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Simulation and optimization of hydraulic performance of small baffled subsurface flow constructed wetland

Rongzhen Wang, Lirong Xu, Xiangxi Xu, Zhenghe Xu* and Xin Cong
School of Water Conservancy and Environment, University of Jinan, Jinan, China
*Corresponding author. E-mail: xu4045@126.com

RW, 0000-0002-1852-4553

ABSTRACT

The water body inside the constructed wetland is affected by various factors, and the flow state is relatively complicated. There will always be a certain degree of low velocity area and rapid outflow phenomenon, which makes part of the space in the wetland unable to be effectively used. Based on Computational Fluid Dynamics (CFD) technology, this paper uses Fluent's porous media model and discrete phase model to establish a hydrodynamic model of up and down baffled subsurface flow constructed wetland system. The internal flow field of the wetland is simulated, and the hydraulic performance of different baffle settings and substrate laying methods in the wetland is systematically evaluated. The results show that when the number of baffles is the same, the hydraulic efficiency is higher when the first baffle is located on the lower part of the substrate. Compared with the position of the baffle, the increase in the number of baffles does not significantly improve the hydraulic efficiency of the constructed wetland. The substrate layer thickness ratio has a significant effect on the two parameters of the variance of the hydraulic residence time distribution (σ^2) and the flow divergence (σ_0^2). By increasing the thickness of the middle substrate, the low flow rate phenomenon caused by the small porosity substrate area of the upper layer and the rapid outflow phenomenon of the lower substrate can be improved to a certain extent, the utilization efficiency of the middle substrate layer is improved, and the hydraulic performance is increased. The research results are of great significance for improving the utilization of wetland space and ensuring its efficient decontamination and purification function.

Key words: baffle setting, fluent, hydraulic performance, modeling, substrate laying

HIGHLIGHTS

- The hydraulic performance of constructed wetland is affected by baffle setting and substrate laying.
- The first baffle is located at the lower part of the substrate with higher hydraulic efficiency.
- The layer thickness ratio of the substrate mainly affects the hydraulic residence time distribution and the flow divergence.

INTRODUCTION

As a water environment ecological restoration technology, constructed wetland can simultaneously remove multiple pollutants in water. Low construction and operation costs, efficient water environment optimization effects and their own inherent landscape value have promoted the widespread application of constructed wetlands worldwide (Macdonald *et al.* 1998; Saeed *et al.* 2018; Udom *et al.* 2018; Li *et al.* 2020). However, in many practical designs and applications, researchers have gradually discovered that the water purification effect of constructed wetlands is not only affected by previously known plants, substrates, microorganisms, and temperature, but also by its internal hydrodynamic processes. The aspect ratio (García *et al.* 2004), water inlet and outlet methods (Wang *et al.* 2014; Sabokrouhiyeh *et al.* 2017), and water depth (Lee *et al.* 2020) of the constructed wetland all have a direct impact on the internal flow pattern. In addition, constructed wetlands usually require a large area, which to a certain extent restricts the further development and application of constructed wetlands (Tatoulis *et al.* 2017). Some scholars have put forward the concept of modular constructed wetlands, and modified traditional constructed wetlands to make them more suitable for decentralized sewage discharge (Choi *et al.* 2012). By optimizing the internal structure of the wetland, the small-area constructed wetland can still have satisfactory hydraulic performance and exert effective water purification capabilities. Adding baffles is a way to directly change the internal structure of the wetland, which is simple and easy to operate. Tee *et al.* (2012) compared the denitrification performance of wetlands constructed with baffles and wetlands constructed with conventional horizontal underground flow under different hydraulic retention times. When HRT was 2, 3, and 5 days, the conventional horizontal subsurface flow constructed wetland removed 55, 70, and 96% of ammonia nitrogen (NH_4^+-N), respectively, while the baffled constructed wetland reached 74, 84, and 99%, respectively. The authors infer that the longer hydraulic path gives the wastewater more contact with rhizomes and microaerobic areas, so the removal rate of ammonia nitrogen is improved. Saeed *et al.* (2014) also reached a similar conclusion. They compared and analyzed the nitrogen and organic matter removal performance of the baffled constructed wetland under different hydraulic loads. The experimental results show that the fluctuation of hydraulic load did not produce obvious deviation in the removal performance of nitrogen and organic matter. This result can be attributed to the existence of the baffle wall, which can prevent the occurrence of short circuits under higher loads and maintain sufficient contact between the water flow and the biofilm and the root area. Afterwards, Cui *et al.* (2015) designed three types of constructed wetlands with baffle structures (horizontal baffle Z1, vertical baffle Z2 and hybrid baffle Z3) and a traditional horizontal subsurface flow constructed wetland Z4 to treat nitrogen and phosphorus in septic tank wastewater. When HRT is 2 days, the Z1, Z2, Z3 and Z4 CWs removed, respectively, 49.93%, 58.50%, 46.01% and 44.44% of total nitrogen (TN) as well as 87.82%, 93.23%, 95.97% and 91.30% of total phosphorus (TP). It can be seen that the baffle can indeed play a certain role in slowing down the internal water flow rate, resisting the impact of load, and extending the hydraulic path. Compared with the traditional constructed wetland, after the baffle is added, the removal rate of pollutants can be improved to a certain extent.

