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## Research Article

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# Flow behaviour in free surface constructed wetlands with different vegetation distribution patterns

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## Abstract

Constructed wetlands (CWs) are known to be more sustainable alternatives compared to conventional treatment systems. However, hydraulic performance aspects have not been extensively emphasized within design guidelines. Given that hydraulic performance plays a critical role in determining the efficiency of CWs, detailed investigation into these aspects is essential. In this paper, ANSYS Fluent was used to model the flow in full-scale CW (108 m<sup>2</sup>) and evaluate the hydraulic performance in the systems. Through validation, R<sup>2</sup> values were obtained between 0.70 and 0.96 indicating that the numerical model results are in good agreement with the experimental residence time distribution curves. Following model validation, simulations for generic full-scale free surface CWs were performed to study the effects of varying vegetation distribution patterns and vegetation densities on hydraulic performance. The three, six banded and fully vegetated CWs consistently outperformed fringing and no vegetation when evaluated across the hydraulic indicators. Flow through vegetation in the banded and fully vegetated cases promote mixing and flow uniformity, enhancing hydraulic performance. Planting density was found to be of secondary importance compared to plant distribution. The findings from this paper provide constructive insights that significantly enhance real world design by bridging the gap between research and practical implementation.

Keywords: ANSYS Fluent, constructed wetlands, density, hydraulic performance, porosity, vegetation

## 1. Introduction

Wetlands play a vital role in water quality improvement, flood regulation, and ecosystem protection. As natural treatment systems, they effectively remove pollutants through physical, chemical, and biological processes, offering a sustainable alternative to conventional treatment systems. However, the design and hydraulic performance of constructed wetlands are often influenced by complex interactions between flow patterns, vegetation distribution patterns, vegetation density and geometry. In many cases, inadequate understanding of these hydraulic behaviours leads to suboptimal treatment performance and inefficient system design. To address these challenges, computational fluid dynamics (CFD) modelling has emerged as a powerful tool for analyzing and visualizing flow characteristics within wetlands. CFD is a division of numerical modelling of fluid flow (León et al., 2008) and is an analysis tool to stimulate flows of gases and liquids, heat and mass transfer, moving bodies, multiphase physics, chemical reactions (Norton et al., 2007) including fluid-solid interaction such as river water flowing or water interaction with hydraulic structures (Kumcu, 2017). As early in the 1970s, CFD is recognized as a part of fluid mechanics that studies fluids in motion and employing mathematics, physics and computer sciences. The Navier-Stokes equations are used as a basis for all CFD problems allowing for detailed assessment of velocity distribution and flow behaviour which may be difficult to capture experimentally. CFD modelling thus provides a cost-effective manner to analyse flow in wetlands providing valuable insights for optimizing wetland configuration and enhancing hydraulic efficiency.

Table 1 summarizes previous studies that applied numerical modelling tools detailing the turbulence models and mesh convergence in free surface constructed wetland (FS CW) studies. The application of ANSYS CFX and ANSYS Fluent has been the dominant trend in recent years. Early studies, such as Machado Xavier et al. (2018) employed the Shear Stress Transport Reynolds Average Navier-Stokes (SST RANS)  $k-\omega$  model in ANSYS CFX to assess nutrient removal potential in floating treatment islands. This model able to improve accuracy in boundary layer flows and regions with adverse pressure gradients. More recent studies, such as Yamasaki et al. (2022) and Nuruzzaman et al. (2023) adopted SST  $k-\omega$  in ANSYS Fluent to investigate floating treatment wetland (FTW) design configurations. These works highlight the influence of plant spacing, root length, and placement on hydrodynamic conditions and

pollutant removal, with numerical predictions validated against experimental data. Sonnenwald et al. (2019) adopted the  $k-\varepsilon$  turbulence model within ANSYS Fluent to develop and validate mixing models for vegetated flows, focusing on shear, mixing, and plant drag. Although widely used due to its computational efficiency, the  $k-\varepsilon$  model is limited in resolving near-wall turbulence and separated flows, which are common in vegetated wetlands. The authors also adopted grid refinement to evaluate turbulence-related parameters such as peak velocity, Reynolds stresses, and wake-scale turbulence kinetic energy (TKE). The trend toward hybrid or modified turbulence models reflects the need for better accuracy in capturing the interaction between vegetation and flow at both local and system scales. Nuruzzaman et al. (2023) employed progressive mesh refinement to evaluate residence time distribution (RTD)-based parameters and adopted <5% variation in the breakthrough curve as the convergence threshold while Yamasaki et al. (2022) employed mesh sizes of 0.01 m to 0.05 m. Most recently, Kabir et al. (2025) utilized ANSYS Fluent to study microplastic transport, settling, and dispersion within FS wetlands. This represents an emerging research direction that goes beyond traditional nutrient or pollutant transport, addressing contemporary environmental concerns. Kabir et al. (2025) adopted fine mesh sizes (0.12–0.01 mm) and evaluated mesh quality metrics such as skewness, aspect ratio, and orthogonal quality, with convergence rate of less than 0.8%. Besides ANSYS, Du (2024) employed COMSOL Multiphysics for tracer-based validation, highlighting hydraulic characterization through RTD analysis and hydraulic indices. Taken together, these tools provide pathways for integrating hydrodynamics with ecological and water quality modelling.

Table 1: Summary of CFD and numerical model used in constructed wetland modelling

| Year | Type of CWs | Tool         | Size of mesh              | Key parameters evaluated               | Convergence criteria          | Turbulence Model           | Aim                                                                                                                        | Reference                    |
|------|-------------|--------------|---------------------------|----------------------------------------|-------------------------------|----------------------------|----------------------------------------------------------------------------------------------------------------------------|------------------------------|
| 2018 | FS          | ANSYS CFX    | NA                        | NA                                     | NA                            | SST RANS k- $\omega$ model | Compare the nutrient removal potential of different FTW configurations in a stormwater pond                                | Machado Xavier et al. (2018) |
| 2019 | FS          | ANSYS Fluent | 0.020, 0.010, and 0.005 m | Peak velocity, Reynolds stresses, TKE  | < 1% GCI                      | k- $\epsilon$ model        | Develop and validate mixing models for vegetated flows to capture shear, mixing and effects of plant drag                  | Sonnenwald et al. (2019)     |
| 2022 | FS          | ANSYS Fluent | 0.01 m and 0.04 m         | NA                                     | GCI                           | SST k- $\omega$ model      | Quantify how FTW spacing, root length and arrangement affect flow distribution and pollutant mass removal                  | Yamasaki et al. (2022)       |
| 2023 | FS          | ANSYS Fluent | Coarse to fine grid       | RTD, flow distribution, residence time | < 5% change in RTD and $\tau$ | SST k- $\omega$ model      | Evaluate different FTW design configurations, study hydrodynamic impacts of FTW placement and validate CFD vs experiments. | Nuruzzaman et al. (2023)     |

| Year | Type of CWs | Tool                | Size of mesh       | Key parameters evaluated                                                    | Convergence criteria | Turbulence Model      | Aim                                                                                      | Reference           |
|------|-------------|---------------------|--------------------|-----------------------------------------------------------------------------|----------------------|-----------------------|------------------------------------------------------------------------------------------|---------------------|
| 2024 | SSF         | COMSOL Multiphysics | NA                 | NA                                                                          | NA                   | NA                    | Provide tracer-based validation of CFD based on RTD comparisons and hydraulic indicators | Du (2024)           |
| 2025 | FS          | ANSYS Fluent        | 0.12 mm to 0.01 mm | Velocities, element quality, skewness, aspect ratio, and orthogonal quality | < 0.8 %              | SST k- $\omega$ model | Simulate dispersion, settling and retention of microplastics in wetland flows            | Kabir et al. (2025) |

88 FS = Free surface; HSSF = Horizontal subsurface flow; SSF = Subsurface flow; TKE = Turbulence kinetic energy; GCI = Grid convergence index; RTD = Residence time  
89 distribution; SST = Shear stress transport; RANS = Reynolds Average Navier-Stokes; k- $\epsilon$  = k-epsilon; k- $\omega$  = k-omega; FTW = Floating treatment plant; NA = Not available

Modelling vegetation flows as flow through porous media (averaging technique) in ANSYS offers an efficient way to model wetland flows at the macroscopic level by homogenizing flow properties by incorporating empirical relationships. However, they introduce approximations that may overlook microscopic interactions. Pore-scale techniques, on the other hand, resolve individual pores and fluid-solid interfaces, capturing phenomena like capillary effects, local flow dynamics, and pore-level heat transfer with high fidelity. While pore-scale simulations provide a detailed and fundamental understanding, they are computationally expensive and often impractical for large-scale systems. Thus, the choice between these approaches depends on the required accuracy and computational resources available, with pore-scale models being ideal for detailed studies and averaged models preferred for engineering applications. Nuruzzaman et al. (2023) represented the root zone using a porous media averaging technique. This technique has also been applied in other wetland and vegetated flow simulations, such as the works of Sonnenwald et al. (2019) Tsavdaris et al. (2013a) and Tsavdaris et al. (2015) where the porous media representation provided computational efficiency while providing understanding of hydraulic behaviour.

The above review shows that CFD can be an effective and reliable tool for analyzing flow behaviour and characterizing hydraulic performance in free surface constructed wetlands. While the general application of CFD in wetland applications is not in doubt, there remains a paucity of studies addressing the hydraulic performance of full-scale FS constructed wetlands with vegetation. Persson (2000) investigate the hydraulic efficiency of CW of different shapes and placements of inlet and outlet, however, to the impact of vegetation distribution patterns and planting densities have not been studied, although these factors are important in hydraulic behaviour. The aims of this study were: (i) Calibrate and validate a CFD model, comparing against breakthrough curves measured in full-scale laboratory experiments; (ii) Develop a generic (rectangular) full-scale free surface (FS) CW CFD model with varying vegetation distribution patterns and planting density; and (iii) Evaluate hydraulic performance of the generic wetland based on an evaluation of commonly used performance indices. The findings from this study are expected to advance understanding of how vegetation distribution patterns can impact flow behaviour and hydraulic efficiency. Hydraulic efficiency is linked to treatment effectiveness and though treatment is not addressed *per se*, the results from this study can serve as a benchmark, enabling consistent comparison across different planting configurations, facilitating future modelling and experimental investigations. Lastly, the improved

understanding of flow behaviour obtained from this study provides a foundation for enhancing the hydraulic performance and overall efficiency of constructed wetland systems.

