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Three-Dimensional Numerical Model to Evaluate the Suspended Solid Removal in Surface Flow Constructed Wetland

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Abstract: Surface flow constructed wetlands (SFCWs) have been widely used to treat various types of wastewater and stormwater due to the advantages such as low costs for operating and maintenance compared with conventional treatment systems. In SFCW, the flow pattern, which is determined by the geometric features including bed morphology and vegetation distribution, significantly influences the removal processes of suspended solids and other pollutants. In this study, a three-dimensional computational fluid dynamics model, that integrates hydrodynamic model and the Lagrangian particle tracking model, is applied to determine the effectiveness of a SFCW in removing suspended solids based on the predicted flow characteristics and distribution of suspended solids in the wetland. After the validation, the three-dimensional numerical model is applied to illustrate the three-dimensional internal flow pattern in the wetland. The predicted concentrations of suspended solids at several cross-sections in downstream direction are compared with the field sampling data and also the results from a traditional first-order decay model. The results show that the 3D model performs reasonably well predicting complex flow fields associated with complex wetland geometry. This study indicates that the 3D model is an effective tool to support the management and operation of field SFCWs. Also, it can help to improve the design of SFCWs providing better understanding of interactions among the geometric features, the flow characteristics and the contaminants behaviors.

Keywords: Hydro-environmental modeling; Removal efficiency; Surface flow constructed wetland; Suspended solids

1. INTRODUCTION

Suspended solids in stormwater are substantial contributor to overall deterioration of receiving waters, and predicting the behavior of suspended solids in a constructed wetland (CW) is critical for assessing the effectiveness of the wetland operation and management. Constructed wetlands are often classified into a surface flow type constructed wetland (SFCW) and a subsurface flow type constructed wetland according to hydraulic and ecological conditions (Vymazal 2010). In North America, SFCWs have been widely adopted to treat wastewater including storm water, wastewater discharges from domestic, agricultural, and industrial practices, and also landfill leachate (Economopoulou and Tsihrintzis 2004). They also provide additional benefits including flow retardation, conservation of biodiversity and public amenity with more aesthetic appearance (Tsihrintzis and Hamid 1997).

The flow fields in deep zones of SFCW (e.g. ponds) are highly three-dimensional with vertical and lateral flow circulations (Lightbody et al. 2007). Also, varying curvatures, widths and depths in shallow channels of SFCWs lead to the development of flow circulation or secondary flows. Hence, 3D models can better predict such flow characteristics and help investigating the consequences of modifications in the wetland morphology on the volumetric and detention time distribution efficiencies of a SFCW (Kadlec and Wallace 2008). Accurate description of the flow pattern in a SFCW is critical to assess the removal efficiency of various contaminants entering the wetland including suspended solids. Especially, the suspended solids are one of the main sources of pollutants entering SFCWs that can also act as sink or source of various pollutant including heavy metals and nutrients (Tsanis and Boyle 2001). Hence, accurate prediction of the flow characteristics and behavior of suspended solids in a SFCW using a 3D model could help reducing the risk of wetland discharge to the human health and environment.

The objective of this study is to develop an appropriate 3D CFD model, based on a finite volume method with a Lagrangian particle tracking method, as a tool for predicting the behavior of suspended solids in a SFCW. The predicted results from the model are compared with field measurements and also the results from a traditional first order decay model. Specifically, the developed model is applied to investigate the Kennedale end-of-pipe constructed wetland located in the city of Edmonton, Alberta assessing the internal flow conditions and the behavior of suspended solids entering the wetland. This study is also to demonstrate that the 3D model can be applied to improve the operation and maintenance of an existing SFCW.

2. METHOD

In order to assess the validity of the 3D CFD model for examining SFCW removal of TSS, the results from the 3D model are compared with the field obtained data and the results from a first-order decay model in this study. Briefly the models are described in the following sections prior to presenting the results.