The substrate plays a central role in the process of removing pollutants in the constructed wetland, and is an important condition for the wetland to exert good hydraulic conductivity (Miranda *et al.* 2019; Wang *et al.* 2020). Most wetlands use a combination of multiple substrate gradations (Prochaska & Zouboulis 2006; Fu *et al.* 2020). The filling method of the substrate has a great influence on the hydraulic performance of the constructed wetland. Through research, Suliman *et al.* (2007) found that the layering of the substrate can improve the efficiency of wetland decontamination. Bai *et al.* (2014) used tracer experiments to show that the hydraulic characteristics of the layered filling structure are significantly better than those of the single-layer structured subsurface flow constructed wetland, and the effective volume ratio of the two is 0.87 and 0.49, respectively. The layered filling method can effectively avoid the occurrence of short flow and dead zone, and improve the hydraulic efficiency of the system. Liu *et al.* (2020) compared double-layer substrate structure constructed wetland composed of shale ceramsite (SC) and activated alumina (AA) (SC-AA-TFCW) with a single-layer substrate structure constructed wetland with only AA or SC. The SC-AA-TFCW removed 86% NH_4^+-N and 79% total nitrogen at hydraulic load of 0.612 m^3/m^2 d, which was better than AA-TFCW (76%) or SC-TFCW (49%). They found that the layered structure of constructed wetland has higher decontamination performance, mainly due to the uneven flow field and the irregular gap distribution in the layered structure, as well as less hole blockage during long-term operation. Previous studies have shown that the layered matrix structure can improve the hydraulic performance and pollutant removal efficiency of constructed wetlands. Therefore, this paper conducts further simulation research on the layer thickness ratio of each matrix on this basis.

Thanks to the continuous maturity of numerical calculation and turbulence theory and the significant improvement of computer performance, Computational Fluid Dynamics (CFD) has developed rapidly and is gradually being applied to hydraulic problems in water treatment facilities. Compared with the expensive and time-consuming tracer test method, the numerical simulation method is more economical and efficient. Liolios *et al.* (2012) numerically simulated Biochemical Oxygen Demand (BOD) fate and transport in horizontal subsurface flow constructed wetlands. The model was calibrated and verified using the measured BOD concentrations, and was used in test runs comparing performance under various vegetation, porous media size, temperature and HRT conditions. Model performance was found acceptable, indicating its usefulness in the simulation of BOD fate in constructed wetlands and in the design of these facilities. Fluent is a very powerful commercial CFD software package released by FLUENT in the early 1980s. It has a wealth of physical models inside, which can be applied to all engineering projects related to fluids, heat transfer and chemical reactions, and the analysis results can also be fast and accurate. Fluent comes with a complete post-processing function, can dynamically simulate the process of fluid movement, and can also import the calculation results into other post-processing software for further analysis, thus becoming one of the mainstream CFD software packages (Tsavdaris *et al.* 2014; Li *et al.* 2018). Yang *et al.* (2017) combined traditional tracer testing and computational fluid dynamics software Fluent to analyze the impact of blockage on hydraulic behavior in a vertical flow constructed wetland experimental system, and used the Nash-Sutcliffe efficiency factor (NSE) to verify the simulation results of computational fluid dynamics. The flow rate in the experimental system increases with the increase in operating time, and accordingly, the time required to pass through the matrix pores is reduced, which leads to an additional decrease in hydraulic retention time and a decrease in porosity. It shows that CFD is not only a useful tool for optimizing the design of constructed wetlands, but also for revealing changes in flow fields with operating time. Fan *et al.* (2009) obtained the liquid residence time distribution in subsurface flow constructed wetland (SSFW) using Fluent's particle orbit model. The simulation confirmed that the effect of the distribution and/or catchment area on the hydraulic efficiency is significant. From the point of view of the engineering design, a small dimension distribution and/or catchment area in the SSFW is advisable, which maintains a considerable hydraulic efficiency of the SSFW.

This study uses Fluent to establish a hydrodynamic model of the horizontal subsurface flow constructed wetland system, analyzes the influence of baffle settings and substrate laying methods on the internal flow pattern and hydraulic efficiency of the constructed wetland, and provides a reference and basis for improving the process design and performance optimization of the constructed wetland.

MATERIALS

Mathematical description of the model

Porous media model

Porous media refers to a substance in which a large number of tiny pores are formed by many frameworks, and the fluid in the pores mainly moves in the way of percolation. The porous media model is used to simulate the fluid flow in the system. In the simulation process, the mass conservation equation and the momentum conservation equation need to be considered under the condition of neglecting heat transfer (Karpinska & Bridgeman 2016; Rengers *et al.* 2016).

The mass conservation equation can be expressed as the increase in mass of the micro-element in a unit time equal to the net mass flowing into the micro-element in the same time interval:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=S_m \tag{1}$$

where ρ is the fluid density [kg/m^3]; u is the fluid velocity vector [m/s]; S_m is the mass source term, [kg/(s·m^3)].