## 2. Methodology

### 2.1 Porous media approximation

In CFD analysis, the flow in a wetland can either be modeled at the pore-scale where vegetation is modelled individually or using the porous media averaging technique where the vegetation is modelled as a porous medium. Porous media are materials characterized by a solid matrix interspersed with voids or pores filled with fluid. The complexities of such systems arise from the heterogeneity of the material, necessitating effective averaging techniques to simplify analysis while retaining physical accuracy. Key parameters include porosity ( $\epsilon$ ), which represents the fraction of the total volume occupied by pores and permeability ( $k$ ), a measure of the ease with which fluid flows through the pores. Table 2 summarises advantages, limitations and applications of porous media averaging and pore-scale technique.

Table 2: Advantages and limitations of pore-scale and averaging techniques

| Technique              | Advantages                                                                                                                                                                      | Limitations                                                                                                                                                         | Applications                                                                                                                                       | References                    |
|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| Porous Media Averaging | <ul style="list-style-type: none"> <li>• Computationally efficient</li> <li>• Easily implemented in ANSYS or CFD tools</li> <li>• Captures bulk hydraulic resistance</li> </ul> | <ul style="list-style-type: none"> <li>• Assumes uniform vegetation density</li> <li>• Limited insight into turbulence mechanisms</li> </ul>                        | <ul style="list-style-type: none"> <li>• Full-scale CW modelling</li> <li>• Root-zone resistance studies</li> <li>• Design optimization</li> </ul> | Sonnenwald et al. (2019)      |
| Pore-Scale             | <ul style="list-style-type: none"> <li>• High accuracy and physical detail</li> <li>• Resolves wakes, turbulence, mixing</li> <li>• Captures heterogeneity directly</li> </ul>  | <ul style="list-style-type: none"> <li>• Extremely computationally expensive</li> <li>• Limited to small domains</li> <li>• Difficult for full-scale CWs</li> </ul> | <ul style="list-style-type: none"> <li>• Mesocosm-scale or laboratory-scale studies</li> <li>• Validation of porous model</li> </ul>               | Ranjbarzadeh and Sappa (2025) |

For flow through porous media, resistance is characterized by a viscous resistance ( $\alpha$ ) or inverse of absolute permeability ( $1/k$ ) and an inertial resistance ( $\beta$ ) to model the pressure drop

139 due to the medium. The viscous resistance coefficient,  $\alpha$  is expressed according to Ergun (1952)  
 140 as;

$$\alpha = \frac{150(1 - \epsilon)^2}{\epsilon^3 d_p^2} \quad (1)$$

141 and the inertial coefficient,  $\beta$  is obtained by Ergun correlation (Ergun, 1952);

$$\beta = \frac{1.75(1 - \epsilon)}{\epsilon^3 d_p} \quad (2)$$

142 where,  $\epsilon$  is the void fraction (porosity);  $d_p$  is the diameter of the particles. As fluid flows  
 143 through a packed bed, pressure drop due to friction between the fluid and the solid particles  
 144 can be quantified using the Ergun equation (Ergun, 1952):

$$\Delta p = \frac{150(1 - \epsilon)^2 \mu v}{\epsilon^3 d_p^2} + \frac{1.75(1 - \epsilon) \rho v^2}{\epsilon^3 d_p} \quad (3)$$

145 where,  $\Delta p$  is the pressure drop;  $\epsilon$  is the void fraction or porosity  
 146 ( $\epsilon = \frac{V_{total} - V_{solid}}{V_{total}}$ ),  $V_{total}$  is the volume of total;  $V_{solid}$  is volume of solid;  $\mu$  is the dynamic  
 147 viscosity of the fluid;  $v_s$  is the superficial velocity;  $d_p$  is the diameter of the particles;  $\rho$  is the  
 148 density of fluid.

149 The computational domain was divided into hybrid mesh elements based on the complexity  
 150 of the geometry and expected flow behaviour consisting of uniform tetrahedral and hexahedral  
 151 elements. A finer mesh was assigned to inlet and outlet and wall boundaries, around vegetation  
 152 distribution patterns, and near the water surface, while coarser mesh elements were used in  
 153 uniform flow regions to reduce computational cost. The near-wall regions were refined using  
 154 inflation layers to model shear effects and turbulence accurately. To ensure numerical stability,  
 155 smooth transitions between fine and coarse mesh regions were maintained. Mesh quality was  
 156 assessed resulting in a maximum aspect ratio of 23.87 and a maximum cell skewness of 0.991.  
 157 This range of aspect ratio and skewness ensures against element stretching and orthogonality  
 158 was checked by aligning mesh elements with the flow direction. Model convergence was  
 159 assessed using mesh resolutions of 8 mm and 10 mm, tracking the  $x$ ,  $y$  and  $z$ -velocities to ensure  
 160 convergence. The final mesh was exported to ANSYS Fluent setup where boundary conditions,  
 161 turbulence models, and solver settings were applied for numerical simulation. The final mesh  
 162 adopted for the wetland can be found in Supplementary Section (Figure S1).

## 2.2 Model setup and validation

### 2.2.1 Validation with experimental data

The model was first validated against a full-scale constructed wetland experimentally under controlled laboratory conditions (Idris, 2026), (Idris et al., 2026). A plan view of the experimental constructed wetland setup is presented in Fig. 1.

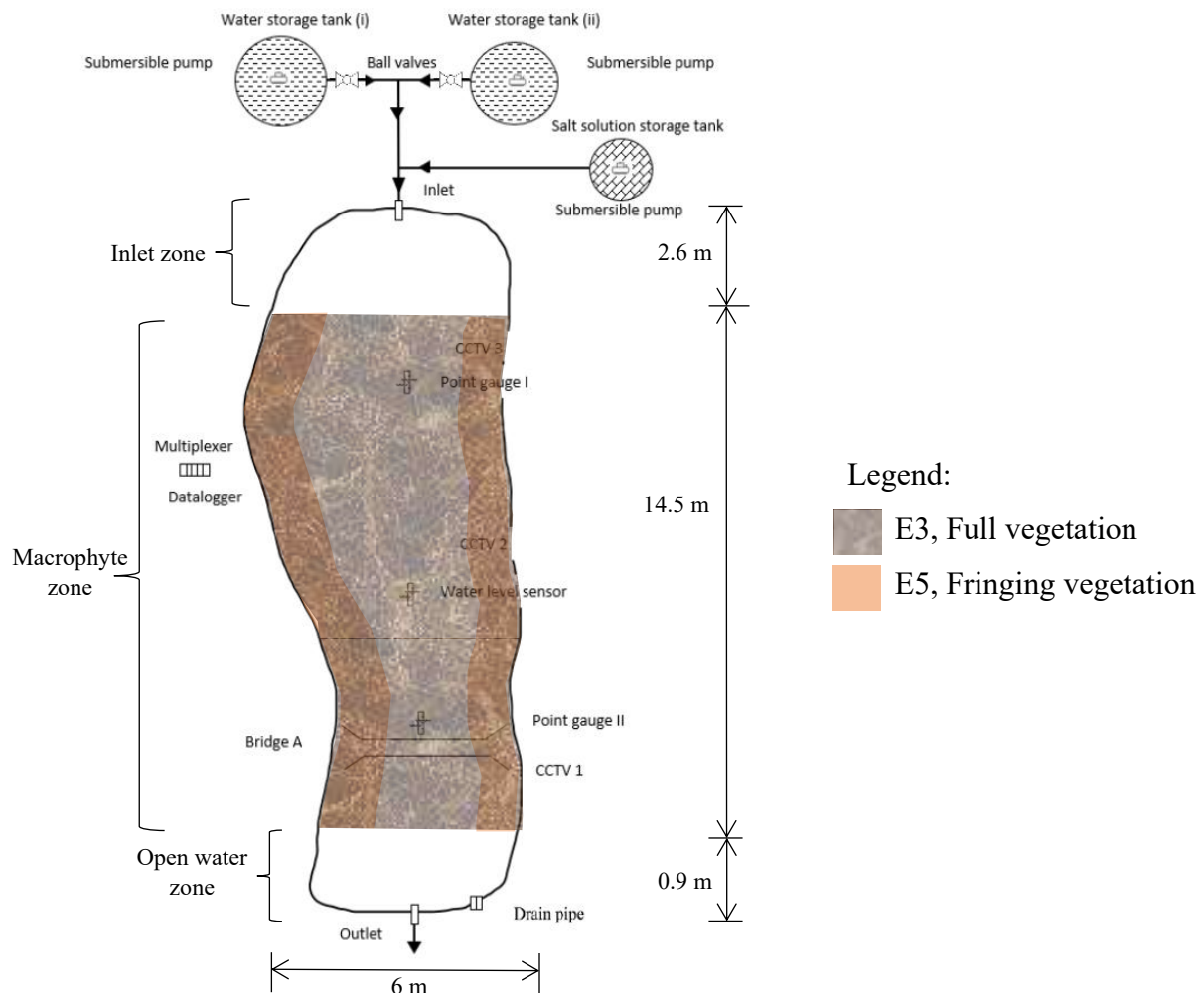


Fig. 1: Plan view of the experimental constructed wetland

The validation of the RTD curves is essential in assessing the accuracy of the simulated wetland model in predicting tracer transport dynamics. RTD analysis provides insights into flow characteristics such as dispersion, short-circuiting, and dead zones, which can significantly influence the performance of constructed wetlands (Kadlec and Wallace, 2008). The modelled cumulative distribution function (F-curve) should closely match experimental data to confirm that the model accurately represents the recovery of tracers under different

vegetation distributions. Hydraulic performance indicators are commonly adopted for evaluating the effectiveness of the constructed wetland in conveying and retaining flow. Previous studies have shown that these indicators are related to treatment performance (Filho et al., 2018; Guo et al., 2017; Idris et al., 2024). The indices compared are the short-circuiting index ( $S$ ), hydraulic efficiency ( $\lambda$ ), effective volume ratio ( $e$ ), and variance of residence time distribution ( $\sigma^2$ ).

