Chapter 6

Fieldwork results and validation of the 3D CFD model

6.1 Introduction

This chapter presents results of the treatment efficiency and the hydraulic performance of the four-baffle pilot-scale primary facultative pond, the two-baffle pilot-scale primary facultative pond and the unbaffled pilot-scale primary facultative pond that were operated for two years. The experimental data of BOD_5, suspended solids, *E. coli*, chlorophyll-a, ammonia and total nitrogen in the influent and effluent are presented as histograms and frequency curves.

The in-situ dissolved oxygen and pH profiles data are presented to assess the initiation of BOD overloading in the two-baffle pilot-scale pond and four baffle pilot-scale pond as the installation of the 70% pond-width baffles does not allow the quick spread of the influent BOD loading over the designed surface area.

Experimental data of temperature profiles are presented to show the development of isothermal and thermo-stratification conditions in the pilot-scale pond that occurred during winter and summer seasons respectively. The data have been used to validate the CFD model with simulated effects of isothermal and thermo-stratification conditions. Normalised residence time distribution curves have been obtained from tracer experiments to validate the CFD. The results of dispersion number and mean hydraulic retention times are presented to assess the hydraulic performance of the three pilot-scale primary facultative ponds.

Finally, the chapter presents the CFD-predicted results of the effluent BOD_5, *E. coli* numbers and the simulated tracer experiment. The CFD-predicted results are compared with the experimental data from the three pilot-scale ponds to validate the CFD that has been employed in this research. The CFD model has included the effects of isothermal and thermal-stratification for more precise simulation of the pilot-scale pond performance during both the winter and summer seasons.

6.2 Physicochemical Parameters

6.2.1 *E. coli* removal

The experimental data of the influent *E. coli* numbers were analysed statistically using descriptive statistics (SPSS version 13.0). The average influent *E. coli* number in the three pilot-scale ponds was 1.0×10^7 per 100 ml with a standard error of $\pm 1.4 \times 10^6$ per 100 ml (see Appendix C). It is interesting to note that the influent *E. coli* numbers compare well with the expected concentration of *E. coli* numbers found in raw sewage (Mara, 2004; Tchobanoglous *et al.*, 2003). Figure 6.1 shows results of the effluent *E. coli* numbers expressed as histograms and frequency curves. It can be seen from Figure 6.1 that, for any cumulative percentile, the effluent *E. coli* numbers in the four-baffle pilot-scale pond and two-baffle pilot-scale pond are generally lower than that of the unbaffled pilot-scale pond.

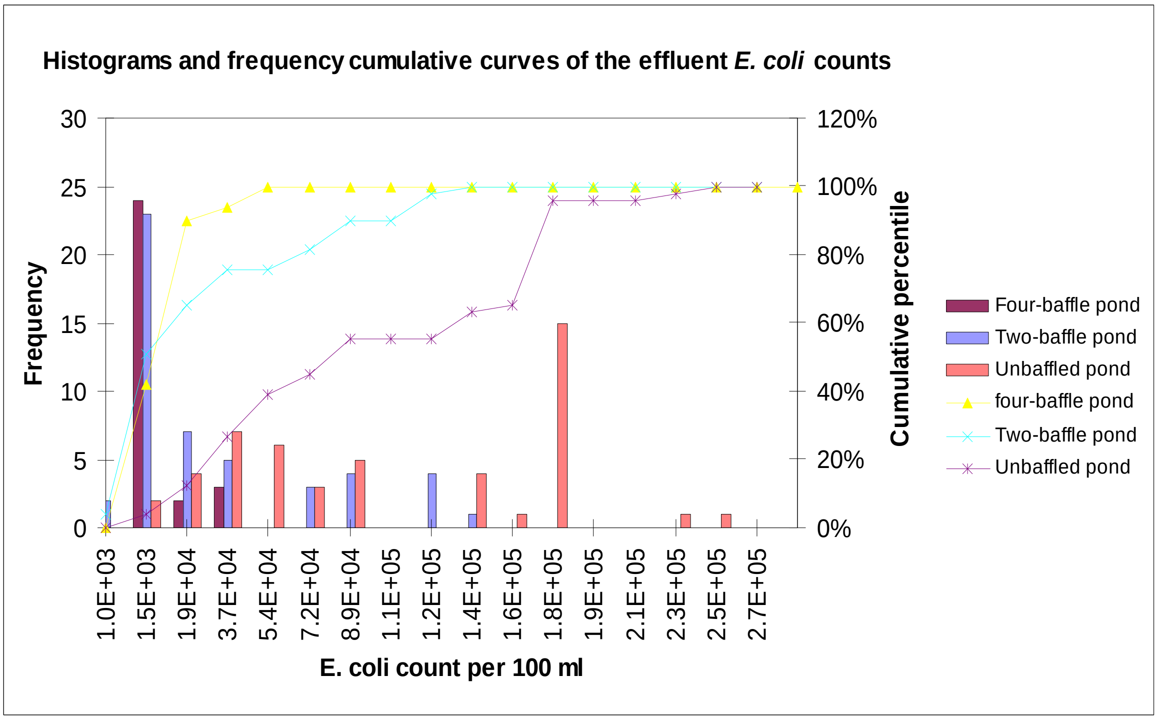


Figure 6.1 Results of *E. coli* numbers in the effluents of the three pilot-scale primary facultative ponds

Using 50% cumulative percentile to characterise the effluent quality from the pilot-scale ponds, the results of the *E. coli* numbers in the unbaffled pilot-scale pond, two-baffle pilot-scale pond and four-baffle pilot-scale pond are 1.1×10^5 per 100 ml, 4.0×10^4 per 100 ml and 9.8×10^3 per 100 ml (i.e., removals of 1.96, 2.42 and 3.02 log-units), respectively.

When the effluent quality from the pilot-scale ponds is assessed at 95% cumulative percentile , *E. coli* numbers in the four-baffle pilot-scale pond and two-baffle pilot-scale pond are again lower than that of the unbaffled pilot-scale pond (1.9×10^5 *E. coli* per 100 ml for unbaffled pilot-scale pond, 1.3×10^5 *E. coli* per 100 ml for two-baffle pilot-scale pond and 3.6×10^4 *E. coli* per 100 ml for four-baffle pilot-scale pond). These results suggest that the treatment efficiency of the pilot-scale primary facultative pond improved significantly when the 70% pond-width baffles were installed in the pond. The public health risks would be low if the effluent from the four-baffle pilot-scale pond and two-baffle pilot-scale pond were used for crop irrigation. The improvement in the treatment efficiency of the baffled pilot-scale ponds could be attributed due to the reduction of hydraulic short-circuiting that usually diminishes pond performance.

The pilot-scale pond effluent is assessed for compliance requirements with restricted crop irrigation (less than 10^5 *E. coli* per 100 ml) and unrestricted crop irrigation (less than 10^3 *E. coli* per 100 ml) based on 50% cumulative percentile (WHO, 2006). It can be seen from Figure 6.1 that the unbaffled pilot-scale pond effluent (1.1×10^5 *E. coli* per 100 ml) does comply with restricted crop irrigation but not with unrestricted crop irrigation. Similarly, the effluent *E. coli* numbers from the two-baffle pilot-scale pond and four-baffle pilot-scale pond comply with restricted crop irrigation (4.0×10^4 *E. coli* per 100 ml and 9.8×10^3 *E. coli* per 100 ml but fail to comply with unrestricted crop irrigation (4.0×10^4 *E. coli* per 100 ml and 9.8×10^3 *E. coli* per 100 ml greater than 10^3 *E. coli* per 100 ml). When compliance requirement is based 95% cumulative percentile, only the effluent from the four-baffle pilot-scale pond satisfies the restricted crop irrigation (4.0×10^4 *E. coli* per 100 ml less than 10^5 *E. coli* per 100 ml).

Marais' (1974) equation is employed to predict the observed effluent *E. coli* numbers in the three pilot-scale primary facultative ponds. This equation is commonly used by designers to model *E. coli* removal in waste stabilization pond series and is presented as:

$$N_i = \frac{N_e}{(1 + K_b\theta)} \qquad 6.1$$

where:

K_b = first-order rate constant removal of *E. coli* ($2.6 \times 1.19^{(T-20)}$) (day^{-1})

N_i = influent *E. coli* numbers per 100 ml

N_e = effluent *E. coli* numbers per 100 ml

T = pond temperature (^{o}C)

θ = theoretical retention time (days)

The average temperatures that were monitored in the pilot-scale ponds during winter and summer seasons (Section 6.4) were 5^{o}C and 14.8^{o}C respectively. Substituting the following design parameters ($N_i = 1.0 \times 10^7$ per 100 ml, $\theta = 30$ days, $K_b = 1.05$ and 0.19 day^{-1} for $T = 14.8^{o}$C and 5^{o}C respectively) into equation 6.1, the predicted *E. coli* numbers are 3.16×10^5 per 100 ml for summer season and 1.53×10^6 per 100 ml for winter season.

It can be seen that there is a satisfactory agreement of the predicted *E. coli* numbers during the summer (3.2×10^5 *E. coli* per 100 ml) when compared with the observed *E. coli* numbers in the unbaffled pilot-scale pond (1.1×10^5 *E. coli* per 100 ml at 50% cumulative percentile and 1.9×10^5 *E. coli* per 100 ml at 95% cumulative percentile). However, the predicted *E. coli* numbers during the winter season (1.5×10^6 *E. coli* per 100 ml) are lower than those observed by 84%. Furthermore, the predicted *E. coli* numbers are significantly different to the observed *E. coli* numbers in the two-baffle pilot-scale pond (4.0×10^4 *E. coli* per 100 ml) and the four-baffle pilot-scale pond (9.8×10^3 *E. coli* per 100 ml) based on effluent quality at 50% cumulative percentile.

The results of the predicted effluent *E. coli* numbers suggest that the Marais' equation is consistent in assessing the *E. coli* removal in all unbaffled waste stabilization pond when the pond temperature (i.e., 5^{o}C and 14.8^{o}C for the case of the pilot-scale pond) is within 2-21^{o}C as observed by (Marais, 1974). However, the equation is not accurate when predicting the *E. coli* removal in baffled waste stabilization ponds. One should realise that the Marais' equation was developed using experimental data of *E. coli* that was obtained from unbaffled waste stabilization ponds. Mangelson and Watters (1972) and Shilton and Harrison (2003a) argue that unbaffled waste stabilization ponds are characterised with poor performance due to the hydraulic short-circuiting that are inherent in these pond systems. Plots of flow patterns from CFD indicate that the hydraulic flow patterns in unbaffled waste stabilization ponds are significantly different to those in baffled waste stabilization ponds (Banda *et al.* 2006a; Wood, 1997; Shilton, 2001; Salter, 1999). In addition, the CFD flow pattern plots show that there is a low degree of hydraulic short-circuiting in baffled waste stabilization ponds compared with those for unbaffled waste stabilization ponds due to the satisfactory mixing of wastewater that occurs in the baffle compartments. It is not surprising to note that the Marais' equation is not precise when predicting the *E. coli* removal in the baffled pilot-scale primary facultative ponds.