The momentum conservation equation of porous media adds viscous resistance and inertial resistance loss source terms to the momentum equation to simulate the hindering effect on the internal fluid (Reint 2000; Boer & Didwania 2004), which can be described by:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial P}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i+S_i \tag{2}$$

where P is the static pressure [Pa]; ρg is the gravitational volume force; τ_{ij} is the stress tensor [Pa]; S_i is the additional momentum loss source [N/m^3], which is the i-direction (x, y, z) momentum source phase, that is, the sum of the source terms of viscous resistance and inertial resistance loss, as shown in Equation (3). The former at the right end of the formula is the source term of viscous resistance loss, and the latter is the source term of inertial resistance loss.

$$S_i=-\left(\sum_{j=1}^{3}\mathrm{D}_{ij}\mu u_i+\sum_{j=1}^{3}\mathrm{C}_{ij}\frac{1}{2}\rho|u_i|u_i\right) \tag{3}$$

D and C are the viscous resistance loss coefficient matrix and inertial resistance loss coefficient matrix. If it is assumed that the constructed wetland filling substrate is an isotropic simple porous medium with uniform particle size and porosity, the diagonal terms in the coefficient matrices D and C can be substituted into $1/\alpha$ and C_2, where $1/\alpha$ is the coefficient of viscous resistance [1/m^2]; C_2 is the coefficient of inertial resistance [1/m].

$$\frac{1}{\alpha}=\frac{150}{d_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{4}$$

$$C_2=\frac{3.5}{d_p}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{5}$$

where d_p is the average diameter of the filler substrate, [m]; ε is the porosity of the substrate [%].

Discrete phase model

The discrete phase model is also called the Euler-Lagrangian model; the main body acts as a continuous phase and the particles act as a discrete phase. Euler method is used to describe the continuous phase of the subject, and Lagrangian method tracks the movement of discrete particles, obtains their instantaneous position from the function of the initial position and time, and records the physical quantity and its changes at any time and position. The discrete phase model is used to study the internal hydraulic efficiency of the wetland; that is, the Euler method is used to describe the internal water flow of the wetland, the Lagrangian method is used to describe the fluid particles at different positions, and the particle trajectory is used to simulate the residence time distribution density of the water flow.

The particle inertia is caused by the combined action of various forces, and its balance equation in the X direction is expressed as:

$$\frac{du_p}{dt}=F_D(u-u_p)+\frac{g_x(\rho_p-\rho)}{\rho_p} \tag{6}$$

$$F_D=\frac{18\mu}{\rho_p d_p^2}\frac{C_D R_e}{24} \tag{7}$$

$$R_e=\frac{\rho d_p|u_p-u|}{\mu} \tag{8}$$

where u_p is the particle velocity; ρ_p is the particle density; F_D (uu_p) is the drag force per unit mass of the particle; d_p is the particle diameter; R_e is the particle Reynolds number; C_D is the drag coefficient. Integrate Equation (6) along each coordinate direction to obtain the trajectory of the discrete phase and the particle velocity at each position.

Model establishment and solution

After two-dimensional simplification of the horizontal subsurface flow constructed wetland system, a constructed wetland model with a three-layer base structure was established. According to the current commonly used substrate laying sequence, the lower layer is a large-diameter substrate, the middle is a medium-diameter substrate, and the upper layer is a small-diameter substrate. The particle diameters are respectively set to 30 mm, 12 mm, and 6 mm, and the corresponding porosity is 60, 42 and 35%; the thickness of each layer is 20 cm. The viscous resistance coefficient ($1/\alpha$) and the inertial resistance coefficient (C_2) are calculated using Equations (4) and (5). The detailed geometric dimensions and model parameters of the two-dimensional model are shown in Table 1.

ANSYS ICEM is professional preprocessing software, which can provide efficient and reliable analysis models and has strong repair ability and solver support ability. Grid generation is flexible and effective, with structured and unstructured grid generation methods. The calculation grid file of the hydrodynamic model of the up and down baffled subsurface flow constructed wetland system is generated by ANSYS ICEM. Since the model structure is relatively regular, a structured grid with better convergence and better quality is selected for division. After setting the number of nodes on each side of the model, a pre-mesh is generated, and a total of 12,798 meshes are divided. Since only unstructured grids can be loaded in Fluent, after checking, the structured grids obtained are converted into unstructured grids, and then imported into Fluent to prepare for solution. Load the grid file obtained by ANSYS ICEM in Fluent. Assuming that each layer of the substrate is isotropic and the water flow in the substrate layer is laminar, a two-dimensional steady laminar flow separation solver based on standard pressure is selected. Select the fluid material as water and set the corresponding boundary conditions.

Table 1 | Model geometry and simulation parameters

Item	Parameter	Data
Model size	Wetland length (L, cm)	240
	Wetland height (H, cm)	60
	Inlet and outlet diameter (d, cm)	5
	Baffle height (h, cm)	30
Initial conditions	Inlet velocity (u, m/s)	0.0003
	Outlet pressure (Pa)	101,325
Large particle size substrate	Porosity of porous media (ε_1, %)	60
	Porous media particle size (d_1, mm)	30
	Viscous resistance coefficient ($1/\alpha$, $1/m^2$)	1.234 × 105
	Inertial resistance coefficient (C_2, 1/m)	2.160 × 102
Medium particle size substrate	Porosity of porous media (ε_2, %)	42
	Porous media particle size (d_2, mm)	12
	Viscous resistance coefficient ($1/\alpha$, $1/m^2$)	4.730 × 106
	Inertial resistance coefficient (C_2, 1/m)	2.283 × 103
Small particle size substrate	Porosity of porous media (ε_3, %)	35
	Porous media particle size (d_3, mm)	6
	Viscous resistance coefficient ($1/\alpha$, $1/m^2$)	4.106 × 107
	Inertial resistance coefficient (C_2, 1/m)	8.843 × 103

