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Application of computational fluid dynamic to model the hydraulic performance of subsurface flow wetlands

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Abstract

A subsurface flow wetland (SSFW) was simulated using a commercial computational fluid dynamic (CFD) code. The constructed media was simulated using porous media and the liquid resident time distribution (RTD) in the SSFW was obtained using the particle trajectory model. The effect of wetland configuration and operating conditions on the hydraulic performance of the SSFW were investigated. The results indicated that the hydraulic performance of the SSFW was predominantly affected by the wetland configuration. The hydraulic efficiency of the SSFW with an inlet at the middle edge of the upper media was 0.584 and the best among the SSFWs with an inlet at the top, the middle, and the bottom edge of the upper media. The constructed media affected the hydraulic performance by the ratio (K) of the upper and lower media resistance. The selection of appropriate media resistance in the protection layer can improve the hydraulic efficiency. When the viscous resistance coefficient of the media in the protection layer changed from 2.315×10^5 to 1.200×10^8, the hydraulic efficiency of the SSFW increased from 0.301 to 0.751. However, the effect of operating conditions on the hydraulic efficiency of the SSFW was slight.

Key words: subsurface flow wetland; computational fluid dynamic; resident time distribution; hydraulic performance

Introduction

The wastewater treatment technology by subsurface flow wetland (SSFW) relies on the functions of media-microorganism-vegetable to achieve efficient removal of pollutants by a combination of physical, chemical, and biological processes. The processes of physical, chemical, and biological treatment in a wetland system depend on the flow of the water. Therefore, the hydraulic characteristics within the system have a significant effect on the efficiency of the wetland as a water treatment device (Hu, 1991; Feng and Molz, 1997; Chazarenc *et al*., 2003). Many wetland management problems can be attributed to poor hydrodynamic characteristics within the wetland system (Persson *et al*., 1999). An appropriate hydraulic design not only can improve the pollutant removal efficiency but also can reduce the cost and achieve optimal benefits of treatment and engineering (Badkoubi *et al*., 1998; García *et al*., 2004a; García *et al*., 2005).

Good engineering design demands a detailed understanding of the hydraulic characteristics within a system. Some studies have been devoted to evaluate the impact parameters of the hydrodynamic behavior of constructed wetlands, including the vegetation (Kadlec, 1990; Jain and Harindra, 1995; Serra *et al*., 2004), flow parameters (Kadlec, 1994), wind (Kadlec and Knight, 1996), temperature (Torres *et al*., 1997), inlet and outlet location (Persson *et al*., 1999; Suliman *et al*., 2006), water depth (USEPA, 2000; Huang *et al*., 2005), aspect ratio, and medium (William *et al*., 1995; García *et al*., 2004b; Wörman and Kronnäs, 2005; Molle, 2006; Suliman *et al*., 2007). However, the hydraulics of the wetland in the above publications was studied by physical tracer experiment that is expensive, time-consuming, and even impossible to perform in the majority of practical cases. Hence, using mathematical models as design tools can contribute to a better understanding of the flow patterns in wetlands.

Computational fluid dynamics (CFD) is a sophisticated design and analysis tool to simulate the flow of mass and momentum throughout a fluid continuum. It is an advantage method to study the hydraulics and reaction in a constructed wetland because it is low cost, can be used to analyze the full flow field and can be scaled up. The technique allows a computational model to be used under many different design constraints and is effective in water treatment device design and optimization, such as wastewater oxidation ponds (Wood *et al*., 1995), sedimentation tanks (Zhou and MeCorquodale, 1994; Matko *et al*., 1996), industrial reservoir (Ta and Brignal, 1998), and aquaculture raceway (Huggins *et al*., 2005). However, the

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flow through the filter constructed in the SSFW is different from that in the above water treatment devices. To the authors' knowledge, no one has provided a CFD model for SSFWs until today.

In this article, the hydraulic characteristics of an SSFW with a layer pattern constructed filter were studied by the CFD model, and the effect of wetland configuration (the inlet location, constructed media, and protection layer) and operating conditions (the inlet velocity (u) and outlet pressure) on the hydraulic performance of the SSFW were discussed thoroughly. This work benefits the engineering design of SSFWs and the further investigation of the CFD simulation on the pollutant removal in SSFWs.

1 Mathematical model

A comprehensive two-dimensional model was developed for the SSFW (Fig.1a) considered using a commercial code Fluent 6.22 (Fluent Inc., USA). The simulated region was chosen utilizing symmetric conditions and reasonable simplifications (Fig.1b). As shown in Fig.2, several kinds of designs of SSFW were studied to examine the effect of the wetland configuration on the hydraulic characteristics. The simulation conditions and geometric parameters of the model can be seen in Fig.1c and Table 1.

In Figs.1a and 1b, the interior of the SSFW was divided into two portions: the upper constructed media made of the soil, gravel, and vegetable roots and the lower constructed media made of gravel only. Upper and lower constructed media was simulated using the upper and lower porous media, respectively, which are shown in Fig.1c. Thus, it is obvious that two different domains can be identified in the wetland model: the liquid domain, the solid wall, and the porous media. The governing equations applied to the heat and mass balances for liquid and solid phases by the program in this specific application are summarized.