Short circuiting,  $S$  occurs when water flows too quickly through the system, bypassing the areas where interaction with the vegetation should take place. This leads to reduced retention times and less effective treatment. According to Guo et al. (2015) and Thackston et al. (1987), the short-circuit indicator  $S$  is defined as:

$$S = \frac{t_{10}}{t_n} \quad (4)$$

where,  $t_{10}$  is the time for 10% of the tracer to exit the wetland (h). For  $S$  values near to 1, the condition indicates low or no short-circuiting, whereas  $S$  values near to 0 indicate high short-circuiting. Hydraulic efficiency,  $\lambda$  provides an overall indicator of how closely the hydraulics of constructed wetlands approach ideal plug-flow behaviour, considering both short-circuiting and dispersion. Higher  $\lambda$  values generally correspond to closer to plug flow, less short-circuiting and dead zones while lower values indicate poorer hydraulic performance. According to Persson et al. (1999) and Shih et al. (2013),  $\lambda$  is defined as:

$$\lambda = \frac{t_p}{t_n} \quad (5)$$

For  $\lambda$  values  $> 0.75$ , the condition indicates good hydraulic efficiency, while  $\lambda$  between 0.5 and 0.75 it indicates satisfactory hydraulic efficiency whereas if  $\lambda \leq 0.5$  it indicates poor hydraulic efficiency. Volumetric efficiency,  $e$  reflects how effectively the wetland volume is utilized. The relationship between  $\tau$  and  $t_n$  can be used to estimate  $e$ . According to Guo et al. (2015), Persson (2000), Sabokrouhiyeh et al. (2017) and Thackston et al. (1987),  $e$  is expressed as:

$$e = \frac{\tau}{t_n} \quad (6)$$

The nominal or hydraulic residence time,  $t_n$  is defined as:

$$t_n = \frac{V}{Q} \quad (7)$$

where,  $V$  is the wetland water volume ( $\text{m}^3$ ), and  $Q$  is the volumetric flow rate ( $\text{m}^3/\text{day}$ ). The mean HRT,  $\tau$  (or  $t_{\text{mean}}$ ) is defined as:

$$\tau = \int_0^{\infty} tf(t)dt = \sum_{i=1}^n tf(t)dt \quad (8)$$

$$f_t = \frac{C(t)}{\int_0^{\infty} C(t) dt} \quad (9)$$

where,  $t$  is the time taken (h),  $dt$  is the lag between sample data (h),  $f(t)$  is the hydraulic residence time distribution function ( $\text{h}^{-1}$ ),  $C(t)$  is the tracer concentration at time  $t$  (mg/L). For  $e$  values near to 1, the condition indicates no dead zone, whereas  $e$  values near to 0, the condition indicates dead zone occur.

Three cases of planting were compared, no vegetation (E1), full vegetation (E3) where plants are placed along the entire 14.5 m macrophyte zone and fringing vegetation (E5) where plants are placed over the same length as E1 but confined to a 1 m width strip along the edges of the wetland (Fig. 1). Artificial emergent plants were planted at a density of 10 plants/ $\text{m}^2$  (Malaysia, 2012). The inflow rate for the experiments was 1.1  $\text{m}^3/\text{h}$ , calculated based on residence time of 24 hrs. Artificial plants were assumed to be rigid and non-deformable, which neglects plant reconfiguration under flow and may overestimate hydraulic resistance under high velocity conditions. However, this assumption is considered reasonable for low flow wetland systems and has also been adopted in previous studies (Aydoğdu, 2025; Tsavdaris et al., 2013b).

### 2.2.2 Generic CFD model

Following validation of the CFD model, the generic (rectangular) FS CWs or generic model, was developed the impact of varying vegetation distribution patterns and planting densities on hydraulic performance. A length:width (L:W) ratio of 3:1 was adopted, consistent with design guidelines for constructed wetlands. A rectangular CW configuration is chosen over an irregular shape due to several key advantages. Firstly, rectangular geometries simplify computational modelling, reducing mesh complexity and processing time in hydrodynamic simulations (Kadlec and Wallace, 2008). This facilitates faster and more accurate numerical analyses, making it easier to test different vegetation distribution patterns and vegetation density. Secondly, a standardized shape improves reproducibility, allowing future researchers to compare results and apply findings to similar systems without extensive shape-specific modifications. Additionally, the rectangular design provides a clear and organized framework for adjusting and testing hydraulic models, ensuring that the simulations align better with experimental data and field measurements (Su et al., 2009; Wei et al., 2025).

Four vegetation distribution patterns were considered comprising no vegetation, full vegetation, fringing vegetation, and banded vegetation. Assuming ideal growth conditions and efficient rhizome packing, planting densities of 36, 17, and 8 plants per square meter are recommended based on a 4 cm rhizome width (Murphy, 2022). These vegetation quantities were then used to calculate the corresponding porosity values, which were determined to be 0.25, 0.65, and 0.84, respectively, where a porosity of 1 is all fluid, and 0 is fully planted. A summary of the generic full-scale FS CW model for numerical simulations is provided in Table 3. The porosity values were adopted for the porous media averaging technique in ANSYS Fluent. Figs. S2 to S7 in the Supplementary Section illustrate the distribution pattern and plant densities for the generic model. Although artificial plants do not capture detailed plant flow structures, it provides a reasonable representation of plants induced resistance at the system scale, which is the primary focus of this study (Aydoğdu, 2025; Liu et al., 2019; Tsavdaris et al., 2013b).

Table 3: Details on generic full-scale FS CW model for numerical simulations

| Case ID | Vegetation distribution type | Velocity (m/s) | Dimension of vegetation coverage ( $w \times l$ ) (m) | Total area of vegetation ( $m^2$ ) | Porosity | Plant density (plant/ $m^2$ ) |
|---------|------------------------------|----------------|-------------------------------------------------------|------------------------------------|----------|-------------------------------|
| FU1     | Full                         | 0.622          | $6 \times 14.5$                                       | 87                                 | 0.25     | 36                            |
| FU2     | Full                         | 0.622          | $6 \times 14.5$                                       | 87                                 | 0.65     | 17                            |
| FU3     | Full                         | 0.622          | $6 \times 14.5$                                       | 87                                 | 0.84     | 8                             |
| FR1     | Fringing                     | 0.622          | $1.5 \times 14.5$                                     | 43.5                               | 0.25     | 36                            |
| FR2     | Fringing                     | 0.622          | $1.5 \times 14.5$                                     | 43.5                               | 0.65     | 17                            |
| FR3     | Fringing                     | 0.622          | $1.5 \times 14.5$                                     | 43.5                               | 0.84     | 8                             |
| FR4     | Fringing                     | 0.622          | $0.75 \times 14.5$                                    | 21.75                              | 0.25     | 36                            |
| FR5     | Fringing                     | 0.622          | $0.75 \times 14.5$                                    | 21.75                              | 0.65     | 17                            |
| FR6     | Fringing                     | 0.622          | $0.75 \times 14.5$                                    | 21.75                              | 0.84     | 8                             |
| BA1     | Banded                       | 0.622          | $6 \times 1.2$                                        | 43.5                               | 0.25     | 36                            |
| BA2     | Banded                       | 0.622          | $6 \times 1.2$                                        | 43.5                               | 0.65     | 17                            |
| BA3     | Banded                       | 0.622          | $6 \times 1.2$                                        | 43.5                               | 0.84     | 8                             |
| BA4     | Banded                       | 0.622          | $3 \times 1.2$                                        | 21.75                              | 0.25     | 36                            |
| BA5     | Banded                       | 0.622          | $3 \times 1.2$                                        | 21.75                              | 0.65     | 17                            |
| BA6     | Banded                       | 0.622          | $3 \times 1.2$                                        | 21.75                              | 0.84     | 8                             |
| NV      | No vegetation                | 0.622          | 0                                                     | 0                                  | 1.00     | 0                             |

245

246 **2.3 Simulation procedure**

247 A total of 19 simulations were carried out, with 3 were used for validation with the NIS  
 248 CW (Section 2.2.2) and the remainder 16 simulations for the generic (rectangle) CWs (Table  
 249 3). The steps adopted for each model run are as follows:

250 **Step 1:** The flow field was solved with the steady state solver to initialise the model. After 900  
 251 s, the solver was switched to transient.

252 **Step 2:** The transition shear stress transport (SST)  $k-\omega$  was adopted as the turbulence model  
 253 as this this model best represented the experimental RTDs conducted compared to other

turbulence models. The model constants were set to default values. The SST k-  $\omega$  model was also used by Machado Xavier et al. (2018), Yamasaki et al. (2022) and Nuruzzaman et al. (2023) where they obtained good agreement of validations.

**Step 3:** Then, salt tracer injection was specified. The salt tracer was injected for 1,800 s with a total mass flow rate of 0.0189 kg/s. The properties for salt tracers were defined as tabulated in Table 4.

Table 4: Properties of salt tracer and water (at 25°C)

| Item       | Parameter                                      | Data     |
|------------|------------------------------------------------|----------|
| Properties | Density of water, $\rho$ (kg/m <sup>3</sup> )  | 998.2    |
|            | Density of tracer, $\rho$ (kg/m <sup>3</sup> ) | 1,029    |
|            | Viscosity of water, $\mu$ (kg/m.s)             | 0.001003 |
|            | Viscosity of saline, $\mu$ (kg/m.s)            | 0.00088  |

**Step 4:** Cell zone conditions: The fluid body was set to all zones, while porous body was assigned to vegetated zones. Viscous resistance ( $\alpha$ ) and inertial resistance ( $\beta$ ) were determined from Equations (1) and (2).

**Step 5:** Boundary conditions settings: The boundary condition of inlet and outlet are velocity inlet and pressure outlet, respectively. The inlet velocity is calculated from the inflow rate used in this paper with given inlet diameter. The outlet pressure is equal to the atmospheric pressure 101,325 Pa. The wall was assumed to be stationary wall boundary conditions with no slip flow. Illustrations of computational domains with specified boundary conditions are provided in the Supplementary Section (Fig. S8) The boundary conditions data are shown in Table 5.

271

Table 5: Boundary condition

| Item                | Parameter                             | Data                                     |
|---------------------|---------------------------------------|------------------------------------------|
|                     | Initial Gauge Pressure                | 0 Pa                                     |
|                     | Velocity Specification Method         | Magnitude, Normal to Boundary            |
|                     | Inlet velocity of water, $V_i$ (m/s)  | 0.622 (24 hrs HRT)<br>1.245 (12 hrs HRT) |
| Boundary conditions | Inlet velocity of tracer, $V_i$ (m/s) | 0.622 (24 hrs HRT)<br>1.245 (12 hrs HRT) |
|                     | Outlet pressure                       | 101,325 Pa                               |
|                     | Wall                                  | No slip flow                             |
|                     | Discrete phase model wall             | Reflect                                  |
|                     | Discrete phase model inlet            | Escape                                   |
|                     | Discrete phase model outlet           | Escape                                   |

272

273 **Step 6:** Solution method setting: Then, the SIMPLE solutions method was adopted. Residuals  
274 for  $x$ ,  $y$  and  $z$ -velocity were set at 0.00001.

275 **Step 7:** The time step was set to 10 s and 18,000 number of time steps was defined,  
276 corresponding to 48 hrs of simulation time.

