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Original Research

Numerical Simulation of Contaminant Removal in a Vertical Subsurface-Flow Constructed Wetland

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Abstract

Hydraulic characteristics and contaminant removal effect in a vertical subsurface-flow constructed wetland were investigated by establishing a numerical model. The results demonstrated that retardation factor decreased with time while wetland substrate was gradually filled with the importation of contaminated water until reaching the saturation state. The flow velocity increased with time when the substrate was not on saturated condition, and decreased rapidly after saturation. The process of the substrate reaching saturation state was layered and gradual. The increased rate of effective saturation in substrate was less than that of the post-period: the higher the saturation level, the more easily water flowed. When the substrate was not completely saturated, pollutant concentration increased sharply to the max value. After the substrate was at the saturation state, concentrations of contaminants decreased slowly with time as adsorption within the solid particles and biodegradation. At the early stage the retardation factor gradually decreased as water depth increased, resulting in a close relationship between effective saturation and the retardation factor. With the increase of porosity and partition coefficient and decrease of degradation rate, hydraulic efficiency of the vertical subsurface-flow constructed wetland lessened.

Keywords: constructed wetland, hydraulics, contaminants, effective saturation, retardation factor

Introduction

With the deepening understanding of wetland value, many countries have begun to establish constructed wetlands for water purification and sewage treatment [1-2]. The treatment effects of a constructed wetland depend mainly on bio-film formation on the surface of filler and root by adsorbing a large number of microbes [3-5]. This utilizes the synergistic action of a substrate, aquatic plants, and microorganisms physically, chemically, and biologically, achieving the efficient purification of sewage through substrate filtration, adsorption, precipitation, ion exchange, plant absorption, and microbial decomposition. The hydraulic characteristics of constructed wetlands have a direct bearing on effluent purification, such as effective volume, the extent of water diffusion, and pollutant removal [6-7]. Some researchers have suggested that aspect ratio, water depth, flow velocity, position of the inlet and outlet, vegetation, or topography could also

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affect a wetland's hydraulic characteristics. Water flow may directly change the physical and chemical properties of wetlands, such as the effectiveness of nutrition, substrate hypoxia and salinity, precipitation properties, acidity, and alkalinity [8-9].

The hydraulic characteristics are more important to subsurface-flow constructed wetlands (VSCWs) as water flow has to be adjusted by human control [2]. Sewage flows from the surface of the wetland to the substrate bottom in the VSCW, which can be actually regarded as a porous medium flow. The substrate is in an unsaturated state and a substance can be transported by atmospheric diffusion and plant growth. The extent of contaminant treatment is a direct result of residence time and contact efficiency within the substrate, such as the efficiency of biological treatment often depending on the contact and duration of the contaminant and microbial population [6-9]. The wetland system is based on theoretical residence time (residence time calculated through volume calculation by ignoring obstructions, dead water zones, and velocity gradients), and the results of the prediction are biased by neglecting the short processing time of partial fluids [8]. At present, there is no accurate and reliable forecasting method for the design of a water quality target and long-term operational experience for a subsurface wetland. Compared with complexity and randomness of experiments, numerical simulation can predict the hydrodynamic conditions and improve the efficiency of these constructed wetland systems.

A VSCW has the potential in greywater treatment to remove more than 80% of water parameters such as total suspended solid (TSS), chemical oxygen demand (COD), and turbidity [10]. Villaseñor et al. [11] studied the performance of a constructed wetland for domestic wastewater depuration also working as a microbial fuel cell (MFC) under two different subsurface flow modes. Wojciech et al. [12] applied subsurface vertical flow constructed wetlands (SSVF) for the treatment of reject water in the biggest dairy wastewater treatment plant (WWTP) in Poland. The research indicated that SSVF beds could be successfully applied to reject water treatment. Pelissari et al. [13] used a partially saturated vertical subsurface flow constructed wetland to characterize the nitrogen transforming.

