Chapter 5

Results of CFD models of waste stabilization ponds

5.1 Introduction

The chapter presents CFD model results of unbaffled facultative pond, two-baffle facultative pond, four-baffle facultative pond, six-baffle facultative pond, eight-baffle facultative pond and ten-baffle facultative pond. The length of baffles that was employed in the numerical tests was in a range of 70% - 82% pond-width. The chapter also presents CFD model results of a facultative pond with short baffles (10% - 30% pond-width) that were placed near the inlet and outlet. This configuration was tested in order to assess whether short baffles can compete with the conventional 70% pond-width baffles in improving the treatment efficiency of waste stabilization pond. The chapter finally presents CFD model results of a facultative pond that include effects of wind speed and its prevailing direction with respect to the wastewater flow in the pond. This test was carried out to investigate whether wind effects could be utilized to improve the hydraulic performance and treatment efficiency of waste stabilization ponds.

5.2 3D CFD model set up

A 3D CFD 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 flow in a facultative pond that is fitted with baffles of various configurations. Earlier findings by Wood (1997) showed that 2D models are severely limited and concluded that they should never be used to determine the treatment performance of waste stabilization ponds due to their inability to represent the actual pond depth leading to inaccurate simulation of thermo-stratification effects in the model. To overcome this, Wood (1997, 1998) suggests that it is necessary to use 3D models so that the effect of depth variation is accounted for.

FLUENT software (version 6.1.22) was used in all simulations that were undertaken. Chapter 2 has presented in detail the CFD equations that were used in the numerical simulations. The treatment performance of waste stabilization pond is usually assessed by comparing the quality of the effluent concentration with that of the influent raw wastewater. This is normally expressed in terms of percentage removal. This principle has been used when assessing the treatment performance of the model results.

Wastewater comprises a number of pollutant parameters such as BOD_5, suspended solids, *E. coli*, nutrients (ammonia, nitrogen, phosphorus) and many others (Tchobanoglous *et al.* 2003). Evaluation was carried out to assess the suitability of using these indicator parameters in the CFD model of the facultative pond. It was found that the use of the scalar transport equation is feasible with pollutant parameters that decay following the first-order kinetic theory. As a result, *E. coli* and BOD_5 were parameters simulated in the CFD model for the assessment of the facultative pond performance. Chapter 3 provides detailed information regarding this approach and the suitability of using these indicator parameters within the CFD model.

5.3 CFD models of waste stabilization ponds

5.3.1 Representation of *E. coli* removal

To simulate *E. coli* removal accurately within FLUENT, the source terms function that represented *E. coli* removal was programmed (Appendix A) and incorporated within the code via the UDF (Chapter 3). The addition of this UDF function modified the standard scalar transport equation to enable simulation of the decay of *E. coli* based on equations 5.1, 5.2 and 5.3:

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\phi U) = div(\Gamma grad\phi) + S_{\phi} \qquad 5.1$$

$$S_{\phi} = -\rho k\phi \qquad 5.2$$

$$k = 2.6(1.19)^{T-20} \qquad 5.3$$

Marais' (1974) equation 5.3 for the first order-rate constant of *E. coli* removal was adopted because Pearson *et al.* (1995) found it satisfactory in predicting the *E. coli* removal in waste stabilization ponds in northeast Brazil that were optimally loaded.

5.3.2 Grid definition

Three different mesh sizes were investigated to find the optimum mesh size that provides CFD solution that is grid-independent (Chapter 3). A hexahedral mesh size of 1.75 m × 1.75 m × 0.1875 m was chosen as the optimum mesh and was used to mesh the geometry of the facultative pond model. The inlet and outlet pipes had diameter of 400 mm and were located 10 m from the side edge of the pond. These inlet and outlet structures were located at the diagonally opposite corners of the pond following the recommendations of the geometric design of waste stabilization pond (Mara, 2004).

In order to improve the accuracy of the solution, 3D with double precision was used during the simulations (FLUENT manual, 2003). The second order-differencing scheme was adopted because it is precise in simulating the recirculation flow pattern that exists in baffled waste stabilization pond (Versteeg and Malalasekera, 1995; Ferziger and Peric, 2002). Tests on lower order differencing schemes showed that these are not suitable as they lose accuracy in simulating some of the strong recirculation features.

5.3.3 Flow regime

Time dependent flow is appropriate for the CFD model of waste stabilization ponds due to the daily variation of the influent flow and operating conditions. However, it was decided to use the steady state flow because the concentration of pollutants profile does not vary significantly over time due to the long period of the pond operation. The Reynolds number at the pond inlet was 3.3×10^5 (See Chapter 3, Section 3.2.1 for detailed calculation of Reynolds number). This suggests that the flow characteristic in the pond is turbulent flow regime. The CFD model used the standard $k-\varepsilon$ model for all simulations that were undertaken.

5.3.4 Boundary conditions

The inlet boundary condition of the model was based on specification of a mass flow rate. This was chosen because it allowed the final check of the net-mass flow rate to be assessed at the pond inlet and outlet when the converged flow solution was reached.

The waste stabilization pond volume and the average hydraulic retention time were 3.1×10^5 m^3 (640 m × 320 m ×1.5 m) and 30 days respectively. This gave the daily flow rate of 1.02×10^4 m^3 per day (0.12 m^3/s). Based on the inlet pipe area of 0.13 m^2 (0.4-m diameter), a fixed velocity of 0.92 m/s was defined at the inlet as the boundary condition of the momentum equations. A zero pressure was defined at the pond outlet to initiate the wastewater flow. The influent *E. coli* count of 10^8 per 100 ml was defined as the boundary condition of the scalar transport equation. The top surface of the pond was assumed horizontal. This condition was applied using a wall with a *free slip* condition specified to simulate a frictionless surface. This simulated the top surface boundary between the wastewater and the surrounding air when the effects of wind are not considered. The diffusivity of *E. coli* (Γ) was assumed to be zero because it was considered to be negligibly small in influencing the results due to circulation flow pattern in the pond (Shilton and Harrison 2003a, 2003b).

5.4 Simulation of the facultative pond

The model was used to simulate a primary facultative pond with dimensions of 640 m long, 320 m wide and 1.5 m deep. This pond had been designed using the standard facultative pond design procedures (Mara, 2004). A series of numerical experiments was undertaken that considered different baffle configurations to modify its flow pattern. Even numbers of baffles were placed equally separated in the longitudinal direction. The lengths of these baffles, expressed as percentage of the pond-width, are 70%, 72%, 74%, 76%, 78% and 82%, and in terms of actual length, are 224 m, 230 m, 237 m, 243 m, 250 m, and 262 m respectively. Figure 5.1 shows the general arrangements of the conventional baffles as used in the model. The facultative pond has a theoretical retention time of 30 days for the design temperature of 14^oC to represent the average summer temperature in temperate climate areas (Shilton and Harrison, 2003a, 2003b).

The convergence measure for the CFD solution was based on two criteria following the recommendations in the Fluent Manual (2003). The first criterion was the satisfaction of the residuals for the momentum, mass and the scalar transport equations that were set to 1×10^{-3}. Although lower residual values in the order of 1×10^{-5} - 1×10^{-6} were not chosen for a more precise simulation of flow and scalar variables in the model, it was considered that the residual value of 1×10^{-3} was appropriate for the adopted mesh size (0.75 m × 0.75 m × 0.1875 m) and would give acceptable precision. Simulations showed that the CFD solution was grid independent at this residual value. The second criterion was the satisfaction of the net mass flow rate. The net mass flow rate at the pond inlet and outlet was checked to ensure that it was close to zero ($< 1 \times 10^{-5}$). When these two criteria were satisfied, the predicted CFD solution was deemed to have converged and to simulate steady state conditions.

5.5. CFD model results

The CFD results of effluent *E. coli* counts in facultative ponds with conventional baffles (2, 4, 6, 8 and 10 baffles) of various configurations are presented in Table 5.1. Figure 5.1 shows the general arrangement of conventional baffles of different lengths and numbers in each simulation that was undertaken.

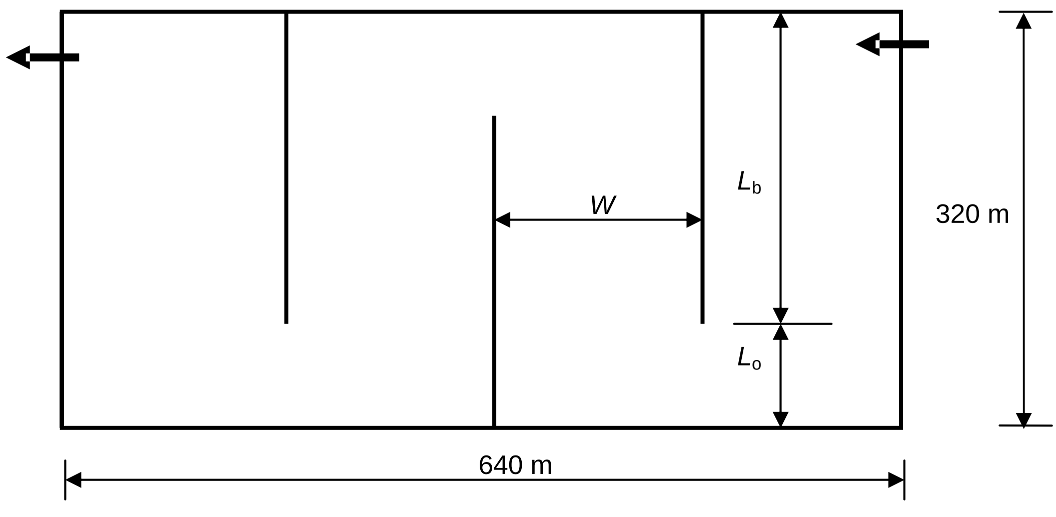


Figure 5.1 The general arrangement of conventional baffles of different lengths in the facultative pond

The unbaffled facultative pond model was simulated first to establish the baseline removal of *E. coli* in the pond. To quantify the treatment efficiency of the facultative pond in the CFD model, a monitoring parameter was required. The area of the outlet pipe (0.13 m^2) was chosen for which the mean value of the *E. coli* count could be monitored. The prediction of the *E. coli* count in the simulation was based on the mass average weight method (FLUENT manual, 2003). Using this measurement as the quantifiable value of *E. coli* count, the results of all simulations for conventional baffles (70% - 82% pond-width baffles) are shown in Table 5.1.

Table 5.1 Predicted effluent *E. coli* counts per 100 ml in the facultative pond with baffles of various configurations (influent *E. coli* count was 1×10^8 per 100 ml)

Number of baffles	Baffle length as percentage of pond width, L_b (Flow channel width at baffle openings, L_o)			Channel width, *W* (m)
	70%	78%	82%	
	224.0 m (96.0 m)	250.0 m (71.0 m)	259.0 m (58.0 m)	
-	4.10×10^6			320.0
2	29 200			213.3
4	2 400			128.0
6	121			92.0
8	162	54		71.0
10	10 000		0.001	58.0

5.5.1 Model results for the unbaffled facultative pond

For the unbaffled facultative pond, a predicted effluent *E. coli* count of 4.10×10^6 per 100 ml (Table 5.1) was obtained from the CFD simulation. Figure 5.2 shows the flow pattern and spatial residence time distributions of wastewater in this pond at a horizontal plane of 0.5 m below the pond water surface. The maximum velocity achieved was at the inlet with a value of 0.92 m/s, the velocity vectors in this figure are scaled uniformly in length (i.e. the size of the arrow does not indicate magnitude of velocity) so that the diagram shows clearly the extent of the hydraulic flow pattern. It can be seen from the diagram of spatial residence time distribution of the wastewater that there are orange/yellow band around the edge of the pond that links directly the inflow to the outflow. This is an indication of short-circuiting. It can also be seen that the circulation flow patterns have initiated stagnation regions to form at the centre of the pond. It was also seen on planes at other levels (not shown here) that there is no significant visible difference of the general flow patterns at these levels.