277 **Step 8:** The model was initialized before running the calculation noting that it is important to  
278 check the solution to see if there is any recommendation from ANSYS Fluent. Tracer mass  
279 exiting at the outlet was sampled over time.

280 **Step 9:** Simulation continued for up to 48 hours after tracer injection, from which the simulated  
281 RTD curves and hydraulic performance indices were derived. Tecplot software (Zhao et al.,  
282 2025) was used to visualize the simulation. To enable realistic comparison with the  
283 experimental results, a noise-reduction filter was applied in MATLAB to reduce high-  
284 frequency noise in the CFD model results, while preserving the underlying physical trends.

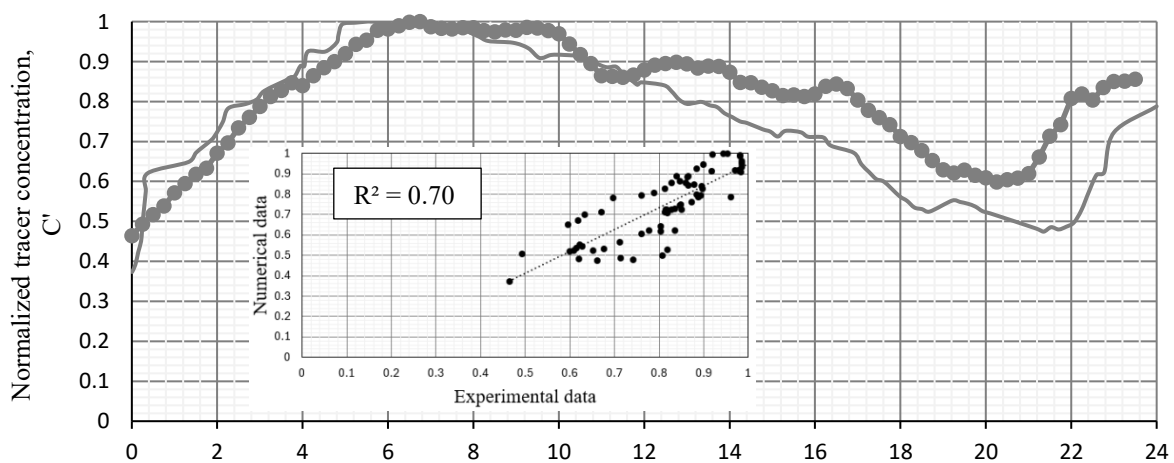
### 285 3. Results and Discussion

#### 286 3.1 Validation

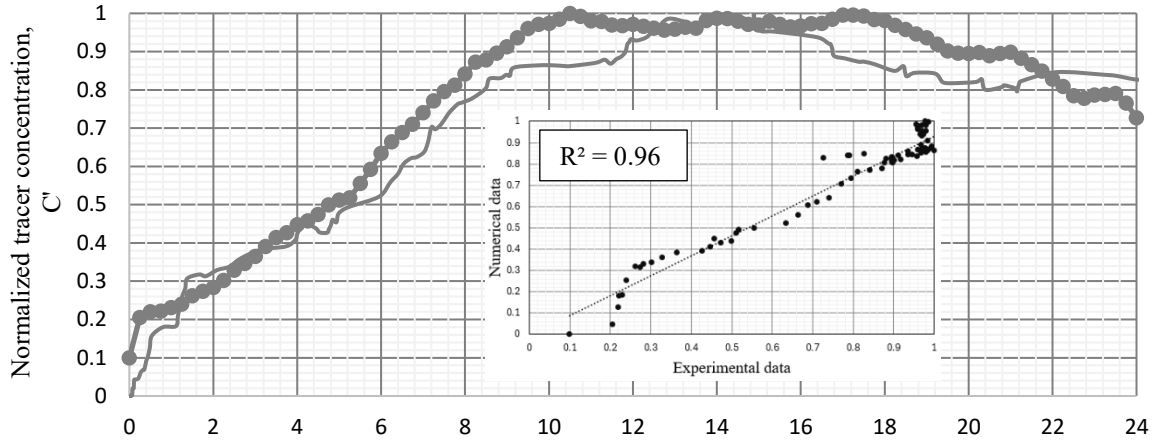
287 In the CFD porous media model, the viscous resistance term was defined using the absolute  
288 permeability ( $1/k$ ) where higher viscous resistance increases the pressure gradient required to  
289 drive flow and attenuates velocity within the porous zone (Ranjbarzadeh and Sappa, 2025). A

sensitivity analysis was conducted to evaluate the influence of  $1/k$  on the model results. Values of  $1/k = 1 \times 10^{-1}$ ,  $1 \times 10^{-3}$ ,  $5 \times 10^{-3}$ ,  $8 \times 10^{-3}$  and  $1 \times 10^{-6} \text{ m}^2$  were tested and the model RTD curves compared with experiments. The value of  $1/k = 7.62 \times 10^{-3} \text{ m}^2$  achieved the best agreement with the experimental RTD curves. This value is between the value of  $1 \times 10^{-7} \text{ m}^2$  reported by Machado Xavier et al. (2018) and  $1.418 \times 10^{-5} \text{ m}^2$  by Yamasaki et al. (2022) who adopted free surface boundary condition in ANSYS for floating wetland applications. Based on the range of  $k$  reported, the value obtained in this study is considered reasonable.

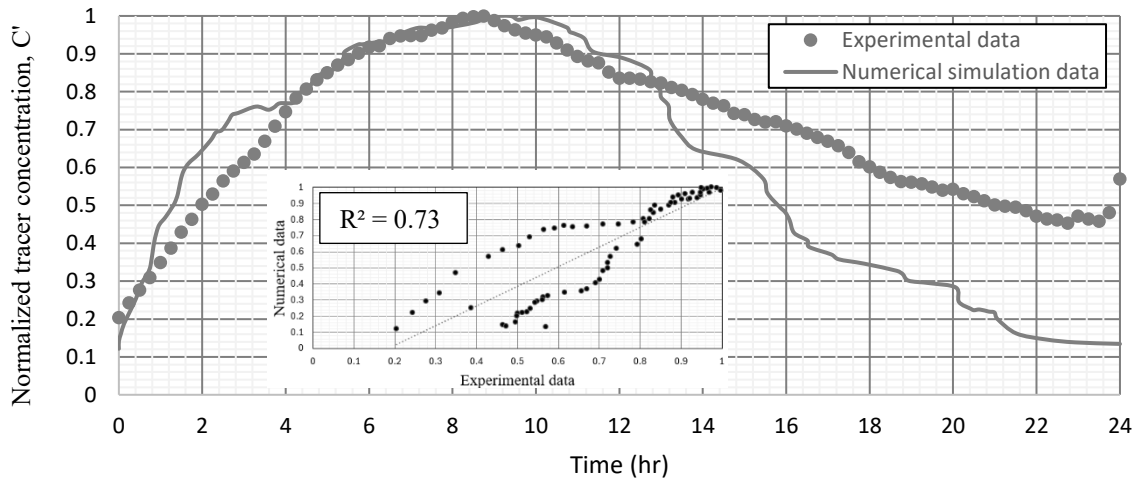
As shown in Fig. 2(a.) the modelled RTD curve for the no vegetation case predicts a peak at about 6 hrs, similar to the experimental results. Both model and experimental results show a slight increase in tracer concentration near the end of the simulation period. The increase might be attributed to delayed tracer release from dead zones and internal recirculation within the wetland. In the absence of vegetation, the flow is less structured, which promotes the formation of large eddies and trapped tracer mass in stagnant zones that gradually re-enter the main flow path (Runkel, 2015; Shih et al., 2017). The full vegetation case (Fig. 2(b.)) shows a more extended tracer retention period, evidenced by the slow decrease in concentration after the peak has passed at about 17 hrs. This delay both in the time to peak and discharge of tracer from the wetland is consistent with the expected increased flow resistance and mixing caused by dense vegetation. The fringing vegetation case (Fig. 2(c.)) demonstrates an intermediate behaviour, where fringing vegetation introduced some dispersion while the open central zone allowed relatively direct and faster flow paths. The  $R^2$  values obtained show that the model results are in good agreement with the experimental RTD curves. In general, the model results exhibit similar trends and peak times compared to the experimental results.



(a) Case E1, no vegetation distribution pattern



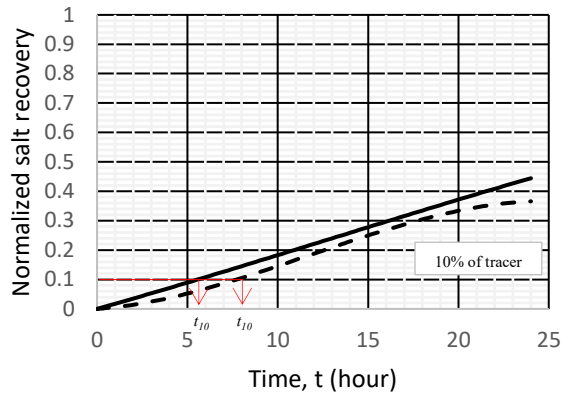
(b) Case E3, full vegetation distribution pattern



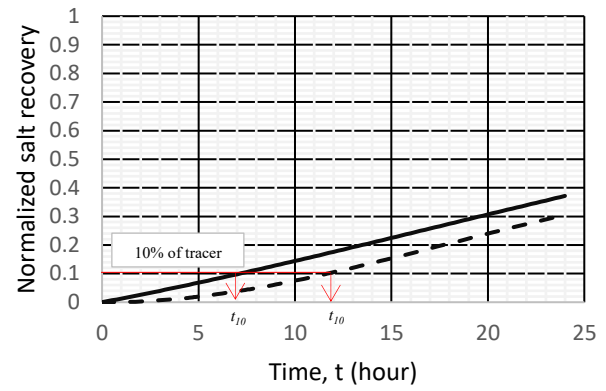
(c) Case E5, fringing vegetation distribution pattern

Fig. 2: Validation of full-scale experimental FS CW CFD model for (a) E1 (no vegetation), (b) E3 (full vegetation) and (c) E5 (fringing vegetation) distribution patterns.