2.1 3D CFD Model

Internal flow patterns and behaviors of suspended solids are modeled using a 3D model based on a commercial CFD code FLUENT (ANSYS 2010). For this study, the hydrodynamic model predicting the internal flow pattern is based on full 3D Navier Stokes equations, and the behavior of suspended solid is modeled using a Lagrangian particle tracking model. These two models are closely coupled to predict the interactions between the flow and the particles.

2.1.1 Modeling of internal flow

The fluid flow equations are solved based on the conservation of mass and momentum. The mathematical description of the flow in CFD consists of the Reynolds-averaged continuity equation and Navier-Stokes equations for conservation of mass and momentum. The continuity and Navier-Stokes equations for incompressible and constant-property flow are given by:

$$\frac{\partial u_i}{\partial x_j} = 0 \qquad (1)$$

$$\rho\frac{\partial u_i}{\partial t} + \rho u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(2\mu S_{ij} + \rho\tau_{ij}\right) \qquad (2)$$

where u_i, x_j, and t are average flow velocity, global Cartesian coordinates (i, j = 1, 2, 3), and time, respectively. p, ρ and μ are pressure, density and molecular viscosity, respectively. S_{ij} and τ_{ij} are the tensors for strain rate and Reynolds-stress, respectively.

Despite the design efforts to control the flow pattern, the actual flow in a SFCW is often turbulent and three-dimensional, especially in the deep zones (Lightbody et al. 2007). Hence, this study adopted the RNG k-ε model (Yakhot et al. 1992) which has shown good performance in predicting the secondary flow motion and the flow separation (Smith and Woodruff 1998). The RNG k-ε model is also computationally less expensive than more complex turbulence models (e.g. Reynolds stress model (RSM); Large eddy simulation (LES)). The turbulence intensity (I) at the inlet boundary is estimated based on the Reynolds number Re (I = 0.16 Re-1/8) (Pope 2003).

2.1.2 Modeling the suspended solids in SFCW

An Euler-Euler or an Euler-Lagrangian approach is often applied to model multiphase flows depending on the extent of phase coupling (van Wachem and Almstedt 2003). In this approach, the transient flow field is solved first using the Eulerian approach. Then, influent suspended solids is numerically injected into the wetland. Particle trajectories for suspended solid of consistent morphology and known diameter are obtained by the integration of the force balance on a particle (Maxey and Riley 1983). This force balance equation can be written as follows:

$$\frac{\partial u_p}{\partial t} = F_D(u - u_p) + g(1 - \frac{\rho}{\rho_p}) \qquad (3)$$

where u (m s^{-1}) is the fluid phase velocity u_p (m s^{-1}) is the particle velocity, μ (Pas) is the molecular viscosity of the fluid, ρ is the fluid density (kg m^{-3}), ρ_p is the density of the particle (kg m^{-3}) and d_p (m) is the particle diameter.

The free water surface is treated as a rigid-lid since the observed variation of water surface is negligible. The effect of vegetation is treated using the estimated bed roughness height of 0.001 m for simplicity without considering the differences in plant species and distribution in wetland that is also seasonally dependent. More precise estimation and survey could be performed in the future study. The evapotranspiration is neglected for this study considering that the simulation time lasts only up to 10 hr. The outlet boundary is considered as a pressure outlet that the pressure field is extrapolated from the flow in the interior (ANSYS 2010).

2.2 First Order Decay Model

The fist-order decay model or so called *k-C** model is widely used to describe the removal of various pollutants including TSS, TP and TN in wetland studies (e.g. Struck et al. 2008). The *k-C** model determines the pollutant removal using two parameters to expresses the rate of pollutant concentration reduction that reaches an equilibrium or background concentration with the distance along the treatment measure (Kadlec and Knight 1996):

$$q\frac{dC}{dx} = -k(C - C^*) \qquad (4)$$

where q is the hydraulic loading time (m/year) (= inflow rate/surface area), x is the fraction of distance from in inlet to the outlet (m), C is the concentration of the water quality parameter, C^* is the background concentration of the water quality parameter, and k is the areal decay rate constant (m/year).