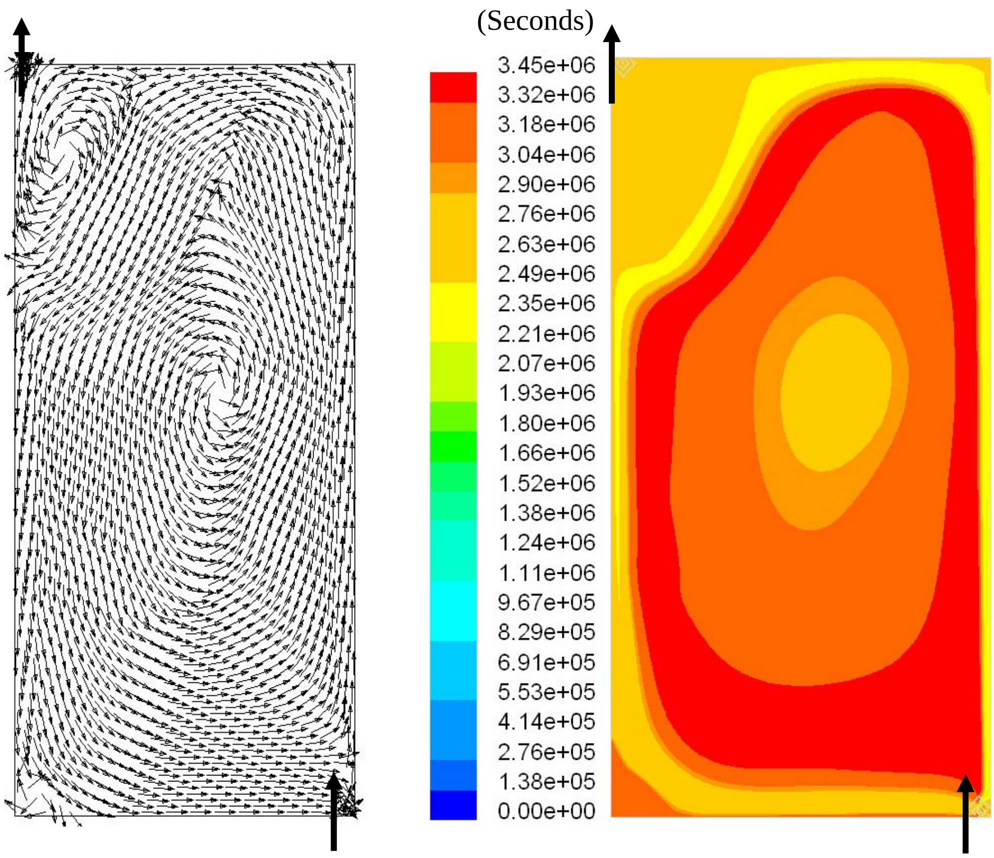


Figure 5.2 Flow pattern and residence time distributions of wastewater in the unbaffled facultative pond with 30 days (2.6×10^6 seconds) theoretical retention time

Shilton (2001) observed similar circulation flow patterns using PHOENICS CFD software to simulate the hydraulic flow pattern in the laboratory pond. It can be suggested that stagnation regions have reduced the effective volume of the pond and this in turn reduced the mean retention time of the pond. The average hydraulic retention time in the unbaffled facultative pond is 24 days (2.1×10^6 seconds) and is less than the theoretical retention time (30 days).

The treatment performance of wastewater in this unbaffled facultative pond could be compromised due to the initiation of the short-circuiting and stagnation regions. Physical design interventions should be provided to reduce the observed short-circuiting and stagnation regions in this unbaffled pond. Baffles could be one of such physical designs that can be fitted in this pond to address these hydraulic problems. Shilton and Harrison (2003a, 2003b) used CFD model to simulate the *E. coli* removal in similar waste stabilization pond. The predicted effluent *E. coli* count from their simulation was 6.0×10^6 per 100 ml. The work presented in this research has predicted the effluent *E. coli* count of 4.2×10^6 per 100 ml. It can be noted that the two predictions do not differ from each other significantly.

5.5.2 Model results for the two-baffled facultative pond

The two-baffled facultative pond used conventional baffles of length (L_b) 70% pond-width (224 m) equally spread in the longitudinal direction of the pond. The arrangement formed a flow channel width (W) of 213 m in the baffle compartments and a baffle opening (L_o) of 96 m (Table 5.1).

Figure 5.3 shows the hydraulic flow patterns and the spatial residence time distributions of the wastewater in the two-baffled pond at a plane of 0.5 m below the pond water surface. The velocity vectors shown in Figure 5.3 represent the hydraulic flow patterns that are scaled uniformly so that the diagram shows clearly the extent of the hydraulic flow pattern. It can be seen that the baffles have forced the wastewater to circulate around in the baffle compartments. There are no contours directly linking the inlet to the outlet so short-circuiting has dramatically reduced when compared with the flow pattern in the unbaffled facultative pond (Figure 5.2). There is, however, an amount of short-circuiting within each compartment, indicated by the constant contour around the edge. The circulation flow pattern in the baffle compartments allows mixing to occur. It can be seen from the diagram of the residence time distribution of the wastewater that stagnation regions appear at the centre of all baffle compartments near the pond outlet. The average hydraulic retention time in the two-baffle facultative pond is 26 days (2.2×10^6 seconds) and is relatively more compared with that of the unbaffled facultative pond (24 days). The simulation of the *E. coli* removal using the scalar transport equation predicted the effluent *E. coli* of 2.92×10^4 per 100 ml in the two-baffle facultative pond (Table 5.1). It is interesting to note that Shilton and Harrison (2003a, 2003b) using

PHOENICS CFD software predicted the effluent *E. coli* count of 3.0×10^3 per 100 ml in a similar two-baffle pond.

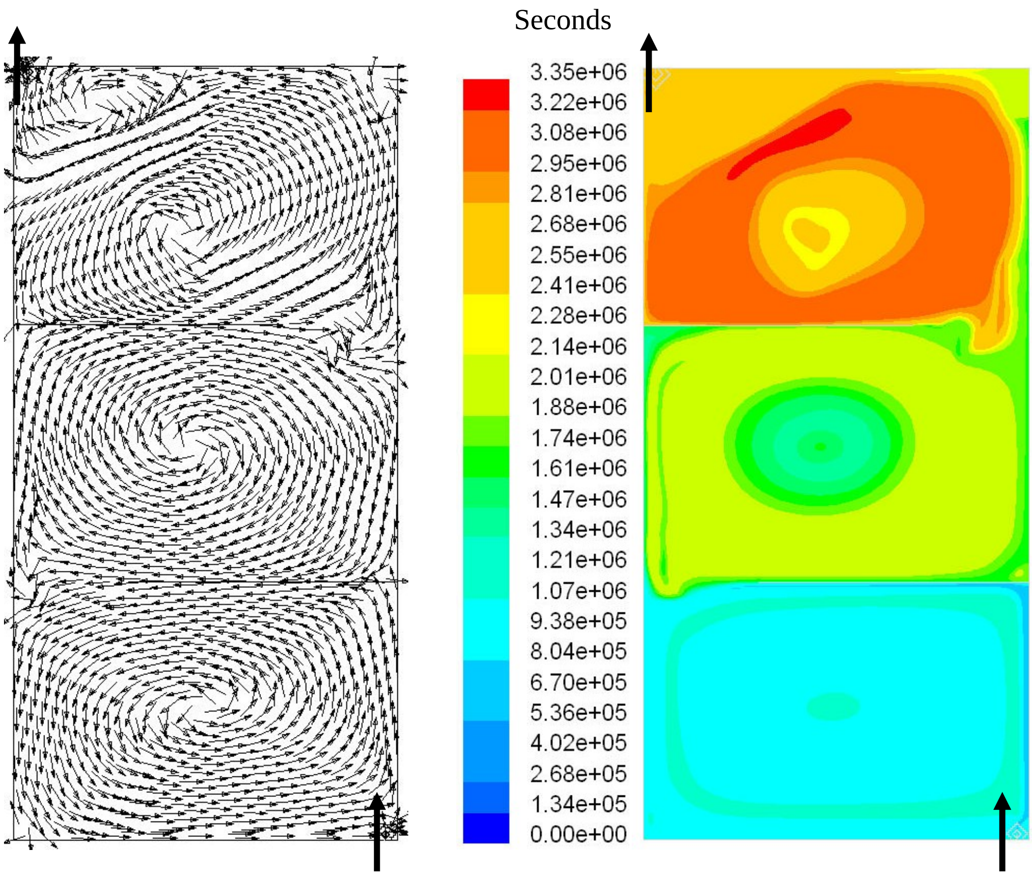


Figure 5.3 Flow pattern and residence time distributions of wastewater in the two-baffled facultative pond model with 30 days (2.6×10^6 seconds) theoretical retention time

This differs from the results reported in this work by 0.60 orders of magnitude. Interestingly, the effluent *E. coli* counts on three replicates from the two-baffle pilot-scale pond gave consistence *E. coli* counts that were in the same order of magnitude (Chapter 6). The failure of the two CFD models in predicting *E. coli* counts of the same order of magnitude indicates that the predicted counts (2.92×10^4 per 100 ml and 3.0×10^3 per 100 ml) are indeed different. This difference could be attributed to the different boundary conditions that were used in the two models as they were not specified clearly in Shilton and Harrison's (2003a, 2003b) publications. Also, there is a question mark over the source term for *E. coli* decay used by Shilton and Harrison. In contrast, the results presented here should be reliable as the source term function that represents the *E. coli* removal has been developed and carefully checked with ideal plug flow model and has been found to be satisfactory (Chapter 3).

5.5.3 Model results for the four-baffled facultative pond

The four-baffled facultative pond used conventional baffles of length (L_b) 70% pond-width (i.e., 224 m) equally spread in the longitudinal direction of the pond. This arrangement formed a flow channel width (W) of 128 m in the baffle compartments and a baffle opening (L_o) of 96 m (Figure 5.1). For the four-baffled pond, a predicted effluent *E. coli* count of 2.40×10^3 per 100 ml (Table 5.1) was obtained from the CFD simulation. Figure 5.4 shows the hydraulic flow patterns with uniformly scaled velocity and the residence time distribution of the wastewater in this pond at a plane of 0.5 m below the pond water surface.

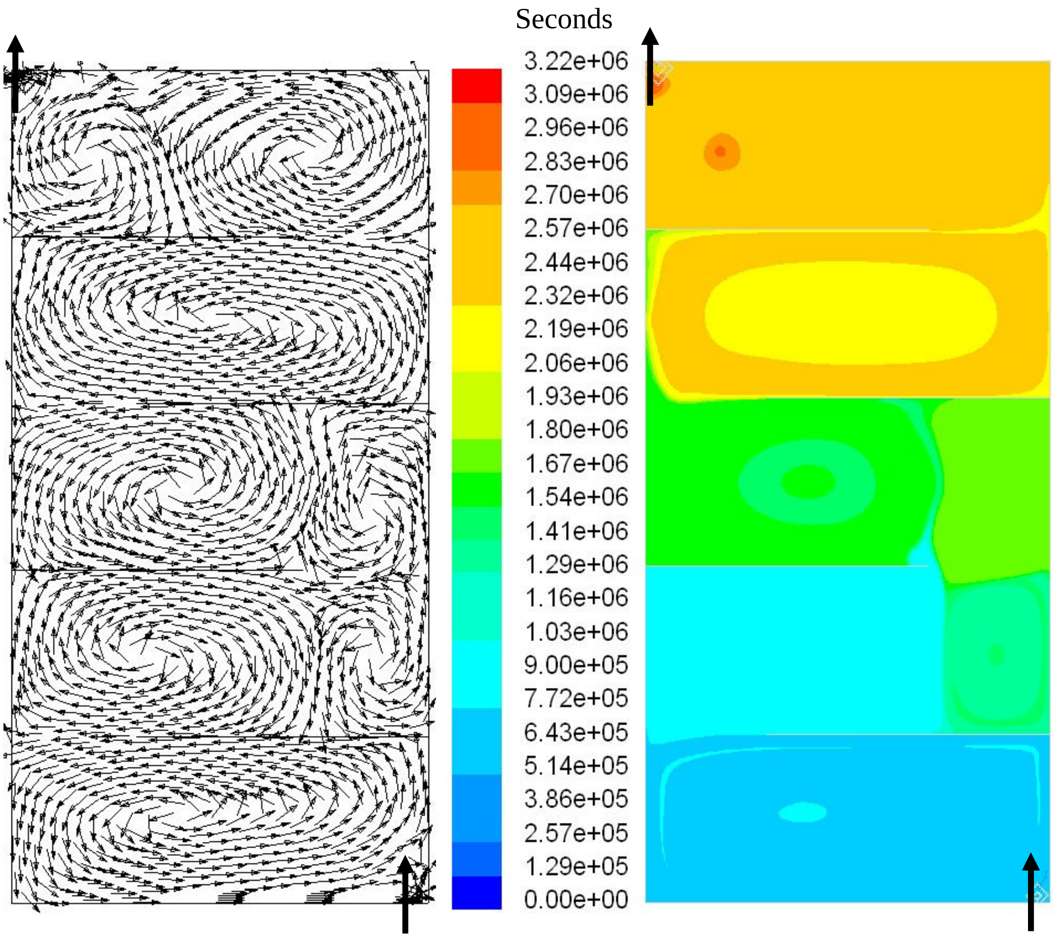


Figure 5.4 Flow pattern and the residence time distribution of wastewater in the four-baffle facultative pond with 30 days (2.6×10^6 seconds) theoretical retention time

The flow pattern diagram in Figure 5.4 show that there is improved mixing of wastewater in each baffle compartment due to circulation of wastewater. It can be seen that there is no short-circuiting visible at this level as they are no contours directly linking the inlet to the outlet. Again not shown, there was no significant visible difference of flow patterns at other levels. The circulating flow pattern of wastewater in each baffle compartments could be responsible for the non-appearance of the hydraulic short-circuiting. There are minimal stagnation regions in the baffle compartments. The spatial residence distribution of the wastewater diagram confirms the initiation of plug flow pattern by the four baffles. The residence time of wastewater in the four- baffled pond is 2.44×10^6 seconds (28 days). Comparing with the theoretical (plug flow) residence time of 30 days, it can be deduced that the four baffles have reduced significantly the hydraulic short-circuiting.

