CFD-Based Design of Waste Stabilization Ponds: Significance of Wind Velocity

C. G. Banda, P. A. Sleigh and D. D. Mara

School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK
(E-mail: cen2cbg@leeds.ac.uk; p.a.sleigh@leeds.ac.uk; d.d.mara@leeds.ac.uk)

Abstract Three-dimensional computational fluid dynamics (CFD) modelling was used to assess the treatment performance (*E. coli* removal) of facultative waste stabilization ponds with particular respect to the effects of wind speed and direction. Wind effects were incorporated into the CFD model as a shear stress on the top surface of the pond. The range of wind speed investigated was 3−6 m/s in different directions to the wastewater flow in the pond. *E. coli* decay was modelled by a scalar transport equation that incorporated a source term representing *E. coli* decay. When the wind was blowing at 6 m/s in the same direction as the wastewater flow, the CFD results showed the *E. coli* count was 13% greater than that in a facultative pond with no wind. However, when a wind speed of 6 m/s was blowing in the opposite direction to the wastewater flow, the *E. coli* count was reduced by 81%; a similar reduction was achieved by a wind speed of 5 m/s, but when it was 3 m/s, the reduction was only 14%. When the wind direction was normal to the wastewater flow, the effluent *E. coli* count was not significantly different to that in a pond with no wind.

Keywords: Computational fluid dynamics; *E. coli*; waste stabilization pond; wastewater flow; wind speed; wind direction

Introduction

Waste stabilization ponds are currently designed based on either classic or modern design methods (Banda *et al*. 2005). These design methods do not take into account the wind speed and its prevailing direction that might be experienced in a particular site. In addition, plug and completely mixed hydraulic flow patterns are assumed either during the design stage of the new pond systems or at the operational stage of existing ponds. However, these ideal flow patterns are not achieved in operational pond systems (Thirumurthi, 1974; Arceivala, 1983).

Effects of wind speed and its direction are one of the physical factors that cause the non-ideal flow pattern in waste stabilization ponds (Tchobanoglous *et al*. 2003). Research into wind effects on pond hydraulics has shown that wind produces a shear stress on top surface of pond and this alters the general flow pattern in the waste stabilization pond (Sweeney, 2004; Shilton, 2001). With advances and availability of computational technology, it is now recommended to use CFD to include wind speed and its direction when designing and evaluating the pond hydraulics (Shilton, 2001; Sweeney, 2004; Wood, 1997). The superiority of CFD design methods of waste stabilization ponds over the classic design methods is that wind shear stress can be included at the design or operational stage of waste stabilization ponds and detailed knowledge of the flow in the ponds can be obtained.

Brissaud *et al*. (2000, 2003), Frederick and Lloyd (1996), Lloyd *et al*. (2003), and Vorkas and Lloyd (2000) noted that wind speed diminishes the treatment performance of waste stabilization ponds due to the initiation of the hydraulic short-circuiting. They observed that even at low wind speeds of 0.5–2.6 m/s short-circuiting can develop in ponds that are isothermal. However, Shilton and Harrison (2003a, 2003b) suggest that the momentum of the influent supplied by the inlet pipe can overcome wind effects thus obviating the concerns of the hydraulic short-circuiting caused by the wind effects. They argue that the inlet momentum can sustain the flow pattern in waste stabilization ponds during the residence time period. However, validation of this theory on existing ponds under windy conditions was not carried out.

In this paper, we apply CFD with the incorporation of wind effects to assess the treatment performance of a facultative pond in terms of *E. coli* removal. The wind effects are applied in the model as a shear stress across the top surface of the pond. The secondary facultative pond was assumed to have isothermal conditions, so there was no short-circuiting associated with thermal stratification.

Methods

A 3-D model was set up such that the flow and transport of a scalar variable, which represented the concentration of *E. coli*, could be used to simulate the wastewater flow in a secondary facultative pond under windy conditions. The CFD software FLUENT version 6.1.22 (Fluent, Inc., 2003) was used. Derivations of the fundamental conservation equations of mass and momentum on which CFD is based are available in several standard textbooks (for example, Pantakar, 1980; Versteeg and Malalasekera, 1995). To accurately simulate the *E. coli* removal within Fluent, it was necessary to program the desired functionality and incorporate this within Fluent via the 'user defined function' (UDF) facility provided by the software. With the addition of this function the scalar transport equation was modified to simulate the decay of *E. coli* based on the following equations:

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\phi U) = div(\Gamma grad\phi) + S_\phi \tag{1}$$

$$S_\phi = -\rho k\phi \tag{2}$$

$$k = 2.6(1.19)^{T-20} \tag{3}$$

where φ is the scalar variable (*E. coli* count per 100 ml); k, the first-order rate constant for *E. coli* removal, day^{-1}; ρ, the density of wastewater, kg/m^3; S_φ, a source term,kg/m^3 s; Γ, coefficient of diffusivity, kg/m s; U, the vector form of wastewater velocity [u, v, w], m/s; and T, temperature, °C.