Gao et al. [14] examined the proportion and changes of five metal species in five mixed substrates and found that the sediment fractions dominated on an exchangeable account. Ren et al. [15] determined the relationship between the accumulated solid material and infiltration rate as well as the ratio of organic and inorganic matter. Boog et al. [16] conducted a side-by-side comparison of two VFCWs' handling primary to understand the relationship between viable and dead bacteria in soil and influent/effluent wastewater. Huang et al. [17] examined VSCW efficacy using a numerical model (SubWet 2.0) originally designed, and results show that the modelling performance for total phosphorus (TP) and biochemical oxygen demand (BOD) is better for these parameters than that observed for ammonium nitrogen. Bai et al. [18] used the numerical simulation method to study the correlation of substrate structure and hydraulic characteristics. Their results show that the substrate permeability coefficient had great influence on hydraulic efficiency, and the greater the permeability coefficient, the more uneven the flow distribution. Bustillolecompte et al. [19] used VS2DTI software to predict effluent BOD and total nitrogen (TN) in a VFCW, and model results indicate that most of BOD and TN are removed by biological activity. Dong et al. [20] investigated the effect of the "dischargeable oxygen release rate" on organic matter and nitrogen removal using an "in-situ test" method, and he pointed out that the role of vegetation should not be ignored in constructed wetlands.

Abdelhakeem et al. [21] carried an eight-month experiment in a VSCW and found that plants have a significant effect on pollutant removal efficiency and mass removal rate. Klomjek [22] compared removal efficiency and grass productivity by planting two species of Napier grass in a VSSF. Wang et al. [23] carried out an experiment treating swine wastewater at four different shunt ratios, and results show that the shunt ratio has significant influence on nitrogen removal. Fakhri et al. [24-27] studied adsorption properties of some materials. Kucerak et al. [28] examined the removal efficiency of ibuprofen and naproxen in a VFCW using hydraulic retention times (HRT) and found that there is no relationship between pharmaceutical removal and HRT. At present, research on simulating a constructed wetland is primarily focused on the state of water flow. There are insufficient studies on the transport and removal of pollutants in wetlands. In order to optimize the flow pattern of different constructed wetlands, we studied the hydraulic characteristics of the VSCW and concentration distribution of dissolved pollutants with time on establishing the variable saturated flow model.

Material and Methods

As gas can enter the substrate through the atmosphere, substrate of a vertical subsurface flow constructed wetland can be regarded as unsaturated porous media. Richard's equation can be used to model the saturated-unsaturated flow in the substrate. It can be considered that the change in air pressure has no effect on the internal substrate flow. Then the governing equation for substrate flow in the pressure head is:

$$(C + SeS)\frac{\partial H_p}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = Q_m \tag{1}$$

…where C represents specific moisture capacity, SeS is effective substrate saturation, S denotes a storage coefficient, H_p is the pressure head, Q_m is the source term, and **u** represents the flow velocity in wetland substrate, which can be given as:

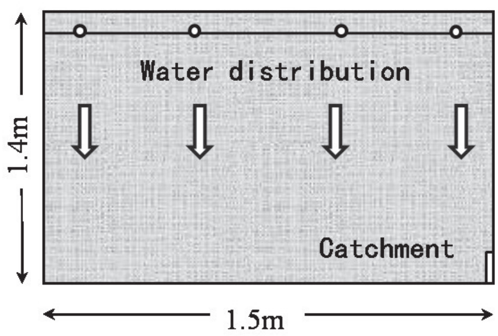

Fig. 1. Schematic mathematical model of the vertical subsurface-flow constructed wetland.

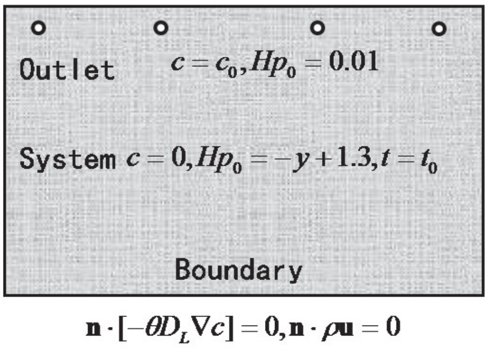

Fig. 2. Initial and boundary conditions.

$$\mathbf{u} = -\frac{K}{\mu}(\nabla p + \rho g \nabla z) \tag{2}$$

…in which K is hydraulic conductivity, p is pressure, ρ is water density, g is acceleration of gravity, and z represents direction.