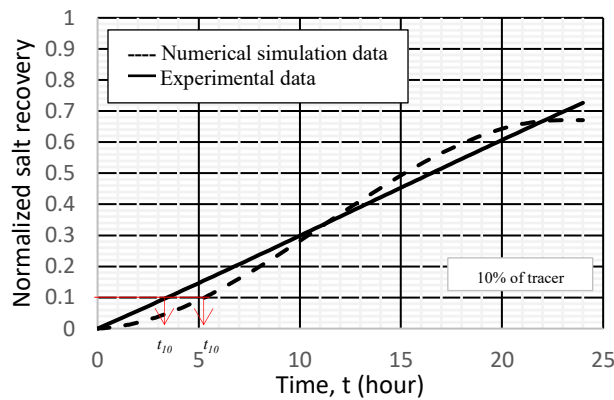
Fig. 3 presents a comparison of F-curve for the three validation cases. The results indicate a good agreement between the simulated and experimental tracer mass recovery rates across all vegetation distribution patterns. The simulated recovery rates for no, full, and fringing vegetation distribution pattern CWs are 36.6, 30.6, and 67.1%, respectively, as compared to experimental values of 44.4, 37.2 and 72.6%. In terms of the total mass (in kilograms) of salt recovered, the model predictions were 20.1, 16.8 and 36.9 (kg) for the no vegetation, full vegetation and fringing vegetation test cases. This compares favourably with the experimental mass recovery rates of 24.4, 20.4 and 40.0 (kg) for the three test cases, respectively. In all three cases, the initial recovery rate for the model is slower compared to the experimental results, which may account for the overall lower rate of recovery in the model results.



(a) Case E1, no vegetation distribution pattern



(b) Case E3, full vegetation distribution pattern



(c) Case E5, fringing vegetation distribution pattern

Fig. 3: Comparison of normalized salt recovery of (a) E1 (no vegetation), (b) E3 (full vegetation) and (c) E5 (fringing vegetation) distribution patterns.

Fig. 4 presents a comparison of the simulated hydraulic performance of a constructed wetland model and experimental data for validation (detailed results can be found in Table S1 of the Supplementary Section). For the short-circuiting index ( $S$ ), the numerical model showed noticeable variation, particularly in E3 and E5 (Table S3 in Supplementary Section), with deviations of 58% and 69%, respectively. This discrepancy may be attributed to the difficulty in capturing early tracer breakthroughs and a less pronounced peak in vegetated configurations, where flow paths become increasingly complex. This is consistent with the observation that the model performed better for E1, in the absence of vegetation, where the deviation in results was lowest. Model and experimental comparisons for the hydraulic efficiency  $\lambda$  showed better agreement, especially for E5, with only a 5% deviation and 21% and 34% for E1 and E3, respectively. The effective volume ratio,  $e$  demonstrated good agreement across all test cases with variation of 2%, 20% and 8% for E1, E3 and E5, respectively. Finally, variance,  $\sigma^2$  which reflects the spread of residence times showed high accuracy in the fringing vegetated case (E5,

7% deviation) but significantly deviations in E1 (37%) and E3 (80%). Larger variation could also be contributed by the choice of boundary conditions in simulations. These findings are consistent with findings by Min and Wise (2009) who highlighted the influence of vegetation distribution on tracer movement and short-circuiting in CWs.

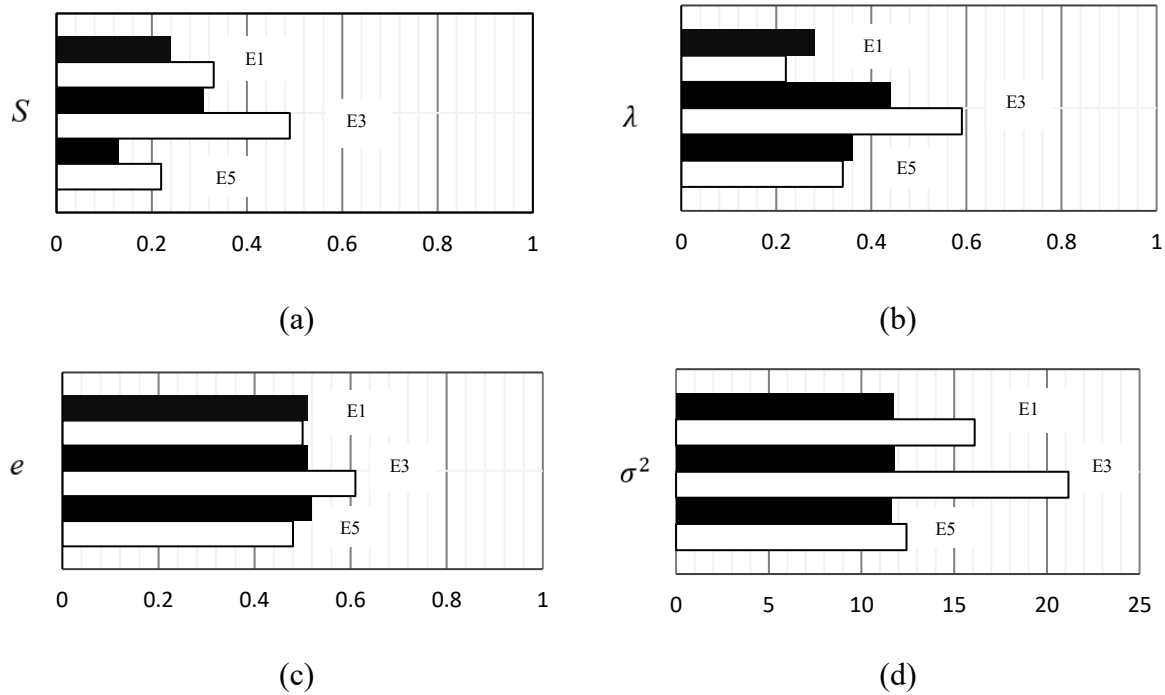
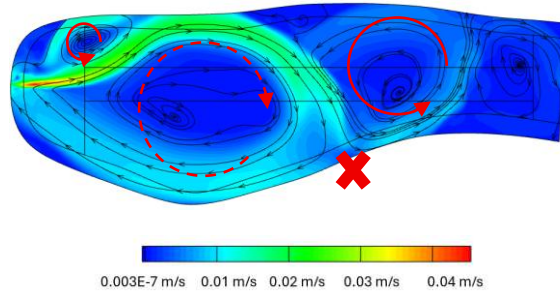


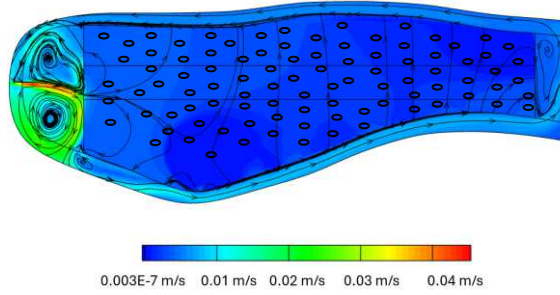
Fig. 4: Comparison of the simulated (hollow bars) and experimental (filled bars) hydraulic performance of a constructed wetland model for validation

Previous research in confined jets such as Jirka and Harleman (1973) demonstrate that a horizontal discharge into a restricted domain develops a momentum-dominated core flanked by shear layers that induce coherent recirculation cells. In the case of buoyant flows, the evolution of a horizontal jet is governed by the densimetric Froude number and the relative channel dimensions, which together determine the extent of lateral spreading, wall interaction, and mixing efficiency. These observations provide a conceptual understanding of jet development in confined environmental flows, which are applicable to conditions characteristic of constructed wetlands. The analysis of velocity contour highlights the impact of vegetation distribution on flow behaviour. Velocity contours and streamlines were generated on a horizontal plane passing through the midpoint of the inlet at a depth of 0.15 m to observe the flow field, shown in Fig. 5(a.). The figures qualitatively reveal nonuniformity, circulation patterns, and stagnation points in the flow field. Without vegetation, the flow is dominated by large scale recirculation patterns, with a primary vortex in the clockwise direction (dashed line),

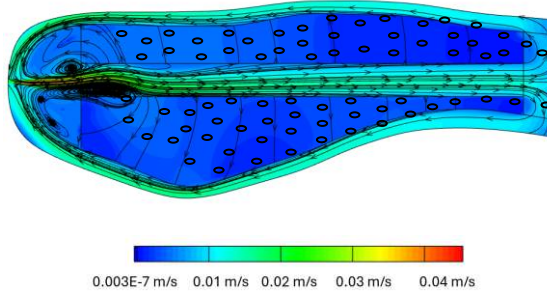
impinging the sidewall at X and the formation of two secondary vortices (solid lines) in the counterclockwise direction, via momentum transfer. The formation of these large-scale vortices supports the observation of delayed tracer release from the recirculation zones evidenced by the increase in tracer concentration at the latter stages of the simulation period as observed in Fig. 2(a.). In contrast, the full vegetation case as shown in exhibits a more uniform flow field, devoid of vortical structures. The flow becomes more diffused and uniform (Fig. 5(b.)) and increase in the residence time as evidenced by the slower rate of concentration reduction observed in Fig. 2(b.). In the fringing vegetation case, flow is channelised within the central portion of the wetland, with dead zones on either side in the vegetated portions of the wetland (Fig. 5(c.)). This channelling of the flow field results in a rapid efflux of the tracer seen from the higher rate of increase initially, resulting in a shorter time to peak, followed by a relatively rapid decrease in tracer concentration (Fig. 2(c.)).



(a) Case E1, no vegetation distribution pattern



(b) Case E3, full vegetation distribution pattern



(c) Case E5, fringing vegetation distribution pattern

Fig. 5: Velocity contours and streamlines: (a) E1 (no vegetation), (b) E3 (full vegetation) and (c) E5 (fringing vegetation) distribution patterns

## 3.2 Generic (rectangle) full-scale FS CW model

### 3.2.1 Tracer distribution curves

Fig. 6 illustrates the normalized tracer concentration over time or RTD curve for the different vegetation distribution patterns cases with porosity of 0.65 and the no vegetation case with complete results shown in Fig. S9 in the Supplementary Section. Of all the distribution patterns considered, the full vegetated case comes closest to complete mixing due to flow dispersion, which can be observed by the near uniform flow field, shown in Fig. 7(a) and the time to peak is close  $t_n = 24$  hrs. The full vegetation and banded vegetation cases show times

to peak that are later than the no vegetation and fringing vegetation Fig. 6 shows that the RTD curves for the 3- and 6-banded cases have times to (first) peak at approximately 23 to 28 hours, close to  $t_n$ . The banded distribution has a similar effect as the fully distributed configuration in flow dispersion; the regular arrangement of vegetation in the banded case straightens the flow, revealing almost parallel streamlines (Fig. 7 (d, e, f, g, h, i)). Clear zones of higher and lower velocities are also evident within the banded and non-vegetated regions of the domain, respectively. All the banded cases reveal that the streamlines are essentially straightened after the first band, with flow converging towards the outlet after the last band. Our simulations show that for all porosities investigated, peaking of the RTD curve is delayed for the 3-banded case and peaks closer to the fully distributed case when more bands are introduced (Fig. 6).

