Chapter 7

Discussion

7.1 Performance assessment of the pilot-scale primary facultative ponds

Table 7.1 summarises the treatment performance of the four-baffle pilot-scale pond, two-baffle pilot-scale pond and the unbaffled pilot-scale pond that is presented in more detail in Chapter 6. The experimental data are recalled here as a reference for the discussion that follows.

Table 7.1 Treatment efficiency (%) and hydraulic performance of the pilot-scale primary facultative ponds

Parameter	Unbaffled pond		Two-baffle pond		Four-baffle pond	
	Cumulative percentile		Cumulative percentile		Cumulative percentile	
	50%	95%	50%	95%	50%	95%
Log-units of *E. coli* removal	1.96	1.72	2.42	1.92	3.02	2.45
BOD	91	88	93	89	96	94
Ammonia	83	74	93	82	91	82
Total nitrogen	84	72	87	75	91	87
SS	84	72	86	72	88	72
Retention time (days)	25	25	28	28	29	29
Dispersion number	0.25	0.25	0.48	0.48	0.49	0.49

It can be seen from the Table that the treatment efficiency of the four-baffle pilot-scale pond and the two-baffle pilot-scale pond at both 50% cumulative percentile and 95% cumulative percentile is generally higher compared to that of the unbaffled pilot-scale pond. The higher treatment performance of the four-baffle pilot-scale pond and the two-baffle pilot-scale pond could have been attributed to the installation of the 70% pond-width baffles that reduced the hydraulic short-circuiting as noted in the normalised residence time distribution diagrams (Section 6.5). The effects of thermo-stratification and wind velocity on the treatment efficiency of the three pilot-scale primary facultative ponds should be assumed to be almost identical as the pilot-scale ponds were operated at similar hydraulic retention time and were exposed to similar environmental conditions (solar radiation, light intensity, wind velocity and air temperature).

Shilton and Harrison (2003), Mangelson and Watters (1972), Muttamara and Puetpailboon (1996, 1997), Kilan and Ogunrombi (1984), von Sperling *et al.* (2002) and Zanotelli *et al.* (2002) all observed higher removal of total nitrogen, ammonia, BOD_5, COD, faecal coliforms and helminth eggs in waste stabilization ponds that were fitted with baffles of various configurations than in those that were not baffled. The results of the treatment efficiency of the three pilot-scale primary facultative ponds presented in this work agree satisfactorily with the findings of these researchers.

The average hydraulic retention time in the pilot-scale pond increased with increasing number of baffles (Table 7.1). However, the average hydraulic retention time in the four-baffle pilot-scale pond and the two-baffle pilot-scale pond was marginally higher compared to that of the unbaffled pilot-scale pond. Thus, the effect of the hydraulic short-circuiting regarding the hydraulic performance of the unbaffled pilot-scale pond was not significant. This could have been attributed to the long hydraulic retention time (30 days) that was employed in the pilot-scale pond. The average inlet velocity of 0.09 m/s was used to attain the 30-days hydraulic retention time in the pilot-scale primary facultative ponds (Section 6.6.1.2). This average inlet velocity is too small to initiate significant hydraulic short-circuiting that could deteriorate the treatment performance of the unbaffled pilot-scale pond.

In tropical climate regions where unbaffled waste stabilization ponds are normally designed at short hydraulic retention times (4- 10 days), the effects of the hydraulic short-circuiting can be significant and the treatment performance of waste stabilization ponds could be diminished. The CFD model of the standard waste stabilization pond (640 × 320 × 1.5 m) with simulated wind effects used the average inlet velocity of 6.92 m/s to achieve the 4-days hydraulic retention time in the facultative pond (Section 5.8.5; Shilton and Mara, 2005). Comparing this average inlet velocity with that of the pilot-scale primary facultative pond (0.09 m/s) of 30-days hydraulic retention time, it can be seen that there is significant increase in the inlet velocity by almost two orders of magnitude. The use of the 70% pond-width baffles could be desirable in this situation to reduce the occurrence of the hydraulic short-circuiting that might deteriorate treatment efficiency and the hydraulic performance of unbaffled waste stabilization ponds.

The results of dispersion number (Table 7.1) suggests that there was a higher degree of wastewater mixing in the four-baffle pilot-scale pond and the two-baffle pilot-scale pond compared to that of the unbaffled pilot-scale pond. The diagrams of the hydraulic flow patterns in the CFD model of baffled waste stabilization ponds (Chapter 5) show that the 70% pond-width baffles encourage the mixing of wastewater in baffle compartments and this mechanism increases the length of flow path from the inlet to outlet. The consequence of this is an increase of the hydraulic retention time that improves the hydraulic performance of the baffled pilot-scale ponds.

