Available online at www.worldscientificnews.com

World Scientific News

An International Scientific Journal

WSN 109 (2018) 60-70 EISSN 2392-2192

Computational Fluid Dynamics Modeling of Residence Time Distribution in a Field-Scale Horizontal Subsurface Flow Constructed Wetland with Palm Kernel Shell as Substrate

Nelson Mbanefo Okoye[1], **Chimaobi Nnaemeka Madubuike**[2], **Ifeanyi Uba Nwuba**[1], **Louis Chukwuemeka Orakwe** and **O. Boniface Ugwuishiwu**[3]

[1]Department of Agriculture and Bioresources Engineering, Nnamdi Azikiwe University Awka, Nigeria

[2]Department of Agricultural Engineering, Federal University of Technology, Owerri, Nigeria

[3]Department of Agriculture and Bioresources Engineering, University of Nigeria, Nsukka, Nigeria

E-mail address: nelsonokoye2003@yahoo.com

Phone: +2348104068474

ABSTRACT

The hydraulic performance of constructed wetlands is often compromised by hydraulic problems. Therefore, the development of an appropriate simulation model to reliably predict how various modifications of bed design and configurations might affect performance will facilitate the design of efficient systems. The aim of this research work is to determine distribution of residence time in a field-scale horizontal subsurface flow constructed wetland with Palm Kernel Shell as substrate. The governing equations of flow in porous media and transport of diluted species were solved using COMSOL Multiphysics 5.3a. The result was validated using experimental data and the model result showed good agreement with a correlation coefficient of 0.99. Alternative wetland designs were assessed for the same flow conditions. The results revealed that a two cell wetland improved short-circuiting flow paths.

***Keywords*:** COMSOL, Constructed Wetland, Computational Fluid Dynamics, Simulation Modelling, Wastewater Treatment

(Received 12 August 2018; Accepted 29 August 2018; Date of Publication 30 August 2018)

1. INTRODUCTION

Constructed wetlands are increasingly being used to handle different types of wastewater e.g. domestic wastewater (Chang et al., 2012); diary effluent (Tanner et al., 2005) and landfill leachate (Johnson et al., 1999). However, the most important controlling factor for various interconnected processes that occur within a constructed wetland is water movement patterns. Poor hydrodynamic behaviour has been reported, especially for horizontal subsurface flow constructed wetlands. This is because substrate heterogeneity, which is influenced by factors such as porosity, root growth, adsorption, sedimentation and precipitation of wastewater compounds, and biofilm development during the operating time, induces preferential flow paths and variations in the hydraulic residence time distribution and consequently the efficiency of treatment (Persson et al., 1999). Many studies have evaluated the hydrodynamics of constructed wetlands (Giraldi et al., 2009; Kadlec, 1994; Chazarenc et al., 2003) and many concluded that conventional designs of the system was favourable for developing preferential flow paths. Efficient pond geometry can help to reduce horizontal velocity gradients by encouraging a more uniform flow profile and minimising the amount of recirculation (Persson, 2000; Peterson et al., 2000). However, the hydrodynamic evaluation of constructed wetlands has in most cases been undertaken using physical tracer experiments that are expensive, time consuming and sometimes impractical (Liwei et al., 2008). Therefore, the use of numerical models as design tools can lead to a much better understanding of the flow patterns in wetlands as well as the suitability of multiple wetland geometries to enable the development of an optimum design in terms of flow characteristics. The aim of the present study is to evaluate the residence time distribution (RTD) of a field-scale horizontal subsurface flow constructed wetland with palm kernel shell as substrate treating effluent from a slaughterhouse in Agulu, Anambra State, Nigeria, using computational fluid dynamics (CFD) code of COMSOL Multiphysics® version 5.3a, a commercial finite element software package.

2. THEORY AND GOVERNING EQUATIONS

2. 1. Flow

The Laminar Flow interface (spf) in COMSOL is based on the Navier-Stokes equations, given as (Comsol, 2017):

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \qquad (1)$$

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla.[-pI + \tau] + F \qquad (2)$$

where:

ρ is the density (SI unit: kg/m3); u is the velocity vector (m/s); p is pressure (Pa); τ is the viscous stress tensor (Pa) and F is the volume force vector (N/m^3).

Equation 1 is the continuity equation and represents conservation of mass. Equation 2 is a vector equation which represents conservation of momentum. For a Newtonian fluid, which has a linear relationship between stress and strain, the viscous stress tensor is given as:

$$\tau = 2\mu S - \frac{2}{3}\mu(\nabla . u)I \qquad (3)$$

where: μ is the dynamic viscosity (Pa.s) and S is the strain-rate tensor given as:

$$S = \frac{1}{2}(\nabla u + (\nabla u)^T) \qquad (4)$$

Thus, for a compressible flow the momentum equation becomes:

$$\rho\frac{\partial u}{\partial t} + \rho u \, . \nabla u = -\nabla p + \nabla \, . \left(\mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla \, . u)I\right) + F \qquad (5)$$

when the temperature variations in the flow are small, a single-phase fluid can often be assumed incompressible; that is, ρ is constant or nearly constant. For constant ρ, the continuity equation (Equation 1) reduces to

$$\rho\nabla . (u) = 0 \qquad (6)$$

and Equation 5 becomes

$$\rho\frac{\partial u}{\partial t} + \rho(u \, . \nabla)u = \nabla \, . [-pI + \mu(\nabla u + (\nabla u)^T)] + F \qquad (7)$$