To improve the standard *k-C** model, instead of considering a whole wetland as a single system with the ideal plug flow condition, wetlands are often treated as a series of continuous stirred tank reactors (CSTRs) (Kadlec and Knight 1996). In this study, the CSTR approach is adopted to determine the removal of TSS in a field SFCW. The Kennedale end-of pipe constructed wetland is divided in to a series of CSTRs, and the TSS concentrations in each CSTR are predicted adopting the Kadlec and Knight's *k-C** model in Equation 2.

$$C_{out\,i} = C^* + (C_{in\,i} - C^*)e^{-kA_i/Q} \qquad (5)$$

where $C_{in\,i}$ and $C_{out\,i}$ are the TSS concentrations entering and leaving a CSTR, respectively, Q is the flow rate, and A_i is the surface area of a CSTR. The subscript i refers to the corresponding CSTR.

3. KENNEDALE CONSTRUCTED WETLAND

The Kennedale end-of-pipe constructed wetland built in 2009 is located in the city of Edmonton, Canada. The Kennedale wetland receives stormwater from Kennedale storm basin with the basin area of 72.5 km^2. The wetland surface area is about 5 km^2 and the storage capacity is 50400 m^2. The storm water entering the Kennedale wetland is controlled in varying range (up to 0.5 m^3/s) to treat the stormwater entering the wetland. Excess flow up to 0.8 m^3/s is diverted to two units of stormwater treatment system removing only large particles and debris. Any additional flow during a severe flooding is directly discharged to the North Saskatchewan River without a treatment.

The wetland has four deep pools and shallow channels connecting them. The deep-pools include the forebay where the flow enters the wetland through a submerged inlet pipe (diameter of 0.74 m), the two deep pools (i.e. deep pool 1 and deep pool 2) for additional settling, and the micro-pool where the flow leaves the wetland through the submerged outlet pipe (diameter of 0.75 m). The wetland is initially designed to receive 44 % of total suspended solids (TSS) loading from the basin area that is about 1100 kg/day. The lowest elevations in the forebay, the deep pool 1, the deep pool 2 and the micro pool are 606 m, 612.5 m, 612 m, and 608 m, respectively. The elevation of water surface level in the wetland is controlled by the weir in the downstream chamber that is connected to the outlet pipe, and the wetland water level has been maintained between 614.5 m and 615.0 m in 2012.

Suspended solid concentrations at predetermined locations in the Kennedale wetland are obtained analyzing the water samples taken on June 24, 2013. The constant inflow rate of 0.3 m^3/s is assumed during the sampling. The measured concentration value of suspended solid at the inlet C_{in} is 125 mg/L. The particle size distribution in the stormwater that the Kennedale wetland receives is estimated based on the data available from the report for the city of Edmonton (Golder Associates 2012). The distribution of particle sizes in TSS and the corresponding mass flows for the inflow rates are shown in Table 1.

4. VALIDATIONS OF THE 3D MODEL

4.1 Comparison of Predicted Velocity from 3D Model and Field Observation

Since the velocity field data during the field observation period are unavailable, a point velocity data taken at the water surface level near the shore of the forebay in the Kennedale wetland as shown in the Figure 1 (a), using a visual observation is adopted for validation. The observation was occurred in June 5, 2012 between 10:00 A.M. and noon. To assess the depth average velocity U_i, the wind driven circulation relationship (Koutitas 1988) is used:

$$U_i = \tfrac{2}{3}\left[u_{surf\,i} - \frac{\tau_{sx_i} h}{4\rho\nu}\right] \qquad (6)$$

where $u_{surf\ i}$ is the water surface flow velocity; τ_{sx_i} is the shear stress at water surface ($= \rho C_s W_i \sqrt{W_i^2 + W_j^2}$); v is the eddy viscosity ($= \bar{\lambda}\, h \sqrt{\frac{\tau_s}{\rho}}$); W_i and W_j are the wind speeds in x and y direction (m/s); $\bar{\lambda}$ is coefficient to determine v (~ 0.1); and C_s is the surface friction coefficient (1.8E-6). The subscripts 1 and 2 are for x- and y-direction, respectively.