The water inlet is the velocity inlet, the outlet is the pressure outlet, and the pressure is a standard atmospheric pressure. Set the 'internal boundaries' between the substrate layers, and the surrounding walls and internal baffles are the 'wall boundaries' – the specific values are shown in Table 1 – and set the release position, number and initial velocity of particles. In this simulation, the initial velocity of the particles is consistent with the flow velocity of the water inlet, the particle diameter is 10^{-6} m, the injection type is group, and the number of streams is 20. Select the fluid material as water, set the corresponding boundary conditions, the viscous resistance coefficient, the inertial resistance coefficient and the porosity of the porous media area, and set the release position, number and initial velocity of the particles. Inject particles into the computational domain, and use particle tracking to obtain the particle's motion state and residence time in the computational domain. When the residual error is less than 10^{-6} and does not change with the calculation, the calculation is considered to be convergent. After the calculation is completed, the post-processing function of Fluent is used to output the velocity distribution map of the two-dimensional hydrodynamic model of the up and down baffled subsurface flow constructed wetland system. Generate *.dpm file for analysis and calculation of hydraulic characteristics.

Evaluation method of hydraulic performance

On the basis of obtaining the liquid phase steady-state flow field, the particle trajectory model is used to approximate the residence time distribution of the particle swarm in the model as the residence time distribution of the water flow inside the wetland, which provides parameters for the quantitative evaluation of the hydraulic performance of the constructed wetland. These parameters include the average residence time (T_m), variance (σ^2), flow divergence (σ_0^2), effective volume ratio (e) and hydraulic efficiency (λ). They are defined by the following equations (Thackston *et al.* 1987; Persson *et al.* 1999; Peterson 2000; Persson & Wittgren 2003; Holland *et al.* 2004).

$$T_n = \frac{V}{Q} \tag{9}$$

$$\sigma_0^2 = \frac{\sigma^2}{T_n^2} \tag{10}$$

$$e = \frac{T_m}{T_n} \tag{11}$$

$$\lambda = e\left(1 - \frac{\sigma^2}{T_n^2}\right) \tag{12}$$

where T_n is the apparent residence time, also known as the theoretical hydraulic residence time [h]; V is the effective volume of the wetland [m^3]; Q is the volume flow rate [m^3/h]; T_m is the average time; σ is the standard deviation from the mean time, and σ^2 is the variance; σ_0^2 is used to judge the flow pattern of the water flow in the constructed wetland, when $\sigma_0^2 = 1$, the water flow is fully mixed flow, and when $\sigma_0^2 = 0$, the water flow is push flow; e is the ratio of T_m and T_n. The closer e is to 1, the fewer dead zones in the system and the higher the space utilization; λ is a simple and effective parameter to characterize the hydraulic performance of the wetland. The larger the value of λ, the higher the internal hydraulic efficiency of wetlands.

Baffle setting and substrate laying

In order to explore the influence of the setting of baffles on the hydraulic performance of the subsurface flow constructed wetland, the position of the water inlet and outlet and the layout of the substrate remained unchanged, and the number and positions of the baffles were combined (Figure 1). The models are named (a) UL, (b) LU, (c) ULU and (d) LUL according to the number and position of the baffles. For example, model (a) UL, being 'U' the baffle is located on the upper part of the substrate and 'L' baffle is located on the lower part of the substrate.

Fix the setting of the baffle inside the model, change the laying thickness of the substrate on the basis of the model (d) LUL, and adjust the thickness ratio of the upper, middle and lower substrates. Three wetland models with substrate layer thickness ratios of 1: 1: 1, 1: 2: 1, and 1: 4: 1 were selected. The specific laying of each model substrate is shown in Figure 2 to further explore the influence of substrate laying on the hydraulic performance of the subsurface flow constructed wetland.

