Effects of scale and Froude number on the hydraulics of waste stabilization ponds

Isabela De Luna Vieira, Jhonatan Barbosa Da Silva, Carlos Nobuyoshi Ide and Johannes Gérson Janzen

ABSTRACT

This paper presents the findings from a series of computational fluid dynamics simulations to estimate the effect of scale and Froude number on hydraulic performance and effluent pollutant fraction of scaled waste stabilization ponds designed using Froude similarity. Prior to its application, the model was verified by comparing the computational and experimental results of a model scaled pond, showing good agreement and confirming that the model accurately reproduces the hydrodynamics and tracer transport processes. Our results showed that the scale and the interaction between scale and Froude number has an effect on the hydraulics of ponds. At 1:5 scale, the increase of scale increased short-circuiting and decreased mixing. Furthermore, at 1:10 scale, the increase of scale decreased the effluent pollutant fraction. Since the Reynolds effect cannot be ignored, a ratio of Reynolds and Froude numbers was suggested to predict the effluent pollutant fraction for flows with different Reynolds numbers.

Key words | computational fluid dynamics, dynamics similarity, Froude, hydraulic indicator, Reynolds, scaled models

INTRODUCTION

Laboratory-scaled models are frequently used to study waste stabilization pond hydraulics since analytical solutions are not available (Shilton 2001). The success of scaled models depends on achieving true similarity between model and prototype. In a geometrically similar pond model, a true dynamic similarity is achieved if Reynolds (Re) and Froude (Fr) numbers have the same value in both model and prototype. However, it is almost impossible to maintain both Fr and Re constants. Since in waste stabilization ponds gravity effects are dominant, scaled ponds are usually designed to maintain Fr similarity (Fr_{model} = Fr_{prototype}) to the full-sized pond (Shilton et al. 2008). A Froude-scale model leads to Re_{model} < Re_{prototype} and, consequently, to an overestimation of boundary-generated turbulence, an underestimation of friction effects (Falconer & Liu 1987), and an underestimation of turbulence-driven mixing (Angeloudis et al. 2015). Hence, there is a concern about the loss of dynamics similarity between prototype and model, since this scale effect may be responsible for failures and/or misleading treatment efficiency in water and wastewater systems (e.g. a water and wastewater system is unable to deal with predicted treatment efficiency) (Heller 2011).

A few researchers have investigated the scale effect on the hydraulics of water and wastewater systems. Mitha & Mohsen (1990) found that the hydraulics of chlorine contact chambers is scale dependent for small models. This contradicts the results obtained by Angeloudis et al. (2015), who found that the small-scale model exhibited similar hydraulics to the prototype. However, contrary to Mitha & Mohsen (1990), Angeloudis et al. (2015) investigated a single set of experimental conditions. For water treatment tanks tending to complete mixing, Teixeira & Rauen (2013) found that hydraulics are insensitive to the variation of scale and discharge; however, for tanks tending to plug flow, the hydraulics are affected by both scale and discharge. Although the studies discussed above are very relevant, they are inconclusive and/or not pertinent for waste stabilization ponds due to at least three issues.

Firstly, the all studies used a poor experimental design, namely a one-factor-at-a-time strategy (Mitha & Mohsen 1990; Teixeira & Rauen 2013; Angeloudis et al. 2015). In a
A factorial design strategy is the only way to estimate these interactions systematically and to simultaneously highlight the relative importance of all the factors (main and interactions) in few experimental runs. Secondly, none of the studies found in the literature investigated the effect of scale and Froude number is a system with hydraulic characteristics similar to waste stabilization ponds. Thirdly, in some studies (e.g. Teixeira & Rauen 2013) the discrepancy between prototypes and scaled models was evaluated using mean error (which cost the researchers measuring precision, since positive and negative errors cancel each other out) and/or absolute error (which for small errors do not create unintended distortions). It was not surprise that in some cases Teixeira & Rauen (2013), for example, found small discrepancies for the residence time distribution (RTD) curves (<10%, using mean error), but relative high discrepancies (around 50%) for the hydraulic indices (using absolute error).