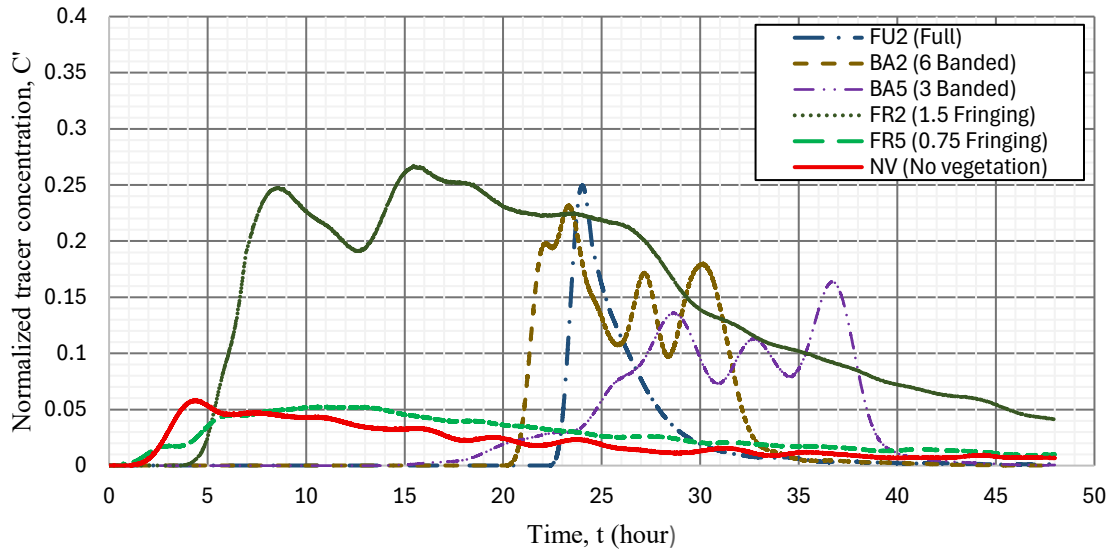
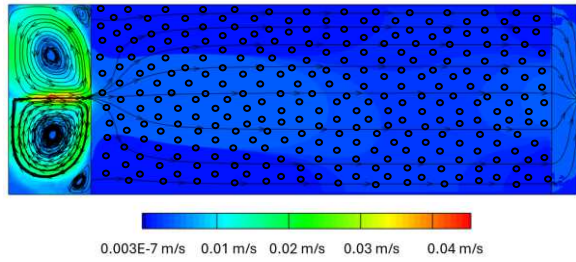


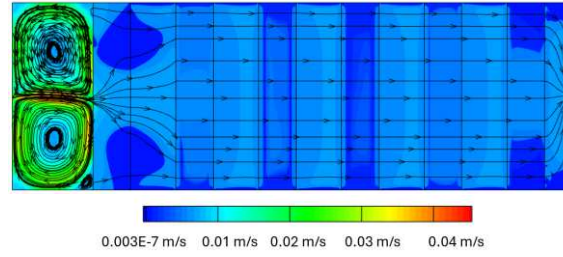
Fig. 6: Normalized tracer concentration over time for the different vegetation cases with porosity of 0.65 and the no vegetation case

In contrast with the fully vegetated and banded distribution cases, the NV and fringing cases show early peaking, with time to (first) peak below  $t_n$ , at about 4 to 8 hrs (Fig. 6). The maximum concentrations are lower with a more gentle tailing of the RTD curve once past the peak. This observation contrasts with the fully or banded vegetation cases where conditions are close to complete mixing resulting in time to peak close to  $t_n$ . Flow patterns for the NV (Fig. 8 (a.)) and FR (Fig. 8(b, c, d, e, f, g)) reveal large vertical structures which scale with the flow width (spacing of clear water between vegetated zones or wall boundary). Flow recirculation results in tracer accumulation and retention that give rise to the occurrence of

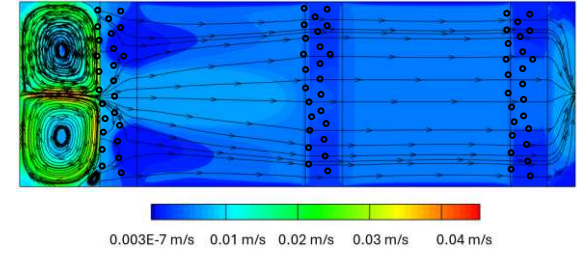
multiple peaks in the RTD curve. FR4, 5 and 6 have a larger flow width and has flow structures that are close to NV; with similar size and number of vortices, resulting in RTD curve close to the NV case This is also observed for other porosities investigated (Fig. S9(c.)). The flow pattern for FR1, 2 and 3 are characterised by a larger number of vortices due to the reduced flow width, resulting in the formation of multiple peaks in the RTD curve. It is also generally (including other porosities tested) observed that concentrations are lower for the 0.75m fringing pattern and the concentration decay less rapidly. The tracer is flushed from the system less quickly (or greater retention) with the narrower 0.75 m fringing. This is a significant result since wetlands are typically planted at the fringes where plants are not completely submerged. These results imply that the fringing pattern is less likely to meet the design residence time requirement.



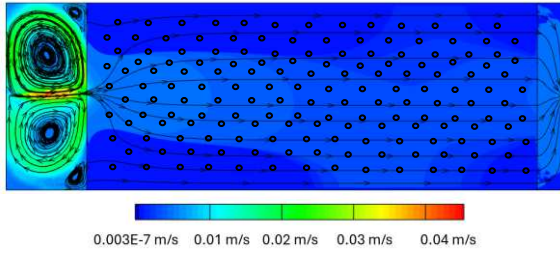
(a) FU1, porosity = 0.25



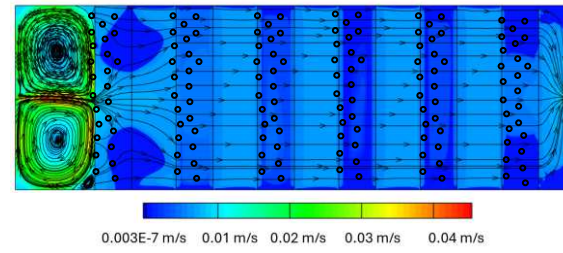
(d) BA1, porosity = 0.25



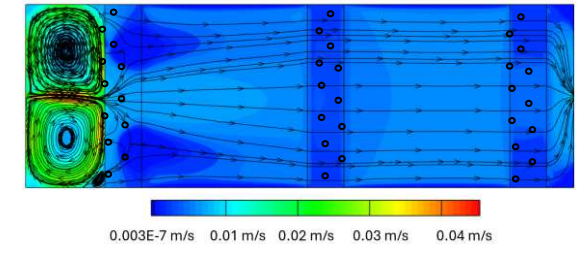
(g) BA4, porosity = 0.25



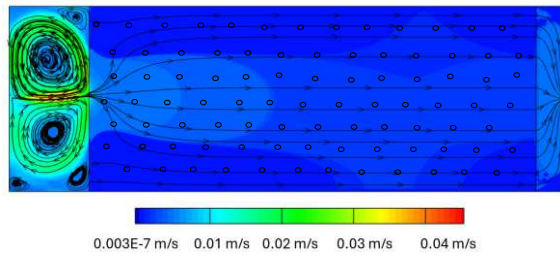
(b) FU2, porosity = 0.65



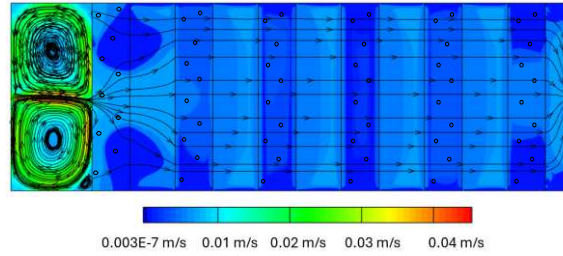
(e) BA2, porosity = 0.65



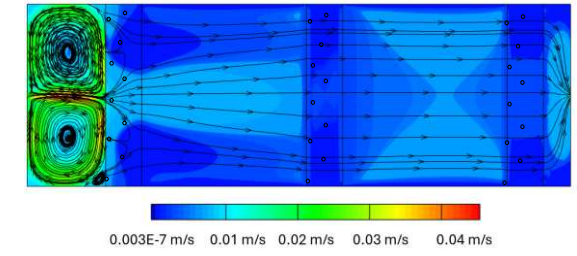
(h) BA5, porosity = 0.65



(c) FU3, porosity = 0.84



(f) BA3, porosity = 0.84



(i) BA6, porosity = 0.84

Fig. 7: Comparison of velocity contours and streamlines for (a, b, c) full vegetation, (d, e, f) 6-banded vegetation and (g, h, i) 3-banded vegetation, for different porosity values