Shilton and Harrison (2003a, 2003b) obtained the effluent *E. coli* counts of 3.9×10^2 per 100 ml when they used PHOENICS CFD software to simulate the treatment performance of similar four-baffled facultative pond. It can be noted again that the result is different from the author’s by 0.80 orders of magnitude and the same reasons stated earlier (Section 5.5.2) could be responsible for the difference. The results of the four-baffle pilot-scale primary facultative pond operated by the author for one year at Esholt sewage treatment work indicated that four baffles could remove up to 4-log units of *E. coli* when optimally loaded. The predicted effluent *E. coli* count in the four-baffle facultative pond model and that of the four-baffle pilot-scale primary facultative pond agree satisfactorily as the counts were of the same order of magnitude (2.40×10^3 for the four-baffle model and 9.80×10^3 for the pilot-scale primary facultative pond). It is interesting to note that the effluent *E. coli* counts on three replicates from the four-baffle pilot-scale pond were of the same order of magnitude although the actual counts were not identical (Chapter 6).

5.5.4 Model results for the six-baffled facultative pond

The six-baffle pond used baffles of length (L_b) 70% pond-width (i.e., 224 m) equally spread in the longitudinal direction. This arrangement formed a flow channel width (W) of 91 m in the baffle compartments and a baffle opening (L_o) of 96 m. Figure 5.5

shows the flow pattern with uniformly scaled velocity (to show the extent of flow pattern) and the residence time distribution of wastewater in this pond at a plane of 0.5 m below the pond water surface. It can be seen that there is no short-circuiting visible at this level as there are no contours directly linking the inlet and outlet. Again, there was no significant visible difference of flow patterns at other levels. The spatial residence time distribution diagram confirms the initiation of plug flow pattern by the six baffles.

The six baffles form a channel flow width of 92 m in the baffle compartments except at the baffle opening where the channel flow width is 96 m. The six – baffle facultative pond model was able to simulate the plug flow model due to its approximate constant flow channel width when compared with other baffle configurations (two and four baffles) as shown in Table 5.1. The simulation predicted the effluent *E. coli* count of 1.21×10^{2} per 100 ml at the pond outlet plane. The average hydraulic retention time in the six-baffle facultative pond model was 29 days and was very close to the theoretical retention time (30 days).

Surprisingly, Shilton and Harrison (2003a, 2003b) found that the four-baffled facultative pond was superior to the six-baffled facultative pond in removing *E. coli* (3.9×10^{2} *E. coli* per 100 ml for the four-baffle facultative pond model, 5.7×10^{2} *E. coli* per 100 ml for the six-baffle facultative pond model). It was suggested that the low removal of *E. coli* in the six-baffled facultative pond model was caused by the channelling flow pattern of wastewater due to the transition from the completely mixed flow pattern to the plug flow pattern.

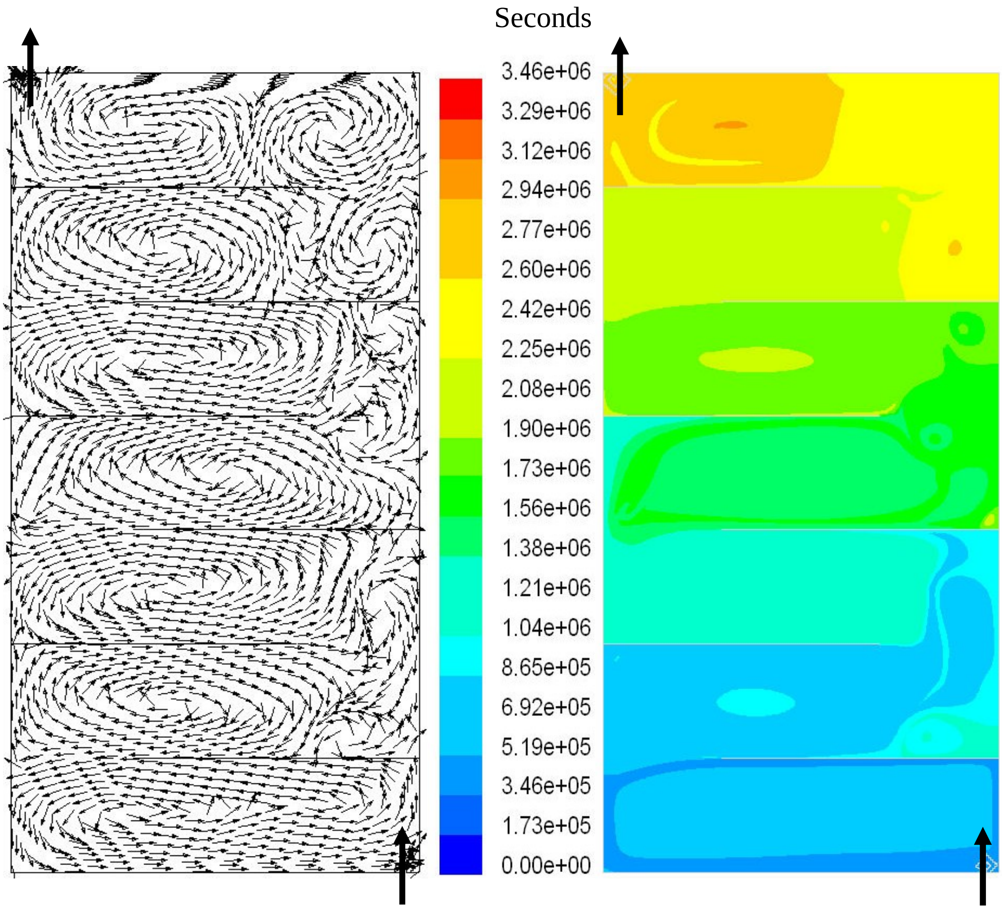


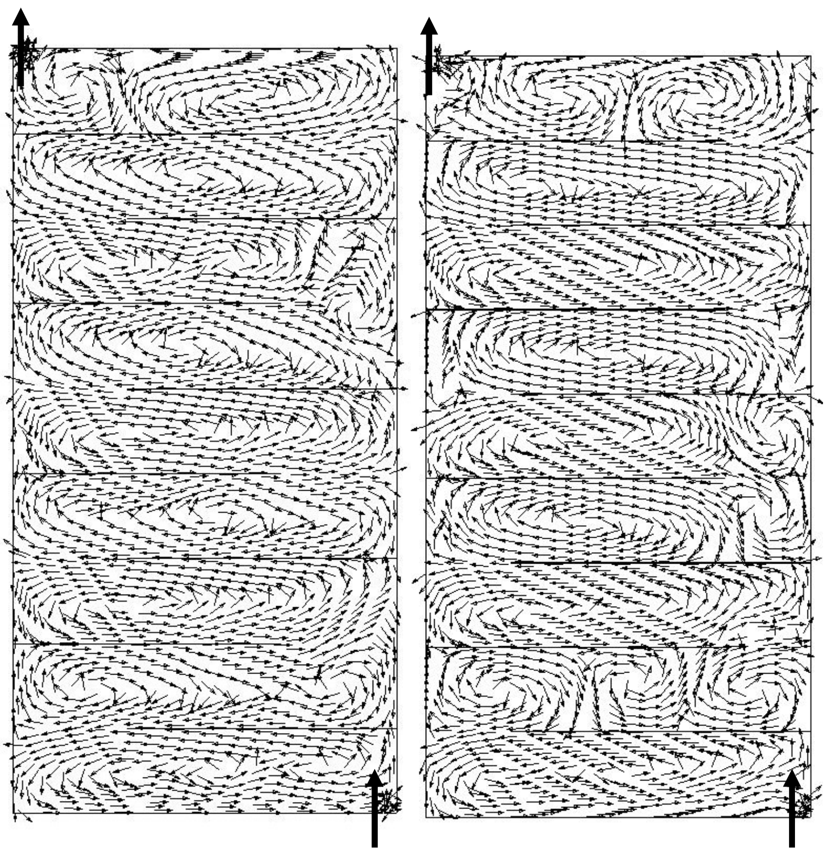
Figure 5.5 Flow pattern and residence time distribution in the six-baffled facultative pond with 30 days (2.60×10^6 seconds) theoretical retention time

However, the hydraulic flow patterns presented in Figure 5.5 do not support the initiation of channelling flow pattern in the six-baffle facultative pond model. It is difficult to accept their reasoning for the poor treatment performance of the six-baffle facultative pond model. From simple consideration of flow continuity, a six-baffle facultative pond model approximates plug flow better than a four-baffle facultative pond model due to the approximate constant channel flow width of 92.0 m in the baffle compartments and a channel flow width of 96.0 m at the baffle openings. However, it can be seen from Table 5.1 that the four-baffle facultative pond forms a channel flow width of 128 m in the baffle compartments and a channel flow width of 96 m at the baffle openings that are quite different.

5.5.5 Model results for the eight-baffled facultative pond

The arrangement with 8 baffles employed two different configurations, A and B. Configuration A had a baffle length of 70% of the pond-width (224 m), a flow channel width of 71 m and baffle opening of 96 m (Table 5.1); and configuration B had a baffle length of 78% of the pond-width (250 m) and the flow channel width and baffle opening were both 71 m along the direction of flow (Table 5.1). For configuration A of the eight-baffled facultative pond with 70% pond-width baffles, a predicted effluent *E. coli* count of 162 per 100 ml (Table 5.1) was obtained from the CFD simulation.

Figure 5.6 shows the flow patterns for configuration A and configuration B at a plane 0.5 m below the pond water surface.



Configuration A **Configuration B**

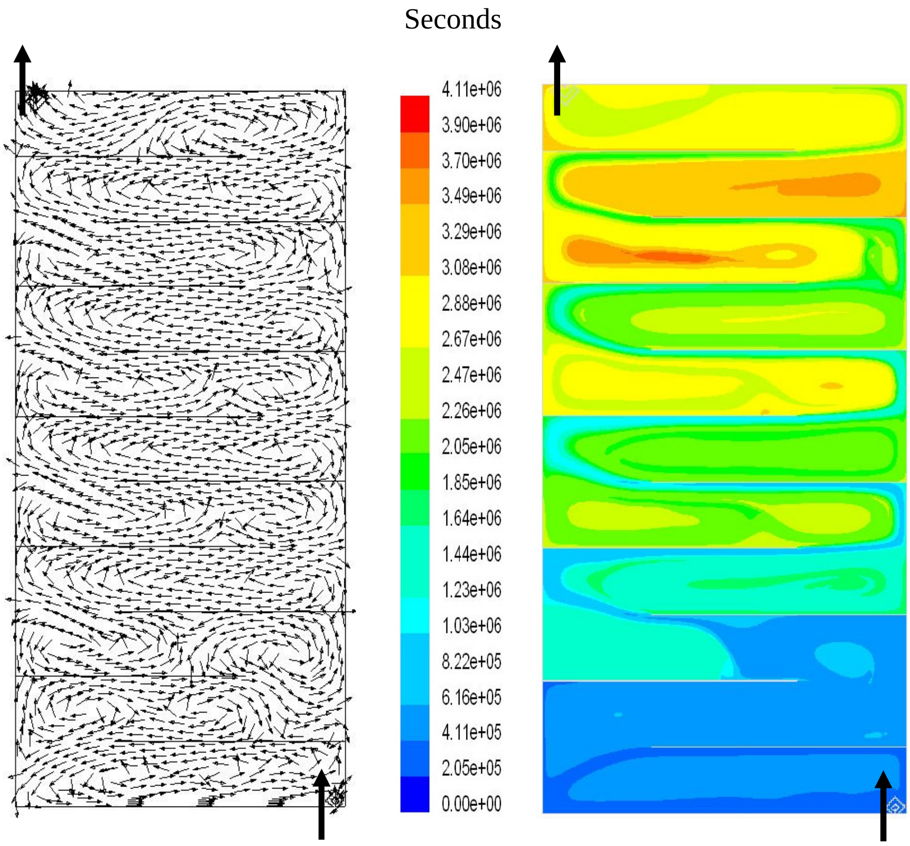
Figure 5.6 Flow patterns of wastewater distributions in the eight-baffled facultative ponds

It can be seen that as with the six-baffle facultative pond, no short-circuiting is apparent for either configuration. The circulating flow pattern of wastewater in each baffle compartments could be responsible for absence of the hydraulic short-circuiting. In addition, there is no significant visible difference of flow patterns between configuration A and configuration B. It is interesting to note that the six-baffle and the eight-baffle facultative models with configuration A that employed the 70% pond-width baffles achieve similar effluent *E. coli* counts (162 *E. coli* per 100 ml for the six-baffled facultative pond and 121 *E. coli* per 100 ml for the eight baffled facultative pond) but at the cost of two additional baffles. For configuration B of the eight-baffled facultative pond, a predicted effluent *E. coli* count of 54 per 100 ml (Table 5.1) was obtained. This is lower by 0.48 orders of magnitude than the configuration A. This can be attributed due to the initiation of plug flow pattern as the flow channel width in the baffle compartments and at the baffle openings are identical (71m). The average hydraulic retention time in the eight-baffle facultative pond with configuration A was 28 days while that of configuration B was 29 days. It can be seen that there is no significant difference between the hydraulic retention times in the eight baffle pond with the 70% pond-width baffles and the 78% pond-width baffles.

