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A contaminant transport model for wetlands accounting for distinct residence time bimodality

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SUMMARY

Vegetation plays a major role in controlling the fate of contaminants in natural and constructed wetlands. Estimating the efficiency of contaminant removal of a wetland requires separate knowledge of the residence time statistics in the main flow channels, where the flow velocity is relatively higher, and in the more densely vegetated zones, where the velocity is smaller and most of the biochemical transformations occur. A conceptual wetland characterized by a main flow channel (MFC) and lateral vegetated zones (LVZs) is modeled here using a two-dimensional depth-averaged hydrodynamic and advection–dispersion model. The effect of vegetation is described as a flow resistance represented in the hydrodynamic model as a function of the stem density. Simulations are performed for a given flow discharge and for increasing values of the ratio between the vegetation density in the LVZs and in the MFC. Residence time distributions (RTDs) of a nonreactive tracer are derived from numerical simulations of the solute breakthrough curves (BTCs) resulting from a continuous concentration input. Results show that increasing vegetation densities produce an increasingly pronounced bimodality of the RTDs. At longer times, the RTDs decrease exponentially, with different timescales depending on the stem density ratio and other system parameters. The overall residence time distribution can be decomposed into a first component associated with the relatively fast transport in the MFC, and a second component associated with the slower transport in the LVZs. The weight of each temporal component is related to the exchange flux at the MFC-LVZ interface. A one-dimensional transport model is proposed that is capable to reproduce the RTDs predicted by the depth-averaged model, and the relationship between model and system parameters is investigated using a combination of direct and inverse modeling approaches.

1. Introduction

The removal efficiency of natural and constructed wetlands is controlled by the time spent by contaminants in the vegetated zones (Persson et al., 1999). Vegetation plays an important role for two main reasons: firstly, dense vegetated zones locally decrease the flow velocity, creating stagnant zones and favoring the sedimentation of suspended solids; secondly, plant roots and associated epiphytic biofilms are responsible for the transformation of the transported substances as a result of biochemical processes. The combined effect of vegetation and wetland topography can also produce hydraulic shortcuts that negatively affects the wetland performance.

Despite their typical heterogeneity, constructed wetlands for waste water treatment are often designed with reference to an average water residence time (Kadlec and Wallace, 2009), which can lead to significant inaccuracies in the evaluation of their performance (Kadlec, 2000). Zero-dimensional models are often used because of their simplicity, but they are inadequate to represent complex spatial patterns resulting from heterogeneous vegetation distributions (Akratos and Tsihrintzis, 2007; Kadlec and Wallace, 2009). One-dimensional transient storage models have been widely used to represent the transport and retention dynamics in rivers due to vegetation and permeable beds (Runkel and Broshears, 1991; Bencala and Walters, 1983; Gooseff et al., 2003), but a major question is whether these models can represent the more complex hydrodynamics found in natural and constructed wetlands. Recent studies (Keefe et al., 2004; Martinez and Wise, 2003) have used transient storage models to assess the contaminant removal in constructed wetlands, providing in some cases good approximations of the breakthrough curves (BTCs). However,

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these models fail to describe in general the different flow paths through vegetation and the main flow channels, which can result in a clear bimodality of the solute breakthrough curves. A bimodal behavior of the hydraulic residence time distributions (RTDs) induced by riparian vegetation has been experimentally observed in a real wetland by Martinez and Wise (2003) and in a conceptualized lowland river by Perucca et al. (2009).

Since spatial heterogeneity plays a fundamental role in controlling the fate of contaminants, a two-dimensional approach is more appropriate to describe transport dynamics in wetlands. Although two-dimensional hydrodynamic models have already been used in the past (Persson et al., 1999; Somes et al., 1999), the formulation of more detailed models accounting for vegetation distribution is relatively recent (Arega and Sanders, 2004; Jenkins and Greenway, 2005), yet none of the suggested models provides a clear relationship between vegetation density and hydraulic RTDs. This relationship is investigated in the present study as a function of the degree of flow channelization of a wetland induced by vegetation. To this end, a two-dimensional depth-averaged flow and solute transport model is applied to a conceptual wetland characterized by a central main flow channel (MFC) and lateral vegetated zones (LVZs), and simulations are performed for different vegetation densities. A one-dimensional transport model is also proposed and calibrated against the RTDs derived from the two-dimensional depth-averaged model. The behavior of the model parameters is analyzed as a function of the system parameters and analytical relationships are provided for the average residence times and flow discharges in the MFC and in the LVZs.

2. 2-D depth-averaged model

Assuming that the vertical gradients are small compared to the horizontal gradients, the transport of a dissolved contaminant in a wetland can be represented by a two-dimensional depth-averaged model. This assumption has often been used in wetland studies (Somes et al., 1999; Arega and Sanders, 2004; Jenkins and Greenway, 2005) and is consistent with the simplified wetland topography and geometry analyzed in this work. It is further assumed that the long-term, average performance of a wetland can be represented by steady state flow conditions. This representation can also be useful to describe gradually unsteady flows, for which variations can be represented as a sequence of steady states.