1.1 Liquid phase

1.1.1 Continuity equation

$$\nabla \cdot (\rho v) = 0 \tag{1}$$

where, ρ is the density of the liquid, and v is the vector velocity of the liquid.

1.1.2 Momentum balance in porous media

Momentum balance equation is shown as Eq.(2):

$$\nabla \cdot (\rho v v) = -\nabla \times P + \nabla \cdot \left(\mu\left(\nabla \times v + (\nabla \times v)^T\right)\right) \tag{2}$$

where, P is the static pressure, and μ is the viscosity.

Porous media were modeled by adding a momentum source term (S_i) to the standard fluid flow equations. Thus, the momentum balance in the porous media could be defined as:

$$\nabla \cdot (\rho v v) = -\nabla \times P + \nabla \cdot \left(\mu\left(\nabla \times v + (\nabla \times v)^T\right)\right) + S_i \tag{3}$$

where, S_i is composed of two parts: a viscous loss term (Darcy, the first term on the right-hand side of Eq.(4)), and

Table 1 Simulation conditions and geometric parameters of the model

Parameter	
Operating conditions	
Feed composition	H_2O
Feed temperature (K)	293.15
Feed flow rate (m^2/s)	4.282×10^{-8}
Inlet velocity (u, m/s)	2.141×10^{-5}
Outlet pressure (Pa)	102,305
Wetland model dimensions	
Wetland length (L, mm)	200
Wetland height (H, mm)	100
Inlet and outlet diameter (mm)	2
Upper porous media	
Height (h, mm)	30
Void fraction (ε, %)	30
Mean diameter (d, mm)	13
Viscous resistance coefficient (1/α, m^{-2})	1.611×10^7
Inertial resistance coefficient (C_2, m^{-1})	6.980×10^3
Lower porous media	
Height (H–h, mm)	70
Void fraction (ε, %)	40
Mean diameter (d, mm)	24
Viscous resistance coefficient (1/α, m^{-2})	1.465×10^6
Inertial resistance coefficient (C_2, m^{-1})	1.367×10^3
Protection layer	
Height (h, mm)	30
Length (a, mm)	20
Length (b, mm)	40

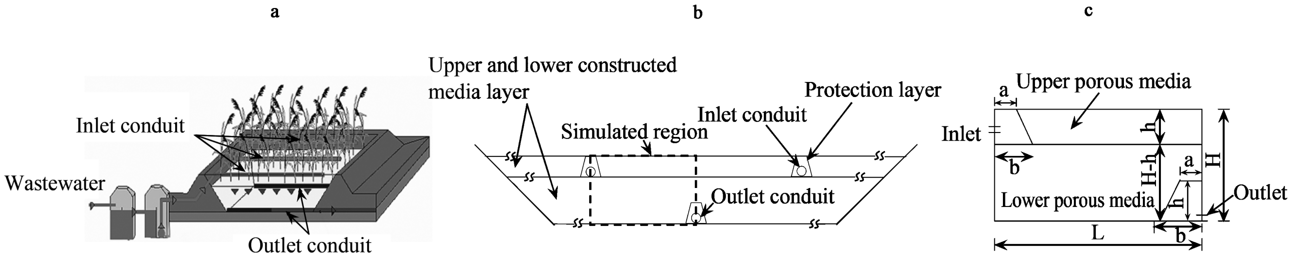

Fig. 1 Sketch (a), cross-section (b), and model (c) of the SSFW.

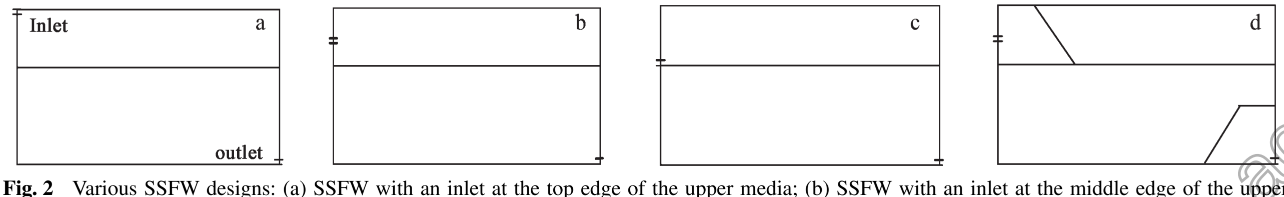

Fig. 2 Various SSFW designs: (a) SSFW with an inlet at the top edge of the upper media; (b) SSFW with an inlet at the middle edge of the upper media; (c) SSFW with an inlet at the bottom edge of the upper media; (d) SSFW with a protection layer (an inlet at the middle edge of the upper media).

an inertial loss term (the second term on the right-hand side of Eq.(4)):

$$S_i = -(\sum_{j=1}^{3} D_{ij}\mu v_i + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho\,|v_i|\,v_i) \tag{4}$$

where, S_i is the source term for the ith (x, y, or z) momentum equation, and D and C are prescribed matrices. For the case of simple homogeneous porous media:

$$S_i = -(\frac{\mu}{\alpha}v_i + C_2\frac{1}{2}\rho\,|v_i|\,v_i) \tag{5}$$

where, α is the permeability and C_2 is the inertial resistance coefficient. D and C are simply specified as diagonal matrices with 1/α and C_2, respectively, on the diagonals.