The Marais (1974) equation for the first-order rate constant of *E. coli* removal was adopted as Pearson *et al.* (1995) found it satisfactory in predicting *E. coli* removal in optimally loaded ponds in Brazil. In order to apply the wind speed within the model, the shear stress was calculated using equation 4 to simulate a frictional wall at the top surface of the pond:

$$\tau = C_D \rho_{air} v^2 \tag{4}$$

where τ is the shear stress, N/m^2; C_D, an empirical constant (= 0.0017); ρ_{air}, the density of air (= 1.225 kg/m^3); and v, the wind speed, m/s.

The other boundary conditions of the model were based on an inlet velocity of 7.09 m/s and a pressure value of zero at the pond outlet. An influent *E. coli* count of 5×10^6 per 100 ml was applied in the inlet as this was chosen to represent the effluent of a one-day anaerobic pond receiving raw wastewater with 5×10^7 *E. coli* per 100 ml. The diffusivity of *E. coli* (Γ) was assumed to be zero because it was considered to be negligible in influencing the results due to the circulation pattern in the pond (Shilton and Harrison 2001). A 3-D turbulent steady state solution of the flow equations was calculated with a second order discretization scheme and a $\kappa - \varepsilon$ closure model. A grid dependence test was carried out to determine the optimum mesh size that provided grid-independent solutions. A grid of this density was then used for all further simulations undertaken.

The model was used to predict effluent *E. coli* count in a secondary facultative pond with a range of wind speed (3−6 m/s) blowing in four directions with respect to the wastewater flow. A hypothetical pond with dimensions of 640 × 320 × 1.5 m deep was used. The inlet and outlet pipes were 400-mm diameter and were located in opposite diagonal corners of the pond at the depths of 0.6 m and 1.0 m, respectively, above the bottom level of the pond. Shilton and Harrison (2003a, 2003b) studied a similar pond but one with a retention time of 31 days at 14°C. We used a 4-day retention time and 25°C to assess performance of tropical facultative ponds since short-circuiting could be significant in these ponds at short retention time. Seventeen simulations were undertaken with different wind speeds and directions. Figure 1 shows the prevailing wind directions in relation to the wastewater flow in the secondary facultative pond.

Four different wind speeds were applied in the model: 3m/s, 4m/s, 5m/s and 6m/s. The directions of wind speed with respect to the wastewater flow were: (i) same direction as the wastewater water flow (+Z in Figure 1), (ii) opposite direction to the wastewater flow (−Z), (iii) two perpendicular directions to the wastewater flow

(+X and –X). Other wind directions with similar range of wind speed to the wastewater flow were not considered because the resolved components of the wind velocity (parallel and normal to the wastewater flow) were lower than the range of the wind speed considered.

Results and discussion

Each simulation was undertaken with a different wind speed and direction. A simulation of the secondary facultative pond with no wind effects was first carried out to establish the baseline *E. coli* removal. Results from this formed the basis of comparison with other configurations that included effects of wind speed. Sweeney (2004) observed the initiation of the hydraulic short-circuiting in a waste stabilization pond model at a wind speed of 3 m/s. Brissaud *et al*. (2000, 2003), Frederick and Lloyd (1996) and Vorkas and Lloyd (2000) observed hydraulic short-circuiting in field ponds subject to wind speeds of 0.1−2.6 m/s. Shilton and Harrison (2003a, 2003b) used an average wind speed of 2.8 m/s to assess wind effects on the performance of field ponds in New Zealand. We therefore chose wind speeds ≥3 m/s for our performance assessment of the facultative pond.