Based on the numerical results of flow field, the governing equation for transport and diffusion of solute is:

$$\frac{\partial(\theta c)}{\partial t} + \frac{\partial(\rho_b c_p)}{\partial t} + \nabla \cdot [-\theta D_L \nabla c + \mathbf{u}c] = \sum R_L + \sum R_p + S_c \tag{3}$$

…where c represents solute concentration, ρ_b is bulk density, $c_p = k_p c$ denotes the mass of adsorbed contaminant per dry unit weight of wetland substrate, k_p is partition coefficient, θ is the volume fluid fraction, and D_L is the hydrodynamic dispersion tensor. R_L is the reaction in water, R_p represents reactions involving solutes attached to substrate particles, and S_c represents solute added per unit volume of substrate per unit time. Thus Eq. (3) can be rewritten as:

$$[\theta + \rho_b k_p]\frac{\partial c}{\partial t} + c\frac{\partial \theta}{\partial t} + \nabla \cdot [-\theta D_L \nabla c + \mathbf{u}c] = \theta \phi_L c + \\ + \rho_b k_p \phi_p c + S_c \tag{4}$$

…where ϕ_L and ϕ_p respectively represent the decay rates for the dissolved and adsorbed solute concentrations.

The hydrodynamic dispersion tensor, D_L, describes mechanical spreading from subsurface flow with adsorption behaviour in wetland substrate:

$$\theta D_{Lii} = \alpha_L \frac{u_i^2}{|\mathbf{u}|} + \alpha_T \frac{u_j^2}{|\mathbf{u}|} + \theta \frac{D_m}{\tau_L} \tag{5}$$

$$\theta D_{Lij} = \theta D_{Lji} = (\alpha_L - \alpha_T)\frac{u_i u_j}{|\mathbf{u}|} \tag{6}$$

…in which D_{Lii} and D_{Lij} are the diagonal entries in the dispersion tensor and the cross terms, respectively. α_L and α_T represent longitudinal and transverse dispersivities, respectively. D_m is the coefficient of molecular diffusion, and τ_L denotes a tortuosity factor and $\tau_L = \theta^{-7/3}\theta_s^2$ in this paper.

Table 1. Simulation conditions and related parameters.

No.	Hydraulic conductivity coefficient K_S	Porosity θ_S	Pollutant partition coefficient k_p	Decay coefficient of dissolved pollutants ϕ_L	Attenuation coefficient of particulate contaminants ϕ_p
1	0.454	0.339	0.0001	0.05	0.01
2	0.454	0.339	0.0001	0.10	0.02
3	0.454	0.339	0.0001	0.15	0.03
4	0.454	0.339	0.0005	0.05	0.01
5	0.454	0.339	0.0005	0.10	0.02
6	0.454	0.339	0.0005	0.15	0.03
7	0.298	0.399	0.0001	0.05	0.01
8	0.298	0.399	0.0001	0.10	0.02
9	0.298	0.399	0.0001	0.15	0.03

According to the experimental data in reference [8], the mathematical model is established as shown in Fig. 1. The initial and boundary conditions of the model are shown in Fig. 2, and the values of the key parameters are shown in Table 1.

Results and Discussion

Hydraulic Characteristics of Subsurface-Flow Constructed Wetlands

The variations of the hydraulic characteristics of subsurface flow constructed wetlands in 0.1, 0.4, 0.7, 1, 3, and 5 days are presented in Fig. 3. Wherein the surface map represents effective saturation, the isogram represents the pressure head, and the arrows show the magnitude and direction of fluid velocity. Fig. 3 shows the process of saturating the substrate in an unsaturated state. At the initial stage, saturation of the lower substrate is much larger than that of the upper part. With the gradual water importing, the substrate is slowly filled with water in order to reach the saturation state. The pressure head in the substrate remains constant throughout the filling process. Fig. 3 also shows the variation of fluid velocity, which near the water distribution area is higher than that of the substrate.

Pollutant Removal Characteristics of Subsurface-Flow Constructed Wetlands

In view of the adsorption effect, pollutant concentration changes with time due to substrate adsorption. To indicate the impact of pollutant concentration variation, the retardation factor is defined as (Van 1980):

$$R_f = 1 + \frac{\rho_b}{\theta}\frac{\partial c_p}{\partial c} \tag{7}$$

When $R_f = 1$, contaminant diffusion is basically consistent with fluid velocity. When $R_f > 1$, the pollutant migration velocity might be behind the flow velocity due to the role of particle adsorption, which reduces the internal diffusion coefficient result of contaminant transfer process retardation.