In order to address the poor experimental design, the lack of investigation of the effect of scale and Froude number on the hydraulics of waste stabilization ponds, and the lack of a more rigorous way of evaluating the discrepancy between prototypes and scaled models, the core objectives of this study were as follows:

- Validate the computational fluid dynamics (CFD) model by comparing the computational and experimental results of a model scaled pond.
- Use CFD to determine the effects of scale and Froude number, and their interaction, on the similarity between model and prototype of waste stabilization ponds, by comparing hydraulic and water quality indices of model scaled ponds to their correspondent prototype ponds.
- Suggest a non-dimensional number that correlates to the effluent pollutant fraction.

**MATERIAL AND METHODS**

The setup consisted of a rectangular pond with a length to width ratio of four (Figure 1). The water flowed into the pond from a horizontal inlet pipe positioned in the centre of the front wall of the pond and exited via a vertical outlet pipe, placed at the bottom of the pond at the opposite end to the inlet.

A factorial design was used to study the effects of geometric scale parameter $\lambda$ ($\lambda = L_p/L_m$, were $L_p$ (m) and $L_m$ (m) are, respectively, prototype and model characteristic dimensions) and Froude number ($Fr = U_0/(gH)^{0.5}$, where $U_0$ (m/s) is the cross-sectional mean velocity, $g$ (m/s$^2$) is the gravitational acceleration, and $H$ (m) is the water depth) on four hydraulic indices (Table 1). The literature suggests that $\lambda$ usually ranges between 4 and 10 (Teixeira & Rauen 2013). Hence, we adopted the values of 5 and 10. The Froude number was varied between 0.366 and 0.695. Since the gravity effects are dominant, the scaled ponds were designed to maintain Froude number similarity with the full-sized pond; hence, the scaling factor for time was equal to $ST = \lambda^{0.5}$ (Shilton 2001). In order to ensure that the same flow that exists in the prototype is maintained in the model, notably for the inlet jet flow, the Reynolds numbers at the inlet on both the prototype and model were both >2,000, indicating turbulent flow in both the prototype and the model (Shilton 2001). This Reynolds condition, associated with the values adopted for $\lambda$, restricted the Froude values to the range already mentioned. The ranges of data tested were not intended to be representative of the entire range of field conditions, but rather intended to determine if the scale and Froude number (and their interaction) had an effect on the results. The main effect is defined as the change in result produced by a change in the level of the factor. The interaction between the factors examines the effects of scale at different Froude numbers.

The response variables for observing the hydraulic and water-quality performances were: short-circuit index, mixing index, moment index, and effluent pollutant fraction. Short-circuiting happens when preferential flow inside the pond effectively shortens the overall residence time ($\tau$), being measured by the time necessary for the pollutant front to be advected from the inlet to the outlet (Teixeira...
The mixing index stands for the random spread of fluid due to the combined action of different phenomena (i.e. turbulent diffusion, recirculation, and dead zones) (Teixeira & Siqueira 2008). The moment index, introduced by Wahl et al. (2010), assumes that residence times of a completely efficient pond will meet or exceed \( \tau \). The pollutant exiting the pond prior to \( \tau \) adversely impacts hydraulic efficiency, with more weight assigned to the very short residence times. If the pollutant exiting is close to \( \tau \) then hydraulic efficiency is high; if the pollutant exits much earlier than \( \tau \), then hydraulic efficiency approaches zero. The effluent pollutant fraction indicates the ratio between effluent and influent pollutant concentrations.

These hydraulic and water-quality performance indices were obtained through the analysis of RTD functions obtained by an instantaneous injection of a known quantity of a conservative tracer mass, \( M \) (kg), at the inlet section of the pond and the subsequent measuring of the tracer concentration, \( C \) (kg/m\(^3\)), along time, \( t \) (s), at its outlet section. In order to allow direct comparison of measured RTDs having dissimilar conditions (e.g. different volumes, flow rates, and tracer masses), they are usually presented in their normalized form (Werner & Kadlec 1996; Wahl et al. 2010). The dimensionless RTD function, \( C'(\theta) \), and the dimensionless time, \( \theta \), can be defined, respectively, as:

\[
C'(\theta) = \frac{C(\theta)V}{MI} \quad \theta = \frac{tQ}{V} \tag{3}
\]

where \( V \) (m\(^3\)) is the system volume, \( Q \) (m\(^3\)/s) is the system volumetric flow rate and \( t \) (s) is the theoretical (or nominal) residence time. As a short-circuit indicator, we used \( \theta_1 = t_{10}/\tau \), which is the nondimensional time necessary for first 10% of the tracer to leave the pond. In an ideal plug flow, this ratio is 1. \( M_2, MI, \) and \( X \) are calculated as follows:

\[
M_2 = \int_0^\infty (\theta - M_1)^2 C'(\theta)d\theta \tag{4}
\]

\[
M_1 = \int_0^\infty \theta C'(\theta)d\theta \tag{5}
\]

\[
MI = \int_1^\infty (\theta - 1)C'(\theta)d\theta \tag{6}
\]

\[
X = \int_0^\infty \frac{C'(\theta)e^{-\lambda t}dt}{\tau} \tag{7}
\]