5.5.6 Model results for the ten-baffled facultative pond

The arrangement with 10 baffles employed two different configurations, A and C. Configuration A had a baffle length of 70% of the pond-width (224 m), a flow channel width of 58 m and baffle opening of 96 m (Table 5.1). Configuration C had a baffle length of 82% of the pond-width (262 m) and the flow channel width and baffle opening were both 58 m (Table 5.1). The ten-baffled facultative pond is included here to investigate whether the optimal baffle length of 70% of the pond-width found by Mangelson and Watters (1972) is appropriate in all circumstances.

For configuration A of the ten-baffled facultative pond with 70%- pond-width baffles, a predicted effluent *E. coli* count of 1.0×10^4 per 100 ml (Table 5.1) was obtained. Figure 5.7 shows the flow patterns and the residence time distribution of wastewater at the 0.5 m plane for this configuration.



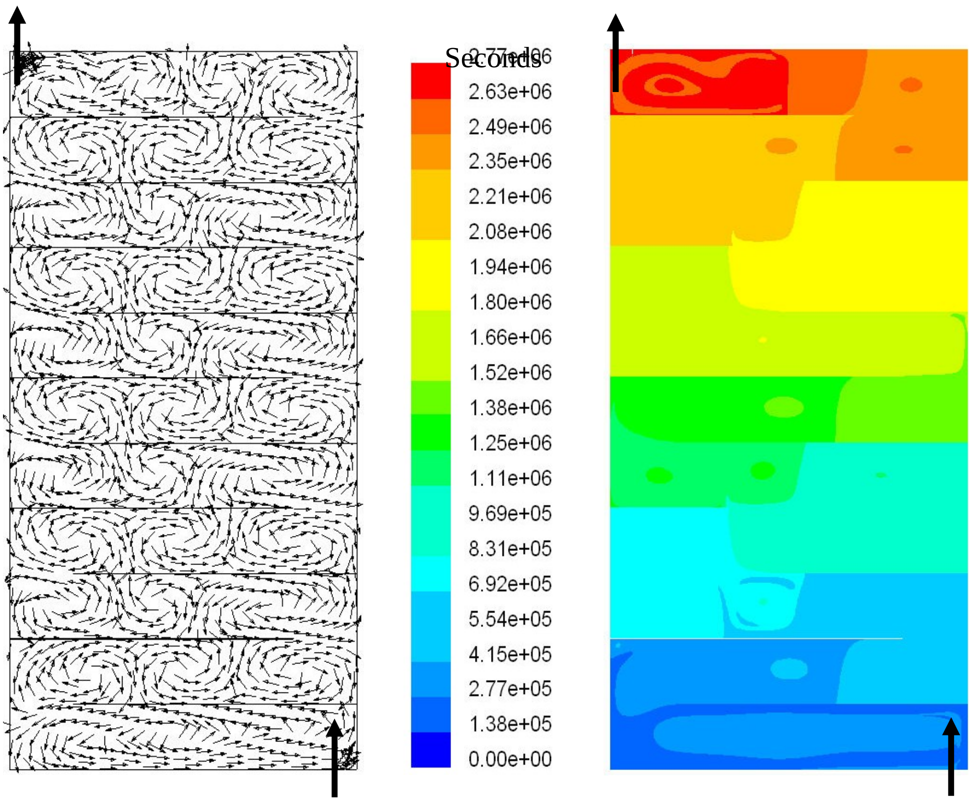
Configuration A

Figure 5.7 Flow patterns and the residence time distributions of wastewater in the ten-baffled facultative pond with the 70% pond-width baffles (theoretical retention time in the model was 30 days).

It can be seen from the figure that configuration A of the ten-baffled facultative pond model shows significant visible short-circuiting at the water surface level and at other levels not shown as the contours are directly linking the inlet and outlet. It can also be seen from the figure that there is significant stagnation regions in baffle compartments and at baffle openings. There is no adequate mixing of wastewater in the baffle compartments due to these hydraulic deficiencies.

The predicted *E. coli* count by this configuration (1.0×10^4 per 100 ml) is equivalent to that of the two-baffle facultative pond model (1.2×10^4 per 100 ml). The treatment performance in this baffle configuration has deteriorated significantly due to the initiation of strong hydraulic short-circuiting. The results indicate that a large number of baffles does not always improve the hydraulic performance and treatment efficiency of waste stabilization ponds. The residence time of wastewater leaving the ten-baffled facultative pond with configuration A is about 2.07 × 10^6 seconds (~24 days), which is lower than the theoretical hydraulic retention time (30 days).

Figure 5.8 shows the flow pattern and the spatial residence time distribution of wastewater in a ten-baffled facultative pond with configuration C that employed the 82% pond-width baffles at the 0.5 m plane below the top surface. For this configuration, it can be seen from Figure 5.8 that there is no hydraulic short-circuiting visible at the level shown. Although not shown, none was present at other levels. The residence time distribution diagram shows that the 82% pond-width baffles initiate a very strong plug-flow pattern. For configuration C of the ten-baffled facultative pond with 82%-pond-width baffles, a predicted effluent *E. coli* count < 0.001 per 100 ml (Table 5.1) was obtained from the CFD simulation This is lower by four orders of magnitude than configuration A with 70% pond-width baffles. The high removal of *E. coli* in configuration C can be attributed to the formation of a very strong plug-flow pattern as the flow channel widths in baffle compartments and at baffle openings are identical (58 m).



Configuration C

Figure 5.8 Flow patterns and the residence time distributions of wastewater in the ten-baffled facultative pond with the 82% pond-width baffles (theoretical retention time in the model was 30 days).

In order to determine the optimal baffle length between 70% and 82% pond-widths, additional simulations with baffle lengths of 72%, 74%, 76% and 78% pond-width were undertaken. Table 5.2 shows the predicted effluent *E. coli* counts for the ten-baffled facultative pond with these baffle length configurations. These results show that *E. coli* removal increases as the baffle length increases from 70% to 82% pond-width. This could be attributed to the initiation of the plug flow pattern as the flow width channel at the baffle opening (L_o) decreases from 96 m to 58 m to form the identical width of the flow channel in the direction of the wastewater flow. The width of flow channel in baffled compartments with the 82% pond-width baffles is 58 m and this is equal to the width of flow channel at the baffle opening. It was not necessary to carry further simulations with baffles greater than 82% pond-width (i.e. baffle opening less than 58 m) because the objective was to investigate the initiation of the plug flow pattern in the facultative pond model.

Table 5.2 Results of *E. coli* count per 100 ml in a facultative pond model with ten baffle configurations

Baffle length as percentage of pond-width (320 m)	Channel width (*W*) in baffle compartments (m)	Channel width (L_o) at baffle opening (m)	Predicted effluent *E. coli* count per 100 ml
70	58	96	10,000
72	58	90	850
74	58	83	143
76	58	77	17
78	58	70	5
82	58	58	0.001

Figure 5.9 shows the flow pattern diagrams for the ten baffle configurations. It can be seen from the figure that the plug flow pattern is initiated when the 76% pond-width baffles were fitted in the ten-baffle facultative pond. It can also be seen from the figure that the hydraulic flow patterns in the pond with 70%- and 74%-pond-width baffles are similar. Interestingly, the 76% pond-width baffle length could be argued to be the optimal baffle length of the ten baffle configurations as the flow pattern

changes from one with a high degree of short-circuiting to one where plug-flow patterns form.

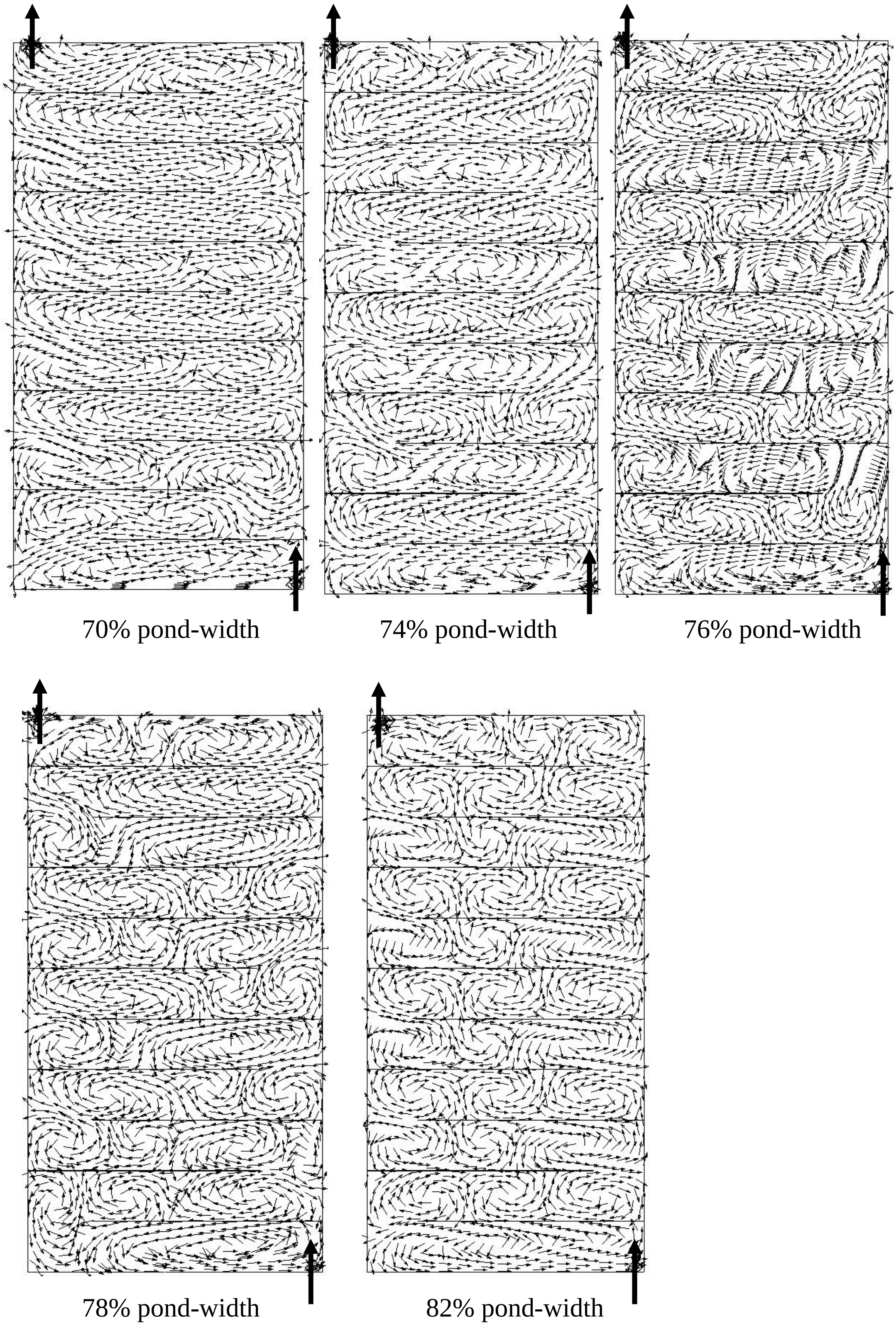


Figure 5.9 Flow patterns in the facultative pond with ten baffles of various configurations

Theoretically, a plug flow model can be presented as a large number of fully mix tanks in series (Tchobanoglous *et al.* 2003; Horan, 1990). The flow pattern diagram in Figure 5.9 shows a number of circulation flow patterns in each baffle compartments and this approximates a series of completely mixed compartments (Levenspiel, 1972). This causes the plug hydraulic flow pattern to develop. The predicted effluent *E. coli* count in the facultative pond with 76% pond-width baffles is 17 per 100 ml and this compares well with results from the configuration that employed the 78% and 82% pond-width baffles that predicted effluent *E. coli* counts of 5 and 0.001 per 100 ml respectively. Note that the predicted *E. coli* counts (17, 5 and 0.001 per 100 ml) are not significantly different from each other considering the fact that *E. coli* counts on three replicates from the pilot-scale pond were not identical (Chapter 6).