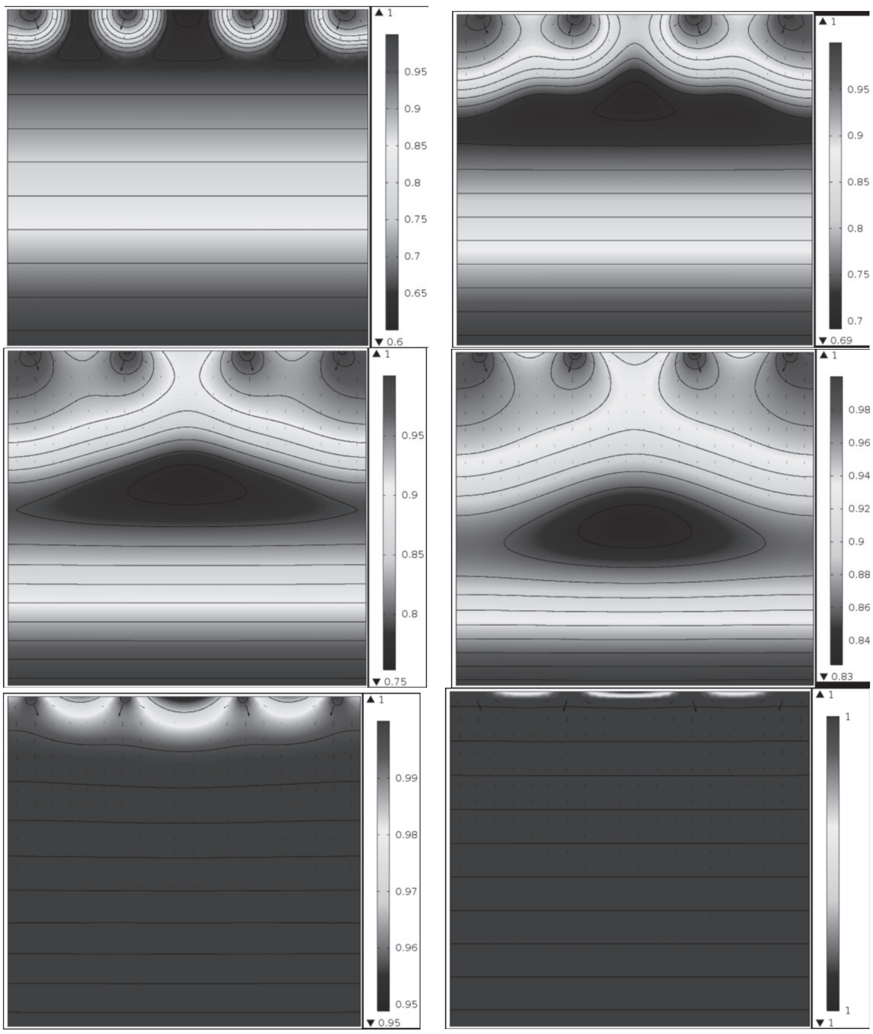

Fig. 3. Estimates of effective saturation, pressure head, and velocity in constructed wetland after 0.1, 0.4, 0.7, 1, 3, and 5 days.

