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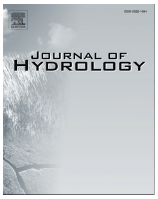

Effect of a meandering channel on wetland performance

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SUMMARY

Vegetation plays an important role in controlling mixing and contaminant removal in wetlands. Recent studies have shown that the hydraulic performance of a wetland can be significantly affected by the presence of a main flow channel (MFC) where vegetation density is much lower than the average vegetation density in the wetland. The existence of a main flow channel induces short-circuiting, which reduces hydraulic and treatment efficiency. A numerical study was carried out to analyze the effect of channel sinuosity and vegetation density on the hydraulic performance of a channelized wetland. A rectangular wetland characterized by a meandering channel and later vegetated zones (LVZs) was considered, and numerical simulations were carried out using a 2-D depth-average hydrodynamic and solute transport model. The hydraulic performance was analyzed as a function of the average vegetation density, channel sinuosity and the ratio of vegetation densities in the LVZs and the MFC. Results show that increasing sinuosity of the main flow channel can promote mixing and improve hydraulic efficiency. Different performance metrics also indicate negligible impact of the average vegetation density on the hydraulic performance, especially when the width of the MFC is relatively large.

1. Introduction

Natural wetlands provide habitat to a variety of microorganisms, plants and animals. Due to their high biological diversity, wetlands are among the most biologically active ecosystems on Earth. Wetlands have great potential for wastewater treatment and can be used as an alternative to conventional treatment processes or as treatment facilities for small communities. Clear environmental and economic advantages have increased the interest in constructed wetlands as low-cost and sustainable alternatives for wastewater treatment. This increased interest has lead to comprehensive field and laboratory studies worldwide.

In wetlands wastewaters undergo physical, chemical and biological treatment processes as in conventional water treatment plants, but under natural conditions which are typically characterized by slower rates of conversion. Therefore, the design of constructed wetlands as wastewater treatment systems requires the analysis of biological, hydrological and hydraulic processes to ensure the achievement of the desired water quality objectives for the treated effluent.

Constructed wetlands are sometimes designed with reference to an average residence time (Kadlec and Wallace, 2009). The actual residence time is a key parameter because it is often used in comparison with the nominal residence time as a measure of hydraulic performance. Depending on the nature of the study, the actual residence time can be derived from a simulated or experimentally measured residence time distribution (RTD) of a passive tracer (Kadlec, 1994; Kusin et al., 2010; Persson et al., 1999).

Several works have analyzed the efficiency of wetlands in terms of residence time distributions. By analyzing the RTDs, Su et al. (2009) and Persson (2005) showed that internal design elements can enhance wetland hydraulic performance by increasing flow path lengths and effective volume ratio. Other studies have investigated the influence of emergent vegetation and showed that vegetation can decrease effective volume and induce short-circuiting in wetlands, thus reducing hydraulic efficiency (Bodin and Persson, 2012; Keefe et al., 2010; Lightbody et al., 2008). On the other hand, vegetation enhances denitrification (Mohammadpour et al., 2014; Bastviken et al., 2009; Thullen et al., 2002) and provides substrate for microbes and epiphytes (Kadlec and Knight, 1996; USEPA, 1999). The optimization of wetland performance

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therefore requires consideration of potentially counteracting hydrodynamic and biochemical processes.

The aim of this study is to investigate the relationship between the hydraulic performance of a channelized wetland, vegetation density and geometry of the main flow channel (MFC). The modelling framework presented in this study is an extension of the model described by Musner et al. (2014), where the flow field and solute transport within the conceptual wetland are solved by a two-dimensional depth-average flow and solute transport models, respectively. The wetland model is characterized by an MFC and lateral vegetated zones (LVZs), where vegetation density is higher and velocities are lower compared to the MFC. Whilst previous studies on channelized wetland systems (Jenkins and Greenway, 2005; Musner et al., 2014) investigated the effect of a straight MFC, this work analyzes the case of a meandering MFC. The goal of this study is to understand how the sinuosity of the main channel and the relative vegetation density in the MFC and the LVZs can affect the hydraulic performance of a wetland. This is achieved by simulating flow and mass transport in a rectangular wetland with a sinusoidal MFC using a 2-D depth-average model, and by calculating different performance indices as a function of channel amplitude and vegetation density.

2. Methods

2.1. Hydrodynamic and solute transport model

The hydraulic performance of a wetland is analyzed here numerically using a 2-D depth-averaged hydrodynamic and a solute transport model. The detailed formulation of the model can be found in Musner et al. (2014). In the hydrodynamic model, the effect of vegetation is represented as an equivalent flow resistance that depends on vegetation density (i.e. number of stems per unit area), n, stem diameter, d, and submerged stem length, l. Since only emergent vegetation is considered in this work, the submerged stem length is equal to the local flow depth, h. The solute transport model relies on the velocity field predicted by the hydrodynamic model and takes into account the additional mechanical and turbulent dispersion induced by vegetation via an appropriately defined dispersion tensor that depends on n and d.