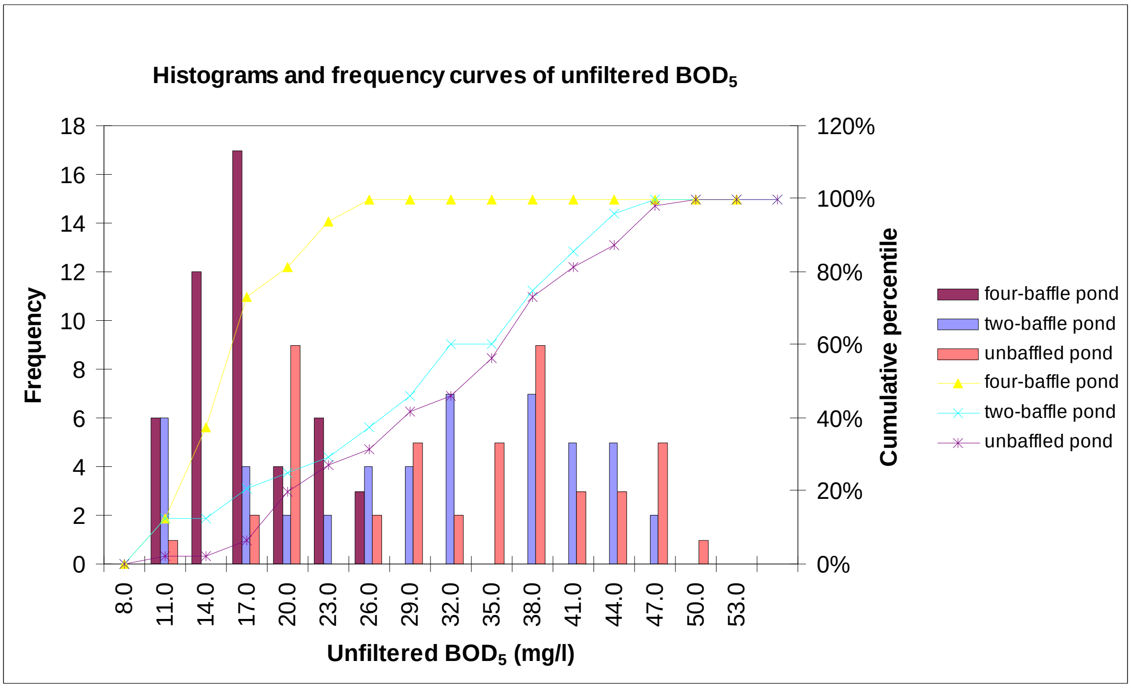
Pearson *et al.* (1995) and Buchauer (2006) argue that the treatment efficiency of facultative ponds with high aspect ratios (length to width > 6:1) is not significantly different from those with low aspect ratios (2- 3:1). It was concluded that the treatment efficiency of facultative ponds could not be significantly improved by modifying the pond geometry through the use of baffles. It was argued that Marais' (1974) equation is adequate and could be used to model the decay of *E. coli* in waste stabilization ponds with complex geometry.

The results presented in this work show that the findings of (Pearson *et al.* 1995; Buchauer, 2006) are not conclusive and could be misleading, as their research was limited to unbaffled facultative ponds. Mangelson and Watters (1972); Shilton, (2001); Abbas *et al.* (2006) observed that the treatment efficiency of facultative ponds is significantly improved when baffles are installed in the pond.

6.2.2 BOD_5 removal

The experimental data showed significant variation of influent BOD_5 in the range of 116- 826 mg/l during the operation of the three pilot-scale ponds (Appendix C). The BOD_5 variation could have been attributed due the industrial wastewater that contributed 50% of the influent flow. The organic strength of the industrial wastewater is usually higher compared to that of the domestic wastewater (Mara, 2004; Moshe *et al.* 1977) and this could probably be the cause of the high BOD_5 that was observed in the influent. The second reason of the influent BOD_5 variation could be dilution of the raw wastewater by the storm water (rainfall). Application of descriptive statistics (SPSS, version 13.0) shows that the average BOD_5 in the influent was 387 mg/l, with a standard error of ± 25 mg/l. This compares well with the findings of Abis (2002) who operated three unbaffled pilot-scale primary facultative ponds at a similar site for three years.

Figure 6.2 shows results of BOD_5 in the unfiltered and filtered effluent expressed as histograms and frequency curves. The results from Figure 6.2 show that both filtered and unfiltered BOD_5 from the four-baffle pilot-scale pond and two-baffle pilot-scale pond effluents are lower than that of the unbaffled pilot-scale pond at any cumulative percentile. The unfiltered BOD_5 in the effluent at 50% cumulative percentile are 17 mg/l, 29 mg/l and 35 mg/l for four-baffle pilot-scale pond, two-baffle pilot-scale pond and unbaffled pilot-scale pond respectively. However, the unfiltered BOD at 95% cumulative percentile is higher than that at 50% cumulative percentile (23 mg/l for four-baffle pilot-scale pond, 42 mg/l for two-baffle pilot-scale pond and 47 mg/l for unbaffled pilot-scale pond). Note that the difference of unfiltered effluent BOD in the unbaffled pilot-scale pond and two-baffle pilot-scale is not significant. This is not surprising to note because algae contributes substantial BOD in the effluent.



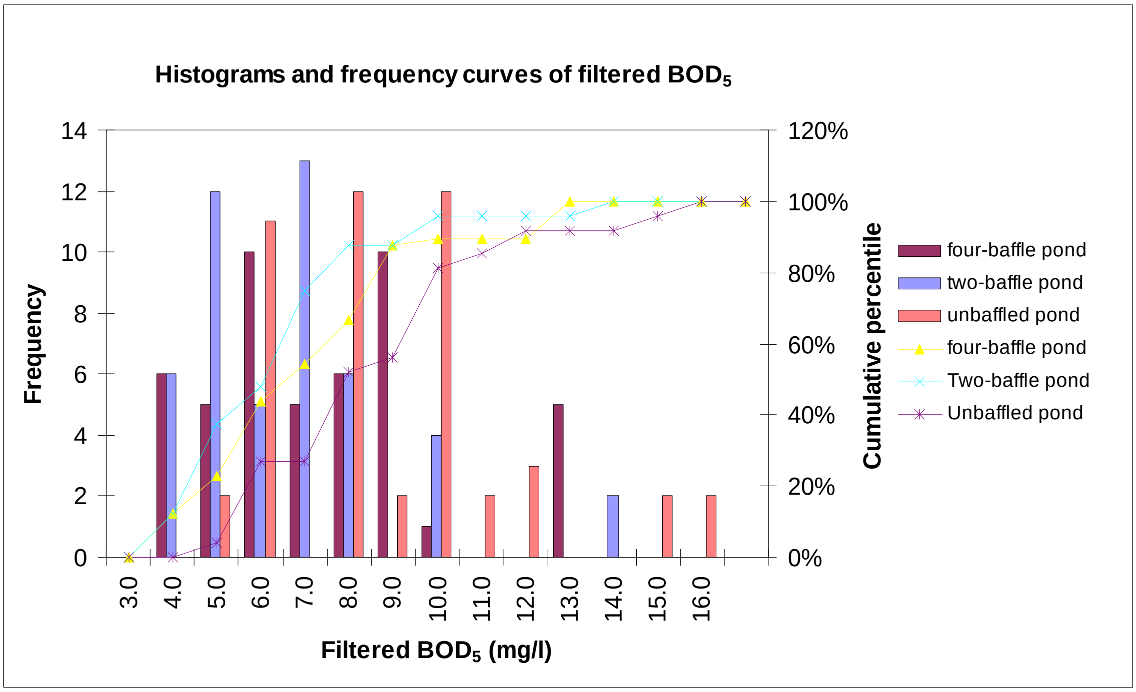


Figure 6.2 Results of BOD_5 in the unfiltered and filtered effluents of the three pilot-scale primary facultative ponds

For the filtered BOD_5 in the effluent, the results at 50% cumulative percentile are 7 mg/l for four-baffle pilot-scale pond, 6 mg/l for two-baffle pilot-scale pond and 9 mg/l for unbaffled pilot-scale pond. The filtered BOD_5 at 95% cumulative percentile is again higher than that at 50% cumulative percentile (8 mg/l for four-baffle pilot-scale pond and two-baffle pilot-scale pond and 14 mg/l for the unbaffled pilot-scale pond).

The treatment efficiency of the three pilot-scale ponds using the unfiltered BOD_5 at 50% cumulative percentile is 96% for four-baffle pilot-scale pond, 93% for two-baffle pilot-scale pond and 91% for unbaffled pilot-scale pond. However, the treatment performance of the three pilot-scale ponds based on unfiltered BOD_5 at 95% cumulative percentile is lower than that at 50% cumulative percentile. The BOD treatment efficiency being 94% for four-baffle pilot-scale pond, 89% for two-baffle pilot-scale pond and 88% for the unbaffled pilot-scale pond. It can be seen that the treatment efficiency of the pilot-scale primary facultative pond in removing BOD improved when the 70% pond-width baffles were installed in the pond.

It is interesting to note that the filtered BOD_5 from the three pilot-scale ponds based on BOD results at 95% cumulative percentile (8 - 14 mg/l < 25 mg/l) comply with the discharge requirements of the European Union water body (Council of the European communities, 1991).

Mara (2004) argued that the filtered BOD_5 in the pond effluent accounts for ~ 10 - 30 % of the total BOD_5. Using 20% to represent the filtered BOD_5 in the pond effluent, it can be seen that the contribution of the non-algal component in the total effluent is 10 mg/l and this predicted-BOD is not significantly different to the observed BOD_5 in the filtered effluent based on 95% cumulative percentile results (8 - 14 mg/l).

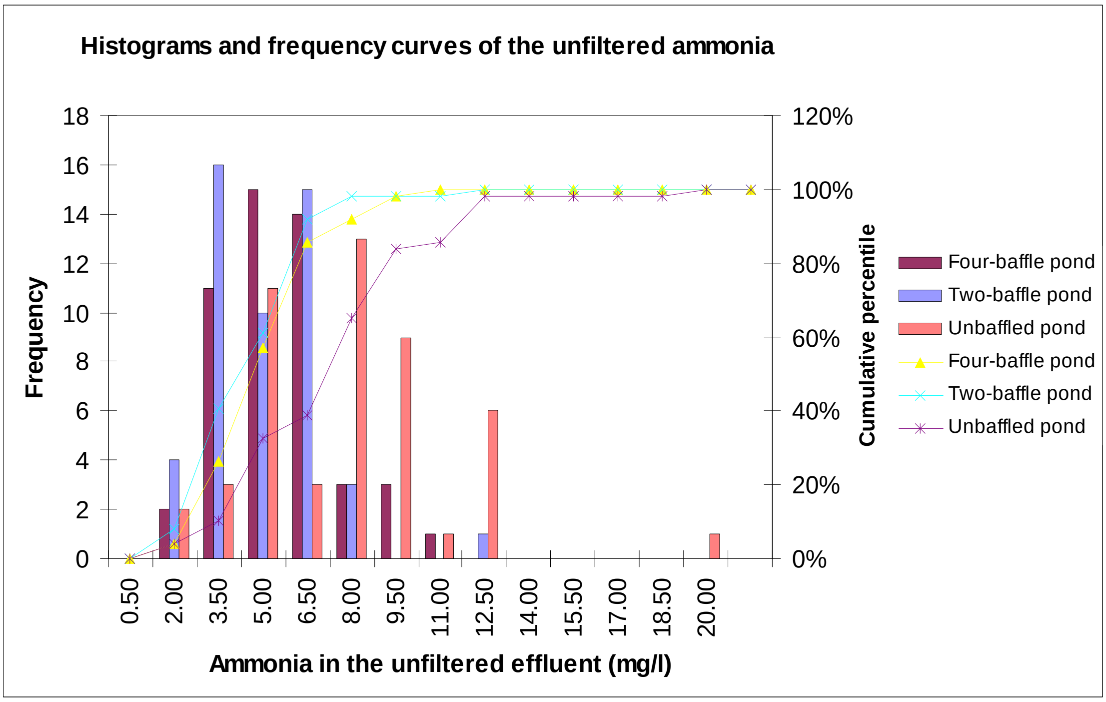
Pedahzur *et al.* (1993) observed that the treatment efficiency of a four-baffle facultative pond was not satisfactory in removing BOD_5. Significant hydraulic short-circuiting was noted in the four-baffle facultative pond due to the thermo-stratification effects. Despite the installation of baffles, the treatment efficiency of the facultative pond did not improve. However, one should realise that the four-baffle facultative pond was overloaded by more than 200%. Conclusions should not therefore be drawn that the poor performance of the four-baffle facultative pond was caused by thermo-stratification effects alone. It is interesting to note that results from other researchers (Muttamara and Puetpailboon, 1996, 1997; Kilan and Ogunrombi, 1984; von Sperling *et al.* 2002; Zanotelli *et al.* 2002) showed that baffles improve the treatment performance of waste stabilization ponds that are optimally loaded.

6.2.3 Ammonia removal

The concentration of ammonia in the influent showed significant variation in a range of 8- 106 mg/l (Appendix C). The reasons that were suggested earlier for the variation of influent BOD_5 could be responsible for the variation of ammonia in the influent. Descriptive statistics (SPSS, version 13) show that the average concentration of ammonia in the influent was 47 mg/l with a standard error of ± 4 mg/l.