Considering the average wind speed W (= 2.0 m/s) in North West direction during the observation period, the estimated depth averaged field velocity U ($=\sqrt{(U_1{}^2 + U_2{}^2)}$) is 0.01 m/s. Considering the model predicted value 0.02 m/s, both values are in similar order of magnitude confirming that the model is capable of predicting internal flow velocity with reasonable accuracy. The discrepancy could be related to the error in visual observations and also the unsteadiness of flow and wind conditions in the field.

Table 1 TSS mass flow rate for different particle sizes

Particle type	Diameter (10^{-6} m)	Distribution (%)	Concentration (mg/L)	Concentration (kg/m3)	TSS Mass flow rate (kg/s)
I	1	43.8	37.1862	0.0372	0.0114
II	8	43.8	37.1862	0.0372	0.0115
III	32	11.4	9.6786	0.0097	0.00290
IV	64	0.8	0.6792	0.0007	0.000204
V	128	0.2	0.1698	0.0002	0.0000500

4.2 Comparison of TSS Values from 3D Model Result and Field Observation

A simulation is executed applying the observed field conditions. The flow rate Q is 0.3 m^3/s, the water surface level (WSL) is 614.7 m, and the loading rate of suspended solids are provided in Table 1. After completing the simulation, the predicted TSS values are obtained at corresponding coordinates from the field sampling locations shown Figure 1a. The comparisons between predicted and observed TSS concentration values are shown in Figure 1b. The TSS values are presented as non-dimensional values by dividing with C_{in}. The results indicate that the predicted TSS values from the 3D model closely matches the observed values except the locations **g** and **f** located in the micro-pool. Although both results show that TSS values are high at locations **c** and **d** which are located in the shallow channel between the forebay and the deep-pool 1, they may not indicate actual increase in TSS concentrations when the flow leaves the forebay. Rather, the increase is due to local variations associated with complex flow pattern in the region such as a large circulation cell developed in the forebay region which be presented in the following section. Such flow condition leads the flow condition in the wetland deviates from ideal flow pattern that is usually assumed in a wetland flows. The results show that the 3D model can predict the variations of TSS concentrations influenced by flow fields reasonably well.

5. RESULTS

The predicted flow fields for Q = 0.3 m^3/s, WSL = 614.7 m, and the loading rate of suspended solids (Table 1) are presented. Also, the predicted TSS values along the flow path in the wetland using the 3D model and the first-order decay model are compared.

5.1 Predicted Flow Pattern

5.1.1 Velocity field

The predicted velocity fields in the Kennedale wetland using the 3D model are shown in Figures 2a-c for different depth elevations (614.7 m, 614.0 m, and 613.3 m) to show details of internal flow pattern. The velocity contours of resultant velocity U_T (= $(U_x^2 + U_y^2 + U_z^2)^{-1/2}$, where U_x, U_y and U_z are the predicted velocities at the grid cell in x, y and z directions, respectively.) near the water surface in Fig. 3a show that the flow velocity in the deep zones (i.e. forebay, deep-pools 1 and 2, and the micro-pool) is significantly low creating favorable conditions for settling of suspended solids. However, large circulations in the deep zones of the wetland, shown as streamlines at the water surface level and other flow depths, are predicted except for the deep-pool 2 indicating that the flow in the wetland is highly three-dimensional. Flow accelerates and decelerates as the flow enters and leaves the shallow channels that connects deep zone in the wetland. The velocity field show large variations of velocity magnitude and changes in flow direction.