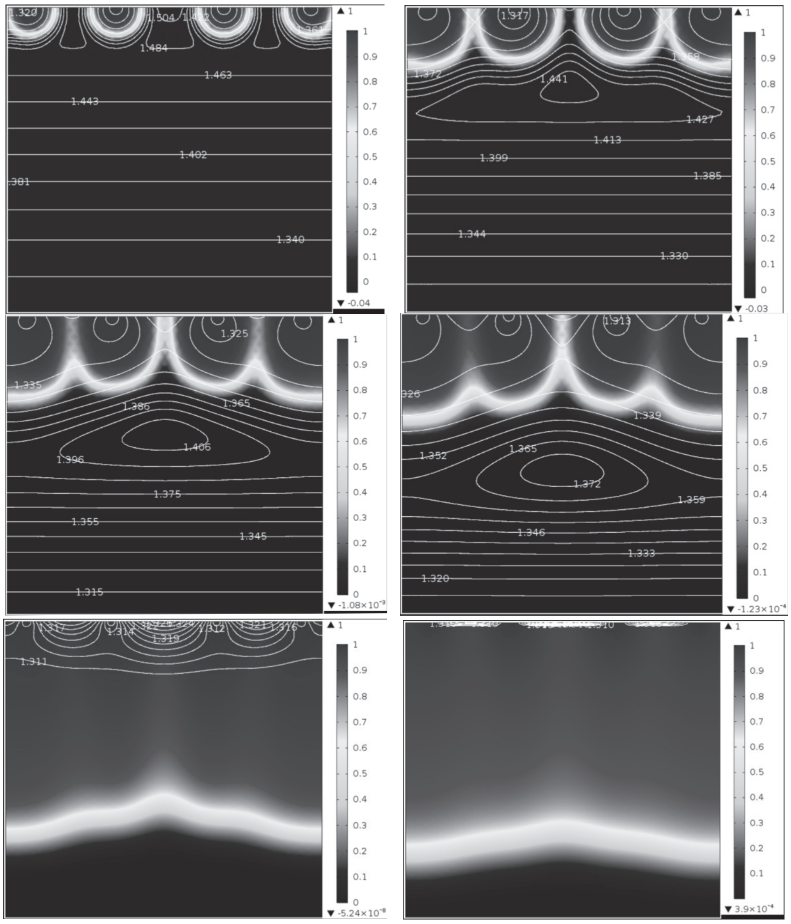

Fig. 4. Solution for dissolved concentrations and retardation factor after 0.1, 0.4, 0.7, 1, 3, and 5 days.

Fig. 4 shows changes in pollutant concentrations and the retardation factor in 0.1, 0.4, 0.7, 1, 3, and 5 days. At the beginning of the wetland operation, Pollutant concentration at the water outlet rose sharply. As time goes on, the pollutants gradually spread to the internal substrate. Fig. 4 also illustrates that the retardation factor decreases over time due to the fact that it is related to the degree of substrate saturation: the higher the saturation, the smaller the retardation factor.

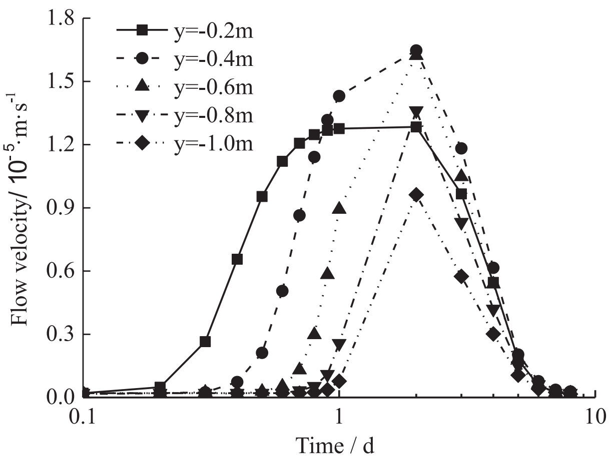

Fig. 5. Changes of flow velocity over time at different locations.

Hydraulic Characteristics of Wetland Substrate and the Distribution of Pollutants Along the Vertical Line

Five points are respectively located below the water outlet in the central axis of the wetland substrate, which are from the distance of 0.2, 0.4, 0.6, 0.8, and 1.0 m. Figs 5 and 6 show variation of flow velocity and effective

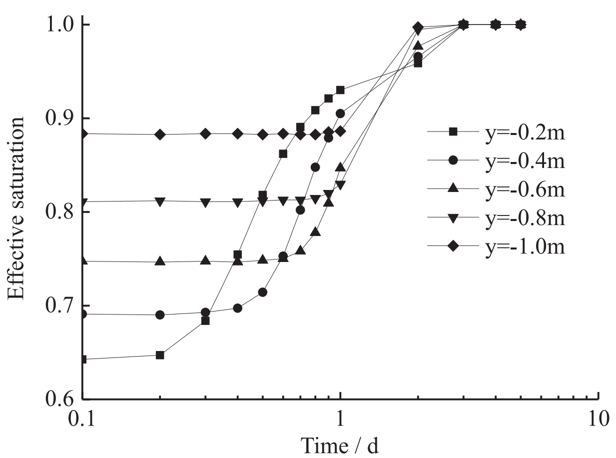

Fig. 6. Changes of effective saturation over time at different locations.

saturation at the five locations. It can be seen that flow velocity increase with time until substrates reach the saturation stage. The farther from the position of the water outlet is, the smaller the flow velocity will be. However, after about 0.8 days the water velocity at 0.2 m is slower than that at 0.4 m, which indicates that there might be water retention in this area. Flow rate decreases rapidly with time while the substrate is in saturation, which may be related to the enhancement of the mechanical diffusion produced by the internal substrate structure as it tends to saturate. The results in Fig. 6 show that the effective saturation within the substrate increases with time until it is completely saturated. The rate of effective saturation increases faster than the others, which further indicates the existence of water retention in this area.