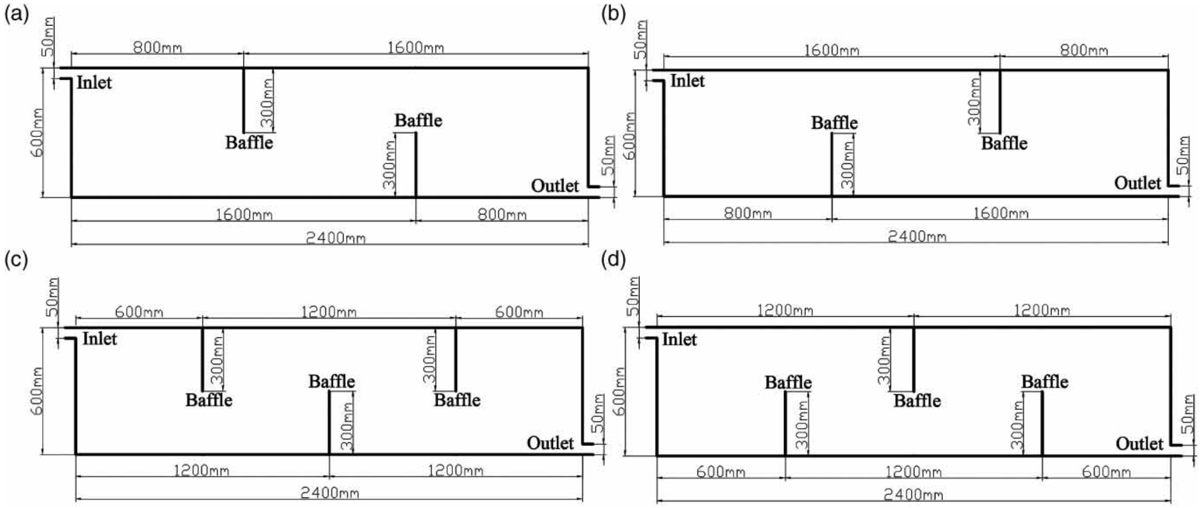

Figure 1 | Schematic diagram of baffle setting of each model. (a) UL. (b) LU. (c) ULU. (d) LUL.

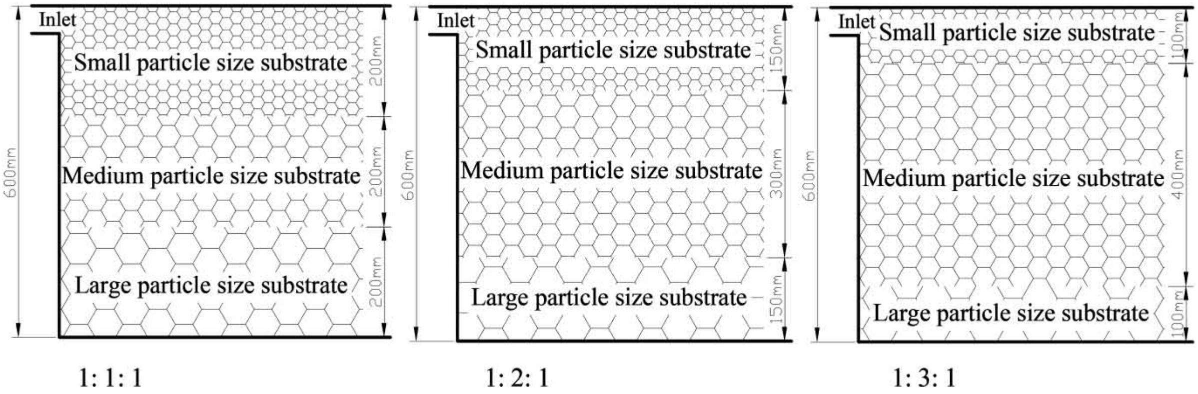

Figure 2 | Schematic diagram of substrate laying of each model.

RESULTS AND DISCUSSION

Influence of baffle setting on hydraulic performance of subsurface flow constructed wetland

Since the particles follow the water flow very well, by tracking the particles in the model and capturing the particles at the water outlet, the motion state of the released particles is obtained, which reflects the flow velocity distribution of the water flow inside the model. After Fluent's simulation and post-processing, the velocity distribution of the wetland model with different baffle settings was obtained (Figure 3). It can be seen that after the water flow enters the wetland, it moves quickly to the middle and lower substrate, and the water flow of the upper substrate is slow. This is consistent with the wetland streamline diagram obtained by Sun *et al.* (2019) using Visual MODFLOW. It can be seen from Figure 3 that the flow velocity on the upper part of the substrate is relatively low. The two sides of the baffle on the upper part of the base plate are dark blue areas, and the water flow speed has no obvious change. Due to the small pores of the upper substrate, there is a natural downward movement tendency under the action of gravity. The water flow moves along the middle and lower substrates with larger porosity, and the closer to the water outlet, the faster the water flow. It is precisely because water flow tends to flow in the pores of large particles in the middle and lower layers that the baffle located on the upper part of the substrate in the horizontal subsurface flow constructed wetland has little effect on the upper water velocity and will not significantly increase the low velocity zone.

The baffle located at the lower part of the substrate has a certain dead zone on both sides of the baffle. The water flow velocity increases in a fan-shaped distribution, and the upper part of the baffle increases the flow velocity significantly due to the circumfluence of the water flow, which also drives the flow velocity in a certain area around. Regardless of the number of baffles inside the model, where the first baffle is located in the lower part of the substrate, such as model (b) LU and model (d) LUL, a dark blue low velocity area appears in the front of the baffle. Because it is close to the water inlet, the fast flowing water encounters the barrier of the baffle, which produces a certain backflow, resulting in a certain retention phenomenon, so this part of the low velocity area appears in front of the baffle. In addition, this part of the low velocity area of the model (d) LUL is significantly smaller than that of the model (b) LU. It can be seen that the increase of the baffle can slow down the low velocity phenomenon in this area. However, the number of baffles is not as large as possible. Too many baffles will inevitably cause irregular water flow inside the wetland, resulting in more dead zones, impaired hydraulic performance, and reduced pollutant removal rates. Yin *et al.* (2016) used tracer experiments to study the hydraulic characteristic parameters of the four-channel up and down baffled wetland and the eight-channel up and down baffled wetland. As a result, the four-channel up and down baffled wetland is the most optimized design. The kinetic energy generated in the process of baffling well eliminates the retention problem caused by the complicated flow pattern, and effectively reduces the dead zone and short circuit. Because the flow process of the eight-channel up and down baffled wetland is too complicated, the tracer recovery rate is very low, while the dead zone and the divergence are very large. Therefore, how to use a limited number of baffles to efficiently improve the hydraulic performance of constructed wetlands is a problem that should be focused on in future research.