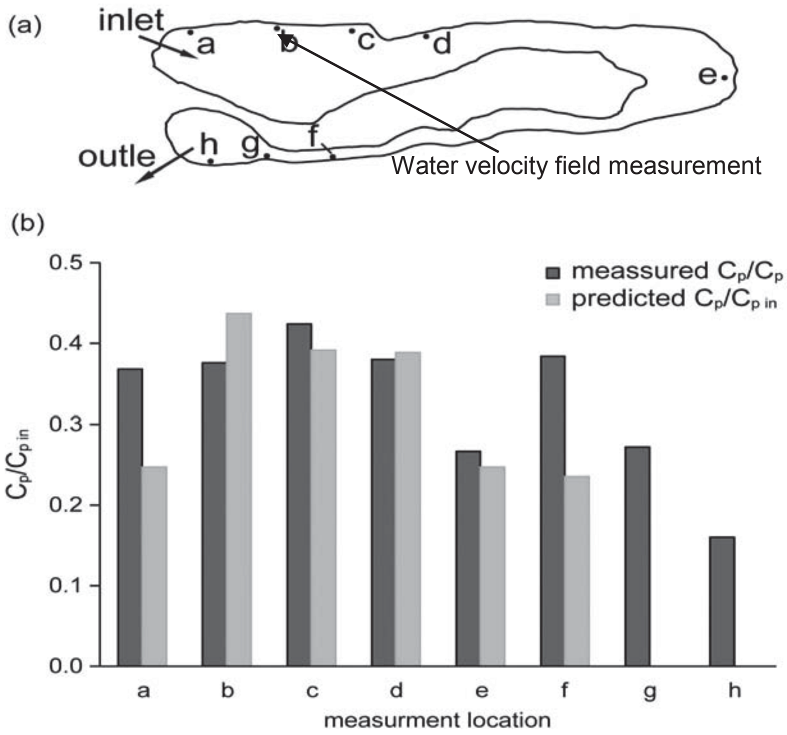

Figure 1. Samples taken in Kennedale wetland

5.1.2 Bed shear stress

The predicted bed shear stress τ_w is shown in Figure 2d using a contour plot. Low values of τ_w are predicted in the deep zones, and the result indicate that the settling of suspended solid would be enhanced in the zones. On the other hand, relatively high bed shear stress zone exists in the channel between the deep pool 2 and the micro pool. The predicted bed shear stress distribution could be used to determine the susceptible bed area for erosion comparing with the estimated threshold shear stress value.

5.1.3 Behavior of suspended solids

Figure 3.e shows the predicted locations of particles that have been continuously injected through the inlet (from t = 0 sec to t =45,000 sec) at t = 45,000 sec (~ 11 hr) in the wetland. The simulation time is determined to ensure that sufficient number of particles reach the micro pool in the downstream and also the number of particles leaving the wetland becomes steady. The particles are also marked with color indicating the particle birth time to show when each particle entered the wetland through the inlet. The extreme colors blue and red refer to the time of injection at 0 second and 45,000 second, respectively. The result shows that most of particles settle in the forebay region due to the low flow velocity in the forebay, but some particles may also reach the micro pool and eventually leaving the wetland.

