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Flow uniformity and hydraulic efficiency improvement of deep-water constructed wetlands

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ABSTRACT

Free-water surface constructed wetlands (FWSs) are designed to treat wastewater. Previous studies have indicated that hydraulic efficiency influences treatment performance and that shallow-water FWSs always yield greater hydraulic efficiency than do deep-water FWSs. This study presents effective ways to improve the flow uniformity and hydraulic efficiency of deep-water FWSs by utilizing different allocations and varying numbers of obstructions. A reliable computational model is employed to simulate the flow conditions and tracer concentrations from numerous hypothetical cases. The differences between emergent obstructions (EOs) and submerged obstructions (SOs) were examined. Improving the efficiency of shallow-water and deep-water FWSs is discussed. Installing obstructions on the same side of the inlet and outlet is recommended for avoiding flow circulation. Meandering flow formed by EOs can avoid short-circuiting flow and reduce dead zones, thus resulting in more uniform flow and greater hydraulic efficiency. SOs were found to have minor and inconsistent effects in improving hydraulic efficiency. We conclude that an alternative method for increasing the aspect ratio of a fixed-dimension wetland is to use EOs to create a meandering flow pattern and longer flow path. The findings of this study encourage wetland scientists and wetland engineers to plan the restoration/creation of deep-water wetlands and combination wetlands with both shallow-water and deep-water areas.

1. Introduction

Wetlands provide considerable environmental benefits and promote biodiversity by providing habitat for water-loving plants, birds and insects. Among various types of wetlands, free-water surface constructed wetlands (FWSs) are artificial wetlands designed to perform multiple functions, such as wastewater treatment (Yam et al., 2013), ecosystem services (Hsu et al., 2011; Zedler and Kercher, 2005), carbon reservoirs (Tranvik et al., 2009), and flood detention (VDOP, 2013). They are widely used as low-cost alternatives to conventional tertiary municipal wastewater treatment worldwide (Verhoeven et al., 2006), and they also play important roles in the reduction of nitrogen concentration through nitrification-denitrification processes, removal of particulates through sedimentation (Kadlec et al., 2010) and removal of organic contaminants through biodegradation (Hsu et al., 2011).

The treatment efficiency of FWSs cannot be determined without understanding the flow dynamics of individual parcels of water through the wetland (Arega et al., 2008; Arega, 2013). Wang and Mitsch (2000) suggested that treatment can be improved by manipulating the hydraulic regime to improve the hydraulic efficiency. FWS parameters such as aspect, bottom topography, water depth, vegetation, obstructions, and inlet/outlet position all influence wetland hydrodynamics, which ultimately determines the retention time and hydraulic efficiency (Persson et al., 1999; Su et al., 2009; Thackston et al., 1987). For practical purposes, USEPA (2000) suggested the use of integrated FWSs with both shallow- and deep-water ponds to enable various biochemical reactions occurring under aerobic and anaerobic conditions. In addition to wastewater treatment, the water depth of FWSs is sometimes designed as deep-water wetlands with more than 1.5 m to reach the detention goal for flood protection (Kuo and Shih, 2013).

Deep-water FWSs have been broadly applied, and the negative impact of the hydraulic efficiency should be noticeable. Holland et al. (2004) and Shih et al. (2013) concluded that increasing the water depth elicits a decrease in the hydraulic efficiency. Many studies have indicated that preferential flow, short-circuiting flow, flow circulation and dead zones may reduce the treatment effi-