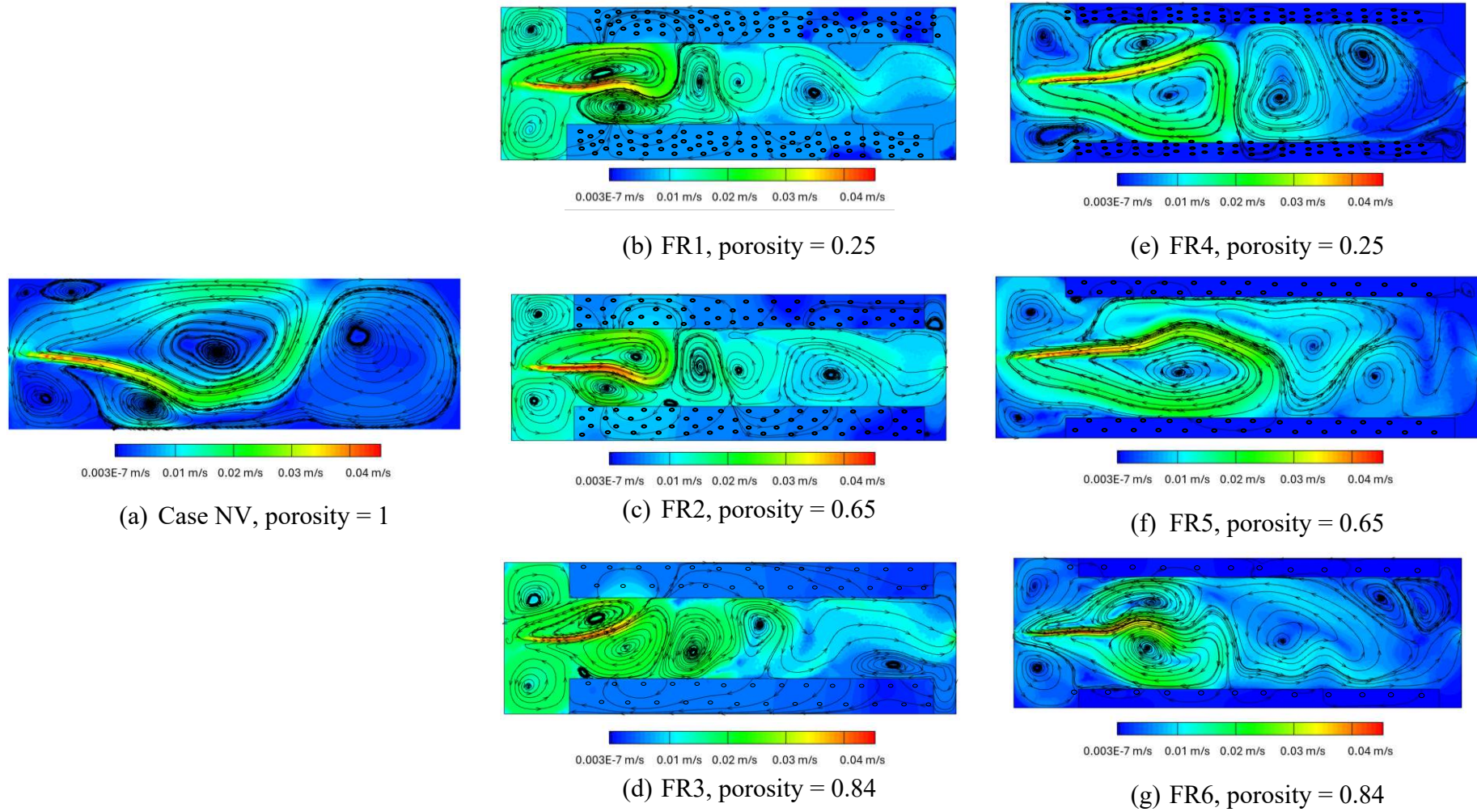


Fig. 8: Comparison of velocity contour and streamline for (a) no vegetation, (b, c, d) 1.5 m fringing vegetation and (e, f, g) 0.75 m fringing vegetation distribution patterns.

The foregoing discussion highlights differences in flow behavior between the FU and BA, and the NV and FR vegetation distribution systems. The fully vegetated and banded cases display similar flow patterns, characterised by a more uniformly distributed flow regime due to the increased dispersion imparted as flow takes place through the vegetation. In contrast, the no vegetation and fringing cases exhibit similar behaviours, with the formation of large recirculation zones with fringing vegetation arrangement further concentrating the flow in the clear water zones between vegetated areas generating multiple, smaller sized eddies. Collectively, these results highlight the dominant influence of vegetation structure and distribution in shaping flow uniformity, mixing, and recirculation within the wetland. This can be further illustrated by the Cumulative Distribution Function or F-curve. Fig. 9 compares the normalized cumulative salt tracer recovery at the outlet for all vegetation distribution patterns, where time ( $\tau$ ) on the  $x$ -axis is normalised by  $t_n$ . The cumulative curves are observed to fall into 2 groups. The FU and BA curves generally show slower initial rate of increase in tracer concentration characterised by the time for the tracer to reach 10% recovery ( $t_{10}$ ), but higher final ( $\tau = 2$ ) recovery. The NV and FR cases exhibit faster initial recovery (smaller  $t_{10}$  values) but having a smaller final recovery. Although these discussions concern CFD simulations for a flat bottom domain, in contrast to field systems which generally have sloping bottom and hence more complicated flow structures, nevertheless, the general conclusions are expected to be applicable to field situations.

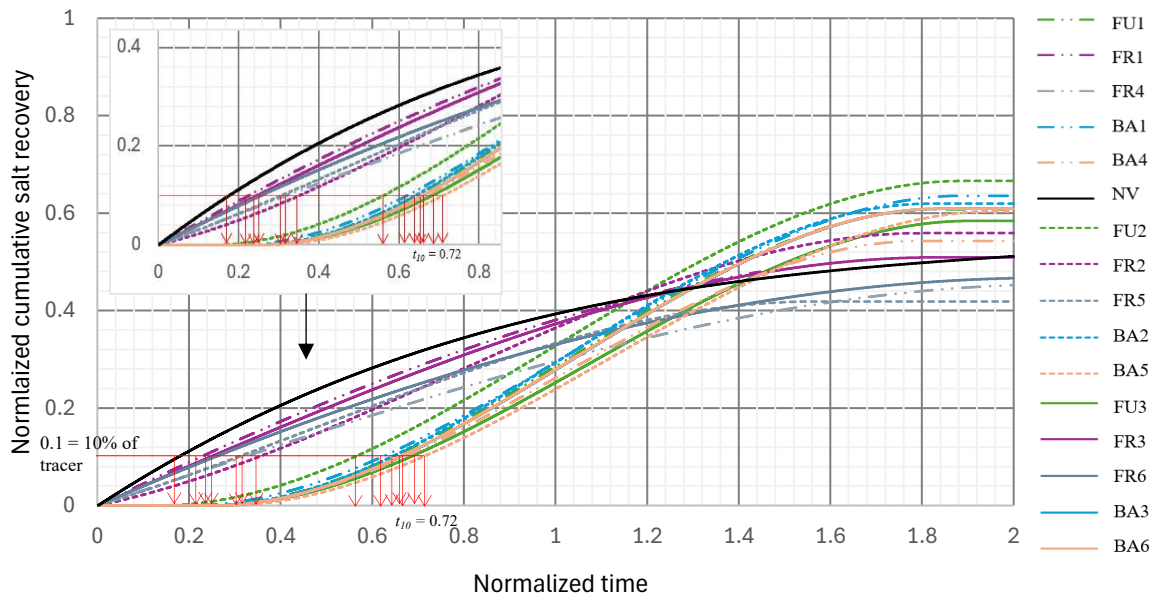


Fig. 9: Normalized cumulative salt tracer recovery at the outlet for all cases.

### 3.2.2 Hydraulic performance

Table 7 summarises results for the hydraulic performance indicators. The FU cases tend to have higher  $S$  values since full vegetation reduces short-circuiting, as obstruction caused by plants enhances dispersion resulting in a fully mixed condition. The fringing vegetation distribution pattern generally results in lower  $S$  values since the space between the vegetation provides a preferential flow path. For instance, FR1 has severe short-circuiting with  $S = 0.24$ , and FR2 shows short-circuiting index,  $S = 0.35$ . The banded vegetation distribution shows relatively less severe short-circuiting, similar to full vegetation, with most cases falling between 0.63 to 0.71. For example, BA1 shows  $S = 0.63$  while BA5 shows a significantly lesser short-circuiting with  $S = 0.71$ . The banded pattern likely allows for greater dispersion within the macrophyte zone, with streamlines parallel to the main axis of flow. The NV case shows the most severe short-circuiting with  $S = 0.18$ . As shown in Fig. 8, the flow is dominated by large vortical structures which are responsible for the early efflux of tracers, giving rise to lower  $t_{10}$  (Fig. 9) and  $S$  values followed by a delay in tracer release from the wetland, as shown by the long tailing in  $C'$  (Fig. 6). The combination of early release and is shows poor hydraulic efficiency as the flow is too rapid to allow for proper interaction with the vegetation.

Table 7: Hydraulic performance of simulated case studies for different distribution patterns and porosity

| Case ID | Case Name          | $t_n$<br>(h) | $t_p$ (h) | $t_{10}$<br>(h) | $S$<br>( $t_{10} / t_n$ ) | $\lambda$<br>( $t_p / t_n$ ) | $e$<br>( $\tau / t_n$ ) | $\tau$<br>(Eq.2-2) | $\sigma^2$<br>(Eq. 2-5) |
|---------|--------------------|--------------|-----------|-----------------|---------------------------|------------------------------|-------------------------|--------------------|-------------------------|
| FU1     | Full 0.25          | 24           | 25.2      | 15.95           | 0.66                      | 1.05                         | 1.03                    | 24.78              | 0.20                    |
| FU2     | Full 0.65          | 24           | 24        | 14.00           | 0.59                      | 1.0                          | 1.00                    | 24.22              | 0.19                    |
| FU3     | Full 0.84          | 24           | 25.5      | 16.50           | 0.69                      | 1.06                         | 1.07                    | 25.81              | 0.22                    |
| FR1     | 1.5 Fringing 0.25  | 24           | 10        | 5.80            | 0.24                      | 0.46                         | 0.69                    | 16.51              | 0.34                    |
| FR2     | 1.5 Fringing 0.65  | 24           | 15.5      | 8.30            | 0.35                      | 0.50                         | 0.81                    | 19.35              | 0.20                    |
| FR3     | 1.5 Fringing 0.84  | 24           | 8.2       | 6.00            | 0.25                      | 0.50                         | 0.70                    | 16.68              | 0.26                    |
| FR4     | 0.75 Fringing 0.25 | 24           | 5.9       | 7.95            | 0.33                      | 0.51                         | 0.79                    | 19.04              | 0.41                    |
| FR5     | 0.75 Fringing 0.65 | 24           | 13.2      | 7.50            | 0.31                      | 0.55                         | 0.64                    | 15.36              | 0.23                    |
| FR6     | 0.75 Fringing 0.84 | 24           | 7.5       | 6.10            | 0.25                      | 0.54                         | 0.72                    | 17.37              | 0.39                    |
| BA1     | 6 Banded 0.25      | 24           | 26.85     | 15.05           | 0.63                      | 0.15                         | 1.04                    | 25.02              | 0.23                    |
| BA2     | 6 Banded 0.65      | 24           | 23.20     | 15.00           | 0.63                      | 1.07                         | 1.03                    | 24.66              | 0.12                    |
| BA3     | 6 Banded 0.84      | 24           | 25        | 15.03           | 0.63                      | 1.13                         | 1.05                    | 25.09              | 0.20                    |
| BA4     | 3 Banded 0.25      | 24           | 27        | 15.95           | 0.66                      | 1.27                         | 1.05                    | 25.17              | 0.21                    |
| BA5     | 3 Banded 0.65      | 24           | 36.5      | 16.95           | 0.71                      | 1.37                         | 1.12                    | 26.85              | 0.23                    |
| BA6     | 3 Banded 0.84      | 24           | 26.85     | 16.90           | 0.70                      | 1.12                         | 1.04                    | 25.07              | 0.20                    |
| NV      | No vegetation      | 24           | 4         | 4.2             | 0.18                      | 0.17                         | 0.64                    | 15.42              | 0.40                    |