\( M_1 \) is the centroid of the RTD and \( M_2 \) is the variance of the RTD, which accounts for the spread of the tracer over time. According to ideal reactor models, an \( M_2 \) value close to 0 indicates plug flow while a value close to 1 indicates that the flow is closer to the complete mixing regime (Rossman & Grayman 1999). Moment index \( (MI) \) is derived from the first moment of the normalized RTD curve; \( MI = 1 \) indicates plug flow and \( MI \) near zero indicates a high degree of mixing or short-circuiting. \( X \) is the effluent pollutant

### Table 1

<table>
<thead>
<tr>
<th>Run</th>
<th>( \lambda )</th>
<th>Fr</th>
<th>Re*</th>
<th>( Q ) (m(^3)/s)</th>
<th>L (m)</th>
<th>W (m)</th>
<th>H (m)</th>
<th>( \theta_1 )</th>
<th>( M_2 )</th>
<th>MI</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1</td>
<td>0.695</td>
<td>120,580</td>
<td>4.27 \times 10^{-3}</td>
<td>24.0</td>
<td>6.0</td>
<td>1.0</td>
<td>0.15</td>
<td>0.81</td>
<td>0.65</td>
<td>0.78</td>
</tr>
<tr>
<td>C2</td>
<td>5</td>
<td>0.695</td>
<td>10,785</td>
<td>7.64 \times 10^{-5}</td>
<td>4.8</td>
<td>1.2</td>
<td>0.2</td>
<td>0.24</td>
<td>0.59</td>
<td>0.71</td>
<td>0.70</td>
</tr>
<tr>
<td>C3</td>
<td>10</td>
<td>0.695</td>
<td>3,813</td>
<td>1.35 \times 10^{-5}</td>
<td>2.4</td>
<td>0.6</td>
<td>0.1</td>
<td>0.20</td>
<td>0.72</td>
<td>0.80</td>
<td>0.63</td>
</tr>
<tr>
<td>C4</td>
<td>1</td>
<td>0.476</td>
<td>82,502</td>
<td>2.92 \times 10^{-3}</td>
<td>24.0</td>
<td>6.0</td>
<td>1.0</td>
<td>0.21</td>
<td>0.68</td>
<td>0.69</td>
<td>0.77</td>
</tr>
<tr>
<td>C5</td>
<td>5</td>
<td>0.476</td>
<td>7,379</td>
<td>5.23 \times 10^{-3}</td>
<td>4.8</td>
<td>1.2</td>
<td>0.2</td>
<td>0.26</td>
<td>0.56</td>
<td>0.72</td>
<td>0.69</td>
</tr>
<tr>
<td>C6</td>
<td>10</td>
<td>0.476</td>
<td>2,609</td>
<td>9.25 \times 10^{-6}</td>
<td>2.4</td>
<td>0.6</td>
<td>0.1</td>
<td>0.20</td>
<td>0.76</td>
<td>0.69</td>
<td>0.63</td>
</tr>
<tr>
<td>C7</td>
<td>1</td>
<td>0.366</td>
<td>63,549</td>
<td>2.25 \times 10^{-3}</td>
<td>24.0</td>
<td>6.0</td>
<td>1.0</td>
<td>0.23</td>
<td>0.65</td>
<td>0.70</td>
<td>0.78</td>
</tr>
<tr>
<td>C8</td>
<td>5</td>
<td>0.366</td>
<td>5,684</td>
<td>4.03 \times 10^{-5}</td>
<td>4.8</td>
<td>1.2</td>
<td>0.2</td>
<td>0.25</td>
<td>0.57</td>
<td>0.72</td>
<td>0.69</td>
</tr>
<tr>
<td>C9</td>
<td>10</td>
<td>0.366</td>
<td>2,009</td>
<td>7.12 \times 10^{-6}</td>
<td>2.4</td>
<td>0.6</td>
<td>0.1</td>
<td>0.20</td>
<td>0.71</td>
<td>0.68</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*Re = \( U_d d/v \) (where \( d \) is the inlet diameter and \( v \) is the kinematic viscosity).
fraction for first-order reactions, depending on some rate constant \( k \) (s\(^{-1}\)) (Wahl et al. 2010).

