follows. (1) When the water depth increased from 20 cm to 60 cm, the hydraulic efficiency λ_m decreased, as did the effective volume ratio e determined by both moment analysis and the OTIS model. (2) A combination of effective volume ratio and the number of continuously stirred tank reactors, N could better reflect the effect of water depth on the removal efficiency. (3) Theoretical analysis showed that the removal efficiency decreased with increasing water depth, which was caused by a decrease of reaction rate. Therefore, the reaction rate has a larger effect on the removal efficiency than residence time. (4) Dye tracer tests showed that the mean residence time and effective volume first rose and then fell slightly with increasing water depth. The changes in the mean residence time and reaction rate suggest that increasing the water depth would do little to improve the removal efficiency.

1. Introduction

Constructed wetlands (CWs) are an increasingly common best practice for sewage treatment. In particular, surface-flow constructed wetlands (SFCW) have gained attention for eliminating agricultural non-point source pollution (Karpuzcu and Stringfellow, 2012; Moreno-Mateos et al., 2010). However, in an irrigated agricultural area, CWs would occupy the land needed for cultivation (Dong et al., 2009; O'Geen et al., 2010; Shan et al., 2002). In such an instance, the operation efficiency of the wetland has to be improved to ensure optimal use of the wetland volume for treating the agricultural drainage water.

In order to estimate the performance of CWs, it is essential to study their hydraulic characteristics, normally characterized as hydraulic efficiency. Various hydraulic conditions could lead to varying hydraulic efficiencies. Usually, the flow in wetlands is presumed to be plug flow or completely mixed flow. As regards plug flow, the solute flows evenly through the wetland from the inlet to the outlet without dispersion. In a completely mixed reactor, the fluid properties are uniform throughout the reactor. In such an instance, ideally, it is assumed that the fluid is instantly dispersed throughout the reactor at zero time. However, since a hydraulic dead zone and short-circuiting phenomenon are present in CWs, the actual flow would be hovering between plug flow and mixing flow. The short-circuiting phenomenon would reduce the contact time between the pollutant and the water body, and the treatment efficiency would therefore decrease. Tracer tests in the field have clearly indicate that the degree of short-circuiting phenomenon fluctuates (Keller and Bays, 2002; Stern et al., 2001). The hydraulic dead zone, characterized by slow velocity, is difficult to exchange, reducing the efficiency of the wetland (Thackston et al., 1987). Various factors influence the hydraulic characteristics of a wetland, such as the length-width ratio (Thackston et al., 1987), the layout of inlet and outlet (Persson, 2000), bottom roughness (Somes et al., 1999), vegetation (Jenkins and Greenway, 2005), and irregular shape of wetland (Keefe et al., 2004; Wei et al., 2012; Wörman and Kronnäs, 2005).

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Nomenclature

Symbols used

A_m	Main channel cross-sectional area (L^2)
A_e	Effective surface area in surface area of wetlands (L2)
A_s	Storage zone cross-sectional area (L^2)
A_t	Total surface area of the wetland (L^2)
C	Main channel solute concentration or outflow concentration of dye tracer (ML^{-3})
C'	Dimensionless RTD function (–)
C_{in}/C_{out}	Ratio between inlet concentration and outlet concentration of pollutant (–)
C_s	Storage zone solute concentration (ML^{-3})
DaI	Damköhler number (–)
D^c	Longitudinal dispersion coefficient ($L^2 T^{-1}$)
D	Dispersion number (–)
e	Effective volume ratio (–)
E	Probability distribution function (–)
f	Inflow percent of CSTRs in CSTRs + PFD model (–)
ϕ	Flow weighted time (–)
h	Water depth of wetlands (L)
k_a	Areal removal rate constant (LT^{-1})
k_V	Volumetric removal rate constant (T^{-1})Volumetric removal rate constant (T^{-1})
L	Distance from inlet to outlet (L)
λ_m	Hydraulic efficiency (–)
M	Mass of dye tracer added to system (M)
M_{out}	Mass of dye tracer exited of the wetland (M)
Mi	Mixing index (–)
N	Number of CSTR (–)
Pe	Peclet number (–)
Q	Volumetric inflowrate (L^3T^{-1})
REC	Rate of pollutant reduction (–)
Sc	Short-circuiting index (–)
σ_m^2	Variance of RTD at outlet (T^2)
σ_{mid}^2	Variance of RTD at mid-point (T^2)
t	Time (T)
τ	Mean residence time (T)
t_{10} and t_{90}	10th and 90th percentiles of dimensionless RTD, respectively (–)
t_m	Mean residence time at outlet (T)
t_{mid}	Mean residence time at mid-point (T)
t_n	Nominal residence time (T)
u	Water average velocity (LT^{-1})
V_m	Volume of main channel (L^3)
V_e	Effective volume (L^3)
V_s	Volume of storage zone (L^3)
V_t	Total volume (L^3)
W	Width of wetlands (L)
x	Distance along main channel (L)
z	Volume percent of CSTRs (–)
α	Storage zone exchange coefficient (T^{-1})