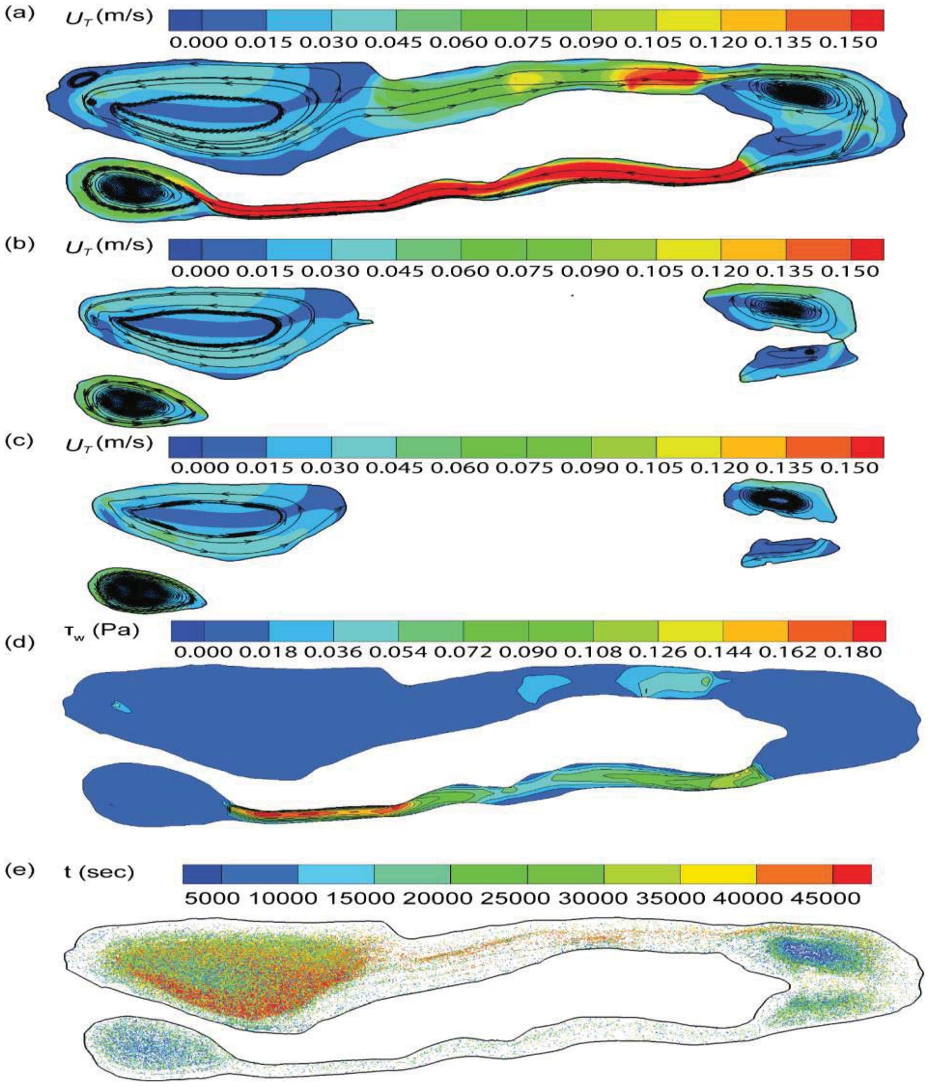

Figure 2. (a) Contours of U_T and streamlines at the water surface (614.7m); (b) contours of U_T and streamlines at 614.0 m; (c) contours of U_T and streamlines at 614.3 m; (d) Contours of predicted τ_w; and (e) predicted particle locations at simulation time t = 45000 sec

5.2 Comparison of the 3D model results with the first-order decay model results

To apply first order decay model, the Kennedale wetland is divided into 18 CSTRs (K1-K18) in series as shown in Figure 3. The value of *k* and *C** determined from the field data are 0.06 and 20.0 mg/L, respectively.