Figure 5.10 presents the spatial residence time distributions in the ten-baffled facultative pond with various baffle length in range of 70% - 82% pond-width. It can be seen from Figure 5.10 that there is similarity in the distribution of the residence time in the facultative pond with 70%- and 74%-pond-width baffles characterised with channelling flow pattern. The figure indicates clearly that plug flow pattern is achieved in the facultative pond with 76%, 78% and 82% pond-width baffles. It can be seen that there is a high degree of short-circuiting and stagnations in the facultative pond with 70%- and 74%-pond-width baffles. The distribution diagrams of the residence time depend on the initiated hydraulic flow patterns. The residence time distribution diagram suggests that the 76% pond-width baffle length is the most robust baffle length (for the pond size of 640 m × 320 m × 1.5 m) that should be used in the physical design of waste stabilization pond to optimise the treatment efficiency of the ten-baffled facultative pond.

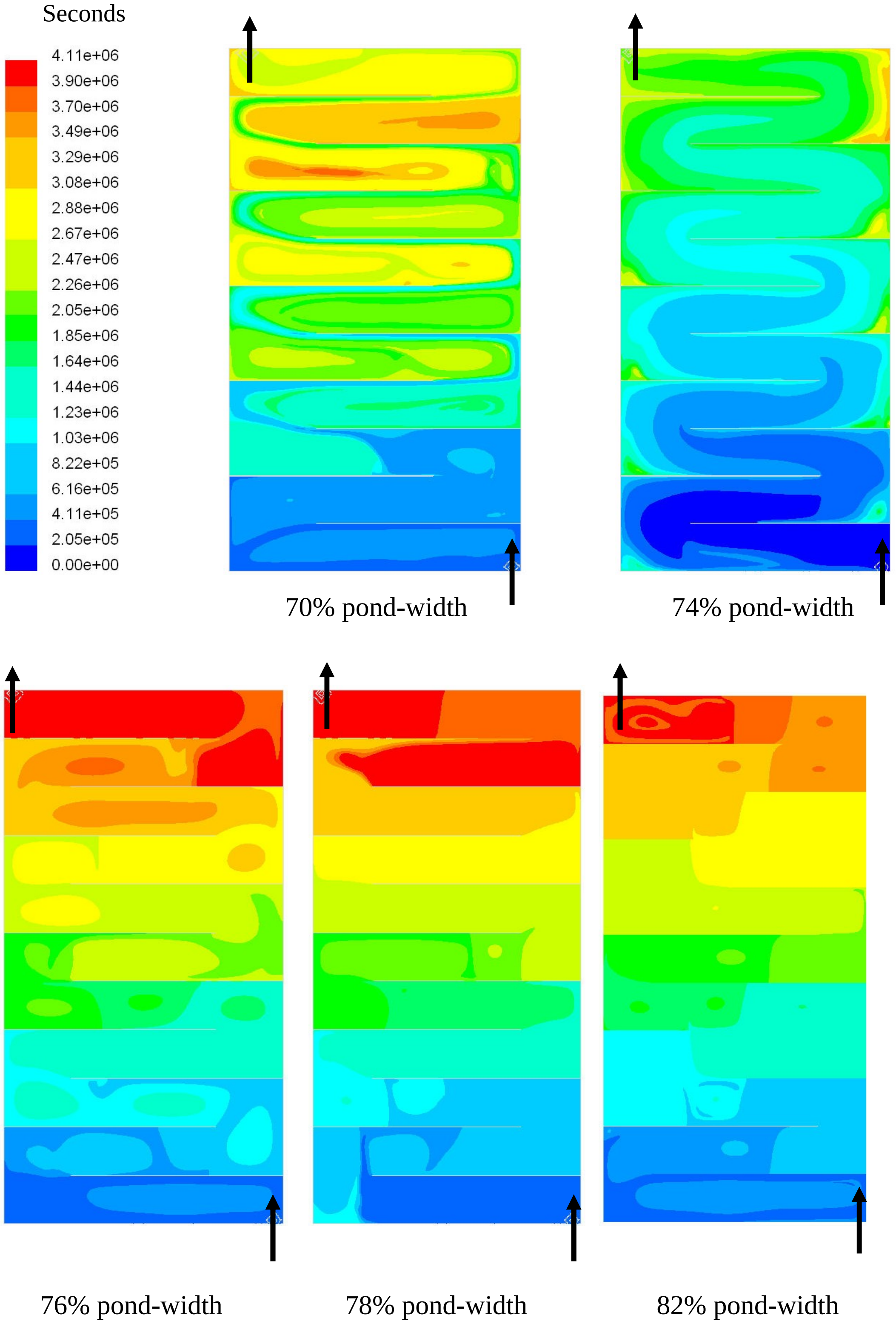


Figure 5.10 Residence time distributions of wastewater in the facultative pond with ten baffles of various configurations with 30 days (2.6×10^6 seconds) theoretical retention time

5.6 Performance assessment of 70% pond-width baffle arrangements

Of the five simulations that employed 70% pond-width baffles, the six baffled arrangements give the lowest effluent *E. coli* count of 121 per 100 ml (Table 5.1). The use of six baffles results in a channel width (W) of 92 m with an approximately equal opening (L_o) of 96 m dimension. Increasing the baffles to eight does not offer any more advantage; in fact the effluent *E. coli* count is marginally higher at 162. Adding a further two baffles then deteriorates the performance dramatically with *E. coli* count of 1×10^4 per 100 ml for ten 70% pond-width baffles.

Examination of the flow patterns in Figure 5.9 and 5.10 shows that significant hydraulic short-circuiting occurs when the width of flow channel in baffle compartments is less than the width of flow channel at baffle openings. This accounts for the high (1×10^4) *E. coli* count as baffles were increased. Interestingly, increasing the length of the baffles to 82% pond-width gave an opening that was the same as the channel width. The 82% pond-width configuration gave a predicted *E. coli* count of 0.001 per 100 ml.

However, it is seen in Table 5.2 that the optimal baffle length in ten baffled configurations is the 76% pond-width baffle as this is the onset point of plug flow pattern with a predicted effluent *E. coli* count of 17 per 100 ml. Increasing the baffle length from 76% to 82% pond width forces a more closely plug flow (Figures 5.9 and 5.10) until it comes so strong that the model predicted effluent *E. coli* count of 0.001 per 100 ml.

Shilton and Harrison (2003a, 2003b) using a 2D model found that a four baffled facultative pond with 70% pond-width baffles (flow channel width in baffle compartments and at baffle openings were 128 m and 96 m) was superior to six baffled facultative pond in removing *E. coli* with counts of 390 per 100 ml for the four-baffle facultative pond and 570 per 100 ml for the six-baffled facultative pond. The work presented in this research has found that six-baffled facultative pond provides superior removal of *E. coli* by 1.30 orders of magnitude than the four-baffled facultative pond (actual figures being 121 *E. coli* per 100 ml and 2 400 *E. coli* per 100ml for the six and four-baffled facultative pond respectively). The six-baffled facultative pond creates an approximate plug flow pattern that performs better than the four-baffled facultative pond, which seems due to the (almost) constant flow channel width (flow channel width in baffle compartments and at baffle openings in Table 5.1 are 92 m and 96 m).

Mangelson and Watters (1972) stated that the 70% pond-width baffles equally distributed in the longitudinal axis of the pond provide optimum hydraulic performance. However, this is misleading as the work presented here demonstrates that the number and length of baffles used is critical to good hydraulic performance. This work shows that the optimal baffle length that provides good hydraulic performance, which results in effective removal of *E. coli,* is the one that forms a uniform width of flow channel throughout the length of the wastewater travel.

5.7 Models results of facultative pond with short baffles

The results of the CFD modelling of *E. coli* and hydraulic flow patterns in facultative ponds with short baffle configurations are presented in this section. The lengths of short baffles that were investigated in terms of the pond-width are 5%, 10%, 15%, 20%, 25% and 30% and in terms of the actual baffle lengths are 16 m, 32 m, 48 m, 64 m, 80 m and 96 m. The baffles were positioned at equal distance from inlet and outlet structures (30 m, 40 m, 50 m, 60 m, 75 m and 100 m). Although there are numerous combinations of baffle positions from inlet and outlet that could have been investigated, the baffle positions considered are practical and comparable to those available in literature (Shilton and Harrison, 2003a; Persson, 2000). Baffle positions of less than 30 m from the inlet were not investigated from a practical point of view because these positions could form small baffle compartment areas that can cause BOD overloading in the facultative pond. The dimensions of the pond simulated here are the same as the facultative pond described in Section 5.3. The inlet and outlet structures were located at a distance of 10 m from the lateral edge of the pond. Figure 5.11 shows the general arrangement of the short baffle configuration in the pond.

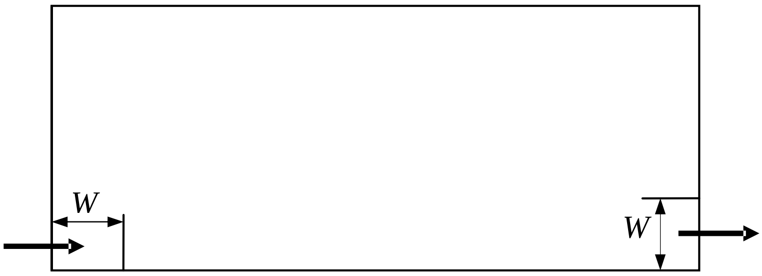


Figure 5.11 General arrangement of short baffle configuration in the facultative pond

The boundary conditions of the model were similar to those described in Section 5.2.4. The CFD simulations were performed in 3D with double precision Fluent solver and run using second-order differencing scheme. The results of the predicted effluent *E. coli* count are presented in Table 5.3. Examining the results shown in Table 5.3, it can be seen that the most effective removal of *E. coli* was achieved when the 10% and 15% pond-width baffles (highlighted in bold) were located at 30 m and 75 m from the inlet and outlet respectively. The configurations predicted the effluent *E. coli* count of 2.25×10^4 per 100 ml and 2.10×10^4 per 100 ml ie., 3.65 and 3.68 log removals respectively. The unbaffled facultative pond with similar geometry and hydraulic retention time but with inlet and outlet located at opposite diagonal corners gave a predicted effluent *E. coli* count of 4.10×10^6 per 100 ml (Table 5.1, a 1.38 log removal).

Comparing the short-baffle performance with that of the two conventional 70% pond-width baffles, it can be noted that the two-baffle pond model with the 70% pond-width baffles predicted the effluent *E. coli* count of 1.2×10^4 per 100 ml (Table 5.1) whereas the short-baffle model with the 10% and 15% pond-width baffles predicted *E. coli* counts of 2.25×10^4 per 100 ml and 2.10×10^4 per 100 ml respectively. Construction of a two-baffle facultative pond with the 10% pond-width baffles would require less constructional material and labour compared to that of the two-baffle facultative pond with the 70% pond-width baffles when achieving similar treatment performance. It can be concluded that the 10% pond-width baffles is the optimal baffle length compared with the conventional 70% pond-width baffles if proper design of the short baffle configurations are followed. The findings of the facultative pond model with short baffles agree satisfactory with the observation of Shilton and

Harrison (2003a) that short baffles can compete with the two-70% pond-width baffles in removing the concentration of *E. coli* levels in waste stabilization ponds.