The public could be exposed to realistic health risk if waste stabilization pond effluent is characterised using the effluent *E. coli* numbers at 95% cumulative percentile. This cumulative percentile indicates the probable performance that waste stabilization ponds could attain during the design period. The effluent *E. coli* numbers at 95% cumulative percentile (3.6×10^4 *E. coli* per 100 ml for the four-baffle pilot-scale pond, 1.25×10^5 *E. coli* per 100 ml for the two-baffle pilot-scale pond and 1.95×10^5 *E. coli* per 100 ml for the unbaffled pilot-scale pond) show that the effluent quality from the three pilot-scale ponds does not comply with the requirement for the unrestricted crop irrigation WHO (2006) as the *E. coli* numbers are more than 10^3 per 100 ml (Section 6.2). However, the effluent *E. coli* numbers from the four-baffle pilot-scale pond satisfies the requirement for the restricted crop irrigation (3.64×10^4 *E. coli* per 100 ml, $< 10^5$ *E. coli* per 100 ml).

In order to reduce the effluent *E. coli* numbers such that compliance requirement for the unrestricted crop irrigation is satisfied, a maturation pond should be added to the pilot-scale primary facultative pond. Johnson and Mara (2002) and Carmago (2007) observed satisfactory removal of *E. coli* when the pilot-scale maturation pond was in series with the pilot-scale primary facultative pond in polishing the pond effluent to comply with the requirements for unrestricted crop irrigation and discharge into a European Union water body.

The use of the 70% pond-width baffles in facultative ponds may be one area of optimizing the classic and modern design methods to design efficient waste stabilization ponds as this might obviate the need for maturation ponds that require substantial land when complying with unrestricted crop irrigation requirement. Less land might be required for the construction of baffled waste stabilization ponds and this may encourage the use of waste stabilization ponds in temperate-climate areas, where the cost of land is usually prohibitive. Shilton and Mara (2005) showed that baffled waste stabilization ponds may need about 50% of the total land required for the construction of unbaffled waste stabilization ponds in complying with the requirements for unrestricted crop irrigation. The recommended number of the 70% pond-width baffles that could be installed in primary facultative ponds based on the experiment data of the pilot-scale primary facultative pond is two or four and the baffled primary facultative ponds should perform satisfactorily without risks of pond failure due to the increased BOD loading in the first baffle compartments.

The experimental data of chlorophyll-a (Section 6.2.6) showed that the concentration of algae in the pilot-scale pond was above the minimum that is found in a healthy facultative pond (Pearson *et al.* 1987; Mara, 2004). However, the concentration of algae was low during the spring season when algae predators fed intensively on algae (Section 6.2.6). Interestingly, the applied BOD loading (80 kg BOD per ha per day) did not affect the concentration of algae in the baffled pilot-scale primary facultative ponds. It can be inferred that the risk of ammonia and sulphide toxicity to algae as a result of the increased BOD_5 loading in the baffle compartments is unlikely to occur in a primary facultative pond that is fitted with two or four baffle configurations. The significance of the research finding is that designers and plant operators can confidently use the Mara's (1987) global equation to determine the optimum BOD_5 loading when designing baffled primary facultative ponds.

Section 5.5.4 has shown that the CFD model of the six-baffle facultative pond could achieve up to 6-log units removal of *E. coli* when the 70% pond-width baffles are spread equally along the longitudinal axis of the facultative pond. Although the results of the CFD model are based on numerical simulations, the satisfactory performance of the four-baffle pilot-scale primary facultative pond at a BOD loading of 80 kg per ha per day indicates that the six-baffle secondary facultative pond at a lower BOD loading than 80 kg per ha per day could perform satisfactorily. However, experiments are required to investigate the treatment performance of the six-baffle secondary facultative pond at the recommended BOD loading as suggested by Mara (1987).

In temperate-climate areas, it is not recommended to use anaerobic ponds because of the low temperature that does not favour the effective removal of BOD in these pond systems (Mara, 2004). In this situation, a baffled maturation pond could be placed in series with the baffled pilot-scale primary facultative pond. The BOD loading in the baffled pilot-scale maturation pond could be much lower than that of the baffled secondary facultative pond (Mara, 2004). Therefore, the number of the 70% pond-width baffles that could be fitted in the maturation pond could be higher than that of the baffled secondary facultative pond.

The high number of the 70% pond-width baffles that could be used in the maturation pond would probably result into significant short-circuiting if the design of baffle configurations is poor (Section 5.5.6). To ensure satisfactory performance of the baffled maturation pond, the design principles of baffle configurations outlined in Section 5.5.7 should be followed (i.e., the widths of baffle compartments and at the baffle opening should be equal). The risk of BOD overloading in a baffled maturation pond is insignificant because the design of these ponds is based on pathogen removal (Mara, 2004).