When modelling a laminar flow through the porous media in this study, which is similar to a packed bed, the permeability and inertial loss coefficients in each component direction could be identified as:

$$\alpha = \frac{d^2}{150}\frac{\varepsilon^3}{(1-\varepsilon)^2} \tag{6}$$

$$C_2 = \frac{3.5}{d}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{7}$$

where, d is the mean particle diameter, and ε is the void fraction.

1.1.3 Energy balance equation

$$\nabla \cdot (\rho c_l v T) = \nabla \cdot (\lambda_l \nabla \times T) + S_T \tag{8}$$

where, c_l is the heat capacity of the liquid, λ_l is the coefficient of heat transfer, T is the liquid temperature, S_T is an energy source term, which was zero in this study because of the assumptions that the solid wall was adiabatic and no reactions occurred.

1.2 Solid phase

Because the adiabatic solid wall of the wetland and the completely open porous media (the porosity is 100%) have no effect on solid media, the mass and heat equations need not be solved in the solid phase in this model.

The density and viscosity of the water were assumed to be constant, and the values were 1,000 kg/m^3 and 0.001 kg/(m·s) at normal temperature, respectively.

To solve the governing equations, appropriate boundary conditions were specified at all external boundaries based on the following assumptions: (1) the liquid velocity and temperature were uniform at the entrance; (2) a fully developed laminar flow characterized the hydrodynamics inside the wetland; (3) the external wall of the wetland was adiabatic, and thus there was no slip condition and there was zero radial concentration gradient at the wall of the wetland.

In addition, the surface mesh of the model was created using Gambit 2.2.30 (Fluent, USA), and the mesh density near the interface between the upper and the lower porous media was increased to improve the computational convergent velocity. The technique of finite volume was selected to solve the governing equations. Frequently, suitable values of the under-relaxation factors were adopted to assure the smooth convergence of the numerical solution.

2 Parameters to estimate hydraulic performance

The liquid resident time distribution (RTD) can be taken from the particle trajectory model based on the steady field of the liquid phase. Then, the mean residence time (t_{mean}) and the standard deviation for the average time (σ) of the liquid in the wetland can also be obtained from the particle trajectory model directly. Some parameters including the normalized retention time (t_θ), normalized variance (σ_θ^2), number of cells (N), and hydraulic efficiency (λ) were introduced to estimate the hydraulic performance of the SSFWs in this study.

2.1 Normalized retention time

The concept of retention time is important for the design of SSFW systems. In order to compare RTDs in different wetlands or dissimilar conditions, each RTD must be normalized (Werner and Kadlec, 2000; Holland *et al.*, 2004). In this study, the retention time is normalized by Eq.(11) (Thackston *et al.*, 1987; Persson and Wittgren, 2003).

The mean residence time (t_{mean}) is a average time that the flow of water spends in the water system, and can be defined by Eq.(9):

$$t_{\mathrm{mean}} = \frac{\int_0^\infty t f(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t} \tag{9}$$

where, $f(t)$ is the RTD function and is represented by the concentration or mass.

The nominal detention time (t_{n}), which is the ratio between the volume and flow, can be defined by Eq.(10).

$$t_{\mathrm{n}} = \frac{V_{\mathrm{R}}}{V_0} \tag{10}$$

where, V_{R} is the wetland volume and V_0 is the inflow volume per time unit.

$$t_\theta = \frac{t_{\mathrm{mean}}}{t_{\mathrm{n}}} \tag{11}$$

2.2 Normalized variance

A constructed wetland can be regarded as a "chemical reactor" and the treatment processes that occur in an SSFW usually are first-order biochemical reactions. Consequently, the plug flow is the optimal and desirable flow since all water packages move in parallel, with no sideways movement, and the removal rates of BOD, TSS, and TN increase with the loading rate (Persson *et al.*, 1999).

However, pure plug flow conditions never occur in actual systems, which instead produce concentration versus time distributions with more or less deviation. The variance

Table 2 Effect of inlet location on the hydraulic performance of wetlands

Case	t_{mean} ($\times 10^5$, s)	σ ($\times 10^5$)	t_θ	σ_θ^2	N	λ
a	3.882	2.906	0.831	0.387	2.583	0.509
b	4.013	2.643	0.859	0.320	3.122	0.584
c	3.930	3.623	0.841	0.602	1.662	0.335

a, b, and c is a SSFW with an inlet at the top, middle, and bottom edge of the upper media, respectively. t_{mean}: mean residence time; σ: standard deviation for the average time; t_θ: normalized retention time; σ_θ^2: normalized variance; N: number of cells; λ: hydraulic efficiency.