The hydraulic indices were obtained through CFD modelling, following the procedure presented in Rengers et al. (2016) and Xavier & Janzen (2016). Initially, the flow field was determined using the CFD code CFX (ANSYS Inc. 2022). This code uses the finite volume method for the spatial discretization of the domain. The governing equations are integrated over each control volume, such that mass, momentum, and energy are conserved, in a discrete sense, for each control volume. The simulations in this study were performed using the three-dimensional steady-state RANS (Reynolds-averaged Navier Stokes) equations with a \( k-\varepsilon \) model. Pressure–velocity coupling was achieved by using the SIMPLE (Semi-Implicit Method for Pressure–Linked Equations) algorithm. A second order upwind scheme was used for spatial discretization of the flow equations. The advection scheme chosen, as well as the turbulence numeric, was the high resolution. Details of the governing equations, turbulence model, and algorithms can be found in the CFX user’s guide.

As a boundary condition, a uniform flow was imposed at the inlet (Table 1). At the outlet, an average static reference pressure of 0 Pa was specified. The free surface was considered a symmetry plane, which implies a zero gradient for all variables normal to that plane (Stamou 2002). A no-slip boundary condition was applied at the walls.

Once the steady-state flow field was achieved, the RTD was calculated from the solution of the three-dimensional Reynolds-averaged advection–diffusion equation. The turbulent Schmidt number was 0.9. At the inlet, a passive and conservative tracer was injected using a square step input having a duration less than 2% of the nominal detention time. The scalar concentration was monitored at the outlet to produce the RTD curve for the pond. The tracer transport simulations ran until at least 95% of the tracer mass had left the pond. The solute transport simulations were carried out using a time step that varied from 1 to 41 s. For the time intervals where there was a high variation of concentration, the time step was smaller. The hydraulic indices presented previously were obtained through analysis of RTD functions originating from these tracer studies.

The grid was unstructured, with about 260,000 elements, having a finer spacing in regions of larger gradients (near the inlet, the wall and the outlet) and coarser spacing in the regions of low velocity gradients. The number of elements was defined using the procedures presented by Celik et al. (2008). More details of the grid independence study can be found in Vieira (2016). The discretization error on average was around 10%. Similar grids were used for all other simulations.

The CFD model was validated experimentally by finding the RTD of a scaled waste stabilization pond (1:10). The model pond was 2.40 m long, 0.60 m wide, and 0.10 m deep. The water flowed into the pond from a 5 mm horizontal inlet pipe positioned in the center of the front wall of the pond and exited via a 5 mm vertical outlet pipe, placed at the bottom of the pond at the opposite end to the inlet. A pulse tracer study was experimentally conducted in the scaled pond following the protocol presented by Teefy (1996). A mass of sodium chloride was injected for approximately 1% of the nominal residence time into the inlet pipe of the pond. Water samples were collected at the outlet, starting at the time of injection. A conductivity probe was used to measure the sodium chloride concentration with time intervals increasing during the crest of the tracer curve and decreasing as it descended (Headley & Kadlec 2007) and an RTD plot was derived. The tracer recovery was near 100%. Discharge was measured by direct volumetric measurements at the outlet, having an average value of 0.01355 L/s. There was a good agreement between experimental and computational RTDs (Figure 2). Confidence in the numerical RTDs was considered high since the maximum difference between numerical and experimental results was in general within experimental uncertainty.