The effluent quality data of the pilot-scale pond presented in Table 6.1 and 6.2 show that there is an insignificant difference of treatment performance of the pilot-scale primary facultative pond when the effects of isothermal and thermo-stratifications are developed in the pond. It can be suggested that the hydraulic short-circuiting that is associated with thermo-stratification effect was not critical in the pilot-scale pond. The density of wastewater in the pilot-scale pond (equation 6.7) at five different wastewater layers that were defined for thermo-stratification (12^{o}C, 14^{o}C, 15^{o}C, 16^{o}C and 17^{o}C) are 999.58 kg/m^3, 999.33 kg/m^3, 999.18 kg/m^3, 999.02 kg/m^3 and 998.86 kg/m^3 respectively. It can be seen that the density variation is small, so much so that the wastewater layers are not prevented from mixing.

Abis and Mara (2006) observed that the effect of thermo-stratification was insignificant on the treatment performance of three unbaffled pilot-scale primary facultative ponds that were operated at the same site for three years. It is worth noting that the hydraulic retention time of the three pilot-scale ponds was in the range of 60-90 days. With this long hydraulic retention time, the effects of the hydraulic short-circuiting due to the thermo-stratification could be insignificant.

Banda *et al.* (2006b) compared the horizontal and vertical flow patterns in the pilot-scale pond using a 3D CFD model that incorporated effects of isothermal and thermo-stratification. The CFD model showed little difference of flow patterns when effects of isothermal and thermo-stratification were included. The vertical flow patterns showed that vertical mixing occurred in the model due to the minimal variation of the wastewater density. Examination of flow patterns showed that there was insignificant short-circuiting that was visible at the horizontal planes, which were below the top surface of the pond. It was considered that the improvement of the hydraulic performance in the pilot-scale pond was almost certainly due to the installation of baffles in the pond. However, the long retention time (30 days) that was used in the CFD model could have also played a significant role in influencing the hydraulic performance of the CFD model that included simulated effects of thermo-stratification.

Pedahzur *et al.* (1993) observed significant hydraulic short-circuiting in the four-baffled secondary facultative pond due to the thermo-stratification effects. It was observed that baffles did not improve the treatment performance of the facultative pond. However, one should note that this four-baffled secondary facultative pond was overloaded by 200% and it is not conclusive to suggest that the poor performance of the four-baffled facultative pond was caused by thermo-stratification effects alone. The research findings could have been different if the recommended BOD loading of Mara's (1987) equation had been used. Pearson *et al.* (1995 and 1996) observed that the treatment performance of waste stabilization ponds deteriorates significantly when the recommended BOD loading is exceeded.

It is also surprising to note that Pedahzur *et al.* (1993) do not detail the design of the baffle configurations that were used in the facultative pond. Mangelson and Watters (1972); Shilton and Harrison (2003a) observed that the hydraulic performance of baffled facultative ponds could deteriorate when 50% pond-width baffles are fitted along the longitudinal axis of the pond. These baffle configurations initiate channelling flow pattern that links directly the inlet and outlet of the pond. Consequently, significant hydraulic short-circuiting and stagnation regions are initiated that reduce the effective volume of the pond. The hydraulic retention times in the baffled ponds are reduced substantially and this deteriorates the treatment and hydraulic performance of baffled waste stabilization ponds.

7.2 CFD model calibration

7.2.1 Simulated tracer experiments

Section 6.6.2 has presented in detail the results of the hydraulic performance of the three pilot-scale primary facultative ponds and the CFD model. Examination of the experimental data in Table 6.3 shows that the average hydraulic retention time in the three pilot-scale primary facultative ponds is marginally higher than that predicted by the CFD model. However, the differences of the average hydraulic retention time of the pilot-scale primary facultative ponds and those predicted by the CFD model (10- 16%) are not significant, taking into account the daily variation of the influent flow (Appendix B), wind velocities and temperature that were observed during the operation of the pilot-scale ponds. It can be suggested that the simplification of the input design parameters (steady state flow, isothermal conditions and zero wind effects) that were used in the CFD is sufficiently accurate to predict the hydraulic flow patterns in waste stabilization ponds.

Shilton and Harrison (2001), Agunwamba (2002) and Peña Váron *et al.* (2002) argue that the variation of the influent flow, temperature, wastewater density and wind velocities significantly affect the hydraulic flow pattern in operational waste stabilization ponds and therefore influence the results of tracer experiments. Mangelson and Watters (1972) and Brissaund *et al.* (2003) observed that results of two or more tracer experiments when carried out in the same waste stabilization pond at different times of operation are not identical. Again, the diurnal variation of the influent flow, effects of temperature and wind velocity are considered to influence the results of the tracer experiments.