Table 1 shows the model results of effluent *E. coli* counts when the wind was blowing from the four different prevailing directions. It can be seen from these results that when the wind was blowing against the direction of the wastewater flow, the effluent *E. coli* counts were all lower than that in a facultative pond with no wind. A similar pattern of *E. coli* removal was achieved when the wind was blowing normal to the direction of the wastewater flow (the +X direction in Figure 1). The results in Table 1 show that a wind speed of 6 m/s predicted an 81% higher *E. coli* removal than that in a facultative pond with no wind. However, wind speeds of 3, 4 and 5 m/s gave *E. coli* counts lower by 15%, 44% and 63%, respectively, than that in the pond with no wind.

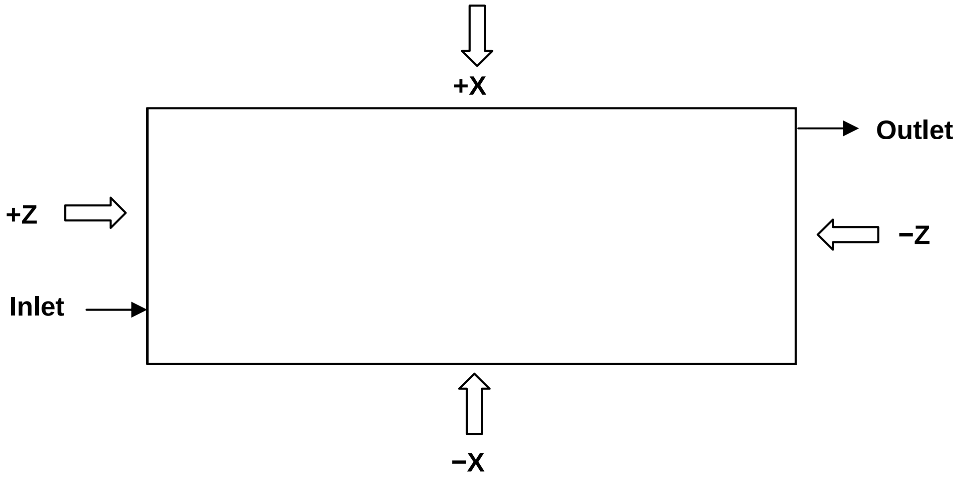

Figure 1. Prevailing wind directions in the secondary facultative pond model

However, when the wind was blowing in the same direction as the wastewater flow (Table 2), the *E. coli* removal lower than that in a facultative pond with no wind: wind speeds of 3, 4, 5 and 6 m/s reduced the *E. coli* removal efficiency by 12%, 31%, 18% and 13%, respectively. Thus there was no direct relationship between the wind speed and the *E. coli* removal in the range studied. This can be partly explained by the complex hydraulic flow pattern that forms when the wind velocity interacts with the surface wastewater velocity interacts with the surface wastewater velocity. Nevertheless, the low *E. coli* removal efficiency could have been caused by the initiation of hydraulic short-circuiting.

Table 1. CFD results of effluent *E. coli* count per 100 ml in a facultative pond with and without wind effects

Wind speed (m/s)	**Effluent *E. coli* per 100 ml**				
	Wastewater flow with zero wind speed	**Wind speed in same direction as wastewater flow (+Z)**	**Wind speed against the wastewater flow (−Z)**	**Wind speed normal to the wastewater flow (+X)**	**Wind speed normal to the wastewater flow (−X)**
3	6.94×10^5	7.78×10^5	5.90×10^5	5.60×10^5	7.40×10^5
4	6.94×10^5	9.08×10^5	3.90×10^5	2.60×10^5	7.50×10^5
5	6.94×10^5	8.20×10^5	2.60×10^5	3.50×10^5	8.20×10^5
6	6.94×10^5	7.80×10^5	1.30×10^5	4.30×10^5	5.90×10^5

Table 2. Change in *E. coli* removal in the facultative pond model with the incorporation of wind speed and direction

Wind speed (m/s)	**Change in *E. coli* removal**			
	Wind speed in the same direction as wastewater flow (+Z)	**Wind speed against wastewater flow (−Z)**	**Wind speed normal to wastewater flow (+X)**	**Wind speed normal to wastewater flow (−X)**
3	+12%	−15%	−19%	+7%
4	+31%	−44%	−63%	+8%
5	+18%	−63%	−50%	+18%
6	+13%	−81%	−38%	−15%

Notes: (a) positive %: higher *E. coli* count than that in a pond with no wind.
(b) negative %: lower *E. coli* count than that in a pond with no wind.