Figs 7 and 8 show vertical distribution variation of effective saturation with time in different porosities. Effective saturation gradually increases with depth at the initial stage of wetland operation. With the increase of time, the effective saturation of the upper part of the substrate increases gradually while the one of the lower part is not obvious. After a period of one day, the entire area of the substrate is slightly saturated, indicating a gradual process of stratified saturation within the substrate. It can also be seen that the increasing rate of initial effective saturation is less than the latter. This indicates that the higher the saturation is , the easier the water flow. From a comparison of the effective saturation changes in Figs 7 and 8, substrate porosity has great influence on effective saturation.

Wetland Substrate Pollutant Changes Along a Vertical Line

Figs 9 and 10 show the variation of pollutant concentration and retardation factor with time. From Fig. 9 we can see that pollutant concentration decreases after an increase stage. During the initial five days of wetland operation, the substrate does not reach the saturation state, and pollutant concentration increases

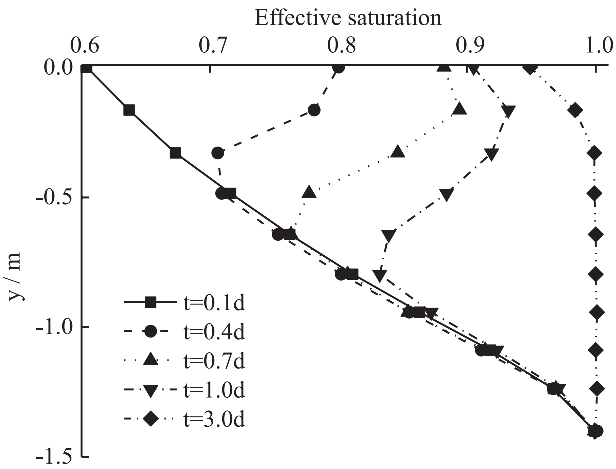

Fig. 7. Changes of effective saturation over time at different locations ($\theta_S = 0.34$).

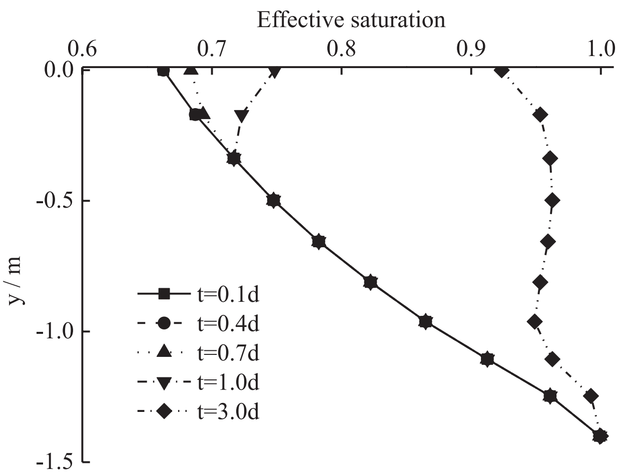

Fig. 8. Changes of effective saturation over time at different locations ($\theta_S = 0.40$).

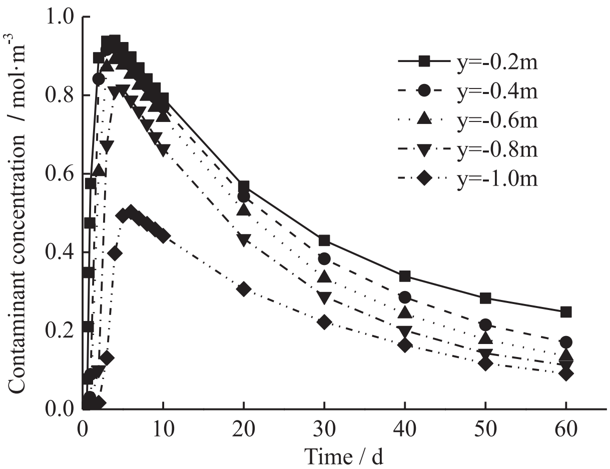

Fig. 9. Changes of contaminant concentrations over time at different locations.