2. 2. Transport

Transport of diluted species in porous media (tds) model was used for the tracer transport in porous media. The phenomena of tracer diffusion and convection are modelled by the mass conservation equations given as:

$$P_{1,i}\frac{\partial c_i}{\partial t} + P_{2,i} + \nabla \, . \Gamma_i + u \, . \nabla c_i = R_i + S_I \qquad (8)$$

$$P_{1.i} = \varepsilon_p \qquad (9)$$

$$P_{2.i} = c_i\frac{\partial \varepsilon_p}{\partial t} \qquad (10)$$

$$N_i = \Gamma_i + uc_i = -D_{e,i}\nabla c_i + uc_i \qquad (11)$$

$$D_{e,i} = \frac{\varepsilon_p}{\tau_{F,i}}D_{F,i} \qquad (13)$$

where: c_i, Γ_i, R_i, S_i, $D_{e,i}$, $D_{F,i}$ and $\tau_{F,i}$ are the concentration, diffusive flux, reaction rate, source, effective diffusion, molecular diffusion and tortuosity of the i-th species [i = 1, 2], respectively. For constant porosity and constant diffusion, $P_{2,i} = 0$ and $\nabla \, . \, \Gamma_i = \nabla \, . \, (-\varepsilon_p D_{F,i}\nabla c_i) = -\varepsilon_p D_{F,i}\nabla^2 c_i$. Also for constant porosity, constant diffusion, Ri = 0, Si = 0 and $\tau_{F,i} = 1$, the system of Equations 8 - 13 reduce to the convection-diffusion equation given as:

$$\varepsilon_p \frac{\partial c}{\partial t} + u \,.\, \nabla c = \varepsilon_p D \nabla^2 c \qquad (14)$$

3. NUMERICAL MODEL

In this study, two different physical interfaces of COMSOL Multiphysics were employed in building the model: the laminar flow interface and the transport of diluted species in porous media interface. They were used to simulate tracer transport in the system. The laminar flow interface was chosen because the flow conditions of the field-scale horizontal subsurface flow constructed wetland were well within the limits of the laminar flow regime. A 2-D geometry of the field-scale horizontal subsurface flow constructed wetland (8.2m length by 2.4m width) was built in the geometry mode of COMSOL. The choice of 2-D model in this research was because it takes a shorter time to run and requires a comparably small amount of computer memory. The macrophyte shoot positions were measured in the constructed wetland and vegetation was modeled as cylinders with uniform diameter (0.06 m representing the stems), as suggested by Kadlec (1990). The physics controlled mesh sequence type was selected and the size of the element was selected to be normal. The mesh partitions the geometric model into small units of simple shape. The model geometry is shown in Figure 1.

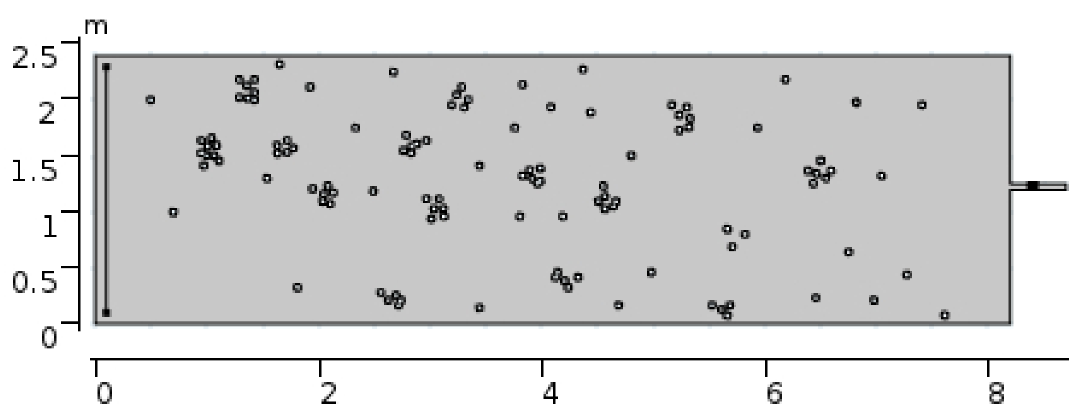

Figure 1. Rectangular geometry of the field-scale horizontal subsurface flow constructed wetland

Apart from the domain equations, proper boundary conditions were selected. For fluid flow, the inlet and outlet boundary condition specified were normal inflow velocity, ($u = -u_o n$) and pressure, $p = 0$, respectively. No slip boundary conditions were specified at the walls. For tracer transport in the porous media, the initial value of concentration inside the constructed wetland was chosen to be zero (since the salt concentration in the borehole water used for the study was negligible). The concentration of tracer at the inlet was specified as a time-dependent inflow value of (85.5*rect1(t[1/s]) mol/m^3. At the outlet, it was specified that the mass flow through the boundary was convective dominated ($-n \,.\, D_i \nabla c_i = 0$). This assumes that any mass flux due to diffusion across this boundary is zero. An insulation boundary condition was specified at the boundaries, thus no mass is transported across the boundaries.