Figures 2 and 3 show the flow pattern (in the form of uniformly scaled velocity vectors) on the top surface of the facultative pond when the wind was blowing in the same direction as the wastewater flow and against the wastewater flow, respectively. It can be seen that the facultative pond with no wind has formed two flow circulation patterns in opposite directions. These appear at the centre and lower left side of the pond. Similar circulation patterns were observed at other levels below the top surface. The similarity in the observed flow patterns may have been sustained by the inlet momentum, which was significantly higher than the wind effects (98% for a wind speed of 3 m/s and 86% for 6 m/s).

Figure 2 indicates that facultative pond models with short retention times are prone to short-circuiting due to the flow circulation paths, which can discharge wastewater at shorter retention times. It can also be seen from Figure 2 that the increase of wind speed has changed the flow pattern. A large single flow circulation pattern has developed with an increase in the number of flow paths that approach the outlet. This circulation pattern could discharge a greater portion of wastewater within a fraction of the designed retention time. The low *E. coli* removal efficiency achieved when the wind was blowing in the same direction as the wastewater flow could be caused by this flow pattern associated with short-circuiting.

The flow patterns shown in Figure 3 are significantly different from those shown in Figure 2. When the wind was blowing against the wastewater flow, the number of the circulatory flow patterns increases. About 3-4 flow circulation patterns are formed in the pond and these increase the length of the flow paths. It is interesting to note that two flow circulation patterns are formed near the pond inlet and this forms a mechanism that reduces hydraulic short-circuiting. This flow pattern increased the *E. coli* removal compared with that in a facultative pond with no wind.

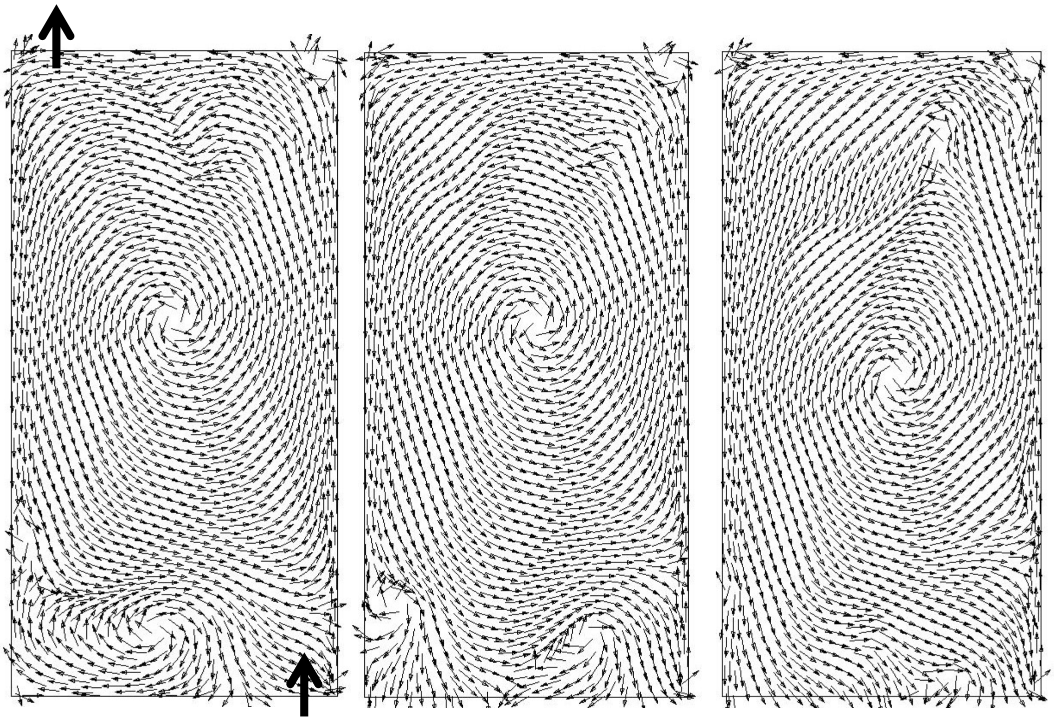
No wind Wind speed 3 m/s Wind speed 6 m/s

Figure 2. Flow pattern in a facultative pond with the wind blowing in the same direction of the wastewater flow.