Figure 6.3 shows the experimental data of ammonia in the unfiltered and filtered effluent of the three pilot-scale ponds. It can be seen from Figure 6.3 that the removal of ammonia in the four-baffle pilot-scale pond and two-baffle pilot-scale pond is generally higher compared to that of the unbaffled pilot-scale pond at any cumulative percentile level. Surprisingly, there is no significant difference in the treatment performance of the four-baffle pilot-scale pond and the two-baffle pilot-scale pond in removing ammonia. The concentration of ammonia in the unfiltered effluent based on 50% cumulative percentile is 4 mg/l for four-baffle pilot-scale pond; 3.5 mg/l for two-baffle pilot-scale pond and 8 mg/l for the unbaffled pilot-scale pond. However, the concentration of ammonia at 95% cumulative percentile in any pilot-scale pond is higher compared to that at 50% cumulative percentile (8.8 mg/l for four-baffle pilot-scale pond, 8.5 mg/l for two-baffle pilot-scale pond and 12 mg/l for unbaffled pilot-scale pond).

It can also be seen from Figure 6.3 that the concentration of ammonia in the filtered effluent is generally lower than that of the unfiltered effluent. The concentration of ammonia in the filtered effluent at 50% cumulative percentile are 2.0 mg/l for four-baffle pilot-scale pond, 2.5 mg/l for two-baffle pilot-scale pond and 4.5 mg/l for unbaffled pilot-scale pond. However, the concentration of ammonia in the filtered effluent at 95% cumulative percentile is relatively higher than that at 50% cumulative percentile (4.5 mg/l for four-baffle pilot-scale pond, 5.0 mg/l for two-baffle pilot-scale pond and 10 mg/l for unbaffled pilot-scale pond).



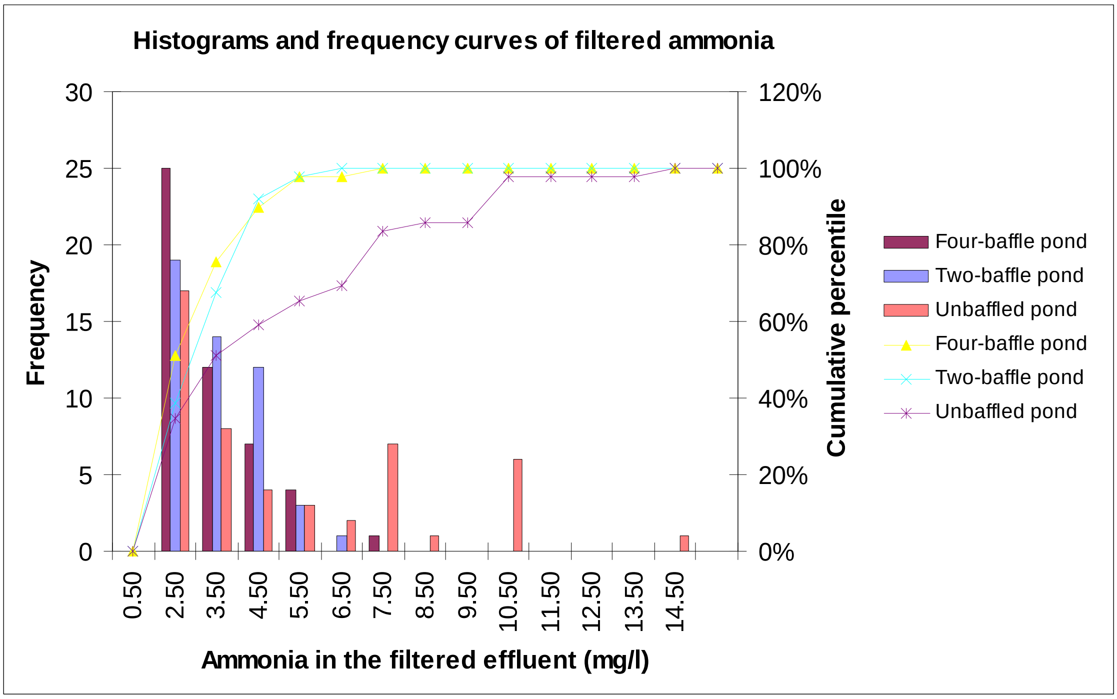


Figure 6.3 The results of ammonia in the filtered and unfiltered effluents of the three pilot-scale primary facultative ponds

The treatment efficiencies of the unbaffled pilot-scale pond, two-baffle pilot-scale pond and four-baffle pilot-scale pond based on concentration of unfiltered ammonia at 95% cumulative percentile were 74%, 82% and 81% respectively. It can be seen that the treatment efficiency of the pilot-scale primary facultative pond increased when the 70% pond-width baffles were installed in the pond.

The Pano and Middlebrooks's (1982) equation is employed to predict the removal of ammonia in the pilot-scale pond during winter and summer seasons when isothermal and thermo-stratification conditions developed (Section 6.4). Equation 6.2 presents the ammonia removal model developed by Pano and Middlebrooks and is written as:

$$C_e = \frac{C_i}{1 + \left(\frac{A}{Q} \left(0.0038 + 0.000134\ T \right) e^{\left(1.041 + 0.044\, T\right)\left(pH - 6.6\right)} \right)} \qquad 6.2$$

where:

C_e = effluent ammonia (mg/l)

C_i = influent ammonia (mg/l)

A = area (m^2)

Q = influent flow (m^3/day)

T = temperature (^oC)

pH = activity of hydrogen ions = $\log_{10}$ (concentration of hydrogen ions)

When the design parameters (temperature T = 5^{o}C, pond surface area A = 39.50 m^2, influent flow Q = 1.04 m^3 per day, pH = 8.5, and average influent ammonia = 47 mg/l) are substituted in equation 6.2, the predicted ammonia concentration in the pilot-scale pond effluent is 22.0 mg/l. The equation is again used to predict the effluent ammonia during the summer season when the average pond temperature and pH were 14.8^{o}C and 9.65 respectively. The predicted ammonia concentration in the pilot-scale pond effluent using equation 6.2 is 7.45 mg/l.

The prediction of ammonia in the pilot-scale pond effluent during the winter season (22 mg/l) was significantly different to the observed concentration of ammonia at 95% cumulative percentile (8.8 mg/l for four-baffle pilot-scale pond, 8.5 mg/l for two-baffle pilot-scale pond and 12 mg/l for unbaffled pilot-scale pond). However, it is interesting to note that the predicted ammonia during the summer season (7.45 mg/l) was not significantly different to the observed ammonia at 95% cumulative percentile. The results of the predicted ammonia suggest that the Pano and Middlebrooks's

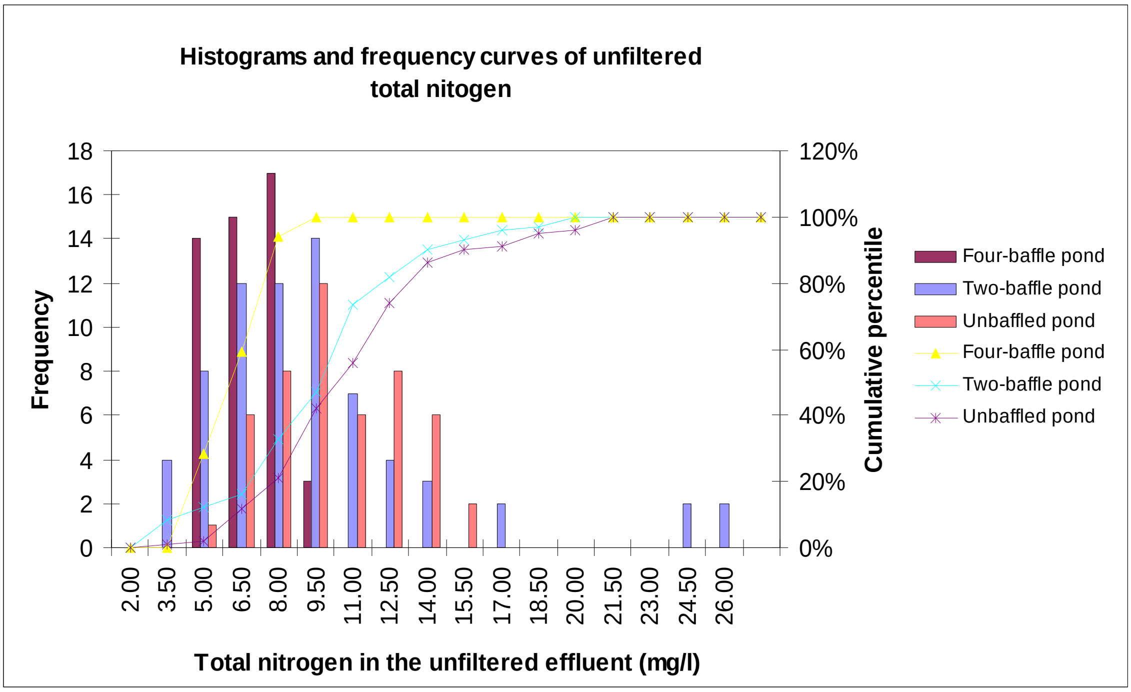
(1982) equation can be used confidently to assess the ammonia removal in waste stabilization ponds when the temperature and pH in the pond are high.

6.2.4 Total nitrogen removal

The experimental data of total nitrogen in the influent showed again significant variation in the range 20-139 mg/l (Appendix C). The average total nitrogen in the pilot-scale pond using descriptive statistics (SPSS version 13.0) was 68 mg/l with a standard error of ± 4.30 mg/l. The concentration of total nitrogen in the influent was relatively higher compared to that of the influent ammonia (47mg/l) described in Section 6.2.3. Figure 6.4 shows the results of total nitrogen in the filtered and unfiltered effluent expressed as histograms and frequency curves.

It can be seen from Figure 6.4 that the concentration of total nitrogen in the filtered effluent is generally lower than that of unfiltered effluent at any cumulative percentile. It is also interesting to note that the removal of total nitrogen in the four-baffle pilot-scale pond and two-baffle pilot-scale pond is relatively higher than that of the unbaffled pilot-scale pond.

The results of total nitrogen in the unfiltered effluent at 50% cumulative percentile are 6 mg/l for four-baffle pilot-scale pond, 9 mg/l for two-baffle pilot-scale pond and 11 mg/l for unbaffled pilot-scale pond while that at 95% cumulative percentile are higher than that at 50% cumulative percentile (9 mg/l for four-baffle pilot-scale pond, 17 mg/l for two-baffle pilot-scale pond and 19 mg/l for unbaffled pilot-scale pond). Note that the concentration of total nitrogen in the filtered effluent is generally lower that that of the unfiltered effluent. The concentration of total nitrogen in the filtered effluent at 50% cumulative percentile is 3 mg/l for four-baffle pilot-scale pond, 3.5 mg/l for two-baffle pilot-scale pond and 5 mg/l for unbaffled pilot-scale pond.



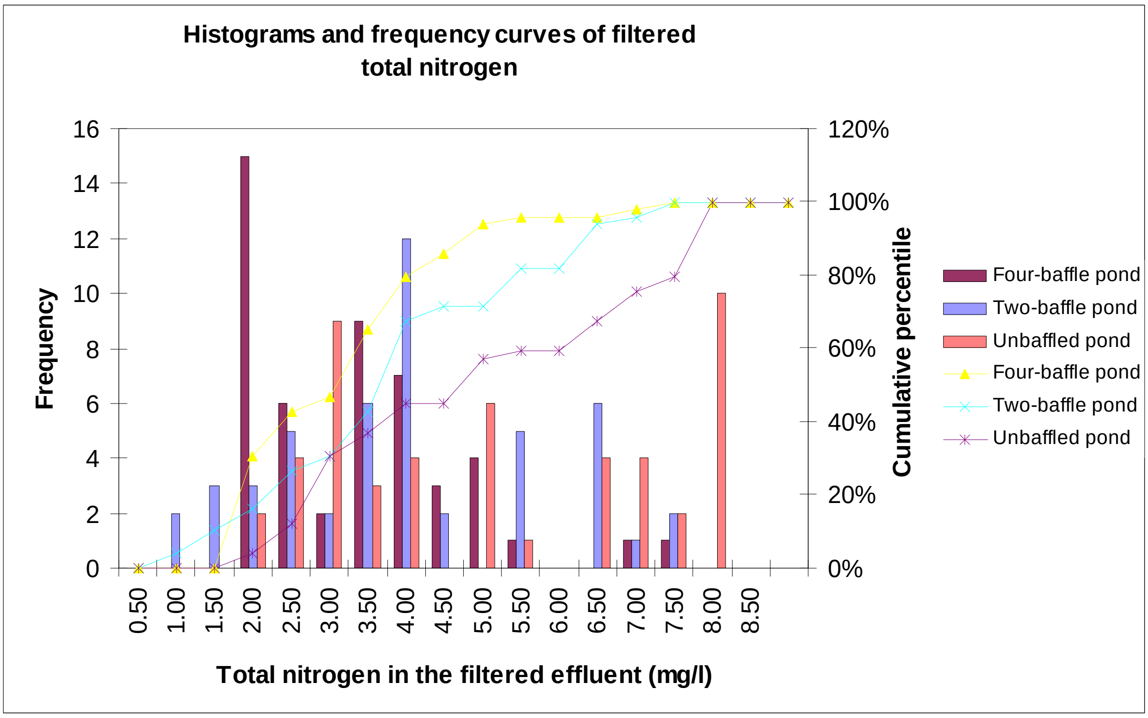


Figure 6.4 Results of total nitrogen in the unfiltered and filtered effluents of the three pilot-scale primary facultative ponds

However, the results of total nitrogen at 95% cumulative percentile are higher than that at 50% cumulative percentile (5 mg/l for four-baffle pilot-scale pond, 6.5 mg/l for two-baffle pilot-scale pond and 7.5 mg/l for unbaffled pilot-scale pond). The treatment efficiency of the three pilot-scale ponds based on unfiltered total nitrogen effluent at 95% cumulative percentile is 87% for four-baffle pilot-scale pond, 75% for two-baffle pilot-scale pond and 72% for unbaffled pilot-scale pond. It can be seen that the treatment efficiency of the pilot-scale primary facultative pond improved significantly when the 70% pond-width baffles were installed in the pond.