(σ^2) rooted from σ is a measure of the spread of the RTD and can be defined by Eq.(12). The dimension variance (σ_θ^2) normalized by Eq.(13) provides information on the amount of mixing present in a SSFW system. A plug flow condition will induce an RTD with a σ_θ^2 equaling 0, whereas a completely stirred flow induces a σ_θ^2 equaling 1.

$$\sigma^2 = (\sigma)^2 = \frac{\int_0^\infty (t_{\mathrm{mean}} - t)^2 f(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t} \tag{12}$$

$$\sigma_\theta^2 = \frac{\sigma^2}{t_{\mathrm{n}}^2} \tag{13}$$

2.3 Number of cells

Another common measure of the degree of plug flow is the number of cells (N) used in a tank-in-series model (Fogler, 1992). The higher the N, the more plug-flow-like the flow is. The measurement of N is:

$$N = \frac{t_{\mathrm{n}}^2}{\sigma^2} \tag{14}$$

2.4 Hydraulic efficiency

Neither t_θ nor σ_θ^2 (or N) is adequate to compare variable designs. In order to determine which design had better hydraulic performance, Persson *et al.* (1999) developed the factor λ, as shown in Eq.(15). The measurement of λ is a simple and effective method of characterizing the hydraulic performance (Holland *et al.*, 2004). The closer to 1 λ is, the better the hydraulic efficiency of the SSFW. The λ factor can be used for comparing different designs.

$$\lambda = t_\theta(1 - \frac{1}{N}) = t_\theta\left(1 - \sigma_\theta^2\right) \tag{15}$$

3 Results and discussion

3.1 Effect of wetland configuration

3.1.1 Effect of inlet location

In order to investigate the effect of the inlet location, three kinds of SSFWs (cases a, b, and c shown in Fig.2) were studied. For each case, μ was 2.141×10^{-5} m/s, and the other parameters are listed in Table 1. The results are shown in Table 2 and Fig.3.

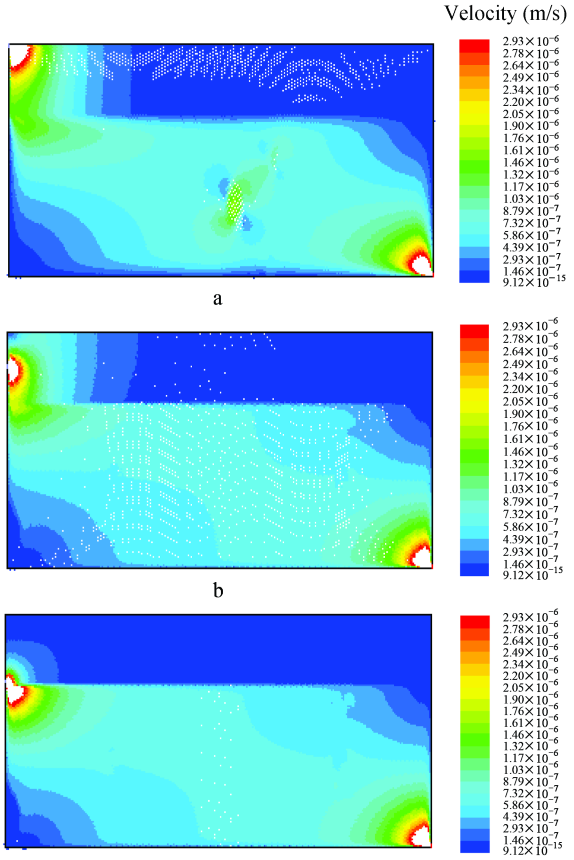

Fig. 3 Velocity vectors figures of SSFWs with different inlet locations. a, b, and c expressed as in Fig.2. The value of the velocity within the white field in the figures is beyond 2.93×10^{-6} m/s.

In Table 2, the hydraulic performance of case b is obviously the best and the hydraulic performance of case c is the worst among the three cases. Case b has higher t_{mean} and t_θ and lower σ_θ^2 than cases a and c. This indicates that the flow in case b not only has a long mean resident time but also the spread of the RTD is very little, which reveals that the flow pattern is much closer to a plug flow. In addition, the highest N and λ further demonstrate that case b has best hydraulic performance.

Compared with case b, t_{mean}, t_θ, N, and λ in case a are lower. This is because, in case a, some back flows occur in the region near the inlet, and a larger scale of mixing flows appear in the region of the lower media (Fig.3a).

As shown in Fig.3c, when the inlet is located at the bottom edge of the upper media, almost all of the upper

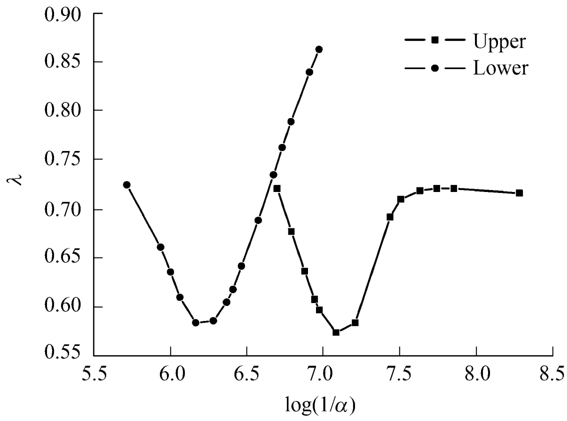

Fig. 4 Variations of the hydraulic efficiency (λ) with the media resistance.

volume is taken up by the region of the low velocity, which causes the big σ_θ^2 and poor hydraulic performance of case c.