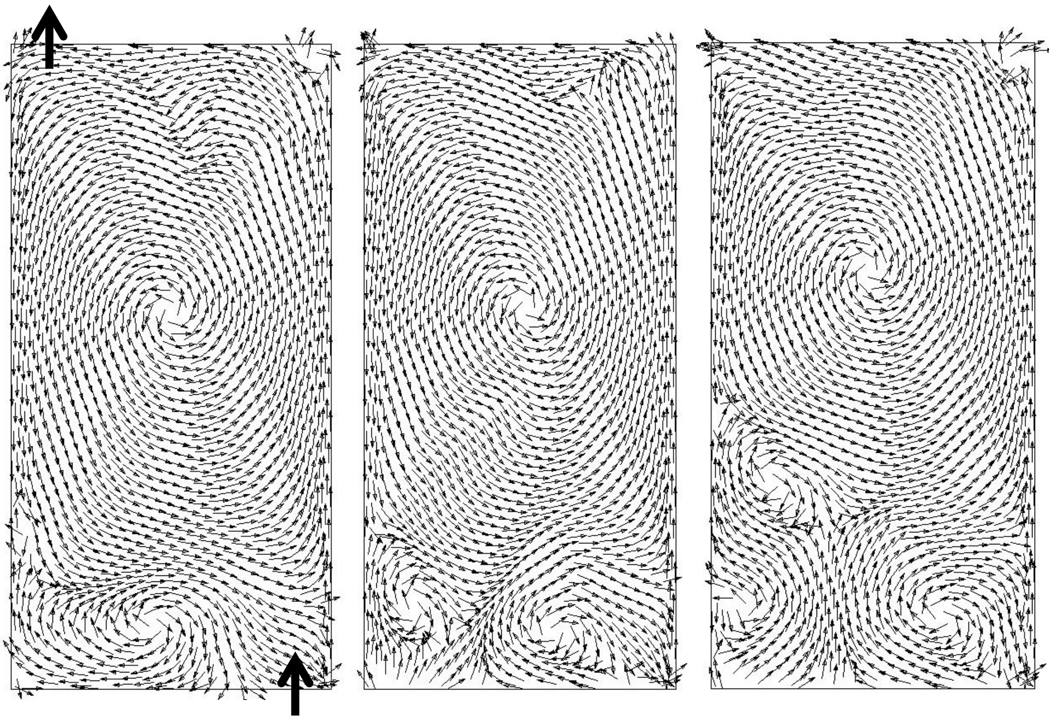
No wind Wind speed 3 m/s Wind speed 6

Figure 3. Flow patterns in a facultative pond with the wind blowing against the direction of the wastewater flow.

When the wind was blowing normal to the direction of the wastewater flow (the −X direction in Figure 1), there is a probability that the effluent *E. coli* count would be slightly higher than that in facultative pond with no wind. However, the +X wind direction predicted a lower *E. coli* count than that in a facultative pond with no wind.

The significance of these CFD model results is that the treatment performance of waste stabilization ponds can likely be improved by utilizing wind effects. This can be achieved by locating waste stabilization ponds such that the wastewater flow is opposite to the prevailing wind direction. However, the results further suggest that the treatment performance of waste stabilization ponds can deteriorate if the location of waste stabilization ponds allows the wastewater flow to follow the wind direction. Mara (2004) advises that waste stabilization ponds should be located such that the wastewater flow is against the prevailing wind direction. This was based on engineering judgement drawn from experience of operational ponds. Our CFD results confirm Mara's recommendation.

Shilton and Harrison's (2003a, 2003b) power theory was used to assess the significance of the inlet momentum and the wind effects with particular respect to the pond hydraulics. Shilton and Harrison used a 31-day retention time to show that the inlet momentum was significant over the wind effects when the wind was blowing at velocity of 2.8 m/s in a similar model. However, our work used a 4-day retention time to increase substantially the inlet momentum. The wind speed of 4 m/s provided power of 0.82 kW over the pond surface area of 640 × 320 m. The power supplied by the influent was 22 kW, so the contribution of the wind effects was 4%. It can be argued that the effect of wind on the flow pattern of the wastewater flow is so small that the resulting flow pattern can be deemed to be sustained by the inlet momentum. With this significant inlet momentum, the wind effects can be negligible in influencing the treatment performance of a facultative pond. Interestingly, the work presented here has demonstrated that a wind speed of 4 m/s blowing in the same direction as the wastewater flow, the *E. coli* removal was reduced by 31% than that in a facultative pond with no wind. If the Shilton and Harrison (2003a, 2003b) theory was satisfactory, the results of wind effects should have nearly agree with that of facultative pond with no wind as the inlet momentum is 96% greater than the wind effects. The design of waste stabilization ponds may be suboptimal if the effects of wind speed and direction are not taken into account in the geometric design of pond systems. It should be noted that even at a low wind speed of 0.5 m/s, Fredrick and Lloyd (1996) observed short-circuiting in ponds that had a 12-day retention time with isothermal conditions. The Shilton and Harrison hydraulic guidelines should be revised to include effects of wind speed and direction on pond hydraulics.