Compared with the model in which the first baffle is located on the upper part of the substrate, the model in which the first baffle is located on the lower part of the substrate has a faster water flow in the middle layer of the substrate and has a higher substrate utilization rate, so the model as a whole has a smaller dark blue low velocity area. Therefore, from the analysis of the internal velocity distribution diagrams of different baffle setting models, it can be seen that when the number of baffles is the same, the arrangement of the first baffle in the lower part of the substrate has better water flow performance than the arrangement in the upper part of the substrate; when the baffle is located in the lower part of the substrate, three baffles inside the wetland perform better than two baffles.

The calculation results of hydraulic evaluation parameters for different baffle setting modes are shown in Table 2. The addition of baffles can effectively increase the hydraulic retention time, but at the same time the internal flow pattern is also affected. The flow divergence (σ_0^2) of the model with two baffles ((a)UL, (b)LU) is closer to 0, the internal water flow is closer to the push flow state, and the variance of the hydraulic residence time distribution (σ^2) is also smaller. However, compared with the model with three baffles ((c) ULU, (d) LUL), the average hydraulic retention time (T_m) is relatively small.

Consistent with the analysis of the internal velocity distribution diagrams of different baffle setting models, the arrangement of the first baffle at the bottom of the substrate has a smaller low velocity area and the effective volume ratio (e) is closer to 1. It shows that there are fewer dead zones in the model. The hydraulic efficiency (λ) of all four models is over 0.5, and the

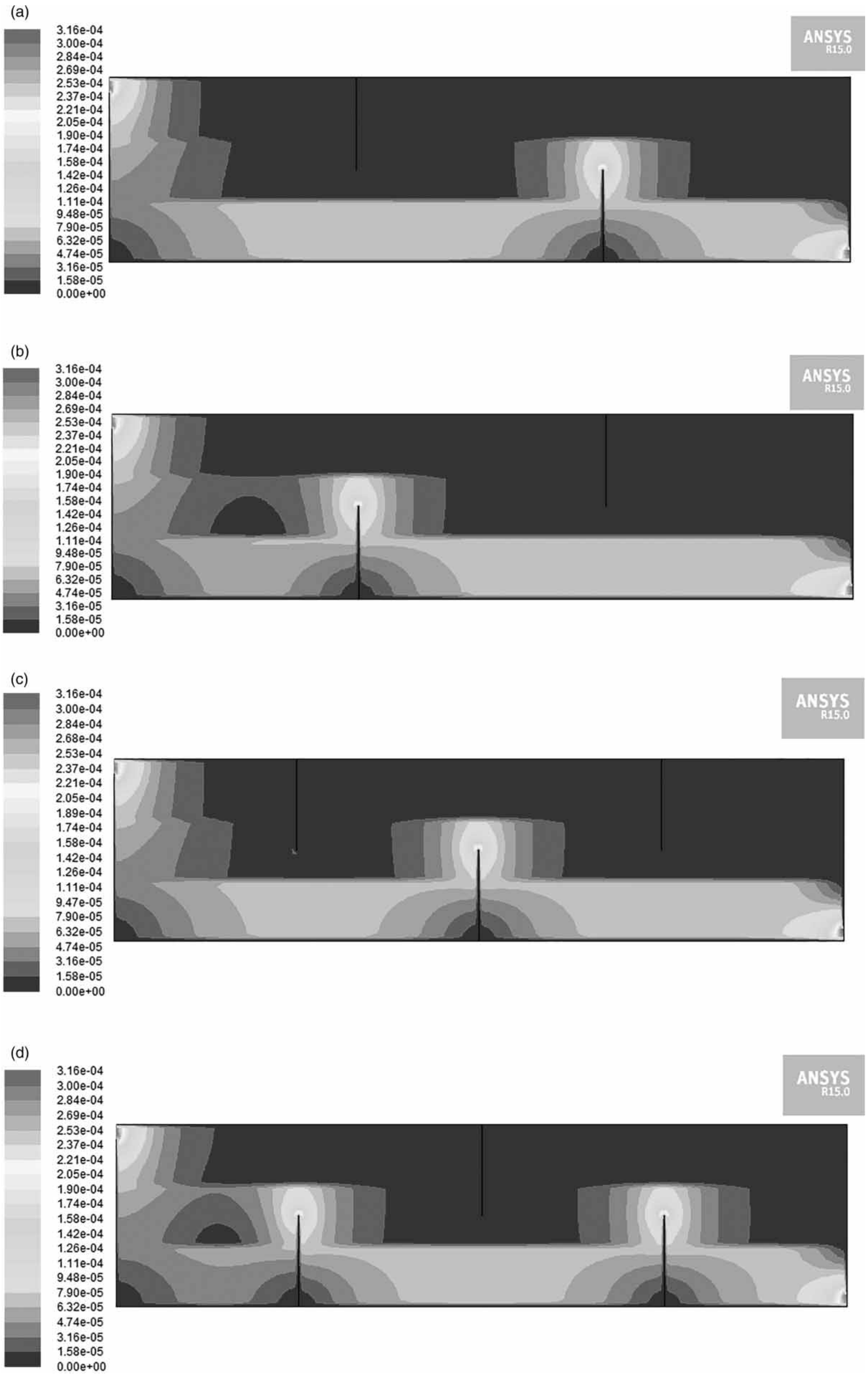

Figure 3 | Internal velocity distribution diagram of different baffle setting models. (a) UL. (b) LU. (c) ULU. (d) LUL.