According to the above analysis, the inlet location has a great effect on the hydraulic performance of a SSFW, which is consistent with the conclusion reported by Suliman *et al*. (2006).

3.1.2 Effect of constructed media

It is well known that the media filled in the constructed wetland is an important factor for the hydraulic performance. In this study, the constructed media is modeled by porous media, and its resistance is constituted by viscous resistance ($1/\alpha$) and inertial resistance (C_2). Eq.(6) and Eq.(7) demonstrate that $1/\alpha$ and C_2 are determined by ε and d. Thus, this study investigated the effect of the upper and lower media on hydraulic performance by changing the ε or d of the upper (or lower) porous media. The wetland configuration is shown in Fig.2b, and the parameters are listed in Table 1.

The value of $1/\alpha$ is much higher than C_2 so that the latter can be neglected. Therefore, the value of $1/\alpha$ has a direct correlation with the media resistance and can reflect the relative magnitude of the media resistance. As shown in Fig.4, when $\log(1/\alpha)_{\text{upper}}$ decreases from 8.28 to 6.70 ($4.993 \times 10^6 \leqslant (1/\alpha)_{\text{upper}} \leqslant 1.900 \times 10^8$) and $\log(1/\alpha)_{\text{lower}}$ increases from 5.72 to 6.97 ($5.210 \times 10^5 \leqslant (1/\alpha)_{\text{lower}} \leqslant 9.375 \times 10^6$), there is a similar tendency of hydraulic efficiency. This indicates that increasing the lower media resistance and decreasing the upper media resistance have the same effect on the hydraulic efficiency.

However, this is insufficient to explain the effect of the media resistance, which includes the upper and lower media resistance on the hydraulic performance. Thus, the parameter K was introduced in this work. K is the ratio of the upper and lower media resistance and is defined as Eq.(16).

$$K = \frac{(\frac{1}{\alpha})_{\text{upper}}}{(\frac{1}{\alpha})_{\text{lower}}} \tag{16}$$

The effect of K on the hydraulic performance is illustrated in Fig.5. As can be seen in Fig.5a, when K increases from 1 to 22, t_θ declines from 0.95 to 0.74 and the higher the value of K, the faster the rate of decline. At the same time, according to the increase of K, the curves of σ_θ^2 and λ can obviously be divided into three phases ($1 \leqslant K \leqslant 9$, $9 < K \leqslant 22$, and $K > 22$): when $1 \leqslant K \leqslant 9$, σ_θ^2 increases sharply from 0.09 to 0.35 and λ decreases rapidly from 0.85 to 0.57; when $9 < K \leqslant 22$, σ_θ^2 decreases to 0.10 and λ increases to 0.70; and when $K > 22$, the variations of σ_θ^2 and λ are little in contrast to the other phases. As shown in Fig.5b, in the first two phases ($1 \leqslant K \leqslant 22$), the variation tendency of N is similar to the variation of λ. However, in the last phase ($K > 22$), deferent from the variation of λ, N also increases clearly.

The reason for the variation of σ_θ^2 with K is that the inlet flow is mainly divided into two parts and passes through the upper and lower media to the outlet. It is well known that the upper flow passing through the upper media (the remaining flow is the lower flow) decreases with the increase of K. In the first phase ($1 \leqslant K \leqslant 9$), when the upper flow decreases (the lower flow increases), the wetland hydraulic performance becomes poor. This is most likely caused by the sharp increase in the mixing flow (the increase of σ_θ^2 in the wetland). The wetland hydraulic performance is mainly controlled by the upper media in the first phase. In the next phase ($9 < K \leqslant 22$), when the lower flow occupies the majority of the inlet flow and increases with the reduction of the upper flow, the wetland hydraulic performance improves since the σ_θ^2 in the lower media decreases. Therefore, the wetland hydraulic performance is mainly controlled by the lower media in second phase. In the last phase ($K > 22$), the lower flow does not increase, or only slightly increases with the increase of K (the upper flow is very small in this phase), so the wetland performance would not be affected by the K and is relatively steady.

The different variation tendency of N and λ in the last phase ($K > 22$) occurs because using $(1–(1/N))$ instead of N decreases the effect of the extremely high N values on hydraulic efficiency (Persson and Wittgren, 2003).

From the above results, it can be seen that the hydraulic efficiency of the SSFW is predominantly affected by the constructed media, which is consistent with the previous study (Sanford *et al*., 1995; Suliman *et al*., 2007; García *et al*., 2004b).