Note that the concentration of filtered total nitrogen at 95% cumulative percentile for the three pilot-scale ponds comply (5 - 7.5 mg/l < 15 mg/l) with the consent requirements for the discharge into water bodies in the European Union (Council of the European Communities, 1991). However, only the unfiltered total nitrogen from four-baffle pilot-scale pond satisfies the discharge requirements into European water bodies (9 mg/l < 15 mg/l) at a similar cumulative percentile.

Reed's (1985) equation is applied to predict the concentration of total nitrogen in the effluent of the three pilot-scale ponds. The model is employed to assess the treatment performance of the three pilot-scale ponds when isothermal and thermo-stratification conditions developed in the pond during winter and summer seasons and the equation is presented as:

$$C_e = \frac{C_i}{e^{\left(-\left(0.0064(1.039)^{T-20}\right)\left(\theta+60.6(pH-6.6)\right)\right)}} \qquad 6.3$$

where:

C_e = effluent total nitrogen (mg/l)

C_i = influent total nitrogen (mg/l)

T = temperature (^{o}C)

θ = mean retention time (days)

pH = activity of hydrogen ions = $\log_{10}$ (concentration of hydrogen ions)

Substituting the design parameters (temperature T = 5^{o}C, retention time θ = 30 days, pH = 8.5, and influent total nitrogen C_i = 68 mg/l) into equation 6.3, the predicted total nitrogen in the pilot-scale pond effluent is 36 mg/l. Reed's equation is again used to predict the concentration of total nitrogen in the effluent during the summer season when the average temperature and pH in the pond were 14.8^{o}C and 9.65 respectively. The predicted total nitrogen in the pilot-scale pond effluent was 22 mg/l. It can be seen that the predicted concentration of total nitrogen in the effluent (22- 36 mg/l) is significantly different to the observed concentration of total nitrogen in the pilot-scale pond effluent. The results of total nitrogen in the unfiltered effluent at 95% cumulative percentile are 9 mg/l for four-baffle pilot-scale pond, 17 mg/l for two-baffle pilot-scale pond and 19 mg/l for unbaffled pilot-scale pond. The results suggest that Reed’s (1985) equation is not precise when predicting the concentration of total nitrogen, especially in baffled waste stabilization pond.

6.2.5 Suspended solids removal

The experimental data of suspended solids in the influent was in a range of 120–392 mg/l (Appendix C). Using descriptive statistics (SPSS, version 13.0), the average concentration of suspended solids in the influent was 254 mg/l with a standard error of ± 9 mg/l. Figure 6.5 shows the results of suspended solids in the effluent of the three pilot-scale ponds expressed as histograms and frequency curves.

The concentration of suspended solids in the effluent at 50% cumulative percentile are 30 mg/l for four-baffle pilot-scale pond, 35mg/l for two-baffle pilot-scale pond and 40 mg/l for unbaffled pilot-scale pond. However, the results of the suspended solids concentration at 95% cumulative percentile in the three pilot-scale primary facultative ponds are similar (70 mg/l). It can be seen that the treatment efficiency of the four-baffle pilot-scale pond and the two-baffle pilot-scale pond were not significantly different to that of the unbaffled pilot-scale pond when the treatment performance was assessed using the concentration of the suspended solids at 95% cumulative percentile.

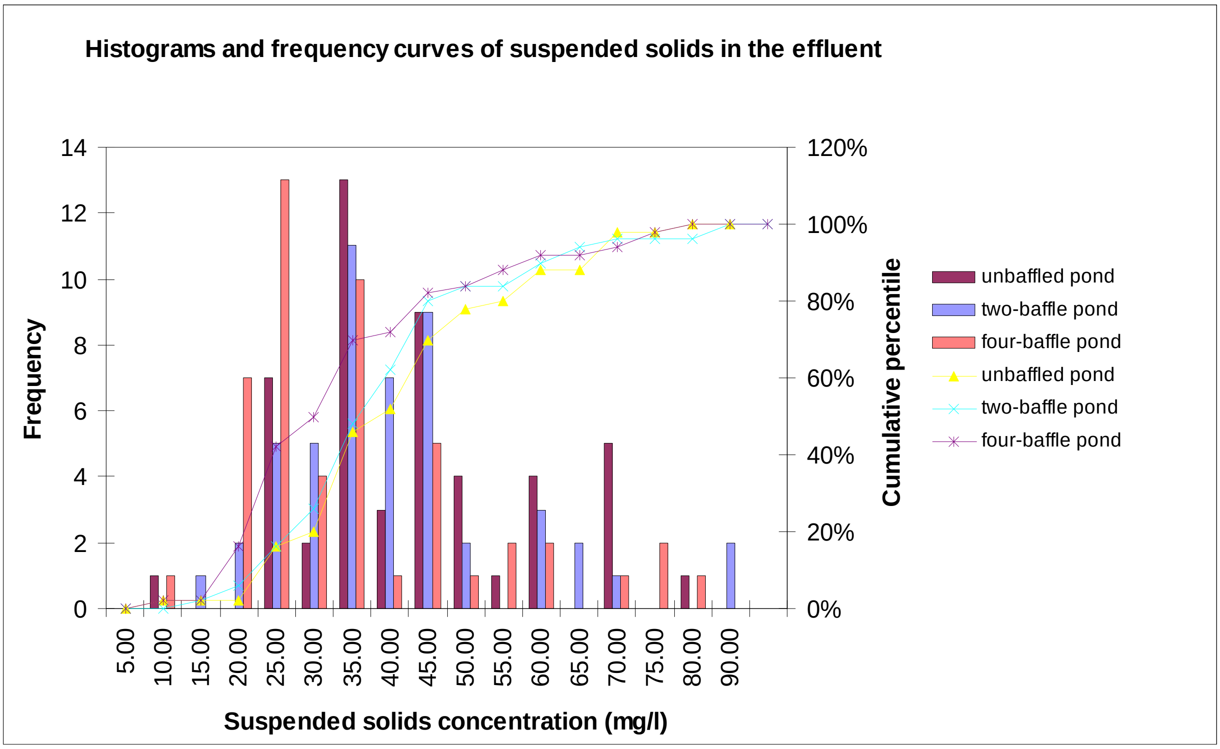


Figure 6.5 Results of suspended solids in the effluent of the three pilot-scale primary facultative ponds

The treatment efficiency of the three pilot-scale primary facultative ponds using the results of the suspended solids at 50% cumulative percentile are 88%, 86% and 84% for four-baffle pilot-scale pond, two-baffle pilot-scale pond and unbaffled pilot-scale pond respectively. However, the treatment efficiency of the three pilot-scale ponds based on results of the suspended solids results at 95% cumulative percentile is 72%. The similarity in the treatment efficiency could have been attributed to the algae that contribute significantly to the suspended solids concentration in the pond effluent. Interestingly, the concentration of the suspended solids based on 95% cumulative percentile complies with the consent requirement (=150 mg/l) for the discharge into water bodies in the European Union (Council of the European Communities, 1991).

6.2.6 Chlorophyll-a

The experimental data of chlorophyll-a in the two-baffle and four-baffle pilot-scale ponds is provided in Appendix D. Column samples were collected in baffle compartments for the analysis of chlorophyll-a (Chapter 4). Using descriptive statistics (SPSS, version 13.0), the average chlorophyll-a in the two-baffle pilot-scale pond was 526±29 µg/l while that in the four-baffle pilot-scale pond was 453±31 µg/l respectively. Interestingly, the concentration of chlorophyll in the two-baffle pilot-scale pond and four-baffle pilot-scale pond were above the minimum (300µg/l) that is reported in a healthy facultative pond (Mara, 2004; Pearson *et al.* 1996, Pearson *et al.*, 1987a). Figure 6.6 shows the variation of chlorophyll-a concentration in the four-baffle pilot-scale pond that was observed during the operational period.

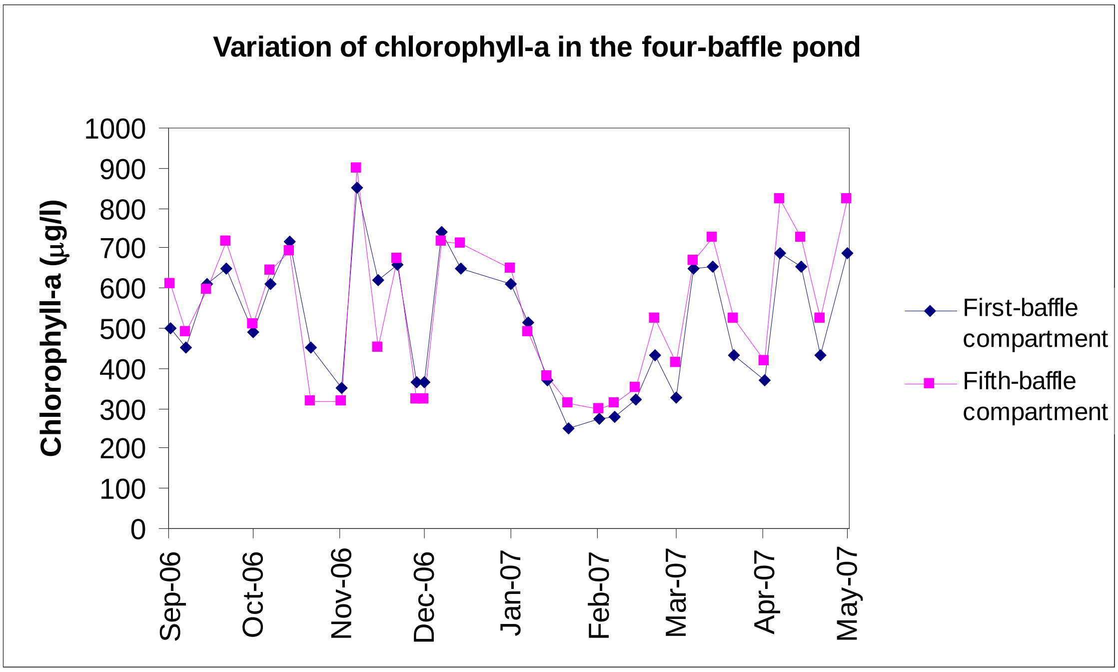


Figure 6.6 Results of chlorophyll-a in baffle compartments of the four-baffle pilot-scale pond

It can be seen from the figure that there is a weekly fluctuation of chlorophyll-a in the four-baffle pilot-scale pond. Similarly, there was a weekly fluctuation of chlorophyll-a concentration in the two-baffle pilot-scale pond (Appendix D). This could have been attributed to the fluctuation of the BOD_5 loading, sunshine intensity and temperature that affects the growth of algae in waste stabilization ponds (Mara, 2004). It was also observed during the operation of the three pilot-scale ponds that algal predators, especially *Daphnia*, fed intensively on the algae.