The CFD model used steady state flow; constant wastewater density (isothermal condition) and zero wind velocity when simulating the tracer experiment in the three pilot-scale primary facultative ponds. It was decided to use these simplifications in the input design parameters in order to present a realistic simple model that is easy to apply when designing and assessing the treatment performance of waste stabilization ponds. It was also noted that developing sub-models that represent the daily variation of influent flow, wind velocity and temperature difference at short time interval (seconds, minutes) over the design period of the pond could in theory be developed. However, the resulting CFD model would be difficult to operate. This model would require very extensive data and it would be very difficult to validate such a complex model.

The small differences of the hydraulic retention time and the dispersion number in the three pilot-scale primary facultative ponds and the CFD model suggest that the simulation of the tracer experiment was reasonably accurate in predicting the tracer experiment in the pilot-scale pond despite the diurnal variation of the influent flow, temperature and wind velocities that were not included in the CFD model. The significance of the accurate prediction of the tracer experiment suggests that the simplification of the input design variables in the CFD model could facilitate the design of waste stabilization ponds. Designers can benefit tremendously using a simple CFD model that realistically assesses the effects of various baffle configurations, inlet and outlet structures on the treatment efficiency of waste stabilization ponds, rather than a complex model that is difficult to apply and validate due to the requirement of extensive experimental data.

7.2.2 Simulation of BOD_5 removal in the CFD model of the pilot-scale pond

The experimental data of the effluent BOD_5 (Table 6.1 and 6.2) showed that the accuracy of the CFD model in predicting the BOD removal in the three pilot-scale primary facultative ponds during the winter season was in range of 62% – 85% while that of the summer season was 37% – 75%. It can be seen that the CFD is not accurate in predicting the BOD removal in the three pilot-scale primary facultative ponds especially that of the summer season. This discrepancy could have been caused by the significant variation of the influent BOD_5 (116 - 826 mg/l), BOD contribution due to algae and the unsteady state influent flow that were observed in the three pilot-scale primary facultative ponds. It is worth noting that the simulation of BOD removal in the CFD model of the three pilot-scale primary facultative ponds was based on steady state flow and a single average value of the influent BOD_5.

Apart from the diurnal variation of the influent flow and BOD_5 that could affect the precise simulation of BOD removal in the CFD, the first-order rate constant for BOD removal, which was used in the source term function (equation 6.4), could also influence the accuracy of the model. The first-order rate constant for BOD removal in facultative ponds varies significantly during the retention time period of wastewater in the pond (Mara, 1976; 2004). In additional, the change in chemistry and toxicity of the influent wastewater could also affect the rate of BOD decay in the pilot-scale primary facultative ponds and these factors were not considered in the CFD model.

Mara (1976), Thirumurthi (1969), Reed *et al.* (1988) and Marais and Shaw (1961) argue that the first-order rate constant for BOD removal is also affected by the variation of BOD loading, sedimentation and the environmental factors (temperature, pH and wind velocities) that influence the treatment efficiency of operational waste stabilization ponds. In addition, Mara (2004) observed that algae contribute approximately 80- 90% of the total BOD_5 in the effluent of waste stabilization ponds and this additional BOD was not included in the CFD model. It can be concluded that the underestimation of the BOD removal in the CFD model may have been attributable to the additional BOD contributed by algae. Thus, designers can indeed use CFD confidently as a reactor model to simulate precisely the removal of wastewater pollutants in waste stabilization ponds using reasonable simplification of the input design variables in the CFD.

7.2.3 Simulation of *E. coli* removal in the CFD model of the pilot-scale pond

The CFD model was also validated using experimental data of the effluent *E. coli* numbers that were observed in the three pilot-scale primary facultative ponds. The experimental data of effluent *E. coli* numbers in the CFD model and the pilot-scale pond show that the CFD was not precise in predicting the observed *E. coli* numbers in the three pilot-scale primary facultative ponds (Table 6.1 and 6.2). Interestingly, the experimental data of the effluent *E. coli* numbers in the three pilot-scale primary facultative ponds and the CFD were in the same order of magnitude. The accuracy of the CFD model in predicting the log-unit removal of *E. coli* numbers in the three pilot-scale primary facultative ponds during the winter season was in the range 81- 93%, while that of the summer season was in the range 78- 85%.

It can be suggested that the difference of the predicted *E. coli* numbers in the CFD and the three pilot-scale primary facultative ponds was not significant noting the wide variation of the influent *E. coli* numbers (1.0×10^6 - 6.0×10^7 per 100 ml) and the influent flow that were observed in the three pilot-scale primary facultative ponds (Appendix C). These design variables were assumed to be constant in the CFD for realistic simulation of *E. coli* removal in waste stabilization ponds.