Conclusions

The effects of wind speed and direction can improve the treatment performance of waste stabilization ponds if they are located such that the direction of the wastewater flow is against the prevailing wind direction. All CFD modelling should take into account wind speed and direction in order to assess pond performance more realistically.

References

Arceivala, S. T. (1983). Hydraulic modelling for waste stabilization ponds: discussion. *Journal of Environmental Engineering Division*, ASCE, **109** (EE1), 265−268.

Banda, C. G., Sleigh, P. A. and Mara, D. D. (2005). *Escherichia coli* removal in waste stabilization ponds: a comparison of modern and classical designs. *Water Science and Technology* **51** (12), 75−81.

Brissaud, F., Lazarova, V., Ducoup, C., Joseph, C., Levine, B. and Tournoud, M. (2000). Hydrodynamic behaviour and faecal coliform removal in a maturation pond. *Water Science and Technology* **42** (10/11), 119−126.

Brissaud, F., Tournoud, M. G. Drakides, C., and Lazarova, V. (2003). Mixing and its impact on faecal coliform removal in a stabilization pond. *Water Science and Technology* **48** (2), 75−80.

Fluent, Inc. (2003). *User's Manual, Version 6.1*. Fluent Inc., Lebanon, NH.

Frederick, G. L. and Lloyd, B. J. (1996). An evaluation of retention time and short-circuiting in waste stabilization ponds using *Serratia marcescens* bacteriophage as a tracer. *Water Science and Technology* **48** (2), 173−180.

Lloyd, B. J., Vorkas, C. A., and Guganesharajah, R. K. (2003). Reducing hydraulic short- circuiting in maturation ponds to maximize pathogen removal using channels and wind breaks. *Water Science and Technology* **48** (2), 153−162.

Marais, G. v. R. (1974). Faecal bacterial kinetics in waste stabilization ponds. *Journal of the Environmental Engineering Division,* ASCE, **100** (EE1), 119−139.

Mara, D. D. (2004). *Domestic Wastewater Treatment in Developing Countries*. Earthscan Publications, London.

Patankar, S. V. (1980). *Numerical Heat Transfer and Fluid Flow*. Hemisphere Publishing Corporation, New York.

Pearson, H. W., Mara, D. D. and Arridge, H. A. (1995). The Influence of pond geometry and configuration on facultative and maturation waste stabilization pond performance and efficiency. *Water Science and Technology* **31** (12), 129−139.

Shilton, A. and Harrison, J. (2003a). Development of guidelines for improved hydraulic design of waste stabilization ponds. *Water Science and Technology* **48** (2), 173−180.

Shilton, A. and Harrison, J. (2003b). *Guidelines for the Hydraulic Design of Waste Stabilization Ponds*. Institute of Technology and Engineering, Massey University. Palmerston North.

Shilton, A. N. (2001). *Studies into the Hydraulics of Waste Stabilization Ponds* (PhD Thesis). Massey University, Palmerston North.

Sweeney, D. (2004). *Integrating Biological and Hydraulic Aspects of Waste Stabilization Ponds* (PhD Thesis). Flinders University, Adelaide.

Tchobanoglous, G., Burton, F. and Sense, H. D. (2003). *Wastewater Engineering: Treatment and Reuse*, 4th ed. McGraw-Hill, New York.

Thirumurthi, D. (1974). Design criteria for waste stabilization ponds. *Journal of the Water Pollution Control Federation* **46** (9), 2094−2106.

Versteeg, H. K. and Malalasekera, W. (1995). *An Introduction to Computational Fluid Dynamics – The Finite Volume Method*. Pearson Education, Harlow.

Vorkas, C. A. and Lloyd, B. J. (2000). The application of a diagnostic for the identification of hydraulic design deficiencies affecting pathogen removal. *Water Science and Technology* **42** (10/11), 99−109.

Wood, M. (1997). *Development of Computational Fluid Dynamics Models for the Design of Waste Stabilization Ponds* (PhD Thesis). Department of Chemical Engineering, University of Queensland, Brisbane.