The residence time distribution (RTD) is an important tool in researching flow characteristics. In this regard, various researchers have proposed different models to explore the hydraulic characteristics and predict the wetland performance. Kadlec and Knight (1996) described the hydraulic process of CWs by using three Continuously Stirred Tank Reactors (CSTRs). A computer model, zones of diminished mixing, was developed by Werner and Kadlec (2000) to reproduce the actual RTDs. The non-ideal flow of CWs was modeled with a network of an infinite number of small stirred tanks, distributed along a set of main plug-flow channels. Because stirred tanks, which represent zones of diminished mixing, undergo only a limited exchange of water with the main channels. Wagner and Harvey (1997) studied tracer experiment design and the reliability of the model parameters within the One-dimensional Transport with Inflow and Storage (OTIS) model. Wang and Jawitz (2006) reproduced RTDs within cell-network treatment wetlands by using four models, namely, the tanks-in-series, the two-path tanks-in-series, OTIS, and the Plug Flow with Dispersion (PFD). Xiao et al. (2012) regarded a wetland as a system with PFD and CSTRs in parallel.

Various factors influence hydraulic characteristics and the focus of this paper is water depth in managing wetlands. Holland et al. (2004) have also studied the effects of water depth (16.6–39.8 cm) on the hydraulic characteristics. However, whether that variations of the hydraulic characteristics follow the same trends in a wider range of water depths remains uncertain. Another uncertainty pertains to the relationship between the hydraulic characteristics and removal efficiency. In this paper, the effect of water depth on the effective volume and removal rate was studied with a combination of tracer tests and models. The aim of the research was to explore the relationship between the hydraulic efficiency and the removal efficiency. Because, in the operation of wetlands, the effective volume corresponds exactly to the actual wetland volume needed for pollution mitigation (Schuetz et al., 2012). Dye tracer experiments were conducted in a CW at different water levels (20 cm, 40 cm, and 60 cm) to obtain the RTDs. The hydraulic parameters, such as effective volume, as well as the degree of plug flow and mixing flow were analyzed with the OTIS (Wagner and Harvey, 1997) and CSTRs + PFD models (Xiao et al., 2012), which were calibrated based on actual RTDs. The effect of water depth on the removal rate was studied by employing the removal equation, and the relationship between removal rate and hydraulic characteristics was also explored.

2. Materials and methods

2.1. Experimental configuration

2.1.1. Site description

Dye tracer experiments were conducted at the Jiangxi Province Center Station of Irrigation Experiment, situated in the Ganfu Plain Irrigation Area, Nanchang City, China. The geographic coordinates of the basin are longitude 115°49′E–116°46′E and latitude 28°24′N–29°46′N. The irrigated area has a typical subtropical, humid, monsoon climate and temperate weather, with abundant rainfall. The annual average temperature is 18.1 °C and the average annual rainfall is 1636 mm. The soil in the experimental area is red paddy soils of the heavy clay soil type. The clay minerals in the soil are mainly kaolinite-quartz-montmorillonite. The layout of the paddy fields and the CWs is shown in Fig. 1a.

2.1.2. Constructed wetlands

The CW in this study is a surface-flow CW (SFCW), whose layout is shown in Fig. 1(c). The dimensions are 40 m, 13 m, and 1.2 m in terms of length, width, and depth, respectively; the surface area is 490 m^2. The wetland area was calculated from a layout diagram of the CW, which was drawn using AutoCAD. The length-width ratio is 3.1:1 and the side slope is 1:0.5, as shown in Fig. 1(b). The inlet and outlet are located as shown in Fig. 1(c). The foundation of the wetland was compressed to reduce infiltration. A 0.2-m-thick layer of activated sludge was placed on the wetland bed at the beginning of 2013. Lotus plants (*Nelumbo nucifera*) were then planted in the wetland at 25 × 25 cm intervals. During the course of the dye tracer experiment, it was found that the lotus plants were growing well and were at a mature stage, with upright stems and an average density of 31.3 plants/m^2 (Fig. 2). Lotus leaves covered the surface