Despite the weekly fluctuation of chlorophyll-a, the experimental data of chlorophyll suggests that the two-baffle pilot-scale pond and four-baffle pilot-scale pond were operating satisfactorily at the optimal BOD_5 loading of 80 kg per ha per day that was employed based on Mara’s (1987) global design equation (Chapter 2, equation 2.2). It can be argued that designers can confidently use the global BOD surface equation when designing baffled primary facultative ponds. The design BOD loading will allow the development of a healthy algal concentration in baffled primary facultative ponds. The results further suggest that the risk of ammonia and sulphide toxicity to algae in primary facultative ponds that are fitted with two and four baffle configurations is not a serious factor of concerned. Thus, designers can confidently use the 70% pond-width baffles (two and four) to improve the treatment efficiency and the hydraulic performance of primary facultative ponds.

6.3 Facultative conditions in the baffled pilot-scale ponds

When facultative ponds are overloaded either permanently or transiently, anaerobic conditions develop and the term ‘pond failure’ is used to describe the overloaded facultative ponds. The appearance of the pond becomes purple in colour (Mara, 2004) due to the purple and green anaerobic photosynthetic bacteria that are predominant in overloaded facultative ponds. This is one of the main physical characteristics of the overloaded facultative ponds. In addition, there will be near zero dissolved oxygen concentration in the facultative pond due to the absence of algae. Hence, the pH in the pond is neutral or acidic as there are no hydroxyl compounds, which are products of photosynthesis. These two criteria were used to assess the BOD_5 overloading conditions in the two-baffle pilot-scale primary facultative pond and four-baffle pilot-scale primary facultative pond.

6.3.1 Anaerobic conditions

The three pilot-scale primary facultative ponds were operated at a BOD_5 loading of 80 kg per ha per day based on average UK temperature of 8^oC (Mara, 1987). This BOD loading was maintained during winter and summer seasons. Although the recommended BOD loading during the winter season was in a range of 28- 55 kg per ha per day for temperature range of 0 - 5^oC that was observed at the site, the pilot-scale pond was overloaded by 31 - 65% when the BOD_5 loading of 80 kg per ha per day was maintained during the winter season. Interestingly, the two-baffle pilot-scale pond and four-baffle pilot-scale pond did not show signs of anaerobic conditions or turn into purple colour as an indication of being overloaded. The two-baffle pilot-scale pond and four-baffle pilot-scale pond were always facultative and appeared dark green colour due to the abundant presence of algae. The evidence of facultative conditions suggest that researchers can indeed use the 70% pond-width baffles (two and four baffle configurations) when improving the treatment efficiency of primary facultative ponds as the risk of BOD overloading in baffle compartments is indeed very minimal.

6.3.2 Dissolved oxygen and pH profile in baffle compartments

Figure 6.7 shows the experimental data of the dissolved oxygen profiles that were monitored in the four-baffle pilot-scale pond at around 11:00 am. It can be seen from the figure that the concentration of the dissolved oxygen in the aerobic zone represented by the upper water layers near the water surface (0 m, 0.25 m, 0. 5 m, 0.75 m) was significantly higher than that in the anaerobic zone (˜ 0.0 mg/l). Similarly, the concentration of the dissolved oxygen concentration in the two-baffle pilot-scale pond was higher in the upper layers compared with the anaerobic zone (See Appendix D for more detail).

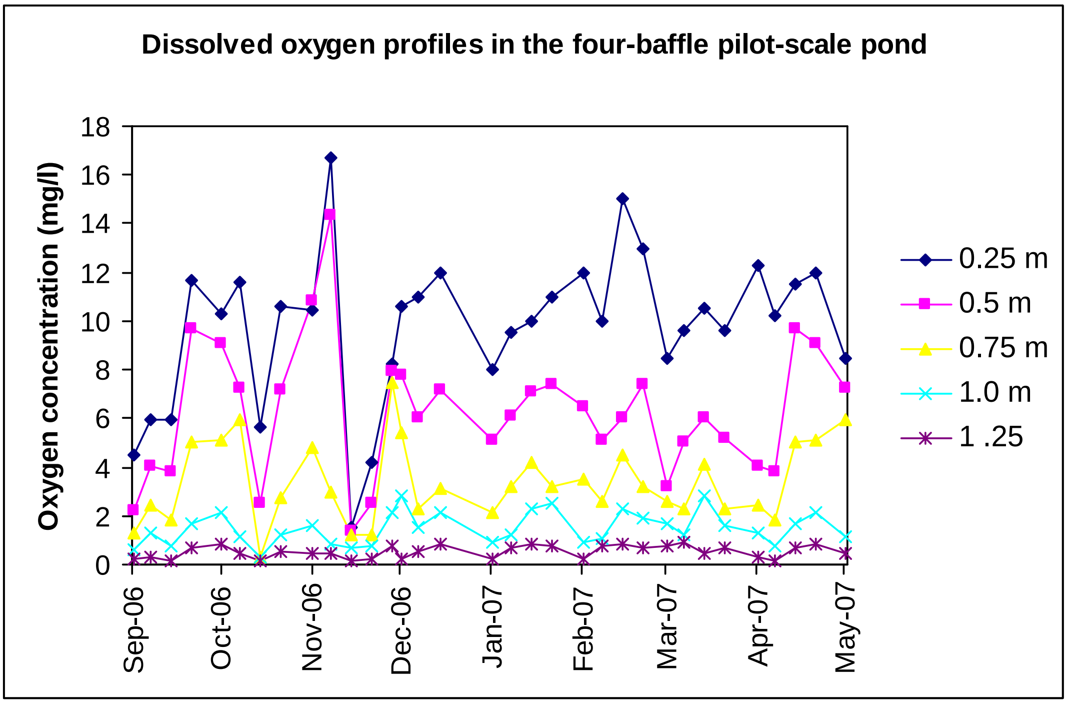


Figure 6.7 Dissolved oxygen profiles in the four-baffle pilot-scale pond

It can also be seen from Figure 6.9 that the concentration of the dissolved oxygen decreases with the pond depth. This is not surprising to note because the concentration of algae in the pond follows similar pattern (i.e., the algae concentration is high near the pond surface and low towards the bottom of the pond). It can also be suggested that the weekly variation of the dissolved oxygen concentration in the defined profile layers (0.25m, 0.5 m, 0.75 m, 1.00 m and 1.25 m) could have been attributed due to the fluctuation of the BOD_5 loading, light intensity, temperature and algae predators that affect significantly the population of algae in waste stabilization ponds. The results of the dissolved oxygen profile indicate that the performance of the two-baffle pilot-scale pond and the four-baffle pilot-scale pond was facultative at BOD loading of 80 kg per ha per day that was employed during the operation of the baffled pilot-scale primary facultative ponds.

The assessment of the BOD overloading in the two-baffle pilot-scale pond and four-baffle pilot-scale pond was also carried out by monitoring the pH profiles. The experimental data of the pH profiles in the two-baffle pilot-scale pond and four-baffle pilot-scale pond are presented in Appendix D. The pH profile in the aerobic zone (layers near the pond surface i.e., 0.25 m, 0.5 m, 0.75m) was generally higher compared to that of the anaerobic zone (1.0 m, 1.25 m). The average pH values in the aerobic zone and anaerobic zone were 8.5 and 7.56 respectively. It is interesting to note that the observed data of pH in the two-baffle and four-baffle pilot-scale ponds compare well with the expected pH that is usually found in unbaffled facultative ponds (Pearson, 1987a; Parhad and Rao, 1974). The results of the pH profiles suggest that BOD_5 overloading did not develop in the two-baffle pilot-scale pond and four-baffle pilot-scale pond because facultative conditions were sustained satisfactory in the baffle compartments due to the occurrence of photosynthesis.

6.4 Thermo-stratification conditions

6.4.1 Temperature profile during the winter season

Thermochrone *i-buttons* were used to monitor the temperature profiles in the three pilot-scale ponds for an approximate duration of 80 days (Abis and Mara, 2006). The temperature data was obtained hourly using six-layers that were spread equally at a distance of 0.25 m. Figure 6.8 shows the results of the temperature profiles that were monitored in the two-baffle pilot-scale pond during the winter season.

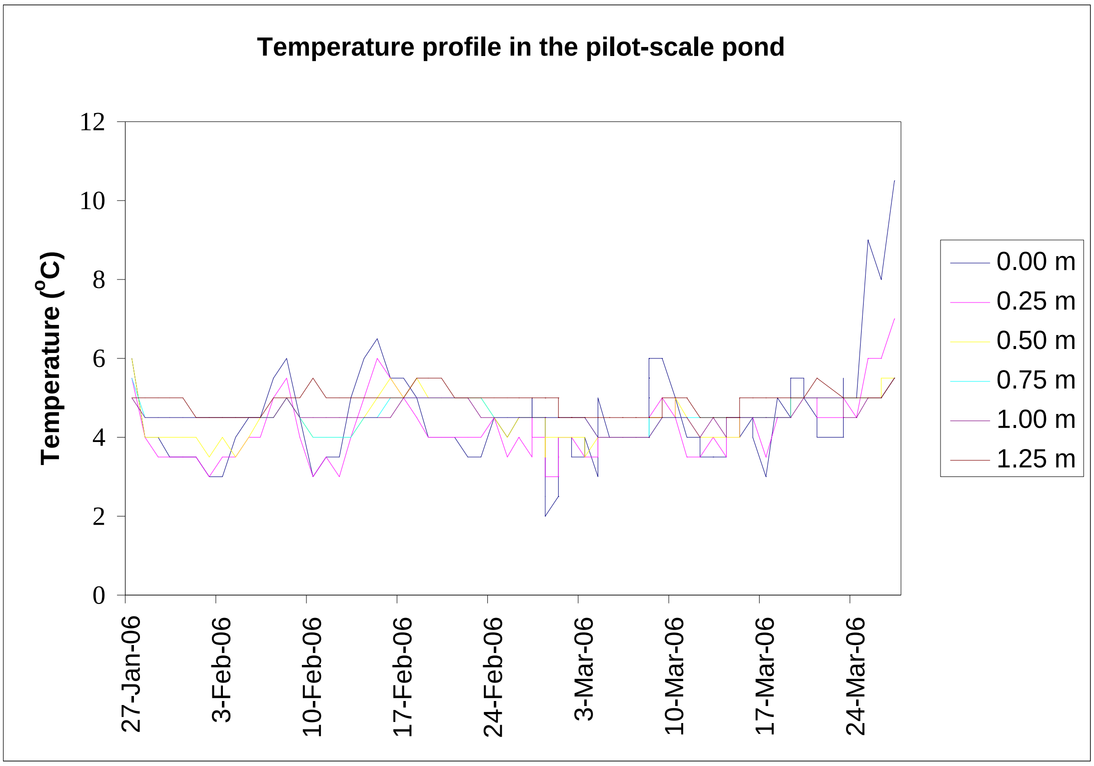


Figure 6.8 Temperature profile in the pilot-scale pond during the winter season

It can be seen from Figure 6.8 that there is no significant difference of temperature at six layers in two-baffle pilot-scale pond that were defined for thermo-stratification. Similarly, there was insignificant difference of the temperature profiles in the unbaffled and four-baffle pilot-scale ponds during the winter season. Using descriptive statistics, the average temperature in the three pilot-scale ponds during the winter season is 5.0^{o}C with a standard error of ±0.1^{o}C. The results suggest that isothermal conditions developed in the pilot-scale ponds during the winter season due to the insignificant difference of temperature at the six-wastewater layers that were defined for thermo-stratification. The significance of this observation is that the CFD simulation of *E. coli* and BOD removal in the pilot-scale ponds could be predicted using constant values of wastewater density and first-order rate constant removal in the source term function of the scalar transport equation (Section 6.6.1).

6.4.2 Temperature profile during summer season

Figure 6.9 presents the experimental data of temperature profiles that were monitored in the pilot-scale pond during the summer season to assess the development of thermo-stratification conditions. It can be seen from the figure that there is significant variation of temperature at the five-wastewater layers that were defined for thermo-stratification (12-17^{o}C). The pond temperature decreases along the pond depth with thermo-stratification gradient of 3.33^{o}C/m. It is interesting to note that the pilot-scale pond remained thermally stratified for a period that exceeded the mean hydraulic retention time of the pond (30 days).