The scalar transport equation of the *E. coli* removal in the CFD incorporated the source term function that represented the decay of *E. coli* (equation 3.13). The source term function included the first-order rate constant removal of *E. coli*, which was assumed to be constant during the retention time period of the three pilot-scale primary facultative ponds. Research findings have showed that the first-order rate constant removal of *E. coli* in waste stabilization ponds depend on many complex environmental factors such as pH, dissolved oxygen concentration, light, algae, pond depth, sedimentation, temperature, retention time and the BOD loading (Marais, 1974; Curtis and Mara, 2002; Mara, 2004; Pearson *et al.* 1987; von Sperling, 2002). These factors are known to affect significantly the decay rate of *E. coli* in waste stabilization ponds.

Different values of the first-order rate constant removal have been developed by various researchers to predict the removal of *E. coli* in waste stabilization ponds. The derivation of the first-order rate constant removal has been based on the assumption of the complete-mix and the plug hydraulic flow model. Table 7.2 presents the reported values of $K_{B(20)}$ and ϕ in the first-order rate constant removal equation ($K = K_{B(20)}\phi^{(T-20)}$).

Table 7.2 Reported values of $K_{B(20)}$ and ϕ in the first-order rate constant removal equation of *E. coli* in waste stabilization ponds

Source	$K_{B(20)}$ (day^{-1})	ϕ
Klock (1971)	1.1	1.07
Marais (1974)	2.6	1.19
Skerry and Parker (1979)	1.5	1.06
Arceivala(1981)	1.2	1.19
Mills *et al.* (1992)	0.7	1.17
Yanez (1993)	1.1	1.07
Mayo (1995)	1.9	1.08
Mara *et al.* (2001)	2.6	1.15
Banda *et al.* (2006a)	4.55	1.19

It can be seen from the table that there is a wide variation of the first-order rate constant removal of *E. coli* especially the $K_{B(20)}$ values in a range of 0.7 - 4.55. The first-order rate constant removal developed by Banda *et al.* (2006a) is relatively higher compared with other first-order rate constants (Table 7.2). This could have been attributed to the improved treatment and hydraulic efficiency that were observed in the baffled pilot-scale ponds. It is interesting to note that the first-order rate constants removal (0.7 – 2.6 day^{-1}) were developed using unbaffled waste stabilization ponds that were characterised with poor hydraulic and treatment efficiency. In addition, the unbaffled waste stabilization ponds could have been overloaded and this could have reduced the *E. coli* removal (Pearson *et al.* 1995, 1996; von Sperling 1999; Banda *et al.* 2005).

The source term function in the scalar transport equation (equation 2.29 and 6.4) used Marais' (1974) equation to simulate the *E. coli* removal in unbaffled pilot-scale primary facultative pond as Pearson *et al.* (1995 and 1996) observed that this equation is satisfactory when optimal BOD loading is applied in waste stabilization ponds. The Banda *et al.* (2006a) equation was used to simulate the *E. coli* removal in baffled pilot-scale primary facultative ponds because this equation is appropriate in baffled waste stabilization ponds due to the improvement of the treatment efficiency caused by the installation of baffles.

Although, the first-order rate constant removal of *E. coli* in the source term function was based on Marais' (1974) equation and Banda *et al*.'s (2006a) equation, it can be seen that the wide variation of the first-order rate constant removal suggest that the simulation of the *E. coli* removal in the CFD could not be precise in predicting the effluent *E. coli* numbers in the three pilot-scale primary facultative ponds. This could be the possible cause of the discrepancy between the predicted *E. coli* numbers in the CFD and the observed *E. coli* numbers in the three pilot-scale primary facultative ponds. The variation of the influent flow could also initiate the difference of the effluent *E. coli* numbers in the CFD and that of the three pilot-scale primary facultative ponds. The hydraulic flow patterns in the pilot-scale pond could have affected by the unsteady state of the influent flow and this could affect the movement of *E. coli* in the pond. High influent flow could reduce the residence time of the pilot-scale pond and this in turn might reduce the removal of *E. coli* in the pond while low influent flow could increase the residence time and this could increase the removal of *E. coli* in the pilot-scale pond.

Although the CFD model is not accurate in predicting the *E. coli* removal in the three pilot-scale primary facultative ponds, the close agreement of the predicted effluent *E.*

coli numbers in the CFD model and the three pilot-scale primary facultative ponds suggest that the CFD model was sufficiently accurate in simulating the *E. coli* removal in the three pilot-scale ponds. It can be concluded that the CFD model has been validated accurately by the experimental data of *E. coli* numbers that were observed in the three pilot-scale ponds. The satisfactory prediction of the effluent *E. coli* numbers in the three pilot-scale ponds suggests that the CFD can be confidently used to design and assess the treatment efficiency of waste stabilization ponds with simulated effects of baffle installation, thermo-stratification and wind velocity, as current classical and modern design methods cannot assess the treatment performance of waste stabilization ponds under these factors.