Density of water was set at 1000 kg/m^3, dynamic viscosity was 0.001 Pa.s, velocity of flow into the constructed wetland was 9×10^{-6} m/s, diffusivity of NaCl was set at 1.607×10^{-9} m/s. Simulations were performed in two stages. In the first stage, steady state simulations were carried out using the laminar flow interface to identify hydrodynamic components of flow such as: velocity field (u) and pressure (p) for each element of the model. These were required in the next stage of simulations. The transport of diluted species interface was employed in the second stage and solved by time-dependent solution where the concentration (c) was the only dependent variable to estimate retention time. The tracer was monitored with two hour resolution at the outlet of basin.

3. 1. Proposed Modification of the Wetland

In order to improve the hydraulic performance of the constructed wetland, modifications of the geometry were evaluated. Alternative wetland geometries evaluated were a rectangular cell with an island and a two cell wetland as shown in Figure 2. They were modelled with a uniformly distributed vegetation of 25 shoots/m^2 density.

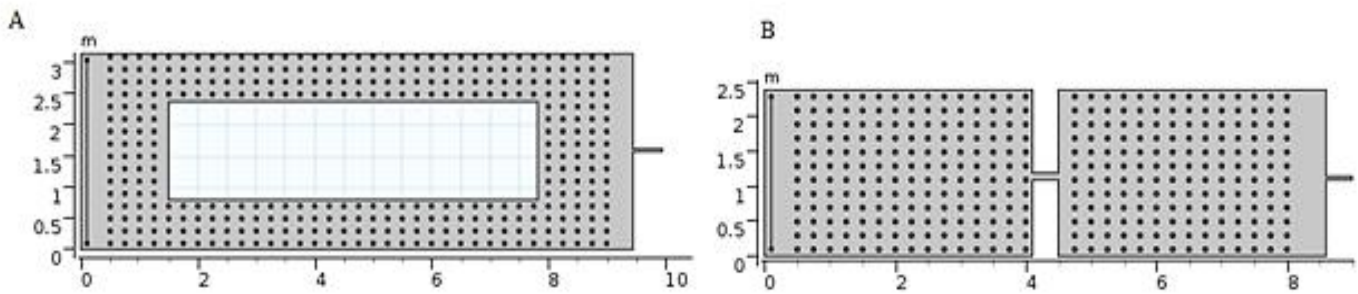

Figure 2. Alternative wetland geometries (A) Rectangular basin with island (B) two cells

4. RESULTS AND DISCUSSION

The two-dimensional velocity fields and streamlines for the field-scale wetland that were obtained in the first stage of simulation is presented in Figure 3. Firstly the direction of flow from the inlet towards the outlet can be identified. Furthermore the parts of the wetland where the flow intensity is greater can be distinct. Longer arrows indicates that the flow intensity in these areas is higher than in neighbouring areas.

From the 2-D plot, it can be seen that dead zones (i.e., areas with very low flow velocity) occurred where the vegetation density was highest which would invariably decrease the hydraulic performance by inhibiting water exchange. A region of short-circuited flow (i.e., a region of high flow velocity) was observed on the right side of the wetland, which would lead to a reduced residence time and flow uniformity and thereby decreased the hydraulic performance and treatment efficiency. Hydraulically, treatment efficiency is considered satisfactory as long as the system is well mixed and the physical characteristics are uniform across the wetland perpendicular to the flow (Williams and Nelson, 2011). The profile of the tracer concentration at various times is presented in Figures 4 to 8.