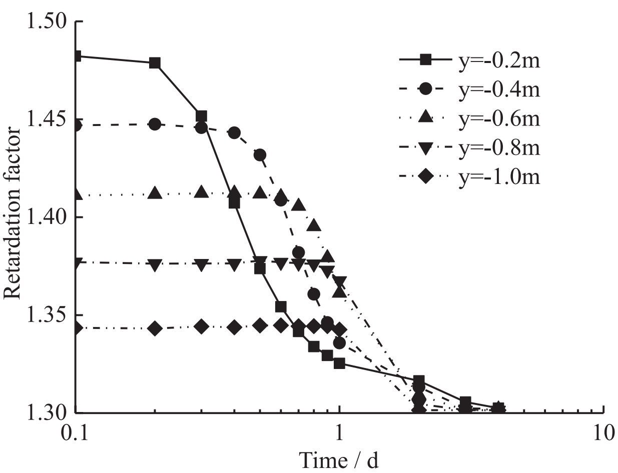

Fig. 10. Changes of retardation factor over time at different locations.

sharply to a maximum value. After five days, the substrate is filled with wastewater and the concentration of contaminants decreases slowly with time as a result of the adsorption of solid particles in the substrate and biodegradation. Fig. 10 shows that the retardation factor at each point decreases with increasing depth at the preliminary stage of wetland operation. This may be because the retardation factor is closely linked to effective saturation. As time goes on, the retardation factor at each point decreases rapidly, reaching a minimum of 1.3 until five days, but the retardation factor is still larger than 1. This shows that the adsorption of substrate solid pollutants has an obvious retardation effect, and is one of the main reasons for contaminant transport retardation.

Hydraulic Efficiency and Influencing Factors of Wetlands

Hydraulic efficiency can be used to analyze hydraulic retention time and dispersion, whose physical meaning is time that a ratio of concentration reached the maximum and apparent hydraulic retention, and can be calculated as follows :

$$\lambda = \frac{T_p}{T_n} \tag{8}$$

…where T_p is the time of maximum concentration, T_n is the time of water retention, $T_n = V/Q$. V represents the volume of wetland pore, and Q denotes flow out rate. According to Eq. (9), the results were shown in Fig. 11 when $T_{p1} = 11d$.

Numerous factors affect hydraulic performance, such as the physical characteristics of the substrate and the sorption and degradation characteristics of pollutants. Figs 12, 13, and 14 show the influence of the above three factors on the time required to reach the maximum concentration.

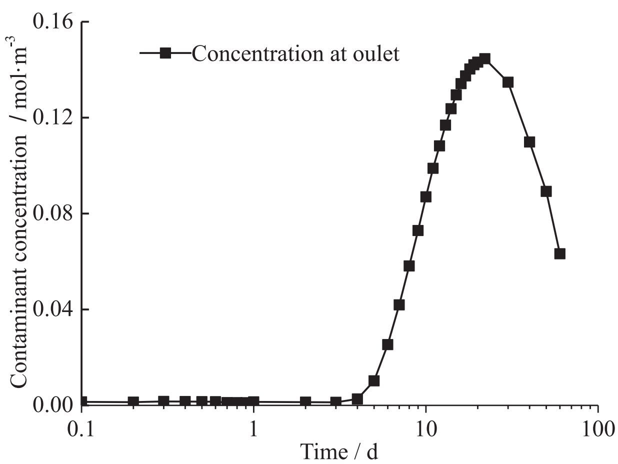

Fig. 11. Changes of contaminant concentrations over time at the outlet.

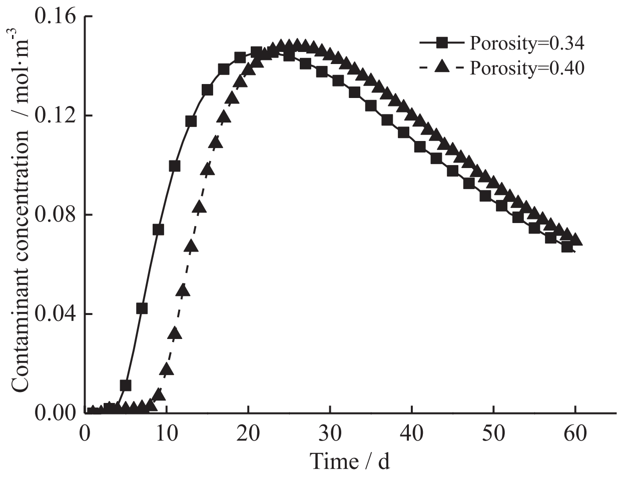

Fig. 12. Comparison of retardation factor at different substrate porosities.