7.3 Performance assessment of the CFD model results

Having validated the CFD model with experimental data from the three pilot-scale primary facultative ponds, it can be argued that the CFD model results of the standard primary facultative pond (Chapter 5) present the probable treatment performance of waste stabilization ponds that are fitted with baffles of various configurations. In order to understand the relationship between the treatment efficiency of the baffled primary facultative pond with the number and length of baffles (70- 82% pond-width baffles), the numerical data of CFD model presented in Chapter 5 are summarised in Table 7.3 for the discussion that follows.

The numerical data in Table 7.3 show that the treatment performance of the baffled facultative pond model is generally higher compared to that of unbaffled facultative pond model. A strong relationship exists between the treatment efficiency of the baffled facultative pond with the number of 70% pond-width baffles. When the number of the 70% pond-width baffles was increased from 2 to 8, the effluent *E. coli* counts decreased significantly from 29,200 to 121 per 100 ml. However, in 10-baffle facultative pond model with 70% pond-width baffles, the treatment efficiency predicted by the CFD model diminished significantly with high *E. coli* numbers of 10,000 per 100 ml. An initially surprising result shows that the treatment performance of the ten-baffle facultative pond model with 70% pond-width baffles is equivalent to that of the two-baffle facultative pond model. An explanation for this is offered by the

CFD model's results which suggest that increasing the number of the 70% pond-width baffles in order to achieve plug flow pond without proper design of baffle configurations could significantly reduce the treatment efficiency of baffled facultative ponds. The spatial residence time distribution diagrams (Figure 5.10) shows that significant hydraulic short-circuiting is initiated and this reduces the hydraulic performance of the ten baffle facultative pond model. When the length of baffles was increased from 70% pond-width (224 m) to 82 % pond-width (262 m) such that the width of flow channel in baffle compartments is equivalent to that of the baffle opening (i.e., constant width of flow channel), there was a significant reduction of *E. coli* numbers from 10,000 to less than 0.001 per 100 ml. Note that the high removal of *E. coli* (< 0.001 *E. coli* per 100 ml) is indeed questionable from practical point of view. However, the CFD model results suggest that the width of baffle spacing and baffle opening is the key factor that may improve the treatment and hydraulic performance of baffled waste stabilization ponds.

Table 7.3 Effluent *E. coli* count per 100 ml in CFD model of the primary facultative pond with various baffle configurations

No. of baffles	Baffle length as % 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
0	-	-	-	4.10×10^6
2	70.0	213.0	96.0	29,200
4	70.0	128.0	96.0	2,400
6	70.0	91.0	96.0	121
8	70.0	71.0	96.0	162
10	70.0	58.0	96.0	10,000
10	72.0	58.0	90.0	850
10	74.0	58.0	83.0	143
10	76.0	58.0	77.0	17
10	78.0	58.0	70.0	5
10	82.0	58.0	58.0	0.001

The numerical results presented in Table 7.3 suggest that the *E. coli* removal in baffled facultative pond depends on the width of baffle compartments and the width of the baffle opening. The diagrams of simulated residence time distributions and flow patterns (Figures 5.9 and 5.10) in ten-baffle pond model with 70- 82% pond-width baffles show that hydraulic flow pattern is changed from one with a low degree of plug flow pattern (ten-baffle pond with 76% pond-width baffles) to one with a very strong plug flow pattern (ten-baffle pond with 82% pond-width baffles) when the flow channel width in baffle compartments is equivalent to the flow channel width at baffle openings.

The *E. coli* numbers in the ten baffle facultative pond with 82% pond-width baffles gave a maximum removal of *E. coli* (0.001 *E. coli* per 100 ml) for all baffle configurations. This baffle configuration is the one that forms a strong plug flow hydraulic pattern. However, the cost effective optimal baffle length (76% pond-width baffle) should be investigated in any baffle configurations, as this initiates the onset of the plug flow pattern (Figure 5.10). Although the plug hydraulic flow patterns and the maximum *E. coli* removal could be achieved using these conventional baffles, the design engineer should assess the available cost of procuring conventional baffles in order to justify the need of achieving high effluent quality.

The use of a large number of the conventional baffles in primary facultative pond has a high risk of pond failure due to the increased loading of ammonia and sulphide in baffle compartments that might be toxic to algae. This is due to the fact that the influent BOD is not spread over the designed surface area. The use of a large number of baffles could be appropriate in secondary facultative ponds where the BOD loading is usually lower compared to that of the primary facultative pond.

The practical use of a large number of conventional baffles is appropriate in tropical climate areas where the use of anaerobic ponds and secondary facultative ponds is desirable due to the availability of high temperatures. A simple design procedure has been suggested in Section 7.1 how to calculate the numbers of conventional baffles in a secondary facultative pond based on the surface BOD loading equation proposed by Mara (1987).