The model flow and solute transport equations are solved in Comsol *Multiphysics* using a Finite Element formulation with quadratic shape functions.

2.2. Hydraulic performance metrics

To provide a comprehensive description of the wetland response, the most common performance metrics were derived from the residence time distributions (RTDs). Under the assumption of a constant inflow and continuous injection of a non-reactive tracer at the inlet, the output concentration from the wetland $C_{out}(t)$ is related to the input concentration $C_{in}(t-\tau)$ by the convolution integral as follows:

$$C_{out}(t) = \int_0^t \phi(\tau)\, C_{in}(t-\tau)\, d\tau \tag{1}$$

where $\phi(\tau)\,d\tau$ is the probability that a particle entered at time $t-\tau$ leaves the system at time t. If the inlet concentration C_{in} is constant in time Eq. (1) becomes

$$C_{out}(t) = C_{in} \int_0^t \phi(\tau)\, d\tau \tag{2}$$

which leads to

$$\frac{C_{out}(t)}{C_{in}} = \int_0^t \phi(\tau)\, d\tau = \Phi(t) \tag{3}$$

The function $\Phi(t)$ represents the cumulative distribution of the hydraulic residence time in the wetland. To obtain the corresponding probability density function, here referred to as RTD, Eq. (3) must be differentiated with respect to time:

$$\phi(t) = \frac{d\Phi(t)}{dt} = \frac{d}{dt}\left(\frac{C_{out}(t)}{C_{in}}\right) \tag{4}$$

The hydraulic performance of a wetland is often measured by the effective volume ratio (Thackston et al., 1987), defined as

$$e = \frac{V_{eff}}{V_{total}} = \frac{t_a}{t_n} \tag{5}$$

which provides a link between the effective wetland volume, V_{eff}, and the total wetland volume, V_{total}. Here, t_n is the nominal residence time and t_a is the hydraulic residence time, representing how long the average tracer particle remains in the wetland.

The wetland response can also be examined in terms of the parameter

$$\theta_{90} = \frac{t_{90}}{t_n} \tag{6}$$

where t_{90} is the time taken for 90 percent of the injected tracer to leave the system. This parameter is derived from the residence time distribution (RTD) in the wetland, and is considered to be a good measure of the mixing degree. Generally, higher values of θ_{90} indicate poor mixing (or flow distribution) within the domain, with $\theta_{90} \approx 1$ in the ideal case of complete uniform mixing.

Furthermore, the hydraulic efficiency parameter was quantified as follows (Persson et al., 1999):

$$\lambda = \frac{t_p}{t_n} \tag{7}$$

where λ is the hydraulic efficiency and t_p is the time-to-peak.

2.3. Model application

Simulations were performed for a rectangular wetland of width $B = 90$ m, length $L = 120$ m and flat topography with zero bed slope, as illustrated in Fig. 1. The assumption of negligible bed slope is consistent with the fact that many natural wetlands have negligible variation of bed elevation between the inlet and the outlet. The wetland inlet and outlet are positioned symmetrically around the wetland central axis, and have the same width as the main flow channel (MFC). Simulations were performed for two different values of the MFC width, $b = 9$ m and $b = 18$ m. Furthermore, the effect of channel sinuosity was analyzed by considering sinusoidal MFCs of different amplitude. Although a variety of meandering channel geometries are possible, in this study the geometry of the channel boundary is described by the following equation:

$$y = a \sin\frac{2\pi x}{L} \pm \frac{b}{2} \tag{8}$$

where the plus and minus operators apply to the left and right boundaries of the MFC, respectively. The lateral regions between the MFC and the domain boundaries are characterized by a uniform vegetation distribution, and are referred to as lateral vegetated zones (LVZs). In the simulations, five different degrees of sinuosity were considered, characterized by the dimensionless amplitudes $a^* = a/b = 0,\ 0.5,\ 1,\ 1.5$ and 2 (Fig. 1), where the case $a^* = 0$ corresponds to a straight channel.

The boundary conditions for the flow equations are given by the constant inflow at the inlet $Q = 0.009\ \mathrm{m^3\ s^{-1}}$ and the water depth at the outlet $h = 0.5$ m. The value of the flow rate was chosen to achieve a nominal residence time of approximately $t_n = 7$ days, and produces laminar flow conditions characterized by Reynolds