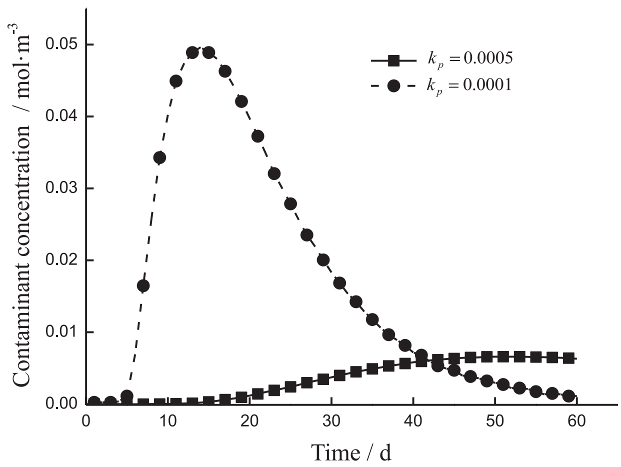

Fig. 13. Comparison of resident time with different partition coefficients.

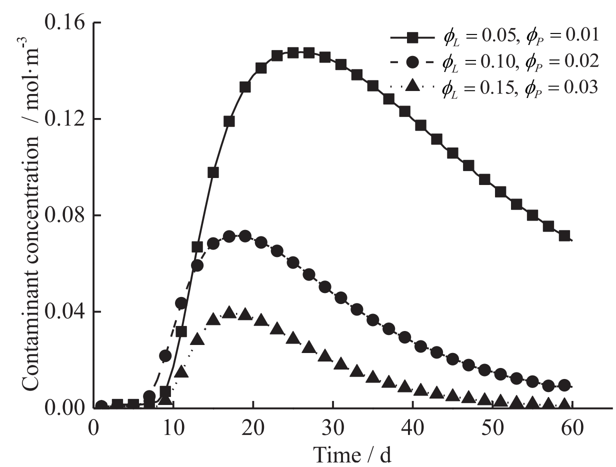

Fig. 14. Comparison of resident time with different degradation rates.

Fig. 12 displays a comparison of the time taken for the maximum concentration in the effluent at different substrate conditions. We can observe that the substrate with a porosity of 0.34 needs 22d to reach maximum concentration while the one with a porosity of 0.40 took 27d. The results show that the time taken increases with the increase of porosity, which is mainly due to the huge volume of the substrate, and the corresponding residence time also increases accordingly.

Comparison of the time spent on the highest contaminant concentration at the outlet for different partition coefficients is shown in Fig. 13. Residence time increases accordingly with the increasing partition coefficient. The case with the smaller partition coefficient is about 15d, while the largest one is 53d – nearly five times as much as the former, which is basically the same as the ratio of the two partition coefficients. This shows that the partition coefficient is closely related to the time spent with water pollutant concentration to reach the maximum, which is apparently a proportional relationship. This may be due to pollutants with larger partition coefficients adsorbing more to the substrate particles, but pollutant degradation rate at the solid state is lower than that of the dissolved state, resulting in time required to increase exponentially.

Fig. 14 shows the comparison of the time spent at the maximum concentration of the tracer concentration at the outlet for different pollutant degradation rates. It can be found from Fig. 14 that as the degradation rate of pollutants increases, the value becomes smaller, and the three are about 26, 20, and 19 days. When the pollutant degradation rate is high, the peak value of pollutant concentration is lower than the case of low degradation rate, thus resulting in the peak of pollutants relatively easier to achieve than the latter.

Conclusions

The flow characteristics and the concentration distribution of dissolved pollutants were simulated by the establishment of a numerical model for a vertical subsurface-flow constructed wetland. Flow velocity near the water distribution area is the largest during the transition from the unsaturated state to the saturated one, and pollutant concentration rises sharply at the outlet and the retardation factor decreases with time, which may be explained by the degree of substrate saturation. Seepage velocity of each point is closely related to the saturation state of the substrate, which increased with time when not saturated and decreased rapidly with time after saturation. The increase of effective saturation near the water outlet is faster than at other points, which further showed a short circuit and retention of water in the area. It appears to be a stratified saturation and gradual process in the substrate. The increased rate of effective saturation is smaller than that of the latter stage. The retardation factor of each point is reduced rapidly over time. The hydraulic efficiency of the wetland system increases with porosity and partition coefficient, and decreases with the degradation rate, which would increase the residence time of the wetland system.

Acknowledgements

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