Table 2 | Performance evaluation parameters of different baffle setting models

Model	T_m/h	σ^2	e	σ_0^2	λ
(a)UL	16.978	73.804	0.637	0.104	0.571
(b)LU	17.318	69.542	0.649	0.098	0.586
(c)ULU	18.043	96.696	0.677	0.136	0.585
(d)LUL	20.324	108.099	0.762	0.152	0.646

hydraulic performance of model (d) LUL is higher than that of the other three models, while the hydraulic efficiency (λ) reaches 0.646.

Compared with model (a) UL, model (b) LU only improves hydraulic efficiency (λ) by 2.6%, while model (d) LUL increases hydraulic efficiency (λ) by 10.4% compared with model (c) ULU. It can be seen that when the number of baffles is the same, the hydraulic efficiency (λ) of the model with the first baffle at the lower part of the substrate is greater than that of the model with the first baffle at the upper part of the substrate, and it becomes more obvious as the number of baffles increases. Compared with the position of the baffle, the number of baffles has no obvious influence on the hydraulic efficiency (λ) of the constructed wetland. As shown in Table 2, the hydraulic efficiency (λ) of the model (b) LU and the model (c) ULU is 0.586 and 0.585, respectively, and there is no significant difference between the two. However, the hydraulic efficiency of the model (d) LUL with the same three baffles is 0.646, which once again verifies the importance of the baffle setting position. Only when the beneficial effect of the additional baffle is greater than the adverse effect can it be reflected in the increase of hydraulic efficiency. If the number and position of the baffles are unreasonable, the dead zone is too large and the space utilization rate is reduced, which will cause the hydraulic efficiency to decrease or even appear inferior to the model without additional baffles under the same conditions.

Influence of substrate laying on hydraulic performance of subsurface flow constructed wetland

The internal velocity distribution diagram of the model with different substrate layer thickness ratios is shown in Figure 4. The internal water flow of the model with the same thickness of the substrate (1: 1: 1) reaches the lower large-diameter substrate quickly after flowing in, and flows quickly along the lower large-diameter substrate until it flows out. As a result, the utilization rate of the upper and lower substrates in the model is not high, and the existence of large low velocity areas and fast channels will inevitably affect the hydraulic efficiency of the constructed wetland. As the proportion of the middle substrate increases, the low flow rate caused by the small porosity substrate area in the upper layer improves, and the water flow velocity inside the middle substrate increases significantly. Especially in the areas on both sides of the baffle, the thicker the middle layer of the substrate, the greater the range of increase in flow velocity on both sides of the baffle, the smaller the range of the dead zone caused by the lower part of the baffle, and the rapid outflow phenomenon in the lower part of the model is also avoided.

The calculation results of the internal hydraulic performance evaluation parameters of the model with different substrate layer thickness ratios are shown in Table 3. Among them, the model with a substrate layer thickness ratio of 1: 4: 1 has the best performance and the highest hydraulic efficiency (λ), reaching 0.775. By comparing the hydraulic characteristics evaluation parameters of the three models, it can be seen that the greater the proportion of the thickness of the middle substrate, the longer the hydraulic retention time and the more uniform water distribution, especially in the middle substrate area, the internal water flow state is closer to the push flow state, and the hydraulic efficiency is greater.

With the increasing proportion of the thickness of the middle layer, the two parameters of average residence time (T_m) and effective volume ratio (e) have increased but not much. However, the variance of hydraulic residence time distribution (σ^2) and flow divergence (σ_0^2) has changed significantly. As shown in Table 3, compared with the model with a substrate layer thickness ratio of 1: 2: 1, the variance of hydraulic residence time distribution (σ^2) of the model with a substrate layer thickness ratio of 1: 4: 1 decreased from 107.083 to 53.376, a decrease of 50.15%; the flow divergence (σ_0^2) decreased from 0.151 to 0.075, a decrease of 50.31%. The value range of flow divergence (σ_0^2) is 0–1, and the closer to 0, the closer the water flow is to the push flow state. Therefore, when laying the constructed wetland substrate, try to increase the thickness of the middle substrate, reduce the thickness of the upper and lower substrate, and make the internal water flow more uniform, so as to achieve the purpose of improving the hydraulic efficiency of the subsurface flow constructed wetland.

