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A numerical study of the effect of wetland shape and inlet-outlet configuration on wetland performance

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ABSTRACT

The hydraulic efficiency of wetlands for wastewater treatment was investigated as a function of wetland shape and vegetation density using a 2D depth-averaged numerical model. First, the numerical model was calibrated and validated against field data and then was applied to 8 hypothetical wetlands of rectangular and elliptical shape and different aspect ratio (i.e. 1:1–4:1). The vegetation density was varied from 0 to 1000 stems/m^2. The effect of inlet-outlet configuration was analyzed by simulating the hydraulic response of wetlands with different alignment of the flow inlet and outlet and wetlands with multiple inlets. The resulting Residence Time Distributions (RTDs) were derived from numerical simulations of the flow field and the temporal evolution of the outlet concentration of a passive tracer injected at the inlet. The simulated velocity field demonstrated that wetland shape can have significant impact on the size of dead zone areas, which is also reflected in the RTD. Efficiency metrics associated with detention time and degree of mixing improved for an elliptical shape compared to a rectangular shape. An ellipse shape improved the wetland performance by reducing the area of dead zones at the corners, and thereby increasing the effective wetland volume contributing to the treatment process. Configurations in which inlet and outlet were located at opposite corners of the wetland, and wetlands with multiple inlets produced smaller dead zones, which reduced the variance of the RTD. The simulation results also revealed an interesting threshold behavior with regard to stem density. For stem density above 300 stems/m^2, which is typical of treatment wetlands, the model predictions were not sensitive to the exact value of stem density selected, which simplifies the parameterization of models. This quantitative analysis of the effect of wetland shape, inlet-outlet configuration and vegetation density can help engineers to achieve more efficient and cost-effective design solutions for wastewater treatment wetlands.

1. Introduction

Free water surface constructed wetlands (FWS CWs) can remove a variety of contaminants from municipal wastewater (Cameron et al., 2003; Kipasika et al., 2014), storm water (Carleton et al., 2001; Mangangka et al., 2015), industrial wastewater (Vymazal, 2014; Wu et al., 2015), agricultural wastewater (Maucieri et al., 2014; Vymazal and Březinová, 2015), road runoff (Gill et al., 2014), wood-waste leachate (Tao et al., 2006), and landfill leachate (Yang and Tsai, 2011). The effectiveness of constructed wetlands in removing different forms of contaminants is well documented (Vymazal, 2013). For example, phosphorus removal has been documented in over 250 FWS wetlands, for a wide range of inflow concentrations, from below 20 µg/L to over 100 mg/L (Kadlec and Wallace, 2009). Hsueh et al. (2014) reported 85% removal of TN (total nitrogen) in a subtropical free water surface CW in Taiwan with retention time of 3.7 days. Batty and Younger (2002) found that where dissolved iron concentrations in wetland waters were at or below 1 mg/L, direct uptake of iron by plants could account for 100% of iron removal. Kotti et al. (2010) investigated the performance of five FWS CWs and observed average removal values of 77.5%, 67.9%, 60.4%, 53.9%, 56.0% and 51.7% for BOD, COD, TKN, ammonia (NH4-N), *ortho*-phosphate (PO4-P) and total phosphorus (TP), respectively. Although CWs have the potential to improve water quality signif-

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icantly, there is a large variability in their hydraulic efficiency and removal rates (Persson et al., 1999). Wetland characteristics including wetland shape, inlet-outlet configuration, vegetation coverage and water depths affect the hydraulics of CWs, which directly influences removal rates. Designing a constructed wetland to achieve a certain performance level requires optimization of these wetland properties (Marion et al., 2014).

The hydraulic design of a wetland has two main requirements: (1) the resulting hydraulic residence time (HRT) must be sufficiently long to allow for the natural treatment processes to remove the contaminants (Thackston et al., 1987); (2) the wetland must provide a condition close to plug flow, for which dispersion is minimum, so that all water parcels experience a residence time close to the HRT (Holland et al., 2004; Persson et al., 1999). Hydraulic retention time (HRT) is the average amount of time a passive solute spends in a wetland system. A longer retention time provides more time for biochemical reactions to occur in the wetland, and thus increases pollutant removal (Kadlec and Wallace, 2009). Toet et al. (2005) evaluated the pollutant removal in a FWS under four hydraulic retention times from 0.3 to 9.3 days and found that increasing HRT led to considerable increase in the removal of total nitrogen, ammonium, and nitrates. A minimum HRT of 4 days was found to be necessary for a nitrogen removal efficiency of approximately 45%, corresponding to an annual mass loading rate of 150 gr m^{-2} yr^{-1}. The hydraulic efficiency of a wetland is characterized in terms of two non-dimensional parameters. The first is the dimensionless retention time, defined as $e = t_m/t_n$, in which t_m is the observed mean residence time, and $t_n = V/Q$ is the nominal residence time, in which V is the volume of the wetland and Q is the input discharge rate (Thackston et al., 1987). The optimum residence time would be achieved when the ratio approaches unity ($t_m = t_n$), which implies that there are no dead zones in the wetland, and the whole wetland volume actively contributes to the treatment processes. The second design criterion describes the departure from plug flow due to dispersion processes. Dispersion arises from inlet and outlet effects, vegetation distribution patterns, bottom topography, wind effects and shear stresses from sides. Dispersion makes some parcels of water exit before and after the nominal resistance time (t_n). Because the biochemical reactions impacting pollutant removal are mostly first-order reactions, there is a greater disbenefit to pollutant removal for parcels of water leaving before t_n compared to the benefit for parcels leaving after t_n, so that any dispersion, which creates a greater variance in individual residence times, will diminish the overall pollutant removal.