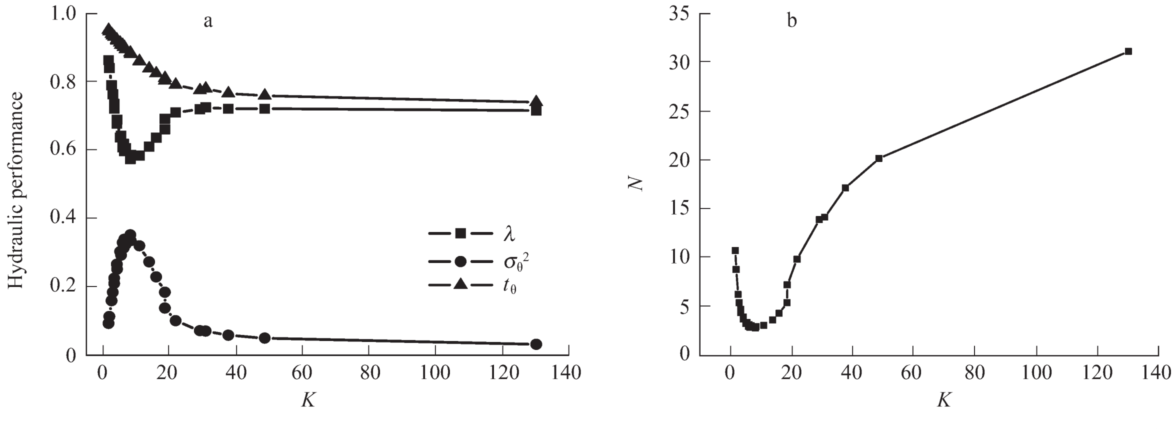

Fig. 5 Variations of the hydraulic performance (a) and of the number of cells (N) (b) with the ratio of the upper and lower media resistance.

3.1.3 Effect of protection layer

Protection layers outside the inlet and outlet conduit are mainly used to improve the distribution of the incoming water and avoid the clogging of the inlet and outlet. Therefore, the effect of protection layers out the inlet and outlet conduit on the hydraulic performance was investigated, and the results are shown in Table 3. The wetland configuration is shown in Fig.2d, and the parameters are listed in Table 1.

As can be seen in Table 3, when $(1/\alpha)_{\mathrm{protection}}$ changes from 2.315×10^5 to 1.200×10^8, λ increases from 0.301 to 0.751. This means that higher media resistance in the protection layer benefits the hydraulic efficiency. The reason for this is that higher resistance in the protection layer has advantages in improving the distribution of the inlet flow.

3.2 Effect of operating conditions

3.2.1 Effect of inlet velocity

Inlet velocity (u) has a great impact on the resident time. The wetland configuration presented in Fig.2b and the parameters listed in Table 1 were used to investigate u effect on the hydraulic performance of SSFWs.

The hydraulic performance of wetlands with different inlet velocities is presented in Table 4. When u ranged from 0.428×10^{-5} to 40.000×10^{-5} m/s, λ increased by 0.023 (from 0.569 to 0.592). This reveals that the effect of u on the hydraulic efficiency is slight, especially after u is increased to 4.283×10^{-5} m/s, and this also can be seen in Fig.6.

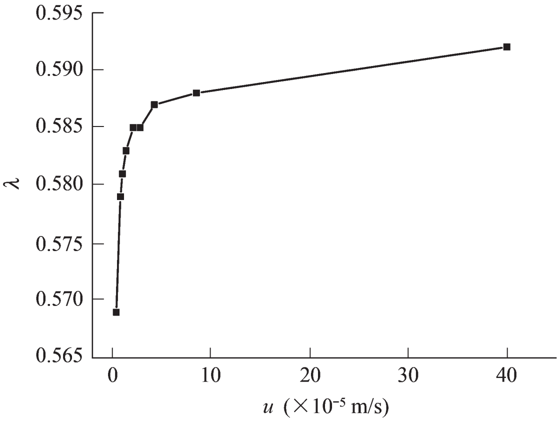

Fig. 6 Variations of the λ of SSFWs with different u.

As shown in Table 4, t_{mean}, which determines the length of treatment time, sharply decreases from 20.100 to 0.215 as u increases. Therefore, u cannot be increased without limit because there must be a long enough treatment time within the wetland system. Giving attention to λ, the inlet velocity is always controlled to guarantee that the

Table 3 Effect of protection layer on the hydraulic performance of wetlands

Case	Protection layer		t_{mean} ($\times 10^5$, s)	σ ($\times 10^5$)	t_θ	σ_θ^2	N	λ
	$1/\alpha$ ($\times 10^5$, m^{-2})	C_2 (m^{-1})						
d_1	2.315	389	4.080	3.781	0.874	0.655	1.526	0.301
d_2	6.510	911	4.087	3.682	0.875	0.622	1.609	0.331
d_3	14.648	1,367	4.087	3.537	0.875	0.574	1.744	0.373
d_4	36.950	2,653	4.080	3.257	0.874	0.486	2.056	0.449
d_5	161.080	3,980	4.029	2.573	0.863	0.304	3.295	0.601
d_6	1,200.000	35,000	3.866	1.422	0.828	0.093	10.787	0.751

d_{1-6}: the simulation cases with different media resistance in the protection layer.