Table 5.3 Predicted effluent *E. coli* counts per 100 ml in the facultative pond model with short baffles of various configurations (influent *E. coli* count was 1×10^{8} per 100 ml)

Length of baffle (% of pond-width)	Positions of short baffles from inlet and outlet structures, *W*					
	30 m	40 m	50 m	60 m	75 m	100 m
5	1.13×10^{6}	5.28×10^{5}	1.36×10^{6}	4.67×10^{5}	9.55×10^{5}	1.11×10^{6}
10	$\mathbf{2.25\times10^{4}}$	7.35×10^{5}	5.40×10^{5}	8.18×10^{5}	2.05×10^{6}	1.68×10^{6}
15	1.83×10^{5}	2.10×10^{6}	1.23×10^{6}	9.80×10^{4}	$\mathbf{2.10\times10^{4}}$	1.26×10^{6}
20	2.18×10^{6}	9.65×10^{5}	9.18×10^{5}	4.67×10^{5}	1.27×10^{6}	4.29×10^{5}
25	8.80×10^{4}	4.60×10^{5}	1.11×10^{6}	2.67×10^{6}	1.31×10^{6}	2.06×10^{6}
30	2.90×10^{6}	9.30×10^{5}	8.86×10^{5}	2.88×10^{6}	1.88×10^{6}	3.20×10^{5}

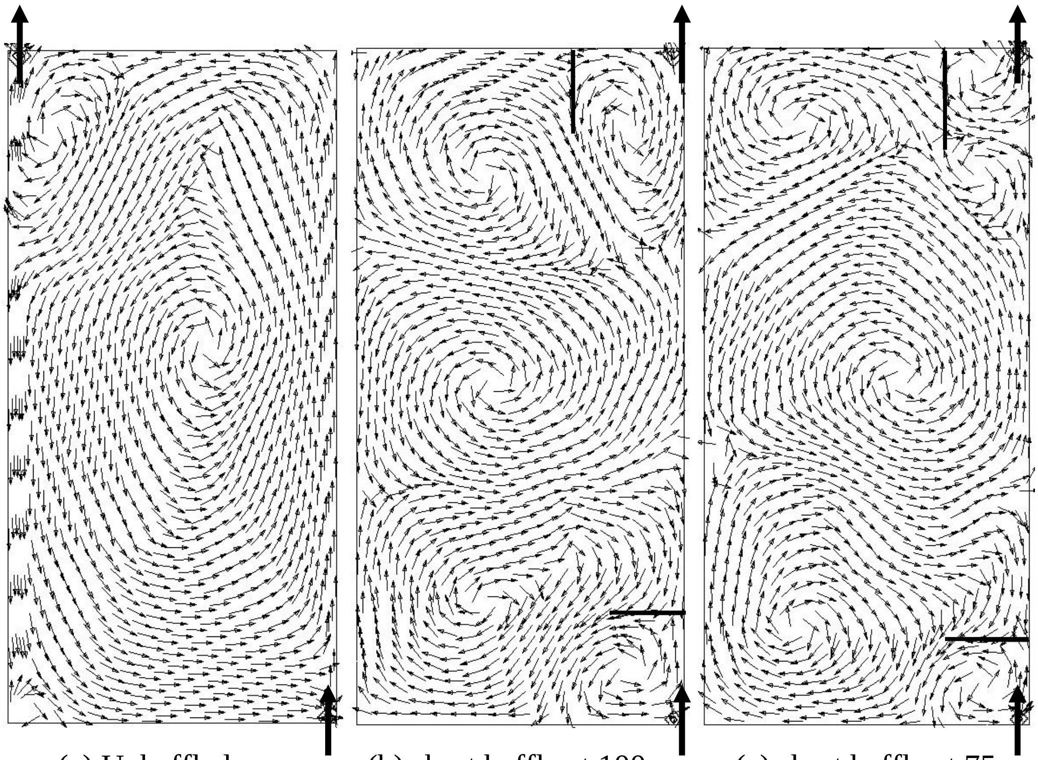
Savings could be realised using short baffles in waste stabilization ponds when targeting approximately 4-log removals of *E. coli*. The model results show that the 15% pond-width baffles could achieve 3.68-log removals of *E. coli* when positioned at 75 m from both inlet and outlet where as the two-baffle model with the 70% pond-width baffles (224 m) equally spread across the longitudinal axis of the pond could achieve 3.92 log removals. Although short-baffles can provide a more cost effective design than the conventional 70% pond-width baffles in removing *E. coli,* the results from Table 5.3 suggest that significant variation of log removals (1.68 – 3.68) is predicted by the various configurations of the short-baffle models. The designers and plant operators could have low confidence in the resultant effluent quality in complying with the consent requirements.

It can also be seen from results in Table 5.3 that when the 15% pond-width baffles were located at a distance of 40 m from the inlet and outlet structures, the short-baffle model predicted the lowest removal of *E. coli*. This short-baffle configuration predicted the effluent count of 2.10×10^{6} per 100 ml giving 1.68-log removal. However, the results of the unbaffled facultative model (Table 5.2) with similar geometry and retention time predicts an effluent *E. coli* count of 4.10×10^{6} per 100 ml equivalent to a 1.39 log removal. Designers should carry out a number of simulations covering a large range of short baffle lengths to identify the optimal baffle length that can compete with the conventional baffles. It is necessary to evaluate the resulting hydraulic flow patterns and the residence time distribution of the wastewater in the unbaffled facultative pond and the facultative pond that is fitted with short baffles.

5.7.1 Flows patterns and residence time distributions in the facultative pond model with short-baffles

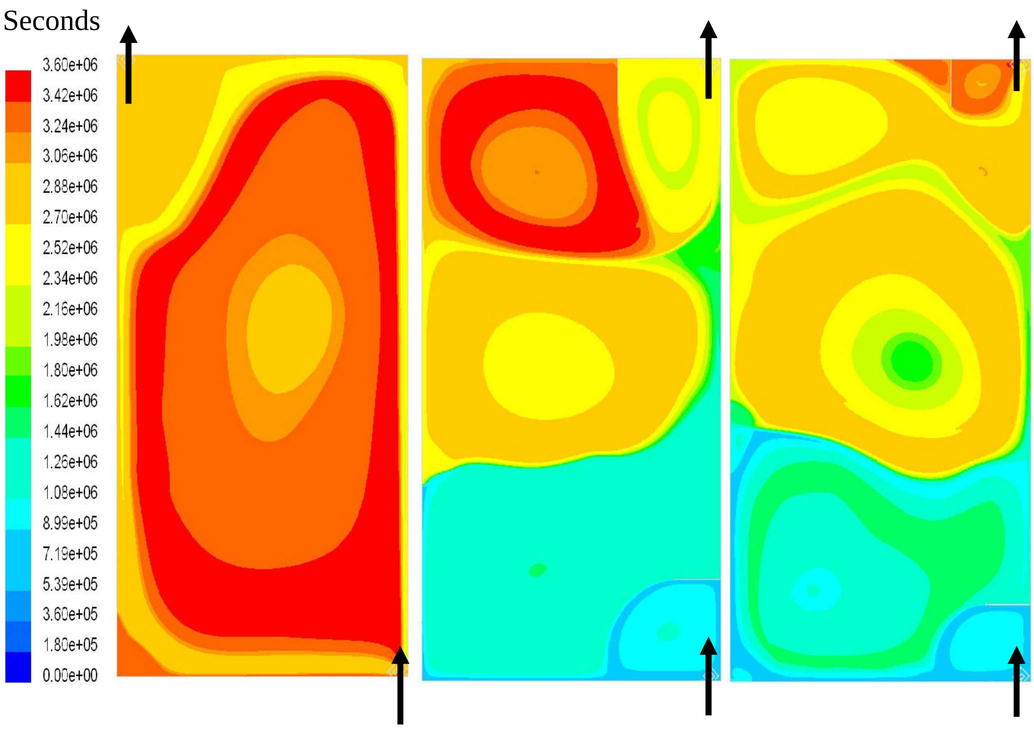
Figure 5.12 and 5.13 show the hydraulic flow patterns and the residence time distributions of wastewater in the unbaffled facultative pond and the facultative pond with the 15% pond-width baffles located at 75 m and 100 m from the inlet and outlet structures respectively. The diagrams are results of the flow pattern and residence time distribution on a horizontal plane 0.5 m below the pond water surface. The maximum velocity achieved in the simulations was at the inlet with a value of 0.99 m/s. It can be seen in Figures 5.12 and 5.13 that the flow patterns and the residence time distributions in the unbaffled facultative pond show significant visible short-circuiting as well as stagnation regions at this level. Although not shown, there was no significant visible difference of flow patterns at other levels.

When the 15% pond-width baffles were located at 75 m from the inlet and outlet structures, it can be seen that the extent of the short-circuiting and stagnation is reduced due to the formation of the circulatory flow patterns. However, there is still visible short-circuiting and stagnation but at a low extent. The initiation of a number of circulating flow patterns is the reason for the reduction of the hydraulic short-circuiting as this increases the length of the liquid travel from the inlet to the pond outlet. It is not surprising then, that this short baffle configuration gives higher removal of *E. coli* than the unbaffled pond (the *E. coli* counts being 2.10×10^4 per 100 ml for the facultative pond with short baffles and 4.10×10^6 per 100 ml for unbaffled facultative pond model).



(a) Unbaffled (b) short baffle at 100m (c) short baffle at 75m

Figure 5.12 Flow patterns in the unbaffled facultative pond and the facultative pond with the 15% pond-width baffles



(a) Unbaffled (b) short baffle at 100m (c) short baffle at 75m

Figure 5.13 Residence time distributions in the unbaffled facultative pond and the facultative pond with the 15% pond-width baffles with 30 days (2.6×10^6 seconds) theoretical retention time

Shilton and Harrison (2003a, 2003b) found that short-baffle configurations predict a wide range of the effluent *E. coli* counts due to the change of the flow patterns, which is initiated by the various short baffle configurations. The results of the predicted effluent *E. coli* counts shown in Table 5.3 support this finding. It was found that between 1.68 and 3.68 log removals of *E. coli* could be obtained when the short baffle position from the inlet and outlet structure was varied. Because of the uncertainty of the flow pattern and variation of possible effluent *E. coli* counts, great care must be taken when designing a pond with short baffles. CFD is an essential tool in this design process. It would be necessary to use CFD to simulate a large range of configurations and flows to identify the baffle configuration that provides the maximum treatment efficiency in a pond system.

Despite their difficulties, short baffle can improve the hydraulic and treatment performance of facultative pond when properly designed. The use of short baffles should be encouraged if designers have the capacity of using CFD to design the hydraulics of waste stabilization ponds.

5.8 CFD models of facultative ponds with simulated wind effects

5.8.1 Inclusion of wind velocity in the CFD model

Simulation of wind effects was included in the CFD model by applying a shear stress due to wind across the horizontal top surface of the pond. Isothermal conditions were assumed in the waste stabilization pond to prevent the hydraulic short-circuiting associated with thermal stratification effects. The CFD model was used to assess the effects of wind on the performance of waste stabilization ponds with small surface area (pilot-scale primary facultative pond of area 42m^2) and large surface area (standard facultative pond with surface area of 204, 800 m^2).

Brissaud *et al*. (2000, 2003); Frederick and Lloyd (1996); Lloyd *et al*. (2003); Vorkas and Lloyd (2000) have observed that wind reduces significantly the treatment efficiency of waste stabilization ponds due to the initiation of hydraulic short-circuiting. Shilton and Harrison (2003a) suggested that proper design of the inlet could obviate the concerns of wind effects as the influent momentum could control the resulting flow patterns in the pond. However, Mara (2004) suggests that wind velocity could be beneficial to the treatment efficiency of the pond if the wastewater flow is against the prevailing wind direction.

In CFD models, effects of wind are included in the momentum equation via the boundary condition. Van Dorn (1953); Olsen and Tjomsland (1998) presented the equation of calculating the surface shear stress due to the wind velocity that acts on the top surface of waste stabilization ponds and the equation is presented as:

$$\tau = C_D \rho_a (U_{10})^2 \qquad 5.4$$

where:

$\tau =$ shear stress (N/m^2)

$C_D =$ the drag coefficient = 0.0017

$U_{10} =$ wind velocity at a height of 10 m above the pond surface (m/s)

$\rho_a =$ density of air (kg/m^3) = 1.225 kg/m^3

Olsen and Tjomsland (1998) suggested that a drag coefficient value (C_D) of 1.1×10^{-3} could be safely used in equation 5.4. Shilton (2001) believes that the drag coefficient value of 1.7×10^{-3} is appropriate in determining the shear stress due to the wind in the CFD model. However, the difference of the proposed drag coefficients is not significant noting that the wind velocity varies substantially during the residence time period of the pond. The calculation of the shear stress due to the wind in the model used the Shilton's (2001) drag coefficient value (1.7×10^{-3}).