2.1. Hydrodynamic model

Under the assumption of hydrostatic pressure, steady-state flow, negligible wind and Coriolis forces, the depth-averaged velocity field and water depth satisfy the following equations (Wu, 2007):

$$\frac{\partial(hU)}{\partial x}+\frac{\partial(hV)}{\partial y}=0 \tag{1}$$

$$\frac{\partial(hU^2)}{\partial x}+\frac{\partial(hUV)}{\partial y}=-gh\frac{\partial z_s}{\partial x}-\frac{\tau_{bx}}{\rho}-\frac{\tau_{vx}}{\rho} \tag{2}$$

$$\frac{\partial(hUV)}{\partial x}+\frac{\partial(hV^2)}{\partial y}=-gh\frac{\partial z_s}{\partial y}-\frac{\tau_{by}}{\rho}-\frac{\tau_{vy}}{\rho} \tag{3}$$

The quantities U and V represent the depth-averaged velocities $(\mathrm{m\,s^{-1}})$ in the x- and y-directions, respectively, h is the water depth, z_s is the water surface elevation (m), and ρ the water density $(\mathrm{kg\,m^{-3}})$. The shear stresses τ_{bx} and τ_{by} account for bed resistance, whereas τ_{vx} and τ_{vy} account for vegetation resistance along the x- and y-direction, respectively. Eqs. (2) and (3) assume that Reynolds stresses are negligible compared to bed and vegetative resistance. In channelized wetlands, Babarutsi et al. (1989) experimentally showed that bed friction dominates and Reynolds stresses can be neglected when $c_{bD}L_h/h > 0.1$, where L_h is the horizontal length scale of recirculation zones, and c_{bD} is the bed drag coefficient. Since typical values of c_{bD} vary between 0.009 and 0.003 in tidal wetlands, this model is expected to resolve recirculation zones where $L_h/h > 10$–30 (Arega and Sanders, 2004).

The contribution of bed friction to bed shear stresses is computed by adapting the one-dimensional relationships proposed by Kadlec (1990) to a two-dimensional velocity field, which leads to:

$$\begin{aligned}\tau_{bx}&=\rho c_{bD}U\sqrt{U^2+V^2}\\ \tau_{by}&=\rho c_{bD}V\sqrt{U^2+V^2}\end{aligned} \tag{4}$$

The bed drag coefficient c_{bD} (–) in Eq. (4) combines both laminar and turbulent stresses, and can be calculated as follows (Kadlec, 1990):

$$c_{bD}=\frac{3\nu}{h\sqrt{U^2+V^2}}+f^2gh^{-1/3}=\frac{3}{Re_h}+f^2gh^{-1/3} \tag{5}$$

where ν is the kinematic viscosity $(\mathrm{m^2\,s^{-1}})$ and f is the Manning's friction coefficient $(\mathrm{s^{-1}\,m^{-1/3}})$. For depth-Reynolds numbers Re_h less than 500 the first term on the right-hand side prevails, whereas the second term prevails for depth-Reynolds numbers greater than 12500 (Kadlec, 1990). The sum of the two terms therefore provides a complete description of the bed shear stresses for a wide range of depth-Reynolds numbers.

Vegetation drag is modeled in a similar way by representing aquatic plant stems as an array of randomly distributed cylinders with a uniform diameter d (m), as suggested by Kadlec (1990) and by Arega and Sanders (2004):

$$\begin{aligned}\tau_{vx}&=\frac{1}{2}\rho c_{vD}nldU\sqrt{U^2+V^2}\\ \tau_{vy}&=\frac{1}{2}\rho c_{vD}nldV\sqrt{U^2+V^2}\end{aligned} \tag{6}$$

where n is the superficial stem density $(\mathrm{m^{-2}})$, l is the submerged stem length (m) and c_{vD} is the vegetation drag coefficient. For fully emergent vegetation, as considered in this work, the submerged stem length can be taken as the water depth. The behavior of the vegetation drag coefficient for an individual cylinder is well known (Bennett and Myers, 1962; White, 1991) and shows a decreasing trend for increasing stem Reynolds numbers, defined as $Re_d=\sqrt{U^2+V^2}d/\nu$. Other studies (Ergun, 1952; Petryk, 1969; Nepf, 1999; Hill et al., 2001; Blevins, 2005) have shown that neighboring cylinders can produce a velocity reduction and, as a consequence, a reduced drag (Tanino and Nepf, 2008). Nevertheless, cumulative effects of multiple wake interactions can be neglected for sufficiently sparse vegetation, i.e. when the solid volume fraction ad is lower than 0.1 (Raupach, 1992). Here, the parameter a represents the plant area projected on a plane perpendicular to the flow direction per unit volume $(\mathrm{m^{-1}})$, and can be written as a function of the superficial stem density, $a=nd$, if the plants are modeled as cylinders.

Nepf (1999) performed numerical and laboratory experiments for superficial stem densities lower than 2500 stems/m^2 and a stem diameter of 2 mm, corresponding to a solid volume fraction $ad=nd^2\approx 0.01$, and found relatively constant values of c_{vD}. Such values are common in natural and constructed wetlands. Tanner (2001) measured the superficial density of vegetation in pilot-scale constructed wetlands and found 1400–1500 stems/m^2 of *Schoenoplectus Tabernaemontani* and densities higher than 2000 stems/m^2 of *Schoenoplectus Validus*. Hocking (1989) and Parr (1990) found superficial vegetation densities of *Phragmites Australis* ranging from 70 to 250 stems/m^2. Other hydraulic studies on diffusion in