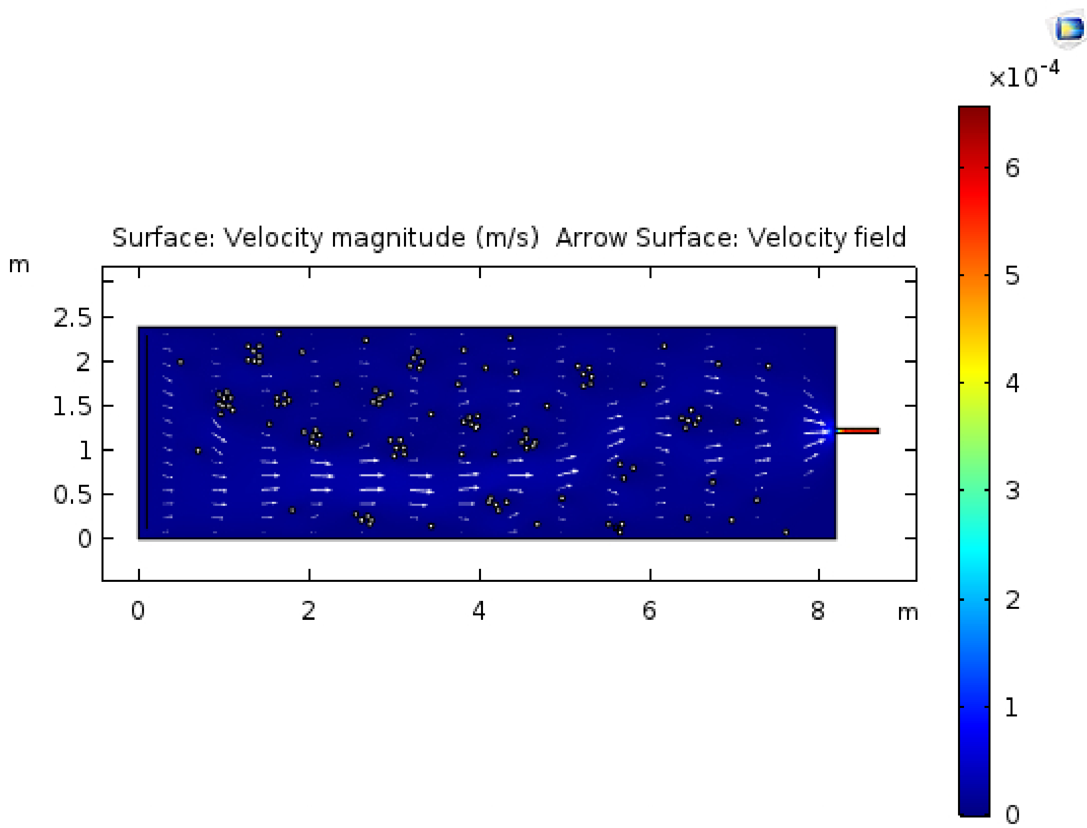

Figure 3. Velocity profile of the field-scale horizontal subsurface flow constructed wetland