**RESULTS AND DISCUSSION**

The prototype ponds were used as a basis for assessing the main effects of scale and Froude number, and their interactions, on the flow pattern, hydraulic indices, and effluent pollutant fraction. Firstly, in relation to the flow pattern, for \( \lambda = 1 \), a very similar flow structure was
observed, despite the difference in the Froude number (Figure 3(a), 3(d), and 3(g)). The horizontal flow field was dominated by three recirculation regions; a small recirculating region formed near the inlet, while two large recirculating regions formed in the central and outlet regions. High velocities were observed in the outer parts of the recirculation regions, while very low velocities were found in the central areas of the recirculation regions. Despite using a different inlet configuration (the inlet was aligned with the width) and length-to-width ratio \((L/W = 3)\), Shilton & Harrison (2003) also found a series of recirculation regions roughly equal to the pond width. For \(\lambda = 5\), despite the difference in the Froude number, the horizontal flow fields were very similar, being dominated by four recirculation regions (Figure 3(b), 3(e), and 3(h)). Finally, the horizontal flow field was also very similar for the different Froude numbers for \(\lambda = 10\), being dominated by three recirculation regions (Figure 3(c), 3(f), and 3(i)); a large recirculating region was formed in the center and two smaller recirculating regions were formed near the inlet and the outlet of the pond. In summary, considering the flow pattern, the main effect of scale seems to be significant; the main effect of Froude number and interaction between scale and Froude number appears to be non-significant.

In order to enhance our understanding of the pond hydrodynamics discussed above, hydraulic indices were calculated to benchmark the ponds across a spectrum of scales and Froude numbers (see Table 1). Model index values higher or lower than 10% of the corresponding prototype values were assumed to be indicative of a significant discrepancy between model and prototype. The value of 10% generally accounted for our computational errors, which were of the same order as the experimental errors described in the literature (Teixeira & Rauen 2013).

The average of \(\theta_{10}\) is 0.22, indicating the presence of short-circuiting and a compromised hydraulic efficiency according to the classification of Van der Walt (2002). The hydraulic short circuit is the most common problem with pond hydraulics because the treatment process is bypassed when the wastewater takes a short-cut through the pond (Shilton et al. 2008). The short-circuit indicator remains

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**Figure 3** | Flow patterns for different scales and Froude number for mid-depth. (a) Scale 1:1, \(Fr = 0.695\); (b) Scale 1:5, \(Fr = 0.695\); (c) Scale 1:10, \(Fr = 0.695\); (d) Scale 1:1, \(Fr = 0.476\); (e) Scale 1:5, \(Fr = 0.476\); (f) Scale 1:10, \(Fr = 0.476\); (g) Scale 1:1, \(Fr = 0.366\); (h) Scale 1:5, \(Fr = 0.356\); (i) Scale 1:10, \(Fr = 0.356\). The velocity intensity was scaled.
unchanged for an increase in Froude number (Figure 5(a)). The $\lambda = 5$ model showed a significant increase in the short-circuit index $\theta_{10}$, which was not the case with the $\lambda = 10$ scale model (Figure 4(a)). Since the effect of scale depends on the Froude number, there is an interaction between scale and Froude number (Figure 6(a)). When scale is
changed from $\lambda = 1$ to 5, for $Fr = 0.366$, $\theta_{10}$ remains unchanged; however, when $Fr = 0.476$ and 0.695, $\theta_{10}$ increased. When scale is changed from $\lambda = 1$ to 10, for $Fr = 0.366$ and 0.476, $\theta_{10}$ remains unchanged; for $Fr = 0.695$, there is an increase in $\theta_{10}$.

The average $M_2$ was 0.67. $M_2$ is a quantitative description of the ponds’ mixing scale. In general, plug flow is desirable ($M_2 = 0$) during the treatment of wastewater in ponds because it shows a greater efficiency than complete mixing flow ($M_2 = 1$). According to Van der Walt’s classification, $M_2$ values indicate a compromising hydraulic efficiency for all ponds, except for pond 1, which showed poor hydraulic efficiency. The $\lambda = 5$ model showed a significant decrease on the mixing indicator $M_2$, which was not the case with the $\lambda = 10$ scale model (Figure 4(b)). Changing the Froude number did not influence $M_2$ (Figure 5(b)). Since the effect of scale depends on the Froude number, there is an interaction between scale and Froude number (Figure 6(b)). When $\lambda$ is changed from 1 to 5, for $Fr = 0.366$, $M_2$ remains unchanged. However, when $Fr = 0.476$ and 0.695, $M_2$ decreased for a change in $\lambda$ from 1 to 5. When $\lambda$ is changed from 1 to 10, $M_2$ remains unchanged with Froude.

The average $MI$ is 0.706. Since the $MI$ values are between 0.653 and 0.803, the hydraulic efficiency is good. The changes in scale and Froude number did not influence $MI$ (Figures 4(c) and 5(c)). When we compare scales 1:1 and 1:5, there was no significant interaction between scale and $MI$ (Figure 6(c)). However, the effect of scale on $MI$ depends on the Froude number when we compare scales 1:1 and 1:10. For $Fr = 0.366$ and 0.476, $MI$ remains unchanged with scale; for $Fr = 0.695$, there is an increase in $MI$ when the scale is changed from 1:1 to 1:10.