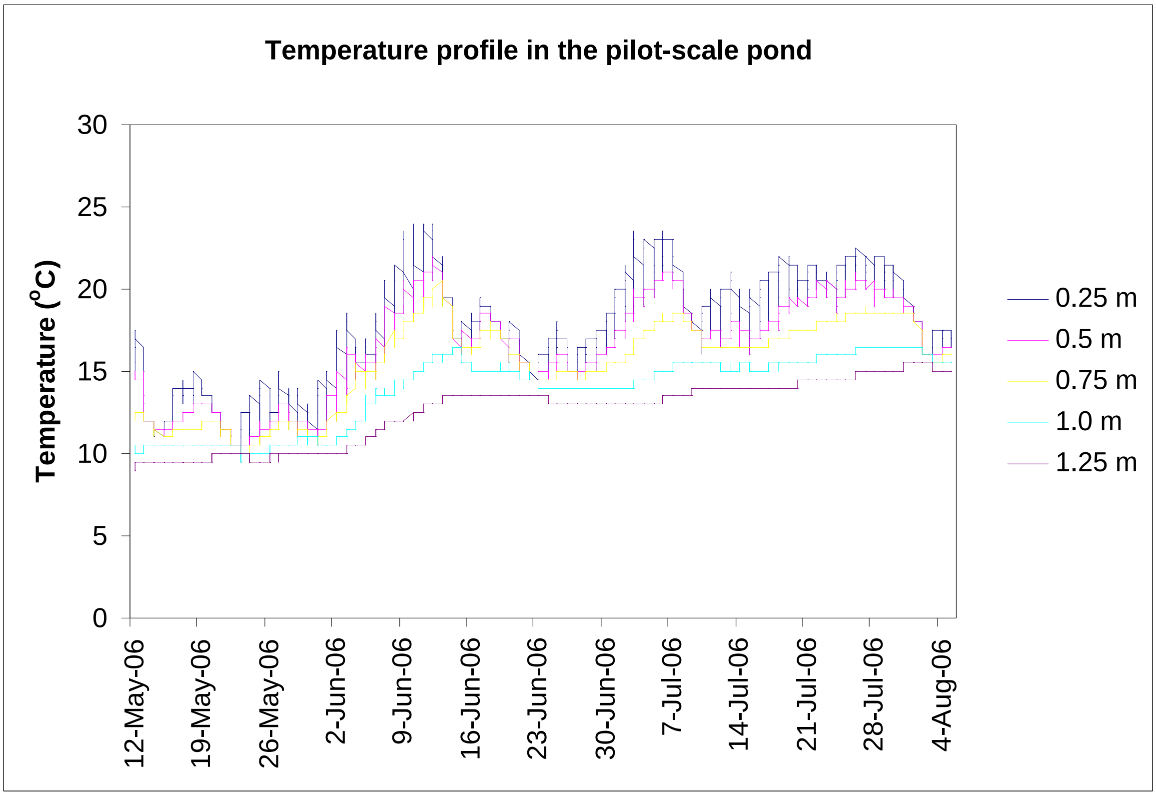


Figure 6.9 Temperature profile in the pilot-scale pond during the summer season

Gu and Stefan (1995) describe this thermo-stratification as type III due to the absence of the complete mixing in the pond. The average temperature of the five-wastewater layers at 0.25 m, 0.5 m, 0.75 m, 1.00 m and 1.25 m below the top water surface were 17^{o}C, 16^{o}C, 15^{o}C, 14^{o}C and 12^{o}C respectively. As a result, different wastewater densities were initiated (Perry and Green, 1984) in the five-wastewater layers that prevented the mixing of wastewater. Hence the volume of the pilot-scale pond was not utilised effectively to ensure the achievement of the theoretical hydraulic retention time (30 days). It is not surprising to note that the difference of the treatment efficiency of the pilot-scale pond during summer and winter season is not significant (Table 6.1 and 6.2). The significance of the temperature data of thermo-stratification could allow the determination of different values of wastewater densities at the defined wastewater layers for thermo-stratification. Hence, the simulation of thermo-stratification effects in the CFD model of waste stabilization ponds could include different temperatures and densities for the defined wastewater layers in the pond. This could enable the precise simulation of the hydraulic performance and treatment efficiency of waste stabilization ponds that develop thermo-stratification conditions during the summer season.

6.5 The hydraulic performance of the three pilot-scale primary facultative ponds

The hydraulic performance of the three pilot-scale primary facultative ponds was assessed using tracer experiments that employed rhodamine WT. Figure 6.10 presents the results of the normalised residence time curves that were observed in the unbaffled pilot-scale pond, two-baffle pilot-scale pond and four-baffle pilot-scale pond. It can be seen from the figure that there is a high degree of short-circuiting in the unbaffled pilot-scale pond compared to that of the two-baffle pilot-scale pond and four-baffle pilot-scale pond due to the early arrival of rhodamine WT at the pond outlet (rhodamine WT was observed at the pond outlet when time “t/t*” was ˜ zero). The shortest residence time that was observed in the tracer experiment was 7 hours (t/t* ˜ 0.01) for the unbaffled pilot-scale pond, 34 hours (t/t* ˜ 0.05) for the two-baffle pilot-scale pond and 38 hours (t/t* ˜ 0.06) for the four-baffle pilot-scale pond. It can also be seen from the figure that the residence time for the peak of the tracer increased with increasing number of baffles. In the unbaffled pilot-scale pond, the peak was observed after 17 days (t/t* ˜ 0.6) while that in the two-baffle pilot-scale pond and four-baffle pilot-scale was 22 days (t/t* ˜ 0.76) and 24 days (t/t* ˜ 0.82) respectively.

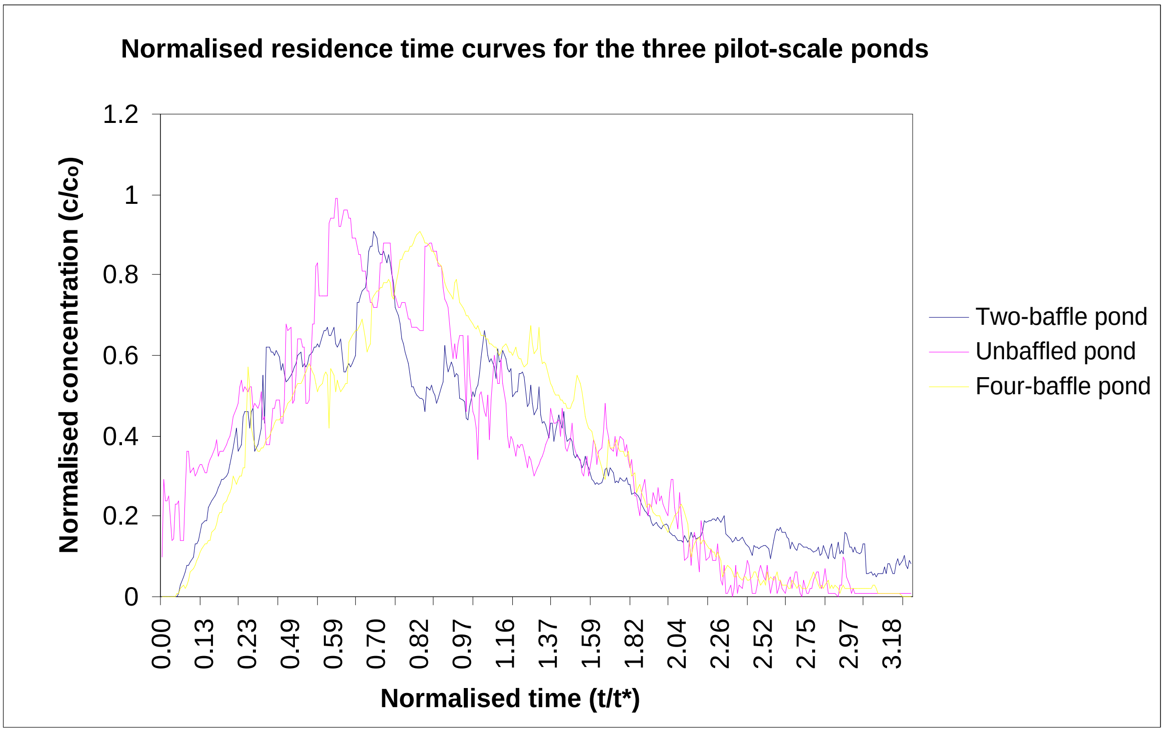


Figure 6.10 The normalised residence time curves in the three pilot-scale ponds

The average hydraulic retention time in the unbaffled pilot-scale pond, two-baffle pilot-scale pond and the four-baffle pilot-scale pond was 25 days, 28 days and 29 days respectively (Table 6.3). Note that the influent flow was not constant during the operational period of the pilot-scale pond (Appendix B). There was a weekly variation of sewage and freshwater flow in the pilot-scale pond due to the sludge build up in the sewage pipe that reduced the cross sectional area and the variation of the water head in the tank that supplied the freshwater. The weekly flow variation could have affected the results of the tracer experiments. Nevertheless, the results suggest that the hydraulic retention time of the pilot-scale primary facultative pond increased with increasing number of baffles.

The dispersion number in the unbaffled pilot-scale pond, two-baffle pilot-scale pond and four-baffle pilot-scale pond was 0.25, 0.48 and 0.49 respectively (Table 6.3). The results indicate that there was a higher degree of the wastewater mixing in the baffled pilot-scale ponds compared to that of the unbaffled pilot-scale pond. The low degree of the wastewater mixing in the unbaffled pilot-scale pond allowed the influent flow to be discharged quickly within a fraction of the theoretical residence time. However, in the two-baffle and the four-baffle pilot-scale ponds, the high degree of the wastewater mixing played a vital role in reducing the hydraulic short-circuiting by increasing the length of the flow path from the inlet to outlet.

6.6 Calibration of the 3D CFD model

6.6.1 Simulation of *E. coli* and BOD$_5$ removal in the three pilot-scale primary facultative ponds

The source term function of the *E. coli* and BOD$_5$ removal in the CFD model of waste stabilization ponds has been developed in Chapter 3 and is recalled here as:

$$S_\phi = -\rho k \phi \qquad 6.4$$

where:

ϕ = *E. coli* numbers per 100 ml or BOD$_5$ concentration per mg/l

k = the first-order rate constant for *E. coli* or BOD$_5$ removal (day^{-1})

ρ = density of wastewater (kg/m^3)

S_ϕ = source term of ϕ (kg/m^3 s)

The simulation of *E. coli* removal in CFD model of waste stabilization ponds using the scalar transport equation (2.29) requires precise values of the first-order rate constant removal (k) and the density of the wastewater (ρ) in the source term function given by equation 6.4. Section 6.2.1 has shown that Marais' (1974) first-order rate constant removal of *E. coli* [$k = 2.6(1.19)^{T-20}$)] is not precise when predicting the *E. coli* removal in baffled waste stabilization ponds. It was found that the equation is reasonably accurate when predicting the *E. coli* removal in unbaffled waste stabilization ponds. As a result, the source term function (equation 6.4) used Marais' (1974) first-order rate constant removal in the CFD scalar transport equation for the simulation of *E. coli* removal in the unbaffled pilot-scale primary facultative pond.

A different equation of the first-order rate constant removal (k) of *E. coli* was used in the source term function for the simulation of the *E. coli* removal in the two-baffle pilot-scale primary facultative pond and the four-baffle pilot-scale primary facultative pond. The first-order rate constant removal of *E. coli* was developed for baffled waste stabilization ponds using the predicted-CFD *E. coli* counts and observed *E. coli* counts. It was observed that the effluent *E. coli* counts were estimated closely when the first-order rate constant removal of *E. coli* in the source term function was $4.55(1.19)^{(T-20)}$ day^{-1}. Figure 6.11 shows the correlation data of the predicted-CFD *E. coli* counts and the observed effluent *E. coli* counts from the baffled pilot-scale primary facultative ponds. It can be seen from the figure that the correlation coefficient of the graph is very high ($R^2 = 0.8267$). This shows that the CFD model predicted reasonably accurately the observed effluent *E. coli* counts in the baffled pilot-scale pond when $4.55(1.19)^{(T-20)}$ day^{-1} was used in the source term function.