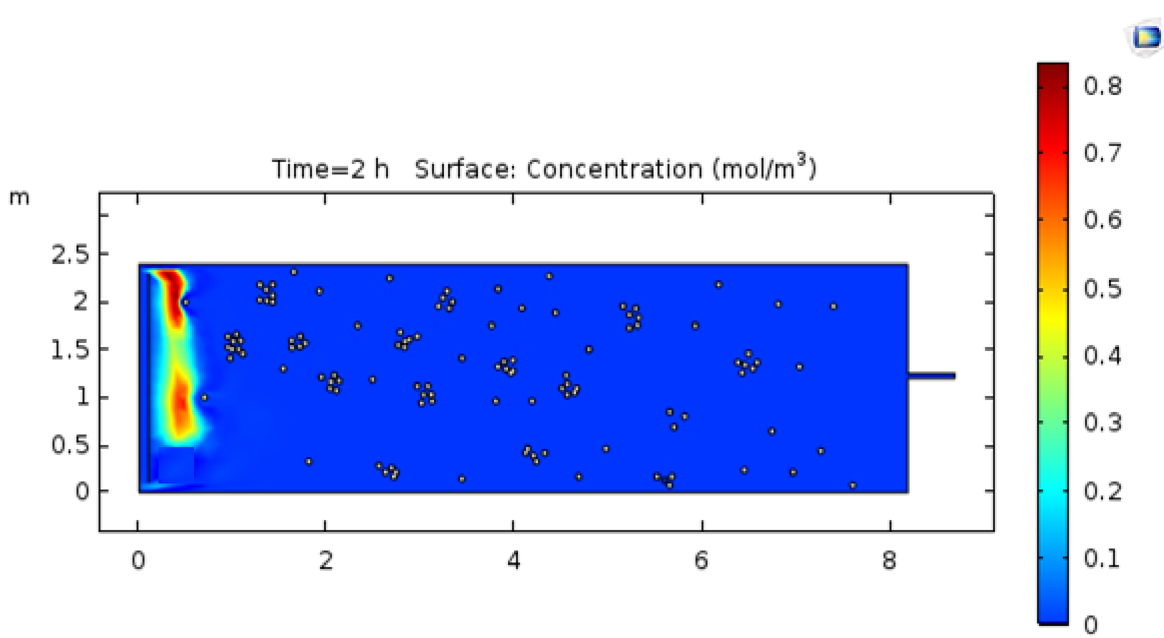

Figure 4. Spatial distribution of tracer concentration 2 hours after injection

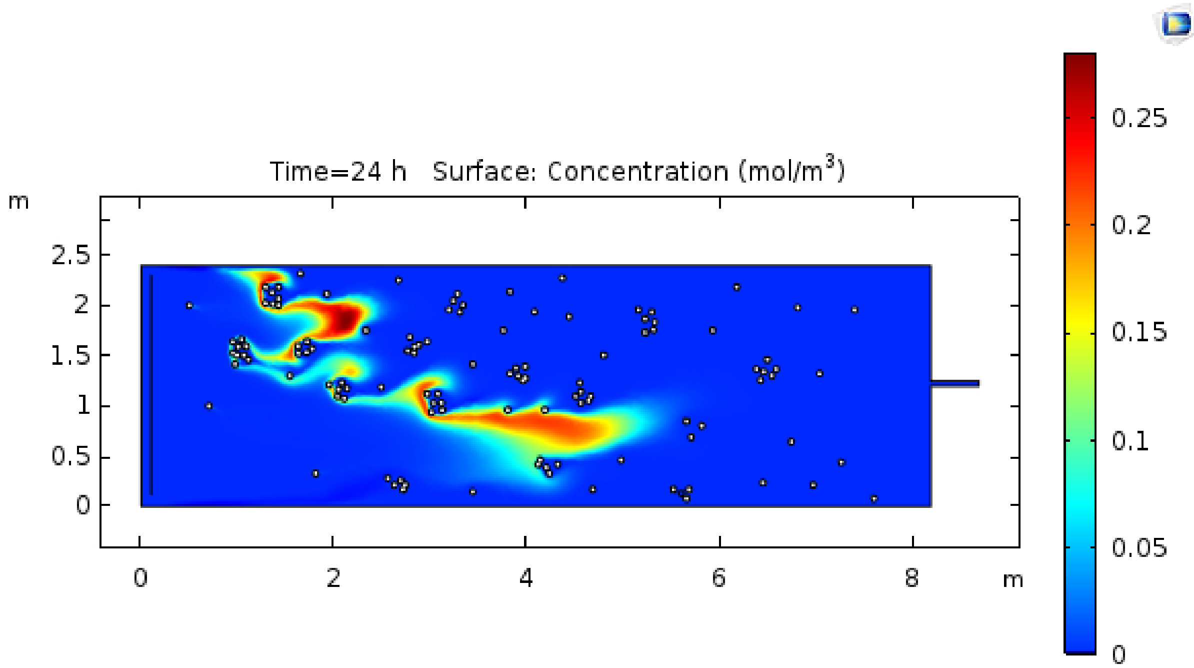

Figure 5. Spatial distribution of tracer concentration 1st day after injection.