Wetland shape can significantly affect both dead zones (Kotti et al., 2010) and dispersion (Holland et al., 2004) in wetlands. Thackston (1987) found that distinct dead zones and mixed zones are present in every wetland, and their size and location varies as a function of wetland shape and inlet-outlet positions. Persson (1999) studied 13 rectangular ponds of different aspect ratio (i.e. *L:W*, length-to-width ratio) and concluded that higher aspect ratios decrease the dead-zone area by as much as 20%. Sabokrouhiyeh et al. (2016) showed that a low aspect ratio in combination with sparse vegetation coverage causes more dispersion and larger dead zones in rectangular wetlands. Despite the importance of the subject, only a few studies have investigated the effects of wetland shape on the behavior of inert tracers and on the performance of ponds and wetlands for pollutant reduction (Kadlec and Wallace, 2009). Instead, the focus of most published studies has been on the effects on wetlands hydraulics as a function of aspect ratio (Jenkins and Greenway, 2005; Persson et al., 1999; Su et al., 2009; Thackston et al., 1987). It has been shown that long, narrow wetlands (high aspect ratios) give rise to plug-flow conditions and consequently provide higher hydraulic efficiencies than wider (low aspect ratio) wetlands. However, narrow, long wetlands can produce operational problems associated with high surface water slopes at high hydraulic loading rates (Koskiaho, 2003). For example, Reed et al. (1995) reported that a FWS wetland constructed with aspect ratio of 20:1 experienced overflow due to a dramatic head drop. In addition, construction costs are higher for a narrow wetland, because such a design requires a larger berm length per wetland area (Kadlec and Wallace, 2009). Therefore, there is a need to further investigate other wetland geometries, and other factors, such as inlet-outlet geometry, that may positively impact wetland performance.

The flow pattern generated by the inlet impacts the distribution of flow within the wetland (Somes et al., 1999). An appropriate design of inlet-outlet configuration increases HRT and enhances the flow uniformity (Persson et al., 1999; Su et al., 2009; Suliman et al., 2006). Su et al. (2009) showed the highest wetland hydraulic performance (greatest pollutant removal) was obtained with a uniform inlet and an outlet located at mid-width. They also found that the use of subsurface berms could be an efficient way to improve the wetland performance. Numerical simulation of a pond with low aspect ratio (L:W = 2:1) indicated that changing a single inlet to multiple inlets increased wetland effective volume ratio from 60 to 75% (Su et al., 2009). For a higher aspect ratio (*L:W* = 5:1), having the outlet placed close to the inlet produced an effective volume ratio of just 40%, compared to nearly 80% if the outlet was placed at the opposite end of the pond (Persson et al., 1999). Numerical simulations by Koskiaho (2003) showed that the number of inlets and their position do not significantly affect flow patterns in wetlands of high aspect ratio, but did have an impact for aspect ratios less than 4:1.

The present study analyzed the impact of different wetland design parameters on wetland efficiency (degree of pollutant removal), considering different wetland shapes, vegetation densities and inlet-outlet configurations. The analysis used 2-D depth-averaged simulations of flow hydrodynamics and mass transport. The objective of the study was to provide quantitative understanding of how different performance metrics are affected by wetland geometry and vegetation density, which can help engineers to achieve more efficient and cost-effective design solutions.

2. Theoretical background

2.1. Two-Dimensional numerical wetland model

A 2-dimensional numerical model of a wetland was developed to simulate the velocity field and the transport of a dissolved tracer under steady conditions. The hydrodynamic model solved the shallow-water equations and a solute transport model solved the depth-averaged advection-diffusion equations.

2.1.1. Hydrodynamic model

Under the assumption of hydrostatic pressure, steady flow, and negligible wind and Coriolis forces, the depth-averaged velocity field and water depth can be described by the following equations (Wu, 2007).

$$\frac{\partial (hU_x)}{\partial x} + \frac{\partial \left(hU_y\right)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial \left(hU_x{}^2\right)}{\partial x} + \frac{\partial \left(hU_xU_y\right)}{\partial y} = -gh\frac{\partial (z_s)}{\partial x} - \frac{\tau_{bx}}{\rho} - \frac{\tau_{vx}}{\rho} \tag{2}$$

$$\frac{\partial \left(hU_xU_y\right)}{\partial x} + \frac{\partial \left(hU_y{}^2\right)}{\partial y} = -gh\frac{\partial (z_s)}{\partial y} - \frac{\tau_{by}}{\rho} - \frac{\tau_{vy}}{\rho} \tag{3}$$

Here, U_x and U_y are the velocity components along the x and y directions; h is the water depth; z_s is the water surface elevation; ρ is the water density; τ_{bx} and τ_{by} are the bed shear stresses in x and y