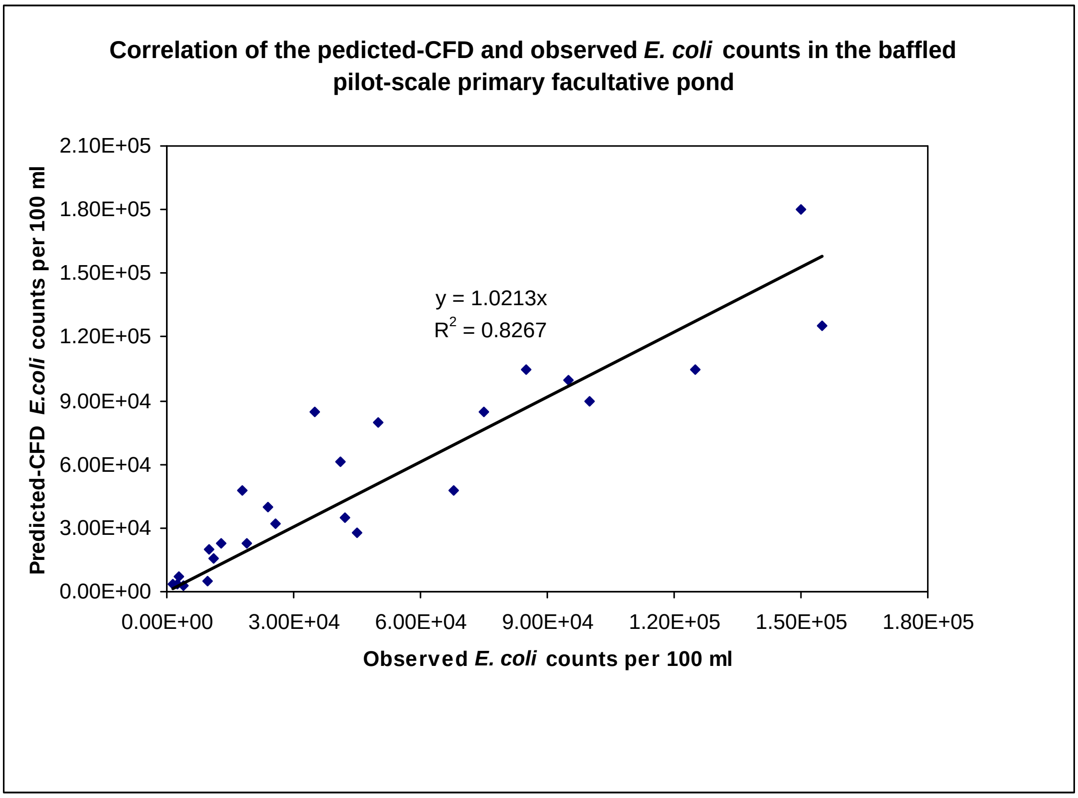


Figure 6.11 Correlation data of the predicted-CFD and the observed effluent *E. coli* counts in the baffled pilot-scale ponds

Therefore, the equation of the first-order rate constant removal (k) in the source term function for the simulation of *E. coli* decay in the CFD model of the two-baffle pilot-scale pond and the four-baffle pilot-scale pond is presented as:

$$k = 4.55(1.19)^{T-20} \qquad 6.5$$

For the simulation of BOD_5 removal in the CFD, Mara's (2004) first-order rate constant removal equation was used in the source term function (equation 6.4). Mara's equation for the first-order rate constant removal of BOD_5 is presented as:

$$k = 0.3(1.05)^{T-20} \qquad 6.6$$

The source term function (equation 6.4) was written in C programming language (Appendix A) using the *user defined function* (UDF) facility that is available in the FLUENT software. This was added to the solver to modify the scalar transport equation 2.29 for the simulation of *E. coli* and BOD removals in the three pilot-scale primary facultative ponds.

6.6.1.1 Simulation of isothermal and thermo-stratification conditions in the pilot-scale primary facultative pond

The experimental data of the temperature profile presented in Section 6.4.1 and 6.4.2 show that the pilot-scale pond developed isothermal and thermo-stratification conditions during winter and summer seasons respectively. The average temperature of 5^oC (winter season) was used in the CFD for the simulation of isothermal conditions in the pilot-scale pond. Using the experimental data of Perry and Green (1984), the wastewater density at temperature of 5^oC is 1000 kg/m^3 and this density value was combined with the first-order rate constant removal (equations 6.5 and 6.6) of *E. coli* and BOD_5 in the development of the source term function in the CFD.

Simulation of thermo-stratification effects in the CFD was based on the temperature data presented in Section 6.4.2 (summer season). The average temperature varied from 17^oC at the pond surface to 12^oC at the bottom level. A density-temperature dependent model (equation 6.7) with correlation coefficient of ($R^2 = 1$) was developed by fitting a curve to a table of density and temperature data of Perry and Green (1984) in the range of 0-40^oC (Appendix B) and this was used in the source term function of the *E. coli* and BOD_5 removal in the CFD. Equation 6.7 presents the density function that calculates the wastewater density at five different layers defined for thermo-stratification simulations.

$$\rho = -6\times10^{-7}T^4 + 9\times10^{-5}T^3 - 0.0095T^2 + 0.0817T + 999.82 \qquad 6.7$$

where:

ρ = density (kg/m^3)
T = temperature (°C)

The CFD model incorporated the following average temperature profile; 12^{o}C, 14^{o}C, 15^{o}C, 16^{o}C and 17^{o}C at 0.25 m, 0.5 m, 0.75 m, 1.00 m, 1.25 m and 1.5 m above the bottom level of the pond respectively. Five different first-order rates constant removal for *E. coli*, BOD$_5$ and wastewater densities based on the above temperature profile were used in the CFD (Appendix A).

6.6.1.2 Boundary conditions of the CFD model of the pilot-scale primary facultative pond

In order to simulate a *free slip* surface on the three pilot-scale ponds surfaces, zero shear stress was applied at the top boundary wall of the model. The boundary conditions of the flow equations were the inlet velocities of 0.05 m/s for wastewater and 0.046 m/s for fresh water to achieve the 30 days average hydraulic retention time. A pressure value of zero was defined at the pond outlet to initiate the wastewater flow. The inlet boundary conditions of the scalar transport equation of the *E. coli* removal were 1.5×10^7 *E. coli* per 100 ml and 5.4×10^6 *E. coli* per 100 ml for the CFD with isothermal and thermo-stratification conditions respectively while that of the scalar transport equation of the BOD removal were 286 mg/l and 457 mg/l for the CFD with isothermal and thermo-stratification conditions (see Appendix C for the statistics summary of the influent). Detailed discussion of grid-dependence tests of the CFD that is employed is provided in Chapter 3. The diffusivity coefficients of *E. coli* and BOD$_5$ in the CFD were assumed to be zero because it was considered to be negligibly small in influencing the CFD results due to the circulation flow pattern in the pond. A laminar steady-state flow and the second order discretization scheme were used in the CFD (See Chapter 3 for more detail).

6.6.1.3 Effluent *E. coli* numbers and BOD_5 in the CFD and the three pilot-scale primary facultative ponds

The 3D CFD model was used to simulate the treatment efficiency of the pilot-scale primary facultative pond with top surface dimensions of 10.2 m long, 3.87 m wide and 1.5 m deep (Chapter 4). The length of baffles, expressed as percentage of the pond width, is 70%, and in terms of actual length, is 2.7 m and these baffles were spread equally in the model. The outlet plane where the effluent leaves the pilot-scale pond was selected to obtain the mean effluent *E. coli* numbers and BOD_5 based on the mass average weight method (FLUENT, 2003). The effluent *E. coli* numbers and BOD_5 in the three pilot-scale primary facultative ponds and CFD during winter and summer seasons are presented in Table 6.1 and 6.2 respectively.

Table 6.1 Mean effluent *E. coli* numbers and BOD_5 in the three pilot-scale primary facultative ponds and CFD with isothermal conditions (5^oC)

Parameter (mg/l)	Unbaffled pilot-scale pond	Unbaffled CFD model	Two-baffle pilot-scale pond	Two-baffle CFD model	Four-baffle pilot-scale pond	Four-baffle CFD model
Influent BOD_5	286	286	286	286	286	286
Effluent BOD_5	35	45	34	21	17	20
Accuracy of the model (%)		78		62		85
Influent *E. coli*	5.4×10^6	5.4×10^6	5.4×10^6	5.4×10^6	5.4×10^6	5.4×10^6
Effluent *E. coli*	1.6×10^5	3.0×10^5	1.4×10^4	4.2×10^4	2.5×10^4	3.7×10^4
Log-units removal	1.53	1.25	2.58	2.10	2.33	2.16
Accuracy of the model (%)		82		81		93

Note: The accuracy of the model for the *E. coli* prediction is based on the percentage of log-units removal while that of BOD_5 is based on effluent values.

It can be seen from Table 6.1 that the accuracy of the CFD model in predicting the effluent BOD_5 in the pilot-scale pond when isothermal conditions developed are 78% for unbaffled pilot-scale pond, 62% for two-baffle pilot-scale pond and 85% for four-baffle pilot-scale pond. For the effluent *E. coli* numbers, the accuracy of the model in predicting the log-units removal in the pilot-scale pond and the CFD is 82% for unbaffled pilot-scale pond, 81% for two-baffle pilot-scale pond and 93% for four-baffle pilot-scale pond. It is interesting to note that the observed effluent *E. coli* numbers in the pilot-scale ponds and the CFD are in the same order of magnitude. It can be suggested that the CFD has estimated satisfactorily the predicted the effluent BOD_5 and *E. coli* numbers in the three pilot-scale primary facultative ponds considering the significant variation of BOD loading (influent flow, BOD_5), influent *E. coli* numbers and the environmental conditions (dissolved oxygen, light intensity, temperature, pH) in the three pilot-scale primary facultative ponds (Sections 6.2.1 and 6.2.2).

When thermo-stratification conditions developed in the three pilot-scale primary facultative ponds, the observed *E. coli* numbers and BOD_5 in the three pilot-scale primary facultative ponds and the CFD are again not significantly different from each other (Table 6.2).

Table 6.2 Effluent *E. coli* numbers and BOD_5 in the three pilot-scale primary facultative ponds and CFD with thermo-stratification effects (12 – 17° C)

Parameter (mg/l)	Pilot-scale Unbaffled	Unbaffled CFD model	Two-baffle pilot-scale pond	Two-baffle CFD model	Four-baffle pilot-scale pond	Four-baffle CFD model
Influent BOD	457	457	457	457	457	457
Effluent BOD	38	40	31	12	17	11
Accuracy of the model (%)		75		37		65
Influent *E.coli*	1.5×10^7	1.5×10^7	1.5×10^7	1.5×10^7	1.5×10^7	1.5×10^7
Effluent *E.coli*	1.3×10^5	3.6×10^5	3.6×10^4	1.2×10^4	1.0×10^4	2.9×10^3
Log-units removal	2.08	1.62	2.62	3.10	3.17	3.71
Accuracy of the model (%)		78		85		85

Note: the accuracy of the model for the *E. coli* prediction is based on the percentage of log-units removal while that of BOD_5 is based on effluent values.

It can be seen from the data presented in Table 6.2 that the accuracy of the CFD model in predicting the BOD removal in the unbaffled pilot-scale pond, two-baffle pilot-scale pond and the four-baffle pilot-scale pond are 75%, 37% and 65% respectively. Generally, the CFD estimates are not satisfactory in predicting the effluent BOD_5 concentration. This could have been attributed due to the failure of the CFD to account for additional BOD contributed by the algae bloom during the summer season. It was argued in Section 6.2.2 that algae contribute about 80–90% of the total BOD in the effluent and this could be the possible cause of the discrepancy of the observed BOD in the pilot-scale ponds and that of the CFD.

For the effluent *E. coli* numbers, the accuracy of the CFD model in predicting the log-units removal in the pilot-scale pond are 78% for unbaffled pilot-scale pond, 85% for two-baffle pilot-scale pond and 85% for four-baffle pilot-scale pond. When the diurnal variation of BOD loading, influent *E. coli* numbers and the environmental conditions that were observed in the pilot-scale ponds are taken into account, it can be suggested that the difference of the effluent *E. coli* numbers and BOD in the pilot-scale ponds and CFD could have been caused by these factors as the CFD did not include these variations. It can be suggested that the difference of the effluent *E. coli* numbers and BOD_5 in the CFD and pilot-scale ponds are not significant noting the significant variation of the influent flow, BOD_5 and *E. coli* that occurred in the three pilot-scale primary facultative ponds. Simulation of design parameters that vary diurnally over the residence time period of the pond could require more computational resources and it would require more experimental data to validate the CFD. In addition, development of complex sub-model in CFD is not realistic for the design and performance assessments of waste stabilization ponds. This suggests that the CFD with simulated effects of thermo-stratification and isothermal is satisfactory in predicting the hydraulic and treatment performance of the three pilot-scale primary facultative ponds.