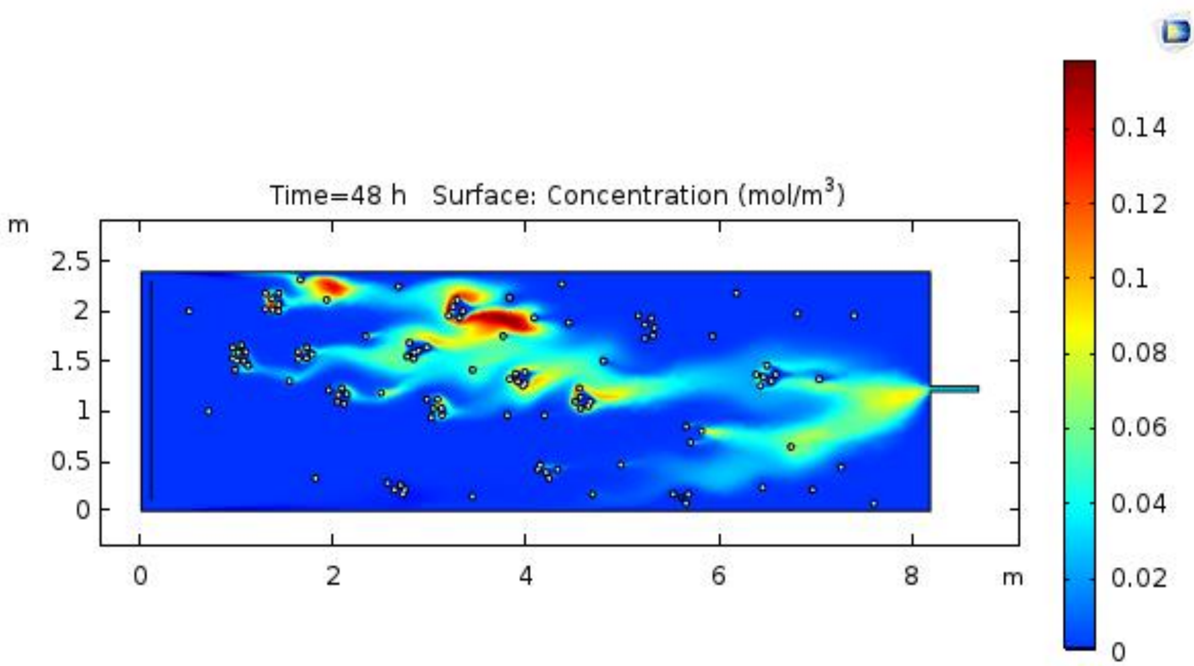

Figure 6. Spatial distribution of tracer concentration 2nd day after injection

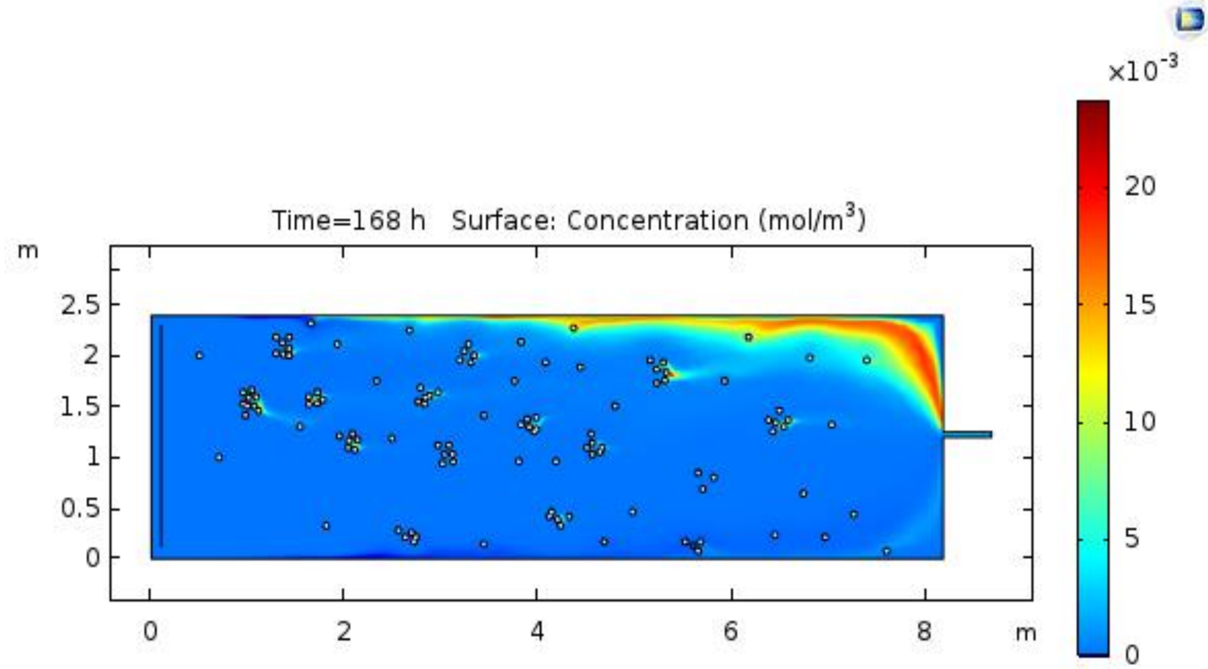

Figure 7. Spatial distribution of tracer concentration 7th day after injection

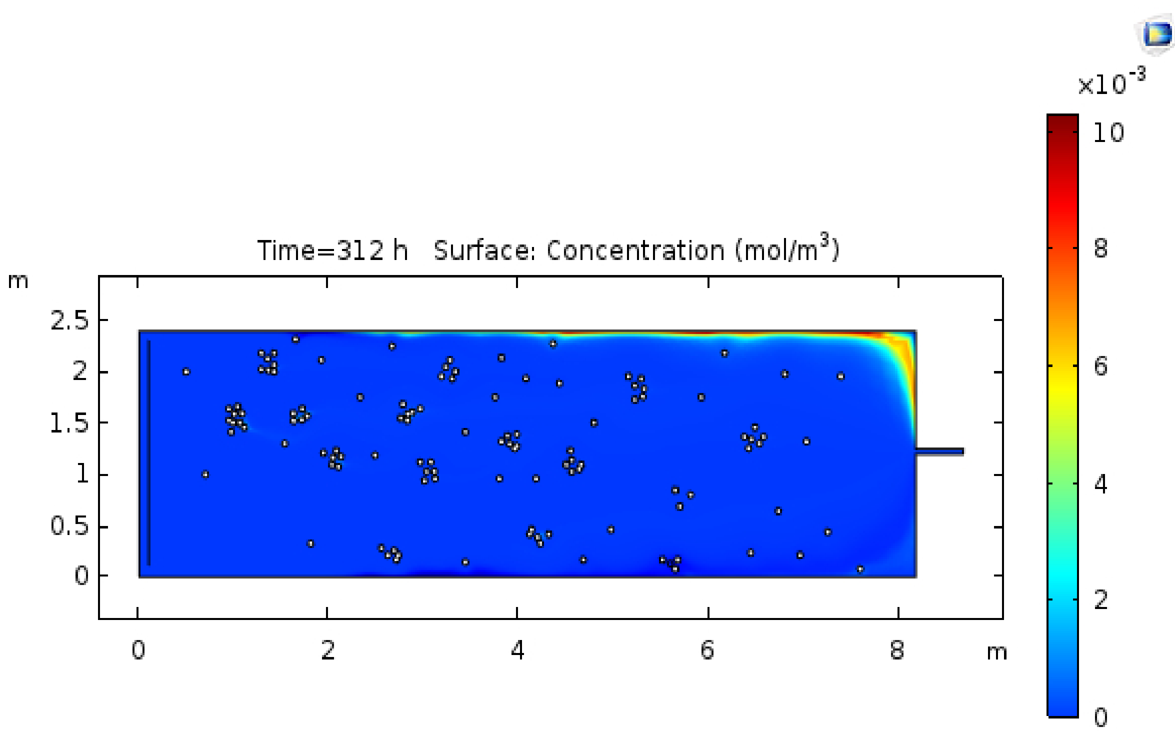

Figure 8. Spatial distribution of tracer concentration 13th day after injection

The behaviour of the tracer concentration provided adequate information about the wetland as well as for the tracer. The spreading of the tracer followed the preferential flow path already identified in the first stage of simulation. The simulated time for the peak outlet tracer concentration was 2 days after tracer injection, which was in line with the measured tracer response curve. To validate the CFD model used in the simulation, concentration data obtained experimentally was compared to those predicted by the model. In order to compare tracer outlet concentrations, graphs were drawn with normalised concentration (tracer concentration measured on time *t*, divided by the integration of all concentration) versus time.