Table 4 Effect of inlet velocity (u) on the hydraulic performance of wetlands

Case	u ($\times 10^{-5}$, m/s)	t_n ($\times 10^5$, s)	t_{mean} ($\times 10^5$, s)	σ ($\times 10^5$)	t_θ	σ_θ^2	N	λ
b_1	0.428	23.351	20.100	13.600	0.861	0.339	2.948	0.569
b_2	0.856	11.676	10.050	6.675	0.861	0.327	3.060	0.579
b_3	1.071	9.340	8.032	5.322	0.860	0.325	3.080	0.581
b_4	1.428	7.006	6.023	3.977	0.860	0.322	3.103	0.583
b_5	2.142	4.670	4.013	2.643	0.860	0.320	3.122	0.584
b_6	2.855	3.503	3.011	1.981	0.860	0.320	3.126	0.584
b_7	4.283	2.335	2.010	1.318	0.861	0.319	3.139	0.587
b_8	8.565	1.1676	1.006	0.656	0.862	0.317	3.151	0.588
b_9	40.000	0.250	0.216	0.140	0.863	0.314	3.184	0.592

b_{1-9}: the simulation cases with different inlet velocity; t_n: nominal detention time.

Table 5 Effect of outlet pressure (P_{outlet}) on the hydraulic performance of wetlands

Case	P_{H_2O} (m)	P_{atm} ($\times 10^5$, Pa)	P_{outlet} (Pa)	t_{mean} ($\times 10^5$, s)	σ ($\times 10^5$)	t_θ	σ_θ^2	N	λ
P_1	0.05	1.013	101,815	4.013	2.643	0.860	0.320	3.122	0.585
P_2	0.1	1.013	102,305	4.013	2.643	0.860	0.320	3.122	0.585
P_3	0.15	1.013	102,795	4.013	2.643	0.860	0.320	3.122	0.585
P_4	0.05	2.026	203,140	4.005	2.614	0.858	0.313	3.192	0.589
P_5	0.1	2.026	203,630	4.006	2.615	0.858	0.314	3.190	0.589
P_6	0.15	2.026	204,120	4.008	2.616	0.858	0.314	3.187	0.589

P_{1-6}: the simulation cases with different outlet pressure. $P_{\mathrm{outlet}} = P_{H_2O} + P_{\mathrm{atm}}$.

treatment time is more than one day. In this study, the inlet velocities in cases b_{2-8} were allowed.

3.2.2 Effect of outlet pressure

In SSFW design, there is usually a weir at the outlet to adjust the water level. The effect of outlet pressure including the water pressure in the weir and atmospheric pressure was studied (Table 5).

The effect of the outlet pressure is not obvious compared with the other parameters such as the inlet location and constructed media. The effect of the outlet pressure caused by the water pressure can be neglected, in contrast with the atmospheric pressure. High outlet pressure benefits the hydraulic efficiency theoretically.

4 Conclusions

In this study, a SSFW was simulated and its hydraulic performance was studied by utilizing a two-dimensional CFD model. The results indicate that the hydraulic efficiency of the SSFW was predominantly affected by the inlet location and constructed media, which was consistent with the conclusions that had been previously reported. Compared with the operating conditions, the effect of the wetland configuration on the hydraulic efficiency of the SSFW was significant.

(1) The inlet location has a great effect on the hydraulic performance. The wetland with the inlet centrally located at the edge of the upper media had better hydraulic efficiency than the wetland with the inlet at the top and bottom edge of the upper media.

(2) The effect of the constructed media on the hydraulic performance is complicated and must be carefully adjusted to increase the hydraulic efficiency. The constructed media affects the hydraulic performance of the SSFW by the ratio of the upper and lower media resistance (K). When $1 \leqslant K \leqslant 9$, the wetland hydraulic performance is mainly controlled by the upper media, and the wetland hydraulic performance decreases with the increase of K. When $9 < K \leqslant 22$, the wetland hydraulic performance is controlled by the lower media, and the wetland hydraulic performance improves with the increase of K. When $K > 22$, the wetland performance is not affected by the K and remains steady.

(3) The protection layer out of the inlet and outlet conduit also has a considerable effect on the hydraulic performance. The higher resistance in the protection layer benefits the hydraulic efficiency.

(4) The effect of inlet velocity (u) on the hydraulic efficiency is slight, although there is some increase in the hydraulic efficiency with its increase. However, it markedly affects the hydraulic performance because it determines the resident time, on which the number of treatments depends. Consequently, it is necessary to determine appropriate u to get not only good hydraulic efficiency but also enough resident time to guarantee that the treatment processes take place.

(5) The effect of outlet pressure on the hydraulic performance is slight. From the viewpoint of actual engineering design and the reduction of energy consumption, it is insignificant and unnecessary to increase the outlet pressure.

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References

Badkoubi A, Ganjidoust H, Ghaderi A, Rajabi A, 1998. Performance of a subsurface constructed wetland in Iran. *Water Sci Technol*, 38(1): 345–350.

Chazarenc F, Merlin G, Gonthier Y, 2003. Hydrodynamics of horizontal subsurface flow constructed wetland. *Ecol Eng*, 21: 165–173.

Feng K, Molz F J, 1997. A 2-D, diffusion-based, wetland flow model. *J Hydrol*, 196: 230–250.

Fogler H S, 1992. Elements of Chemical Reaction Engineering. Englewood Cliffs, NJ: Prentice-Hall. 838.

García J, Aguirre P, Barragán J, Mujeriego R, Matamoros V, Bayona J M, 2005. Effect of key design parameters on the efficiency of horizontal subsurface flow constructed wetlands. *Ecol Eng*, 25: 405–418.