In order to estimate the treatment efficiency, $X$ was calculated. The average $X$ is 0.70. Scale 1:5 presented the same $X$ as scale 1:1 (Figure 4(d)). However, the difference in $X$ between scales 1:1 and 1:10 is significant: changing the scale from 1:1 to 1:10 diminished $X$. The change in the Froude number did not influence $X$ (Figure 5(d)). There was no significant interaction between scale and Froude number on $X$ (Figure 6(d)).

In summary (Table 2), in terms of the hydraulics, in general the main effect of scale, particularly for scale 1:5, and the interaction between scale and the Froude number are significant. In relation to effluent fraction $X$, the main effect of scale, particularly for scale 1:10, is significant. Hence, the effect of scaling up is significant for evaluating the hydraulics and treatment efficiency of waste stabilization ponds.
Table 2 | Effect of scale and Froude number, and their interaction, on flow pattern, hydraulic indexes, and effluent outlet fraction

<table>
<thead>
<tr>
<th>Result/effect</th>
<th>$\lambda$</th>
<th>$Fr$</th>
<th>$\lambda-Fr$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow pattern</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Short-circuit $\theta_{10}$</td>
<td>Yes (only $\lambda = 5$)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mixing $M_{2}$</td>
<td>Yes (only $\lambda = 5$)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Moment $MI$</td>
<td>No</td>
<td>No</td>
<td>Yes (only $\lambda = 10$)</td>
</tr>
<tr>
<td>Effluent fraction $X$</td>
<td>Yes (only scale 1:10)</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Yes, significant effect; No, no significant effect.

In terms of the hydraulics, our results are comparable to those found by Teixeira & Rauen (2013) for the L-shaped tank, which has hydraulics similar to our waste stabilization ponds. Teixeira & Rauen (2013) studied the influence of discharge (Froude number) and scale on the hydraulics of an L-shaped tank. Using factorial plots and an uncertainty of 10%, we reinterpreted the data of Teixeira & Rauen (2013) and found that the discharge and scale have an influence on the short-circuit and the mixing indicators. Furthermore, there is an interaction between discharge and scale on both indicators. Hence, our results are in good agreement with the data found in the literature.

The influence of scale and Froude number and its interaction on hydraulic and water quality indices seems to be due to the scale effect of Reynolds number. In order to account for the Reynolds effect, a non-dimensional number $Z$ (ratio of Reynolds number to Froude number), suggested by Sarkar et al. (2007), was calculated and its effect on $X$ was plotted (Figure 7). An excellent correlation was observed between $X$ and $Z$. The relation between these variable is:

$$X = 0.0403 \ln(Z) + 0.2941$$  (8)

Equation (8) suggests that $X$ is a function of $Z$ and that Equation (8) can be used to calculate $X$ in geometrically similar systems. Hence, the next step will be the study of the relationship between $X$ and $Z$ for a wide range of $Z$ values.

CONCLUSION

In this study, a RANS-based CFD technique was employed to predict flow and pollutant transport in waste stabilization ponds. In the validation phase, a good match was observed between the computational and the experimental RTDs. The analysis was then extended to investigate the effect of scale and Froude number on hydraulic performance and effluent pollutant fraction of scaled waste stabilization ponds designed using Froude similarity. Our results showed that the Froude criterion alone is not valid for simulating the hydraulics and effluent pollutant fraction in scaled water treatment pond models, even though the scaled models are geometrically similar to the prototype. The scale and the interaction between scale and Froude number has an effect on the hydraulics of the pond. At 1:5 scale, the increase of scale increased short-circuiting and decreased mixing. Furthermore, at 1:10 scale, the increase of scale increased short-circuiting and decreased mixing. Hence, even though the Reynolds number is less relevant for ensuring that the same hydraulics that exists in the prototype are maintained in the model, it cannot be ignored. In order to account for the Reynolds effect, our results suggest that the ratio of Reynolds to Froude numbers has an excellent correlation to effluent pollutant fraction. Therefore, the next step will be the study of the relationship between the effluent pollutant fraction and the Reynolds-to-Froude ratio for a wide range of Reynolds-to-Froude ratio values.

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