A series of anaerobic pond and a secondary facultative pond with 6- 8 baffles could perform satisfactorily as noted by the excellent performance of the four-baffle pilot-scale primary facultative pond. When the design and construction of the anaerobic pond is not appropriate due to the existence of low temperature as in temperature climate regions, efficient design of waste stabilization ponds could be accomplished using baffled primary facultative ponds (2 or 4 baffles) and baffled maturation ponds (any practical number of baffles). The effluent quality should easily comply with the consent standards of the particular environmental protection agency.

The CFD model results of the facultative pond with short-baffles (Section 5.7) showed that the 10% pond-width baffles predicted the treatment performance that is equivalent to that of the primary facultative pond with two-70% pond-width baffles. However, the drawback of the short baffle configurations is the significant variation of the effluent *E. coli* numbers that is predicted by the CFD model. Surprisingly, there is no direct design method that could be suggested to determine the position and length of short-baffles for effective removal of wastewater pollutants in the primary facultative pond. The use of short-baffles in primary facultative pond should be based on a number of simulations in order to identify the most economic and safest baffle configuration.

The risk of BOD overloading in primary facultative ponds that are fitted with short-baffles is minimal because the influent flow is not confined in the baffle compartment. The influent BOD is spread over the designed surface area. It is interesting to note that the purpose of short baffles is to reduce the influent momentum such that there is no direct path of wastewater flow that directly links the inlet and outlet. Shilton and Harrison (2003a) observed that short baffles are cost effective and could perform more satisfactorily than the conventional baffles in removing *E. coli* numbers up to 3-log units removal when fitted near the inlet and outlet in secondary facultative ponds.

7.4 Performance assessment of CFD model with simulated wind effects

The numerical data of the CFD model of a standard facultative pond that included wind speed and direction (Section 5.8) showed that wind effects could either be beneficial or detrimental to the treatment and hydraulic performance of waste stabilization ponds depending on the prevailing wind direction in relation to the wastewater flow in the pond. When the wind blows in the same direction as the wastewater flow, the CFD model predicted a treatment performance that is lower than that of the pond with no wind (Table 5.8). However, when the wind blows against the direction of the wastewater flow in the pond, the CFD predicted higher treatment efficiency than that of the pond with no wind. The numerical results further showed that the treatment efficiency of the facultative pond is not significantly affected when the prevailing wind direction is normal to the wastewater flow in the pond.

Wind velocities set up circulation flow mechanisms that change the basic flow patterns in waste stabilization ponds (Banda *et al.* 2006a). When the wind blows in the same direction as the wastewater flow, there are a large number of flow paths that link directly the inlet and outlet of the facultative pond (Figure 5.14). The consequence of this is the reduction of the average hydraulic retention time in the pond and this reduces the removal rate of pollutants in waste stabilization ponds. It has been observed by Mara (2004), Brissaud *et al.* (2000, 2003), Frederick and Lloyd (1996), Lloyd *et al.* (2003) and Vorkas and Lloyd (2000) that wind velocity initiates hydraulic short-circuiting that reduces the treatment performance of waste stabilization ponds.

It is interesting to note from the flow pattern diagrams (Figure 5.15) of the CFD model with wind blowing in the opposite direction of the wastewater flow that there are a number of the circulation flow patterns that increase the length of the flow paths from the inlet to outlet. This forms a flow mechanism that reduces the extent of the hydraulic short-circuiting in waste stabilization ponds. Mara (2004) suggests that wind velocity could be beneficial to the treatment efficiency of waste stabilization ponds if the wastewater flow is against the prevailing wind direction. Although the findings of Mara (2004) were based on engineering judgement following assessment of pond performance under wind effects, the results of the CFD model with simulated wind effects agree satisfactorily with these findings. For the design of waste stabilization ponds with wind effects, a simple CFD model that assumes a constant wind velocity over the hydraulic retention time period of the pond is adequate to assess reasonably the hydraulic and treatment performance of waste stabilization ponds under windy conditions.

In order to sustain the satisfactory performance of waste stabilization ponds when the effects of wind are significant, the use of 70% pond-width baffles could help in reducing the hydraulic short-circuiting associated with wind effects. The numerical results of the two-baffle facultative pond model and four-baffle facultative pond model with wind effects (Section 5.9) showed that the treatment performance of facultative ponds with wind blowing in the same direction as the wastewater flow is not significantly different to that of the model without wind effects. It can be suggested that baffles could play a significant role in reducing the hydraulic short-circuiting associated with wind effects.

Shilton and Harrison (2003a) suggested that proper design of pond inlet could obviate the concerns of the hydraulic short-circuiting associated wind effects as the influent momentum could control the resulting flow patterns in the pond. Shilton and Harrison's (2003a, 2003b) power theory could be 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 30-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 across a similar facultative pond.