5.8.2 Model simulation of facultative pond with small surface area

The pilot-scale pond discussed in Chapter 4 with top surface dimensions of 10.2 m × 3.87 m was simulated in the CFD model with the incorporation of wind effects. An unstructured tetrahedral grid of 0.1 m was used to mesh the geometry of the pilot-scale pond (See Chapter 3 for the mesh independent test for this grid). In order to apply the wind speed within the model, the wind shear stress was calculated using equation 5.4. Wind speeds of 4 m/s, 5 m/s, 6 m/s and 8 m/s were investigated and these gave shear stresses of 0.033 N/m^2, 0.052 N/m^2, 0.075 m/s and 0.133 N/m^2 respectively. This range of wind speeds (4- 8 m/s) was adopted because it was higher than the average wind speed of 3 m/s that has been observed in full-scale waste stabilization ponds (Brissaud *et al*. 2000, 2003; Frederick and Lloyd, 1996; Lloyd *et al*. 2003; Vorkas and Lloyd, 2000; Shilton, 2001; Abis, 2002). The average wind speed was calculated using the arithmetic mean of the wind data that was observed during the operational period of the studied waste stabilization ponds.

5.8.3 Boundary conditions and flow regime

The inlet velocities of 0.05 m/s and 0.046 m/s were defined as the boundary conditions for momentum equations for the wastewater and freshwater respectively and these achieved the 30-days retention time of the pond. The influent *E. coli* count of 1.00×10^8 per 100 ml was defined as the boundary condition of the scalar transport equation. A pressure value of zero was defined at the pond outlet to initiate the wastewater flow. The diffusivity coefficient of *E. coli* (Γ) was zero (see Chapter 3). A steady state with laminar flow was used in the simulation as the Reynolds number was less than 2000 (Chapter 3). The inlet and outlet pipes were located at mid position of the pond at the depths of 0.75 m and 0.01 m, respectively, above the bottom level of the pond. Numerical experiments were undertaken to investigate the effect of changing wind speed and its prevailing wind direction. Figure 5.14 shows the prevailing wind directions in relation to the wastewater flow in the pilot-scale pond.

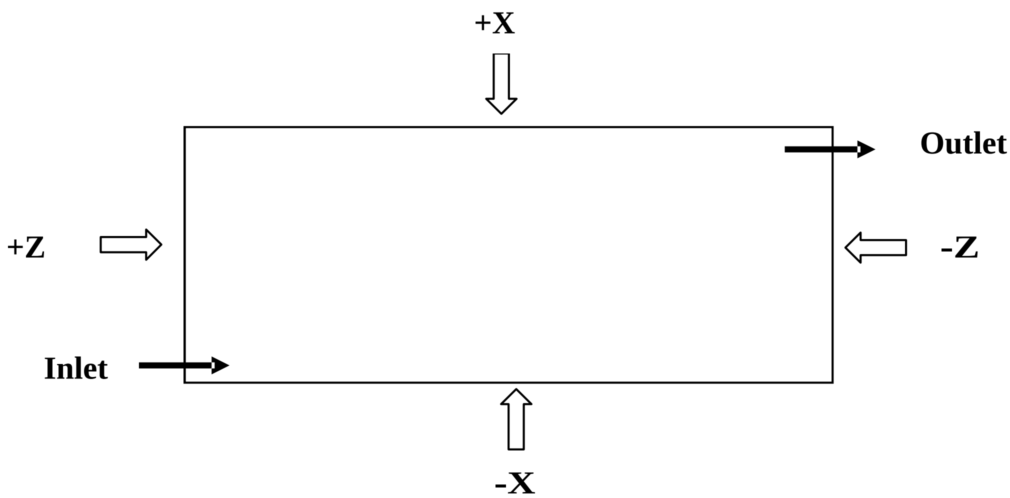


Figure 5.14 Prevailing wind directions in the pilot-scale primary facultative pond

The directions of wind speed with respect to the wastewater flow were: (i) same direction as the wastewater water flow (+Z), (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) are lower than the range of the wind speed considered.

5.8.4 Model results of the facultative pond with small surface area

Table 5.4 shows the model results of effluent *E. coli* counts when the wind was blowing from the four different prevailing directions.

Table 5.4 CFD results of the effluent *E. coli* count per 100 ml in a pilot-scale pond with and without simulated 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)
4	1.15×10^5	2.98×10^5	3.00×10^5	2.89×10^5	2.92×10^5
5	1.15×10^5	2.97×10^5	2.95×10^5	2.94×10^5	2.93×10^5
6	1.15×10^5	2.99×10^5	2.98×10^5	2.95×10^5	2.92×10^5
8	1.15×10^5	3.00×10^5	2.96×10^5	2.98×10^5	2.99×10^5

It can be seen from these results that there was no significant difference of the treatment performance of the pilot-scale pond with or without wind effects. The similarity in the performance of the ponds could be explained because of the small size of the pond surface area. The influent momentum in the pilot-scale pond was relatively higher than that due to the wind power as this depends on the surface area (Shilton and Harrison, 2003a). The surface area of the pilot-scale pond is very small compared to typical waste stabilization ponds that are sometimes hundreds – thousands of times bigger than this pond. The results suggest that it is not necessary to take into account wind effects or pond location in relation to the prevailing wind direction during the design stage of waste stabilization ponds with small surface area.

5.8.5 Model simulation of the facultative pond with large surface area

A 3D model was set up for a waste stabilization pond with top surface dimensions of 640 m × 320 m. The hydraulic retention time of the facultative pond was 4-days so as to increase the effects of the hydraulic short-circuiting associated with wind velocity. The effects of wind speed were incorporated in the model as described in Section 5.8.1. A mesh size of 1.75 m × 1.75 m × 0.1875 m was used to mesh the geometry of the pond (See Chapter 3 for the grid independence tests). 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.
The waste stabilization pond volume and the average hydraulic retention time were 3.1×10^5 m^3 (640 m × 320 m ×1.5 m) and 4 days respectively. This gave the daily flow rate of 7.75×10^4 m^3 per day (0.90 m^3/s). Based on the inlet pipe area of 0.13 m^2 (0.4-m diameter), a fixed velocity of 6.90 m/s was defined at the inlet as the boundary condition of the momentum equations. This high velocity (6.90 m/s) was adopted in order to demonstrate that wind effects could affect the hydraulic flow patterns in waste stabilization pond despite the existence of the high influent momentum. The influent *E. coli* count of 5×10^6 per 100 ml was the boundary condition of the scalar transport equation and 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 other boundary conditions used in the model were similar to the unbaffled pond model (Section 5.3.4). The directions of wind speed in the model are described in Section 5.8.3.

5.8.6 Model results of the facultative pond with large surface area

Table 5.5 show the model results of effluent *E. coli* counts when the wind was blowing from the four different prevailing directions with respect to the wastewater flow in the pond.

Table 5.5 CFD results of effluent *E. coli* count per 100 ml in a standard facultative pond with and without simulated wind effects (influent *E. coli* count in the model was $5×10^6$ per 100 ml)

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)
4	6.94×10^5	7.78×10^5	5.90×10^5	5.60×10^5	7.40×10^5
5	6.94×10^5	9.08×10^5	3.90×10^5	2.60×10^5	7.50×10^5
6	6.94×10^5	8.20×10^5	2.60×10^5	3.50×10^5	8.20×10^5
8	6.94×10^5	7.80×10^5	1.30×10^5	4.30×10^5	5.90×10^5

It can be seen from Table 5.5 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 Table 5.5). The numerical data from Table 5.7 show that wind speeds of 4 m/s, 5 m/s, 6 m/s and 8 m/s predicted higher log-units removal of *E. coli* by 8%, 30%, 50% and 86%, respectively than that in a facultative pond with no wind.

Table 5.6 The predicted log-units removal of *E. coli* in a standard facultative pond with and without simulated wind effects

Wind speed (m/s)	Predicted log-units removal of *E. coli*				
	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)
4	0.86	0.81	0.93	1.00	0.83
5	0.86	0.71	1.11	1.33	0.82
6	0.86	0.79	1.29	1.15	0.79
8	0.86	0.81	1.60	1.07	0.93

Table 5.7 Change in *E. coli* removal based on log-units removal in the standard facultative pond model with and without wind effects

	Percentage (%) change of log-units removal of *E. coli*			
Wind speed (m/s)	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)
4	- 6	+8	+16	- 4
5	- 18	+30	+55	- 5
6	- 8	+50	+34	- 8
8	- 6	+86	+25	+8

Notes: (a) Positive %: higher log-units removal of *E. coli* than that in a pond with no wind.
(b) Negative %: lower log-units removal of *E. coli* than that in a pond with no wind.

When the wind was blowing in the same direction as the wastewater flow, the effluent *E. coli* counts were all higher than that in a facultative pond with no wind (Table 5.5). Wind speeds of 4, 5, 6 and 8 m/s gave lower log-units removal of *E. coli* by 6%, 18%, 8% and 6%, respectively than that of the facultative pond with no wind (Table 5.7). Thus there appears to be 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. Nevertheless, the low *E. coli* removal efficiency could have been caused by the initiation of hydraulic short-circuiting.

Figure 5.15 shows the diagrams of the flow pattern at the top surface of the pond. The flow pattern diagram is scaled uniformly to show the extent of the hydraulic flow pattern in the waste stabilization pond. It can be seen from Figure 5.15 that the facultative pond with no wind has formed two circulation flow 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 influent momentum could be suggested to sustain the observed flow patterns. It can also be seen from Figure 5.15 that facultative pond models that are designed at short hydraulic retention times are prone to short-circuiting due to the flow circulation paths that link directly the inlet and outlet.

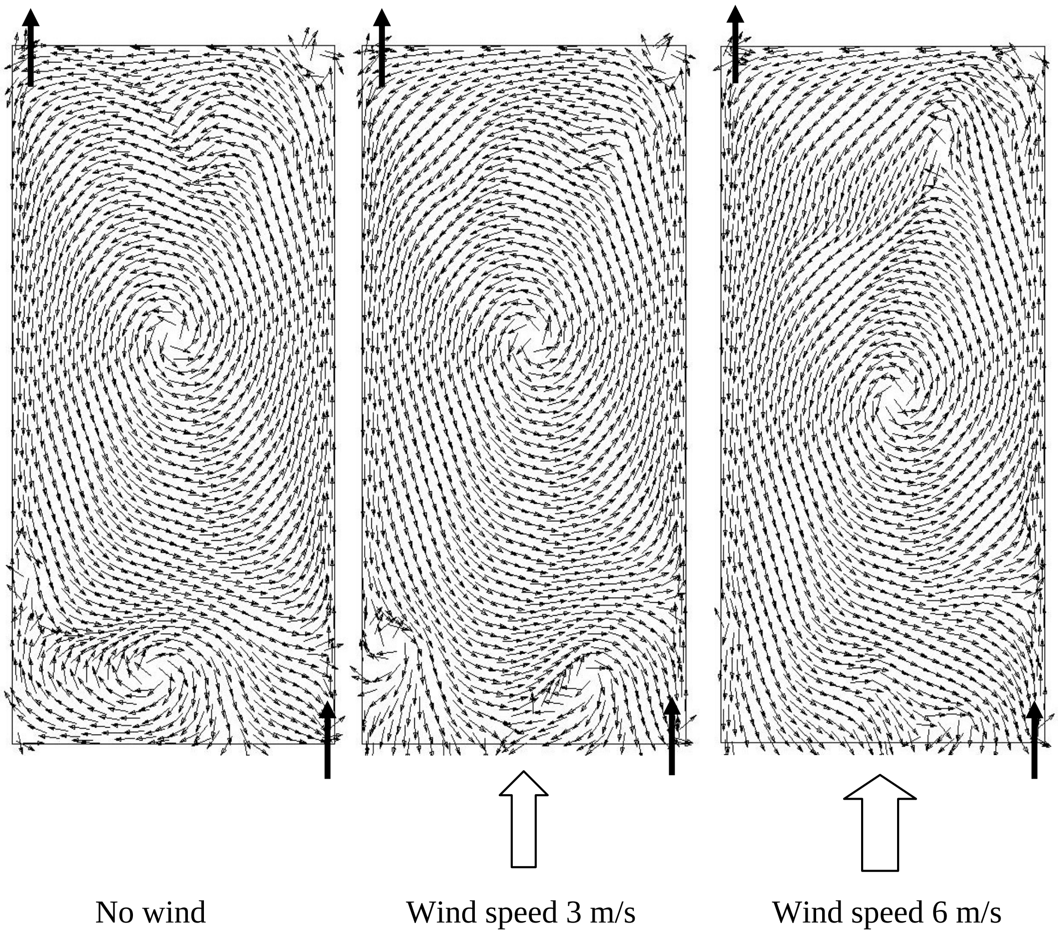


Figure 5.15 Flow pattern in a facultative pond with wind blowing in the same direction of the wastewater flow

It can also be seen from Figure 5.15 that the increase of wind speed has changed the flow pattern. A large single flow circulation pattern has developed with increase in the number of flow paths that approach the outlet. This circulation flow pattern could discharge a greater portion of wastewater within a fraction of the designed retention time. The low *E. coli* removal efficiency that was achieved when the wind was blowing in the same direction as the wastewater flow could have been caused by this flow pattern associated with short-circuiting.