Nominal residence time,  $t_n$  (h); Time to peak,  $t_p$  (h); Time at 10% tracer response,  $t_{10}$  (h); Volumetric efficiency,  $e$ ; Short-circuit,  $S$  ( $t_{10} / t_n$ ); Hydraulic efficiency,  $\lambda$  ( $t_p / t_n$ )

The results show a wide range of  $\lambda$  values from 0.17 to 1.37. For cases with multiple peaks, the average peak time ( $t_p$ ) was considered in this paper, with the full and banded vegetation distribution patterns having higher  $\lambda$  values. For the full vegetation case, the hydraulic efficiency remains relatively unchanged as porosity increases from 0.25 to 0.65 and 0.84. This is evidenced by the uniformity of the flow patterns between the different porosity cases, even at high porosity values. By contrast,  $\lambda$  reduces to 0.17, in the NV case, with the lower hydraulic efficiency linked to the formation of large recirculation patterns. The reduction in  $\lambda$  associated with the large flow patterns is also evidenced from the lower  $\lambda$  values for FR, intermediate between the NV and FU cases (Table 7). The full (FU1, FU2 and FU3) and banded (BA1 to BA6) vegetation distribution patterns cases demonstrate high volumetric efficiency,  $e \geq 1.0$  which indicates a slower rate of tracer release from the wetland, where the flow has been retained beyond nominal time due to formation of stagnation zones. The fringing vegetation distribution patterns cases have much lower volumetric efficiency,  $0.64 < e < 0.81$ . For example, in Case FR6,  $e = 0.64$  shows that most of the flow exits early before reaching the nominal residence time, leaving little utilization of the remaining volume. An extreme case is the NV case which has a volumetric efficiency,  $e = 0.64$  indicating quicker tracer exit due to the lack of dispersion by vegetation.

### 3.2.3 Comparison between hydraulic indicators

Hydraulic efficiency and short-circuiting are closely related indicators as both describe how effectively inflow mixes within a wetland. Constructed wetland with high hydraulic efficiency typically promotes uniform flow distribution and longer residence time thus reducing the likelihood of short-circuiting, where flow bypasses the vegetation zone too quickly. Conversely, increased short-circuiting often reflects uneven flow paths and stagnant zones, which lower overall hydraulic efficiency. Fig. 10 presents a comparison of hydraulic efficiency and short-circuiting in relation to porosity across different vegetation distribution patterns. The data fall into two groups, the full distribution and banded group which have higher  $\lambda$  and  $S$  values, and the fringing and no vegetation distribution which have lower  $\lambda$  and  $S$  values. The lower  $\lambda$  values associated with no vegetation and fringing distributions are attributed to the non-uniform flow patterns and in the case of the fringing distribution, flow exits more quickly, bypassing the macrophyte zones thus increasing short-circuiting. The no vegetation scenario shows a relatively low short-circuiting value ( $S = 0.18$ ) and a low hydraulic efficiency ( $\lambda = 0.17$ ) reinforcing the idea that vegetation significantly contributes to better flow streamlining

by reducing short-circuiting and enhancing hydraulic efficiency, as evidenced by the location of the data points for the fully planted and banded distributions. The fully planted and banded systems result in flow that is more uniform, and therefore similarity in hydraulic behavior; the large variation in flow patterns in the NV and FR cases account for the larger variation in  $\lambda$  values compared to the closer agreement in  $\lambda$  values for the banded cases. The higher variability in flow behavior and resulting variance can also be demonstrated by comparing the variance  $\sigma^2$  (Fig. S10) indicating that  $\sigma^2$  is generally higher for the fringing and no vegetation cases.

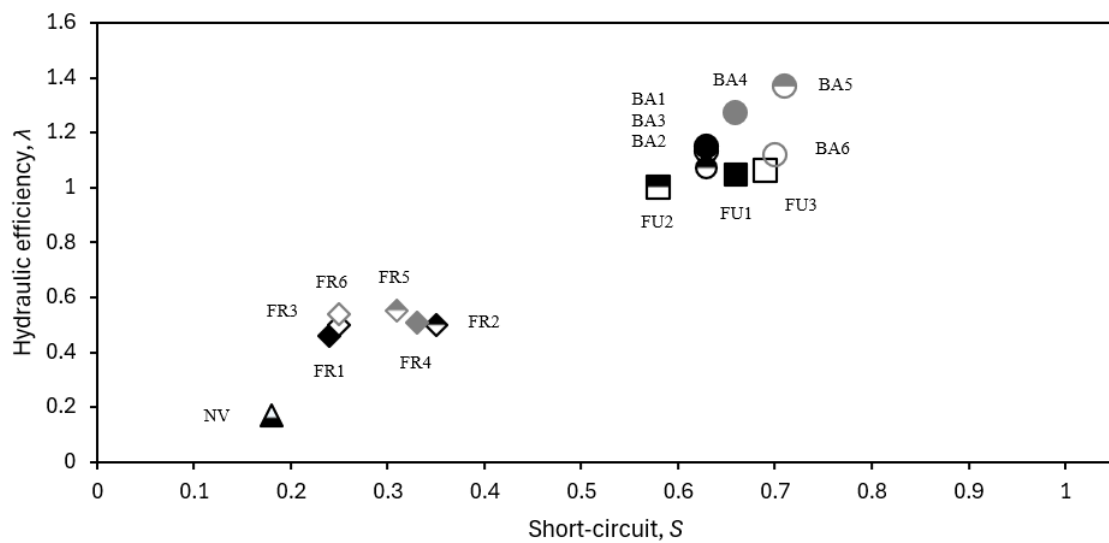


Fig. 10: Comparison of hydraulic efficiency and short-circuiting to porosity.

The analysis of hydraulic efficiency and short-circuiting in relation to porosity validates that these two metrics are closely tied. Good hydraulic efficiency is generally associated with less or no short-circuiting indicating that improving hydraulic efficiency also improves the ability of the system to interact effectively with the vegetation. Vegetation distribution patterns such as full vegetation and banded encourage mixing and reduce short-circuiting, enhancing hydraulic performance. In contrast, systems with either no vegetation or provide a preferential flow path promote short-circuiting and are hydraulically inefficient. Interestingly, porosity plays only a secondary role, the data points are segregated primarily by how vegetation is distributed over the domain with less dependence on the planting density. It should also be obvious that this discussion does not consider the role of plants in biological uptake, in which case, having a higher planting density may be advantageous, particularly for the banded and fully distributed cases.

The results obtained from this study are useful during the selection of planting configuration in design. Either the full or banded configuration is recommended, whereas fringing configuration should be adopted with caution. Basins without plants are not recommended since their hydraulic efficiency is the poorest; however, this might be superfluous since wetlands usually contain plants as plants provide other benefits such as promote microbial activity and nutrient trapping (Idris et al., 2024; Shih and Wang, 2020). For designs where a hydraulic efficiency typically  $\lambda > 0.7$  is specified, targeting enhanced treatment performance or longer hydraulic residence times, 3-banded, 6-banded, or full vegetation configurations should be adopted. Although fringing vegetation or no vegetation systems are not recommended for design based on reduced levels of hydraulic performance, such may be the case during periods of plant die off. In such situations, replanting to preserve the fully planted or banded configuration should be undertaken to maintain an acceptable level of hydraulic efficiency.

#### 4.0 Conclusions

Validation of the CFD model was studied through a quantitative comparison with experimental data. The CFD results demonstrated varying degrees of agreement with experiments across different vegetation configurations, reproducing the experimental RTD behaviour with  $R^2$  values of 0.70, 0.96 and 0.73 for the no vegetation, full vegetation and fringing vegetation distribution patterns, respectively. Also, a value of  $1/k = 7.62 \times 10^{-3} \text{ m}^2$  was obtained based on comparison with the experimental RTD curves. This value falls between those reported by Machado Xavier et al. (2018) ( $1 \times 10^{-7} \text{ m}^2$ ) and Yamasaki et al. (2022) ( $1.418 \times 10^{-5} \text{ m}^2$ ). Model results were also compared against indicators indicating good agreement with the experimental results. The model reported 5% difference (E3, full vegetation) in hydraulic efficiency, which is an often-used indicator. Similarly, the effective volume ratio ( $e$ ) was predicted with accuracy of 2% for E1 (no vegetation) and 8% for E5 (fringing vegetation), although short-circuiting index ( $S$ ) and variance ( $\sigma^2$ ) showed greater discrepancies.

A rectangular CW configuration was selected to allow generic comparisons of vegetation patterns also in a computationally efficient manner. Based on the analysis of the streamline and velocity contour, the full vegetation and banded distributions exhibit flow that is more streamlined and uniform with minimal recirculation compared to other systems resulting in improved hydraulic performance. Upon analysis of hydraulic performance indicators, these distributions resulted in high hydraulic efficiency, greater effective volume ratios, reduced short-circuiting, and low variance. These configurations promote better flow distribution and

mixing, resulting in enhanced hydraulic function. Porosity was found to play a secondary role in influencing the commonly used hydraulic indicators. It was found that the distribution pattern plays a key role in hydraulic performance as its determinant affecting flow behaviour. An examination of the streamlines and velocity contours produced by the CFD model showed that uniform and banded distributions result in flow that is uniform as compared to the banded and no vegetation cases where the flow is dominated by large scale vortices that promote tracer retention formation of stagnation zones. Although the analysis was conducted on a rectangular and flat-bottomed basin, the results offer valuable insights that can be applied to a broader range of constructed wetland applications.

Current guidance in most design guidelines primarily emphasize treatment objectives and structural design, with comparatively less explicit consideration of internal hydraulic efficiency. The findings of this study suggest that vegetation configurations incorporating banded or full vegetation may promote improved flow distribution and effective volume when compared with predominantly fringing vegetations. These results may offer useful insights to support future enhancements of vegetation configuration guidance, with the aim of better integrating hydraulic performance considerations into wetland design practice.

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### **Competing Interests**

The authors have no relevant financial or non-financial interests to disclose.

### **Author Contributions**

All authors contributed to the study conceptualization. Formal analysis, investigation, resources and methodology were performed by Nurul Neesa Idris. The original draft of the

manuscript was written by Nurul Neesa Idris. Lloyd HC Chua and Zahiraniza Mustaffa have reviewed, commented and validated on previous versions of the manuscript. Subrat Das has provided technical support on ANSYS model and Husna Takaijudin has supported laboratory experimental works. All authors approved the final manuscript.

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