The result is shown in Figure 9. The modelling of the wetland showed good agreement with the experimental tracer response curve, with a correlation coefficient of 0.99.

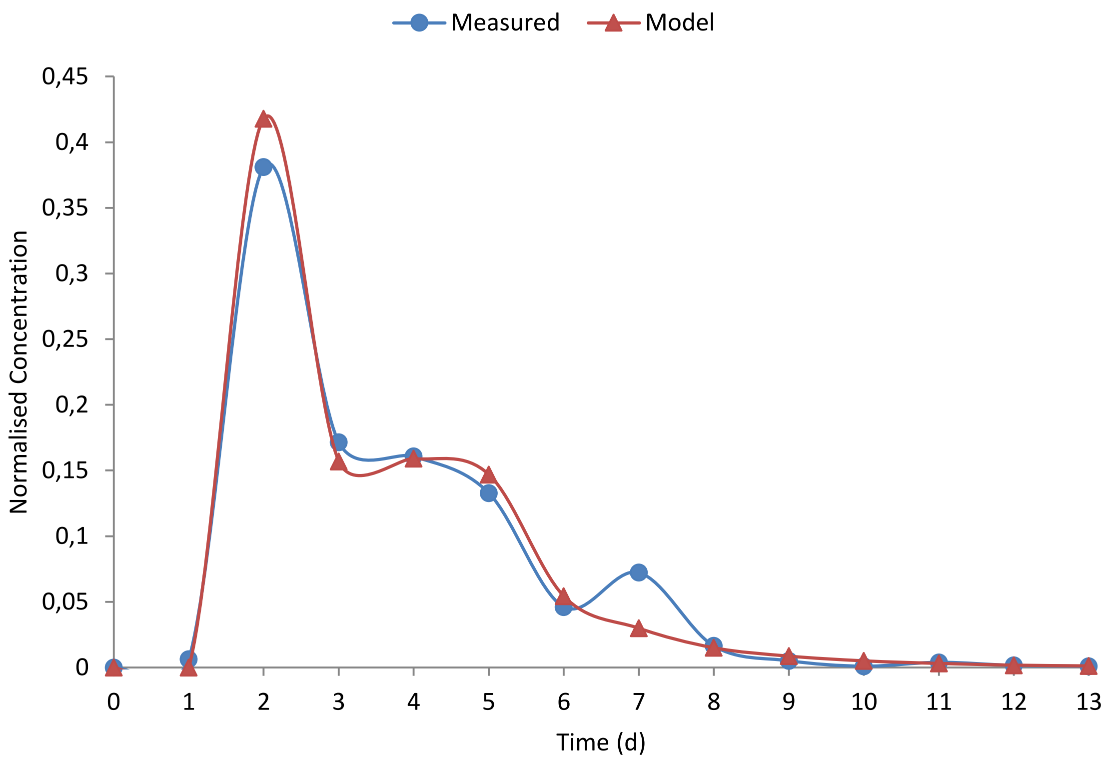

Figure 9. Model and measured tracer breakthrough curves

The tracer response curves for the design alternatives evaluated are shown in Figure 10.

It can be seen that two cells alternative design generated less re-circulating fluid and short-circuiting flow paths, compared to the rectangular basin with island, indicating that the flow is more homogeneous; consequently, preferred ways are not favoured. While the two cell system had comparable time of peak concentration values with the conventional wetland, the two cells design is particularly important as it can be designed to allow cleaning and other maintenance activities in one cell while the other cell is still functional, unlike the conventional single cell system. The wetland with island show serious short-circuiting flow paths, with the time of peak concentration value of 2 days. Persson (2000) evaluated alternative pond configurations using a 2-D numerical model and reported improved hydraulic performance in terms of short-circuiting, effective volume, and the amount of mixing.

Thackston *et al.* (1987) also showed that pond geometry is one of the most important factor affecting hydraulic efficiency. Therefore, It is evident that geometry is fundamental to determining flow fields and the corresponding RTDs.