Figure 5.16 shows the flow pattern diagrams when wind was blowing against the direction of the wastewater flow in the pond. It can be seen from the figure that the wind direction has increased the number of the circulatory flow patterns.

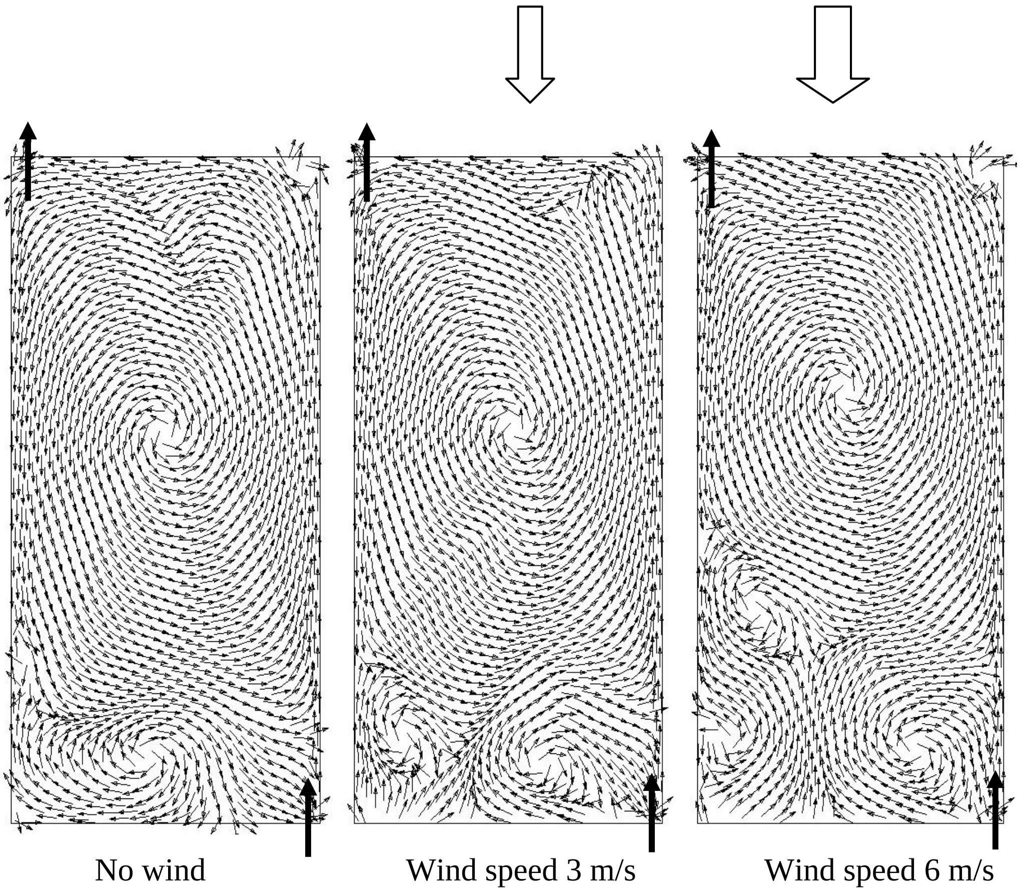


Figure 5.16 Flow patterns in a facultative pond with wind blowing against the direction of the wastewater flow

About 4 circulation patterns are formed in the pond and these increase the length of the flow paths from inlet to outlet. Two circulation flow patterns are formed near the pond inlet and this forms a mechanism that reduces the hydraulic short-circuiting.

The significance of these CFD model results is that the treatment performance of waste stabilization ponds with large surface area can likely be improved by utilizing wind effects. This can be achieved by locating waste stabilization ponds such that the wastewater flow in the pond is against 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 prevailing wind direction.

Mara (2004) advises that waste stabilization ponds should be located such that the wastewater flow in the pond is against the prevailing wind direction. This was based on engineering judgement drawn from experience of operational ponds. The results presented in this work confirm Mara's recommendation.

5.9 Two-baffle facultative pond model with simulated wind effects

The results of unbaffled facultative pond model with incorporation of wind effects (Table 5.7 and 5.8) have shown that the treatment efficiency of waste stabilization ponds could diminish when the wind blows in the same direction of the wastewater flow. The results further suggested that wind effects could be beneficial to the treatment performance of waste stabilization ponds if the wastewater flow in the pond is against the prevailing wind direction. However, the shape of the available land could limit the exploitation of the wind benefits when designing the geometry of waste stabilization ponds. To overcome this problem, it is necessary to investigate whether baffle intervention could reduce the hydraulic short-circuiting associated with wind effects.

5.9.1 Simulation of the two-baffle facultative pond

The simulation of the two-baffle facultative pond was similar to that of the unbaffled facultative pond described in Section 5.8.5. The wind speeds investigated were 4 m/s, 5 m/s, 6 m/s and 8 m/s. The prevailing wind direction was similar to the wastewater flow because this direction diminishes significantly the pond performance (Table 5.7 and 5.8). The boundary conditions of the model were similar to that of the unbaffled facultative pond model with wind effects (Section 5.8.5).

5.9.2 Results of the two-baffle facultative pond model

Table 5.8 shows results of the effluent *E. coli* counts in the unbaffled facultative pond and two-baffle facultative pond with and without wind effects. It can be seen from the table that there is no significant difference in the treatment performance of the two-baffle facultative pond with and without wind effects.

Table 5.8 Effluent *E. coli* counts per 100 ml in the two-baffle facultative pond and unbaffled facultative pond with and without wind effects (wind direction similar to the wastewater flow)

Wind speed (m/s)	Unbaffled pond with wind effects	Two-baffle pond without wind effects	Two-baffle pond with wind effects
4	7.78×10^5	2.0×10^4	3.74×10^4
5	9.08×10^5	2.0×10^4	2.03×10^4
6	8.20×10^5	2.0×10^4	2.70×10^4
8	7.80×10^5	2.0×10^4	3.52×10^4

The average effluent *E. coli* count in the two-baffle pond without wind effects is 2.0×10^4 *E. coli* per 100 ml while that with wind effects is 3.0×10^4 *E. coli* per 100 ml giving a difference of 33%. Interestingly, the effluent *E. coli* numbers in the two-baffle facultative pond model with and without wind effects are in the same order of magnitude. It can also be seen from Table 5.8 that the average effluent *E. coli* counts in the two-baffle facultative pond with wind effects (2.99×10^4 *E. coli* per 100 ml) is lower by 96% than that in the unbaffled facultative pond with wind effects (8.2×10^5 *E. coli* per 100 ml). The results suggest that the installation of the 70% pond-width baffles could play a significant role in reducing the hydraulic short-circuiting associated with wind effects.

5.10 Four-baffle facultative pond model with simulated wind effects

Using 3D CFD model, Shilton and Mara (2005) found that a series of 1-day anaerobic pond with 4-days two-baffled facultative pond, followed by 4-days two-baffled maturation pond predicted an effluent *E. coli* count of 3.4×10^2 per 100 ml. They suggested that the combination of these baffled waste stabilization ponds could use 50% of the land required for the construction of unbaffled waste stabilization ponds series in satisfying the requirements for the unrestricted crop irrigation. However, these researchers did not investigate the combination of 1-day anaerobic pond and a 4-days four-baffled facultative pond in meeting the WHO (2006) guidelines for the unrestricted crop irrigation as this pond series could use less land compared with the findings of Shilton and Mara (2005).

Chapter 6 shows that the performance of the four-baffle pilot-scale primary facultative pond is relatively higher than that of the unbaffled pilot-scale primary facultative pond and the two-baffle pilot-scale primary facultative pond when operated at similar BOD loading and hydraulic retention times. The results show that BOD overloading was not initiated in the first baffle compartment of the two-baffle and four-baffle primary facultative ponds when the recommended BOD loading is used. With this satisfactory performance of the four-baffle primary facultative pond, there is a high probability that the pond effluent from a 1-day anaerobic pond and a 4-days four-baffle facultative pond could comply with requirements of the crop irrigation (WHO, 2006).

The combination of the anaerobic pond and four-baffled facultative pond could be appropriate in developing countries where phased construction of waste stabilization pond is required to meet the minimum project costs due to the financial constraints that are encountered when procuring full-scale waste stabilization pond systems.

5.10.1 Simulation for the four-baffle facultative pond model

Simulation of the four-baffle facultative pond was similar to that of the two-baffle facultative pond with simulated wind effects (Section 5.9). The range of the wind speeds investigated was 4 – 8 m/s. The direction of the wind speed was in the same direction of the wastewater flow so as to increase significantly the hydraulic short-circuiting associated with wind effects. The boundary conditions of the model were similar to that of the unbaffled facultative pond model with wind effects (Section 5.8.5)

5.10.2 Results of the four-baffle facultative pond model

The predicted effluent *E. coli* count of the four-baffle facultative pond without wind effects was 1.15×10^2 per 100 ml. When the wind speed (4 – 8 m/s) was incorporated in the CFD model, the effluent *E. coli* counts were higher than that of the four-baffle facultative pond without wind effects by 1.19 - 1.50 orders of magnitude (1.78×10^3 - 3.61×10^3 per 100 ml). The results suggest that the four-baffle facultative pond with wind effects has not achieved the baseline removal of the *E. coli* in the four-baffle facultative pond model without wind effects (1.15×10^2 *E. coli* per 100 ml).

The direction of the wind speed was reversed in the four-baffle facultative pond model (i.e., opposite direction to the wastewater flow) to utilise the benefit of wind effects. The predicted effluent *E. coli* count in the model was 1.0×10^2 per 100 ml. This effluent quality satisfies the requirement of the unrestricted crop irrigation (WHO, 2006). In order to sustain the satisfactory performance of a 1-day anaerobic pond and a 4-days four-baffle facultative pond, wind effects should be utilized at the design stage. This can be achieved by locating the pond series such that the wastewater flow is against the prevailing wind direction.

5.11 Summary of the CFD model results

The chapter has presented results of numerical experiments that were achieved using CFD models of unbaffled and baffled waste stabilization ponds. The results showed that the treatment performance of waste stabilization ponds could be improved significantly by installing the 70% pond-width baffles across the longitudinal axis of the pond. The predicted effluent *E. coli* counts per 100 ml in the unbaffled facultative pond, two-baffle facultative pond, four-baffle facultative pond, six-baffle facultative pond, eight-baffle facultative pond and ten-baffle facultative pond were 4.10×10^6, 2.92×10^4, 2.4×10^3, 1.21×10^2, 1.62×10^2 and 1.00×10^4 respectively. The results showed that the *E. coli* removal increases as the number of baffles increased from 2 to 8.

However, when the number of the 70% pond-width baffles was 10, the treatment performance of the pond deteriorated significantly with an effluent *E. coli* count of 1.0×10^4 per 100 ml, which is equivalent to that of the two-baffle pond model. When the length of ten baffles was increased from 70% pond-width to 82% of the pond-width such that the width of flow channel in baffle compartments and at baffle opening is the same, the effluent *E. coli* count was less than 0.001 per 100 ml. The results suggest that the 70% pond-width baffle configurations do not *always* improve the hydraulic flow patterns and treatment performance to the extent previously reported. The effective baffle length that achieves the maximum treatment performance in baffled waste stabilization ponds is one that forms uniform width-flow channel in baffle compartments and at baffle openings as this creates a strong plug flow pattern.

When the short-baffles (10%, 15%, 20%, 25% and 30% pond-width) were fitted near the inlet and outlet, the 10% pond-width baffle was the most effective in improving the *E. coli* removal with count of 2.10×10^4 per 100 ml. This predicted effluent count is equivalent to that of the two-baffle pond with the 70% pond-width baffles. The results (2.10×10^4 per 100 ml for facultative pond with short-baffles and 2.92×10^4 per 100 ml for two-baffle pond with 70% pond width-baffles) suggest that short-baffles can compete with the conventional baffles (70% pond-width baffles) in improving the treatment efficiency of facultative pond.

Wind effects may affect the performance of waste stabilization ponds with large surface area. When the wind blows in the direction of the wastewater flow, the pond performance could be diminished due to the initiation of the hydraulic short-circuiting. However, when the wind blows against the direction of the wastewater flow, the treatment performance of the pond could be improved.

Baffles can play a significant role in reducing the hydraulic short-circuiting associated with wind effects. The predicted CFD results show that effluent quality of a 1-day anaerobic pond followed by a 4-days four-baffled facultative pond when located against the prevailing wind direction could comply with the requirement of the unrestricted crop irrigation WHO (2004). This could be one way of optimizing the available land for the construction of efficient waste stabilization ponds.