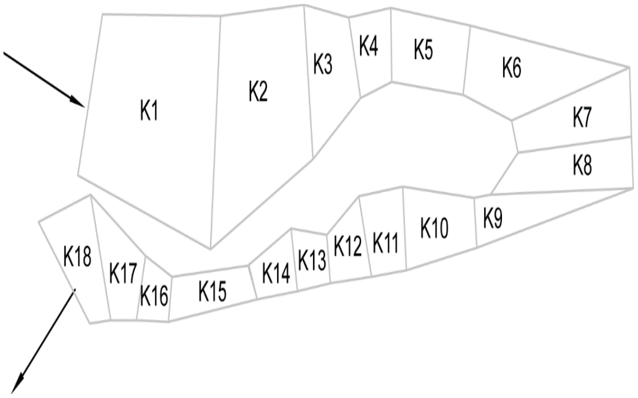

Figure 3. CSTRs in series for Kennedale

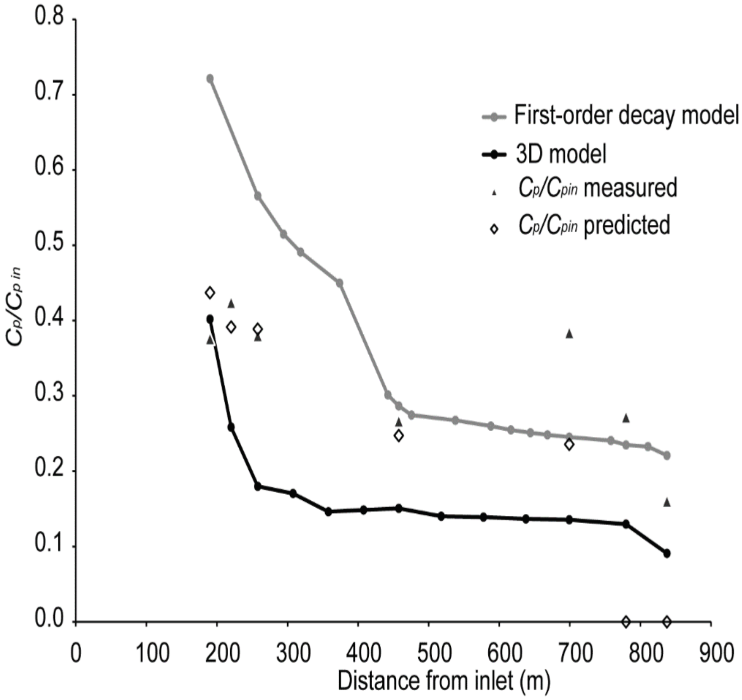

Figure 4. Comparisons of predicted TSS concentrations from the first-order decay model and the 3D model

The comparisons between predicted C/C_{in} values using the k–C* model and the 3D model are shown in Figure 4. The results in Figure 4 show that both models predict significant decrease of TSS concentration in the forebay region where major settling is expected. The first-order decay model predicts large decrease of TSS concentration values starting from the forebay to the two deep-pools, but the decrease rate becomes less significant in the channel between the deep-pool 2 and the micro-pool. The 3D model also predicts similar rapid decrease of TSS concentrations in the forebay region. However, the values are lower than the predicted ones from the first-order decay model already reaching up to 80 % removal of TSS in the forebay region. The decrease rate of C/C_{in} in the rest of wetland area is comparable with the result of first-order decay model. This indicate that the significant difference between two results is related to the flow condition in the deep zones, especially in the forebay region.

The wetland has complex geometry deviating from an ideal uniform cross-section shape. For instance, the forebay is deep and the variation of width to depth ratio along the flow path is large leading to the development of complex three-dimensional flow patterns in the region despite low velocity magnitude. The inlet flow condition may also play a role to determine the flow pattern in the forebay region influencing the settling process. As the CSTR model based on the first-order decay model ignores the three-dimensional flow pattern in the forebay, it underestimate or overestimate the removal of TSS.

The removal efficiency ζ may be calculated as the difference in TSS concentrations at the inlet and outlet ($\zeta = (C_{in} - C_{out})/C_{in}) \times \%100$); C_{in} is the particle concentration at the inlet which is 125 mg/L, C_{out} is the mean concentration measured at the outlet. The predicted values of ζ are 78 % and 90 % for the first-order-decay model and the 3D model, respectively. As described, the discrepancy is linked to the flow pattern in the Kennedale wetland, particularly in the deep zones presented in section 5.1.

6. CONCLUSION

In this study, a 3D CFD model was developed to investigate the flow fields, suspended particle distribution, and the TSS removal efficiency in the surface flow constricted wetland. The predicted TSS concentration values are compared with the field observation and the results from the first-order decay model.

The comparisons show that the 3D model can predict the removal process in the wetland with reasonable accuracy. The results show that the flow field in the wetland is highly three-dimensional especially in the deep zones. The particle distribution pattern associated with the velocity field and the bed shear stress in the wetland indicate that high removal of particles are expected in the forebay region. The predicted behaviors of suspended particles indicate that the particles may leave the wetland much earlier than the flow retention time based on a simple assessment using the wetland volume and the inflow rate which is frequently used to estimate the removal efficiency of TSS and other pollutants.

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