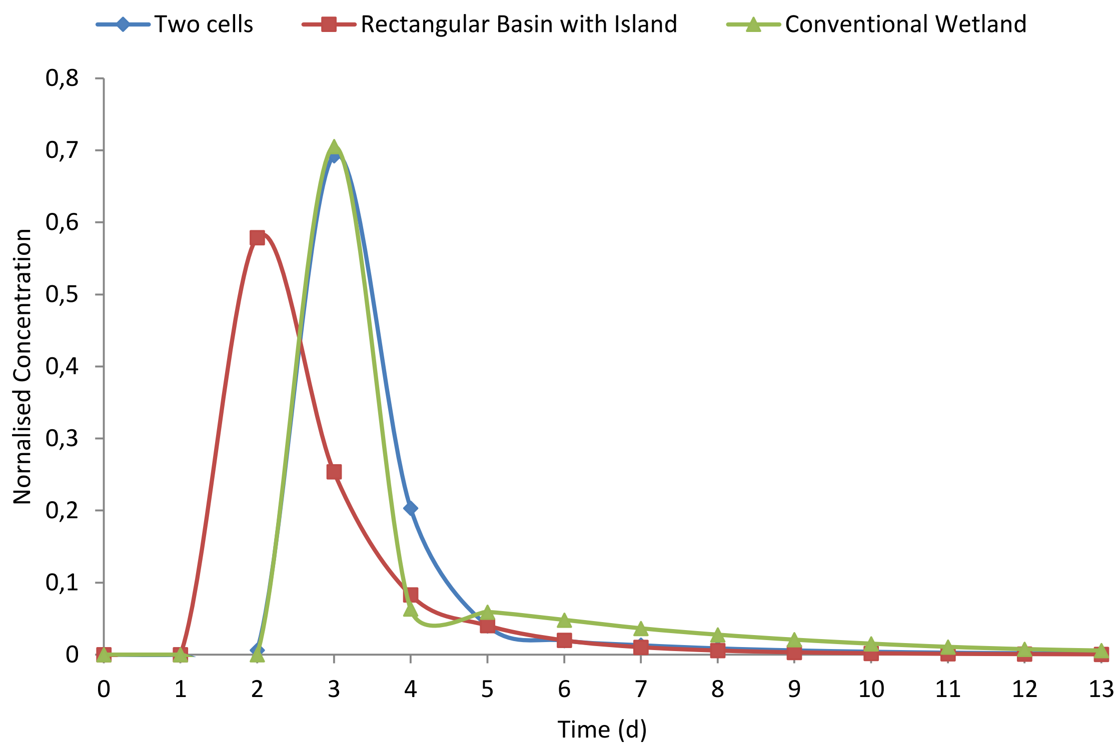

Figure 10. Tracer response curves for the different design alternatives

5. CONCLUSION

CFD is a sophisticated engineering tool for evaluating flow behaviour in a constructed wetland. The alternative designs evaluated had a significant influence on retention time and flow patterns. These can consequently have a substantial impact on the efficiency of the purification process. The results obtained in this study indicate that 2-D CFD modelling using COMSOL is an effective tool for simulation and optimization during the research or design phase of a wetland and can also reduce the operating and maintenance costs.

References

[1] Chang, J., Wu, S., Dai, Y., Lianga, W. and Wu, Z. (2012). Treatment performance of integrated vertical-flow constructed wetland plots for domestic wastewater. *Ecological Engineering* 44; pp. 152-159

[2] Chazarenc, F., Merlin, G. and Gonthier, Y. (2003). Hydrodynamics of horizontal subsurface flow constructed wetlands. *Ecol. Eng.* 21; pp. 165-173.

[3] COMSOL Multiphysics Reference Manual Version 5.3a (2017) COMSOL AB, USA.

[4] Giralgi, D., Vitturi, M., Zaramella, M., Marion, A. and Iannelli, R. (2009) Hydrodynamics of vertical subsurface flow constructed wetlands: Tracer tests with rhodamine WT and numerical modelling. *Ecol Eng* 35(2); pp.265-273

[5] Johnson, K. D.; Martin, C. D.; Moshiri, G. A. and McCrory, W. C. (1999). Performance of a constructed wetland leachate treatment system at the Chunchula landfill, Mobile County, Alabama. In Constructed wetlands for the treatment of landfill leachates; Mulamoottil, G., McBean, E.A., Rovers, F., Eds.; CRC Press/Lewis Publishers: Boca Raton, FL, USA, 1999; pp.57-70.

[6] Kadlec, R. (1990), Overland flow in wetlands: Vegetation resistance, *Journal of Hydraulic Engineering*, 116(5); pp.691-706.

[7] Kadlec, R. H. (1994). Detention and mixing in free water wetlands. *Ecol Eng* 3, pp.345-380

[8] Liwei, F., Reti, H., Wenxing, W., Zexiang, L., Zhiming, Y. (2008). Application of computational fluid dynamic to model the hydraulic performance of subsurface flow wetlands. *J. Env. Sci.*, 20; pp.1415-1422.

[9] Persson, J., Somes, N. L. G., and Wong, T. H. F. (1999). Hydraulic efficiency of constructed wetlands and ponds. *Water Sci. Technol.* 40(3); pp. 291-300

[10] Persson, J. (2000). The hydraulic performance of ponds of various layouts. *Urb. Wat.*, 2; pp. 243-250.

[11] Peterson, E. L., Harris, J. A., Wadha, L. C. (2000). CFD modelling pond dynamic processes. *Aquacult. Eng.*, 23 (1-3); pp. 61-93.

[12] Tanner, C. C., Nguyen, M. L. and Sukias, J. P. S. (2005). Nutrient removal by a constructed wetland treating subsurface drainage from a grazed dairy pasture. *Agric. Ecosyst. Environ.* 105; pp. 145-162.

[13] Thackston, E. L., Shields Jr., F. D. and Schroeder, P. R. (1987). Residence time distribution of shallow basins. *ASCE. J. Environ. Eng*. 113; pp. 1319-1332.

[14] Williams, C. F.; and Nelson, S. D. (2011). Comparison of rhodamine-WT and bromide as a tracer for elucidating internal wetland flow dynamics. *Ecol. Eng.* 37; pp. 1492-1498.