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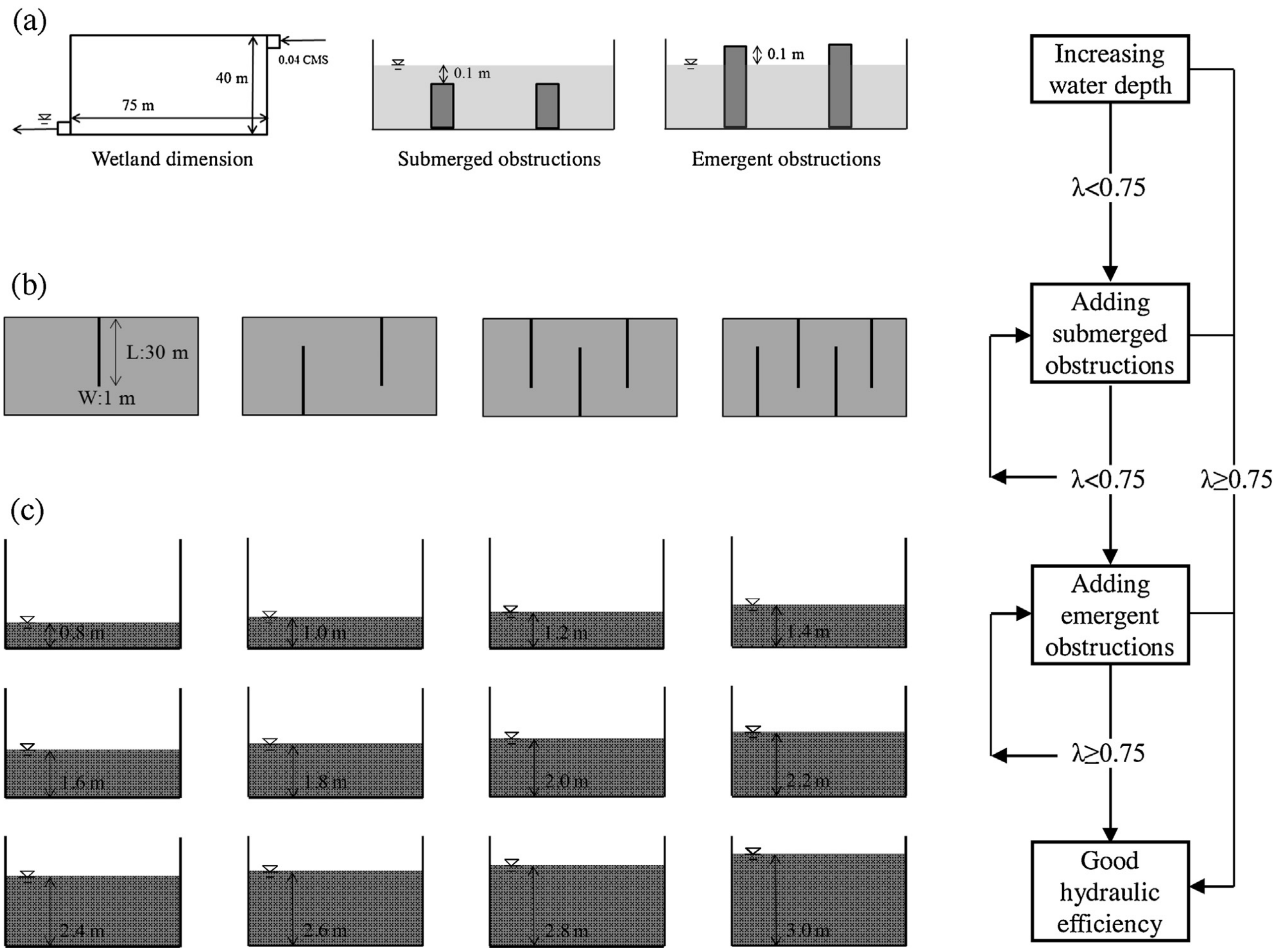

Fig. 1. The setup of the computational experiments: (a) The scale and inlet and outlet configuration with submerged and emergent obstructions, (b) the spatial allocation of obstructions, and (c) variants of water depths from 0.8 m to 3 m.

ciency of wetlands (Bracho et al., 2006; Dierberg et al., 2005; Holland et al., 2004; Min and Wise, 2009). These synthetic effects may appear as low flow uniformity and hydraulic efficiency. However, the improvement of the flow uniformity and the relevant hydraulic efficiency in deep-water FWSs has not been well studied. The objective of this study is to determine whether there are effective ways to improve the hydraulic efficiency of deep-water FWSs by utilizing different allocations and varying numbers of obstructions. A reliable horizontal two-dimensional model is employed to simulate the flow conditions and tracer concentrations from 96 hypothetical cases. The differences between submerged and emergent obstructions for improving the hydraulic efficiency are examined. The ecological benefits of the obstruction features in deep-water FWSs are also discussed.

2. Methods

To evaluate the flow uniformity and hydraulic efficiency of deep-water FWSs, 96 computational experiments with two types of obstructions (submerged and emergent) with varying numbers of obstructions (1, 2, 3 and 4) and water depths (from 0.8 m to 3 m) were considered. An optimized numerical model, TABS-2, was employed to simulate the flow conditions and tracer concentration, which can be used to calculate the hydraulic efficiency. The hydraulic performance was illustrated using the classification scheme suggested by Persson et al. (1999). The flow condition, residence time and hydraulic efficiency without obstruction, with emergent obstructions (EOs) and with submerged obstructions (SOs) were examined and discussed.

2.1. Hydraulic efficiency

Treatment potential and efficiency of wetlands are usually related to the residence time of the individual parcels of water within the wetland (Chang et al., 2013; Wahl et al., 2012). Wetland residence time describes travel time from inlet to outlet and is sometimes considered the residence time distribution (RTD) (Persson et al., 1999; Su et al., 2009). To characterize the treatment performance of a wetland, it is useful to reduce the RTD to a single number, the hydraulic efficiency (Holland et al., 2004). Persson et al. (1999) introduced the hydraulic efficiency, as shown in Eq. (1).

$$\lambda = e_V\left(1 - \frac{1}{N}\right) \quad (1)$$

where e_v is the effective volume ratio and N is the number of continuously stirred tank reactors in series. The hydraulic efficiency λ can be categorized into three levels: (1) good hydraulic efficiency, with $\lambda \geq 0.75$; (2) satisfactory hydraulic efficiency, with $0.5 < \lambda < 0.75$; and (3) poor hydraulic efficiency, with $\lambda \leq 0.5$.

According to Thackston et al. (1987), e_v measures the effective volume ratio utilization of a detention system, which is calculated