However, the work in this research has used a 4-day retention time to increase substantially the inlet momentum. The wind speed of 5 m/s provides power of 0.82 kW over the pond surface area of 204, 800 m^2 (640 m × 320 m. The power supplied by the influent is 22 kW, so the contribution of the wind effects is 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 in Section 5.7 has demonstrated that for a wind speed of 5 m/s blowing in the opposite direction to the wastewater flow, the *E. coli* removal was reduced by 30% more than that in a facultative pond with no wind.

If Shilton and Harrison's (2003a, 2003b) theory was satisfactory, the results of wind effects should have closely agreed with those from the 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 waste stabilization pond systems. There is a question mark regarding the power theory proposed by Shilton and Harrison for designing the pond hydraulics in waste stabilization ponds without taking into account the wind speed and prevailing direction. It should be noted that even at a low wind speed of 0.5 m/s, Frederick and Lloyd (1996) observed hydraulic short-circuiting in waste stabilization ponds that had a 12-day retention times with isothermal conditions.

7.5 Practical application of CFD-based design of waste stabilization ponds

The classical and modern design methods could be used simultaneously with CFD to include effects of environmental conditions (thermo-stratification and wind velocity) and baffles when assessing the treatment efficiency and hydraulic performance of waste stabilization ponds. Section 5.8.5 has shown that wind effects could improve the treatment efficiency of waste stabilization pond when the wastewater flow is against the prevailing wind direction. In addition, it has been shown that baffles could improve significantly the treatment efficiency and the hydraulic performance of waste stabilization ponds following the recommended design of baffle configuration (Chapter 5). These benefits could be utilized when sizing waste stabilization ponds as the current design methods do not include these performance benefits at the design stage.

CFD can provide high confidence to plant operators and designers in the resultant effluent quality because the numerical simulation of the pond effluent is predicted with high accuracy. However, reasonable simplification of the input design parameters should be made in the CFD as this enables the realistic simulation of the hydraulic and treatment performance of waste stabilization ponds. It is not recommended to use complex sub-models to represent the input design variables such as *E. coli* numbers, BOD concentration, wind velocity and influent flow as these parameters are difficult to obtain accurately due to their significant variation.

When simulating hydraulic flow patterns in waste stabilization ponds, a steady state flow regime is adequate to design the pond hydraulics. Although quasi–steady state flow is suitable in waste stabilization ponds due to the diurnal variation of the influent flow, it is interesting to note that this flow regime is difficult to validate in CFD as extensive influent flow data is required at short time intervals (seconds, minutes) to describe accurately the flow patterns in the pond. In addition, expensive laboratory instruments would be required to implement the field work.

Using CFD as a reactor model, the simulation of the pollutant removal in waste stabilization ponds could be predicted with a higher degree of accuracy compared to that of the classic and modern design methods. This is due to the fact that the transport of the wastewater pollutants depends significantly on the hydraulic flow patterns in waste stabilization ponds. The scalar transport equation should be modified appropriately to include the source term functions to represent the decay of pollutants in the pond. Development of source term functions should use dimensional analysis principles and the first-order rate constant removal that reasonably represents the decay of pollutants in waste stabilization ponds. Otherwise, the scalar transport equation could not be precise in simulating the pollutant decay in the CFD.

Examination of the scalar transport equation 2.29 shows that the input design variables (influent *E. coli* numbers, BOD_5 concentration) should be assessed accurately for the precise simulation of the pollutant concentration in the pond effluent. Sections 6.2.1 and 6.2.2 have showed that these input design variables vary significantly in operational waste stabilization ponds. To overcome this uncertainty, adequate field data should be obtained from field waste stabilization ponds that should be analysed statistically to characterise the raw wastewater. Ideally, average values of *E. coli* numbers and BOD concentration are sufficient to represent the boundary conditions of the scalar transport equation of the *E. coli* and BOD removal in the CFD.

The diffusion coefficients of wastewater pollutants in the pond should also be investigated adequately to improve the accuracy of the scalar transport equation in CFD. In waste stabilization ponds where circulatory hydraulic flow patterns are dominant, the transport of the wastewater pollutants could be due to the wastewater velocity and the diffusivity term of the scalar transport equation could be negligible. However, when the hydraulic flow patterns in the CFD model are not obvious, the diffusion coefficient of the wastewater pollutants should be researched adequately as this could be the source of the imprecision of the CFD solution. The CFD user should also think about other design variables that could be simplified when developing the model that is more realistic for the design of waste stabilization ponds.

The satisfactory validation of the CFD (Section 6.6) with experimental data from three pilot-scale primary facultative ponds demonstrates that the CFD has the capacity of predicting reasonably the treatment efficiency and the hydraulic performance of waste stabilization ponds. Numerical results of the CFD model can help designers and plant operators to make informed decision regarding the physical design interventions that could be employed to improve the performance of waste stabilization ponds. Furthermore, the numerical results could enable realistic assessment of the public health risks when the waste stabilization pond effluent is used for crop irrigation.