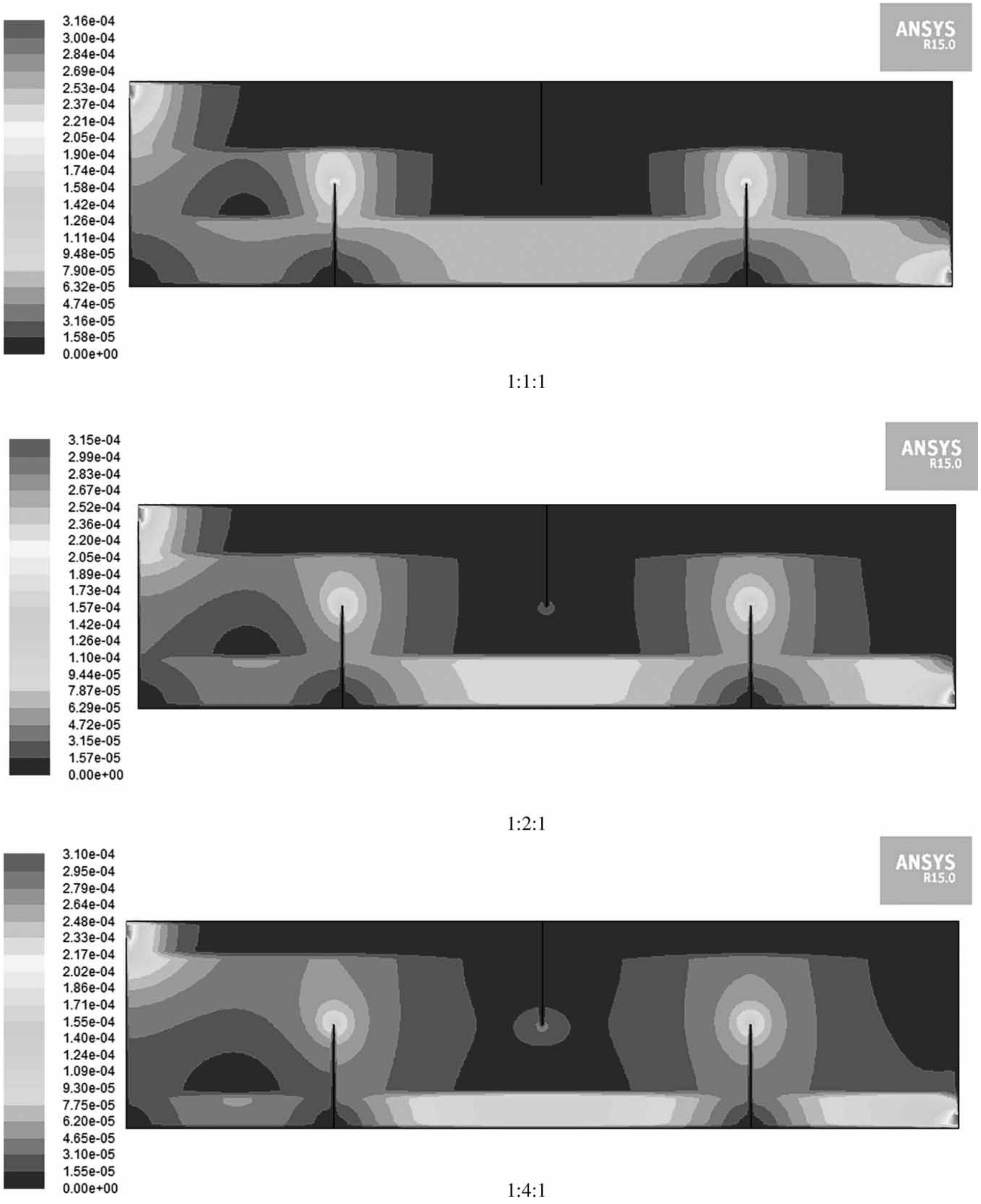

Figure 4 | Internal velocity distribution diagram of different substrate layer thickness ratio models.

Table 3 | Performance evaluation parameters of different substrate layer thickness ratio models

Model	T_m/h	σ^2	e	σ_0^2	λ
1: 1: 1	20.324	108.099	0.762	0.152	0.646
1: 2: 1	21.928	107.083	0.822	0.151	0.698
1: 4: 1	22.342	53.376	0.838	0.075	0.775

CONCLUSIONS

By establishing a hydrodynamic model of the up and down baffled subsurface flow constructed wetland system, the influence of baffle setting and substrate laying on the hydraulic performance of the subsurface flow constructed wetland was analyzed. The hydraulic efficiency of the model with the first baffle on the lower part of the substrate is greater than that of the model with the first baffle on the upper part of the substrate, and it becomes more obvious as the number of baffles increases; the substrate layer thickness ratio has a significant effect on the two parameters of the variance of the hydraulic residence time distribution (σ^2) and the flow divergence (σ_0^2); among the three models designed in this research, the model with a substrate layer thickness ratio of 1: 4: 1 shows the best performance in the evaluation parameters of hydraulic characteristics and the highest hydraulic efficiency (λ), reaching 0.775.

Based on this, for the design and construction of small subsurface flow constructed wetlands, if baffles are used to increase the utilization of the internal space of the wetland, the first baffle should be located at the lower part of the substrate. In addition, the thickness of the middle substrate should be increased as much as possible to make the water distribution more uniform, reduce the variance of the hydraulic residence time distribution (σ^2) and the flow divergence (σ_0^2), and achieve the purpose of optimizing the internal structure and improving the hydraulic efficiency.

Further research requires a more in-depth analysis of the influence of the size and water permeability of the baffle, the particle size of the substrate, and the order of laying on the hydraulic properties of the subsurface flow constructed wetland. Form certain process design specifications to provide a reference and basis for the design parameters of constructed wetlands.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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