García J, Aguirre P, Mujeriego R, Huang Y, Ortiz L, Bayona J M, 2004a. Initial contaminant removal performance in horizontal flow reed beds treating urban wastewater. *Water Res*, 38(7): 1669–1678.

García J, Chiva J, Aguirre P, Álvarez E, Sierra J P, Mujeriego R, 2004b. Hydraulic behavior of horizontal subsurface flow constructed wetlands with different aspect ratio and granular medium size. *Ecol Eng*, 23: 177–187.

Holland J F, Martin J F, Granata T, Bouchard V, Quigley M, Brown L, 2004. Effects of wetland depth and flow rate on residence time distribution characteristics. *Ecol Eng*, 23: 189–203.

Huang Y M, Ortiz L, Aguirre P, Garcłab J, Mujeriegob R, Josep M, Bayona J M, 2005. Effect of design parameters in horizontal flow constructed wetland on the behaviour of volatile fatty acids and volatile alkylsulfides. *Chemosphere*, 59(6): 769–777.

Huggins D L, Piedrahita R H, Rumsey T, 2005. Use of computational fluid dynamics (CFD) for aquaculture raceway design to increase settling effectiveness. *Aquacultural Engineering*, 33(3): 167–180.

Hu K P, 1991. Hydraulic factors in constructed wetlands design. *Research of Environmental Sciences*, 4(5): 8–12.

Jain S, 1995. Three-dimensional simulation of turbulent particle dispersion. PhD thesis, University of Utah, Utah.

Kadlec R H, 1990. Overland flow in wetlands: vegetation resistance. *J Hydraul Eng*, 116: 691–705.

Kadlec R H, 1994. Detention and mixing in free water wetlands. *Ecol Eng*, 3: 345–380.

Kadlec R H, Knight R L, 1996. Treatment Wetlands. Boca Raton, FL: CRC Press. 893.

Molle P, Liénard A, Grasmick A, Iwema A, 2006. Effect of reeds and feeding operations on hydraulic behaviour of vertical flow constructed wetlands under hydraulic overloads. *Water Res*, 40(3): 606–612.

Matko T, Fawcett N, Sharp A, Shephenson T, 1996. A numerical model of flow in circular sedimentation tanks. *Process Safety and Environmental Protection*, 74: 197–204.

Peterson E L, Harris J A, Wadhwa L C, 2000. CFD modeling pond dynamic processes. *Aquacult Eng*, 23(1-3): 61–93.

Persson J, Somes N L G, Wong T H F, 1999. Hydraulic efficiency of constructed wetlands and pond. *Water Sci Technol*, 40 (3): 291–300.

Persson J, Wittgren H B, 2003. How hydrological and hydraulic conditions affect performance of ponds. *Ecol Eng*, 21(4-5): 259–269.

Sanford W E , Steenhuis T S, Parlange J Y, Surface J M, Peverly J H, 1995. Hydraulic conductivity of gravel and sand as substrates in rock-reed filters. *Ecol Eng*, 4(4): 321–336.

Serra T, Harindra J S F, Rodríguez R V, 2004. Effects of emergent vegetation on lateral diffusion in wetlands. *Water Res*, 38(1): 139–147.

Suliman F, Futsaether C, Oxaal U, Haugen L E, Jenssen P, 2006. Effect of the inlet-outlet positions on the hydraulic performance of horizontal subsurface–flow wetlands constructed with heterogeneous porous media. *J Contam Hydrolo*, 87(1-2): 22–36.

Suliman F, Futsaether C, Oxaal U, 2007. Hydraulic performance of horizontal subsurface flow constructed wetlands for different strategies of filling the filter medium into the filter basin. *Ecol Eng*, 29(1): 45–55.

Ta C T, Brignal W J, 1998. Application of computational fluid dynamics technique to storage reservoir studies. *Water Sci Technol*, 37(2): 219–226.

Thackston E L, Shields J, Schroeder P R, 1987. Residence time distributions of shallow basins. *J Environ Eng*, 113(6): 1319–1332.

Torres J J, Soler A, Saez J, Ortuno J F, 1997. Hydraulic performance of a deep wastewater stabilizing pond. *Water Res*, 31: 679–688.

USEPA (U.S. Environmental Protection Agency), 2000. Constructed Wetlands Treatment of Municipal Wastewaters. EPA/625/R-99/010. Office of Research and Development, Cincinnati, OH: United States Environmental Protection Agency. 165

Werner T M, Kadlec R H, 2000. Wetland residence time distribution modeling. *Ecol Eng*, 15(1-2): 77–90.

Wood M G, Greenfield P F, Howes T, Johns M R, Keller J, 1995. Computational fluid dynamic modeling of wastewater ponds to improve design. *Water Sci Technol*, 31(12): 111–118.

Wörman A, Kronnäs V, 2005. Effect of pond shape and vegetation heterogeneity on flow and treatment performance of constructed wetlands. *J Hydrol*, 301(1-4): 123–138.

Zhou S P, MeCorquodale J A, 1994. Modeling of rectangular settling tanks-closure. *J Hydraul Eng*, 120(2): 279–281.