6.6.2 Results of the tracer experiments in the CFD and the three pilot-scale primary facultative ponds

The simulation of the tracer experiment in the CFD was carried out using a species transport equation (FLUENT, 2003). Rhodamine WT was the species that was simulated in the CFD to provide the normalised residence time distribution curves. In one-dimensional form, the species transport equation that was used in the CFD is written as:

$$\frac{\partial(\rho Y_i)}{\partial t}+\frac{\partial(\rho u Y_i)}{\partial x}+\frac{\partial}{\partial x}\left(\rho D_{i,m}\frac{\partial Y_i}{\partial x}\right)=S_i \qquad 6.8$$

where;

Y_i = mass fraction of tracer (ratio of mass flow rate of tracer to mass flow rate of the influent)

u = velocity in x direction (m/s)

$D_{i,m}$ = diffusion coefficient for rhodamine WT = $0.92\times10^{-6}/\text{m}^2\text{s}$

ρ = density of the mixture (kg/m^3)

S_i = source term ($\text{kg/m}^3\text{s}$)

The source term (S_i) in equation 6.8 was zero because there was no creation or destruction of rhodamine WT during the tracer experiment. The boundary conditions of the CFD were similar to that presented in Section 6.6.1.2. The steady state flow equation was solved first while the species transport equation was not solved. When the converged flow solution was obtained, the time-dependent species transport equation was solved while the flow equation was not solved. The CFD solution of mass fraction of rhodamine WT was obtained at the outlet surface over the flow time. Figure 6.12, 6.13 and 6.14 show normalised residence time distribution diagrams that were obtained from the tracer experiment in the CFD and the three pilot-scale primary facultative ponds. It can be seen from Figure 6.12 that the normalised residence time of the CFD is different to that of the unbaffled pilot-scale pond. Nevertheless, the CFD has predicted the shortest residence time (hydraulic short-circuiting) taken by the wastewater to reach the pond outlet ($t/t^* \sim 0$).

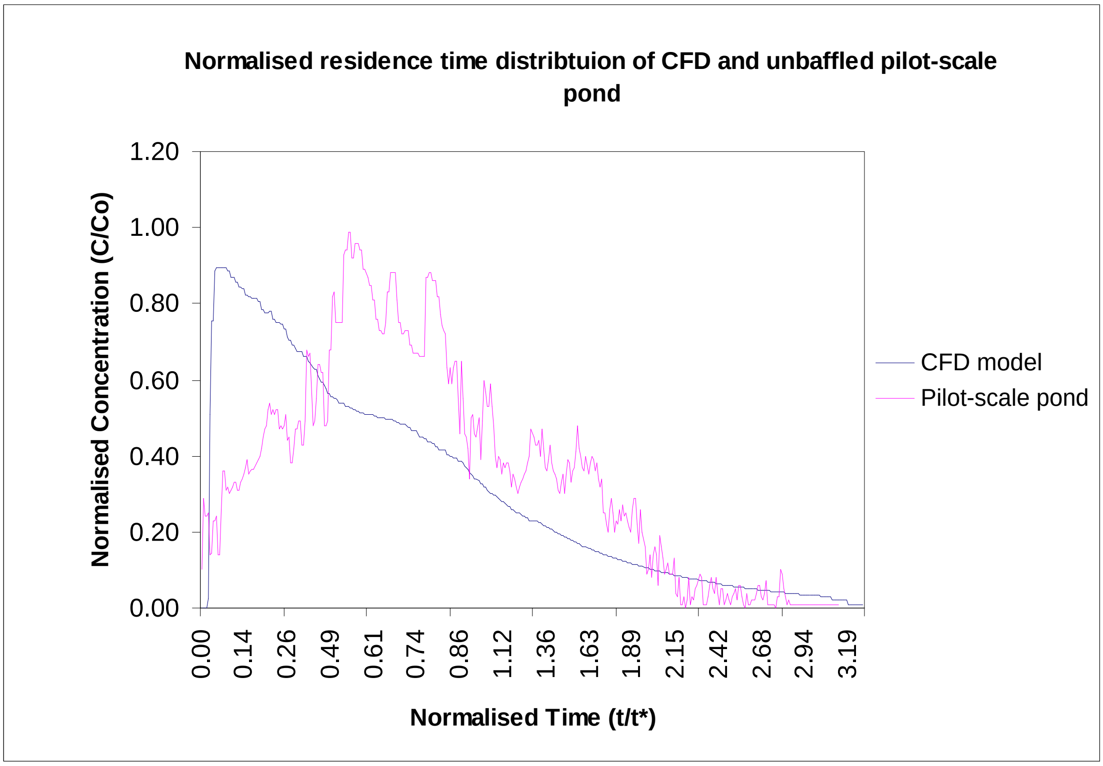


Figure 6.12 Normalised residence time distributions of CFD and the unbaffled pilot-scale primary facultative pond

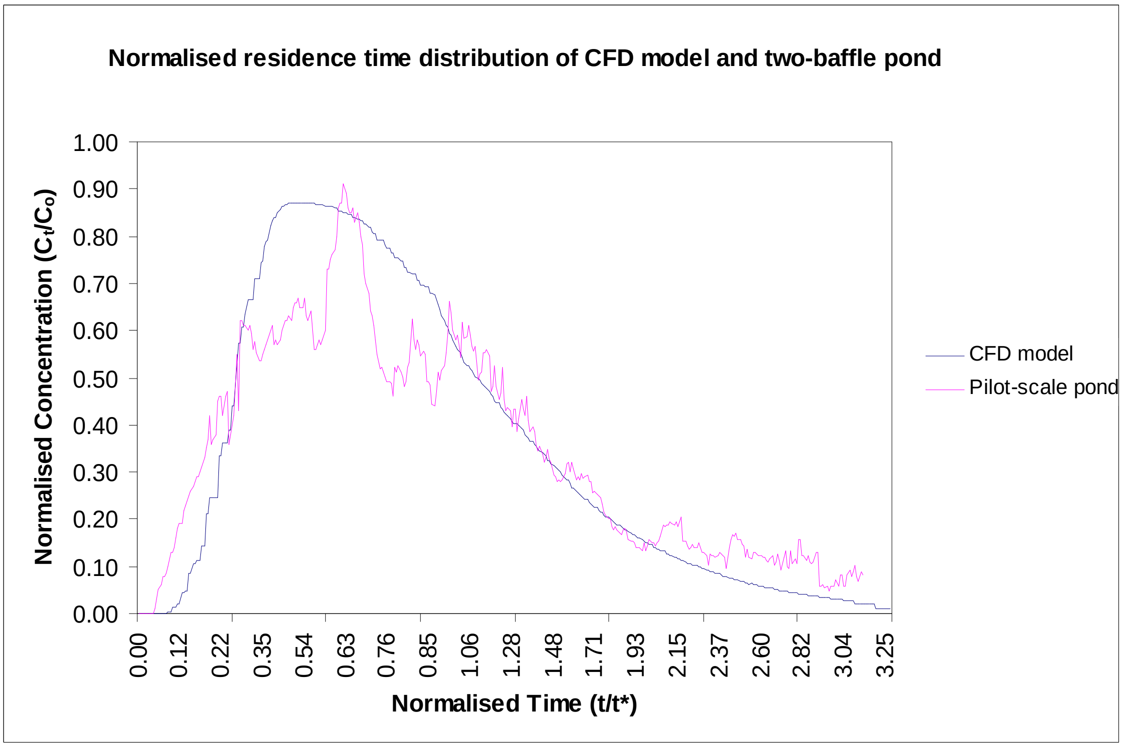


Figure 6.13 Normalised residence time distributions of CFD and the two-baffle pilot-scale primary facultative pond

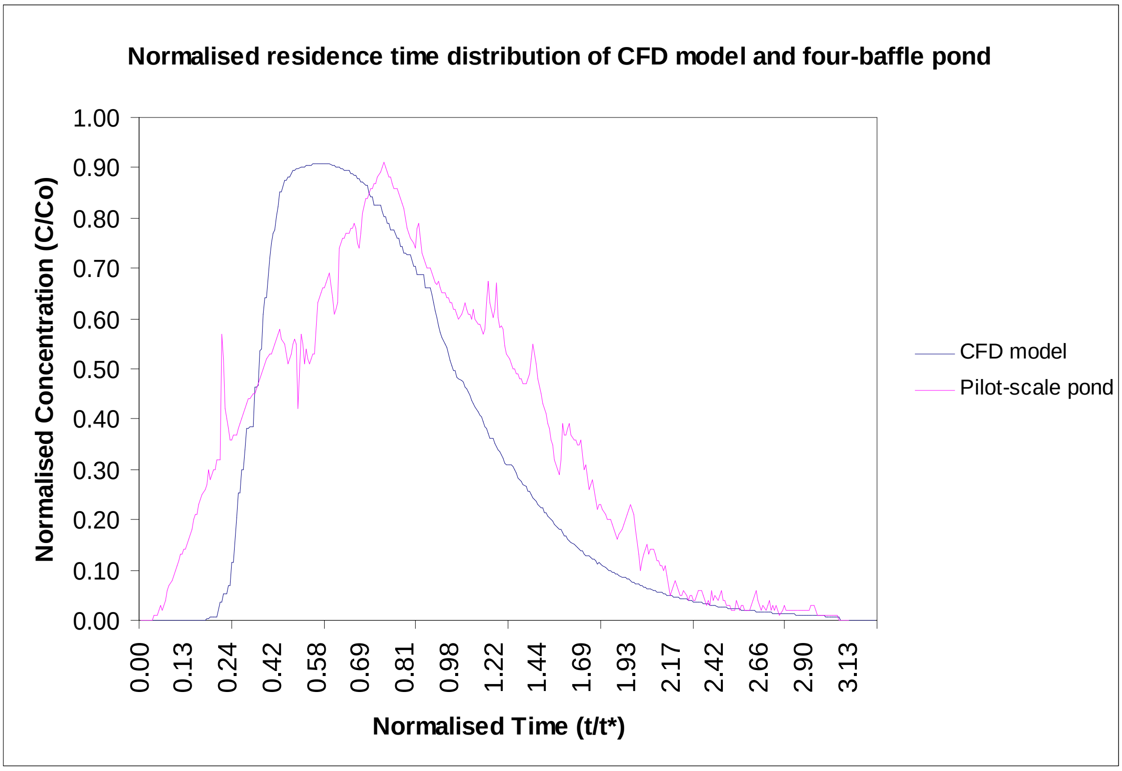


Figure 6.14 Normalised residence time distributions of the CFD and the four-baffle pilot-scale primary facultative pond

It can be seen from Figure 6.13 that the CFD has satisfactorily predicted the normalised residence time distributions in the two-baffle pilot-scale primary facultative pond. The shortest residence time and the peak of the two normalised residence time diagrams are very similar. It can also be seen from Figure 6.14 that that the normalised residence time distribution diagrams of CFD and the four-baffle pilot-scale pond are only slightly different from each other. It is interesting to note that the peaks of the two residence time distribution diagrams are also similar.

Table 6.3 shows the results of the average hydraulic retention times and dispersion number that were determined using the experimental data of the normalised residence time distribution diagrams plotted in Figure 6.12, 6.13 and 6.14.

Table 6.3 The average hydraulic retention time and dispersion number in the three pilot-scale primary facultative ponds and CFD model

Hydraulic parameter	Pilot-scale primary facultative pond			3D CFD model		
	Unbaffled pond	Two-baffle pond	Four-baffle pond	Unbaffled pond	Two-baffle pond	Four-baffle pond
Retention time (days)	25	28	29	21	24	26
Accuracy of the model (%)				84	86	90
Dispersion number	0.25	0.48	0.49	0.21	0.37	0.43
Accuracy of the model (%)				84	77	88

It can be seen from Table 6.3 that the difference of the hydraulic retention time and the dispersion number in the three pilot-scale primary facultative ponds and the CFD is not significant. The accuracy of CFD in predicting the hydraulic retention in the three pilot-scale primary facultative ponds was 84% for unbaffled pilot-scale pond, 86% for two-baffle pilot-scale pond and 90% for four-baffle pilot-scale pond while that for the dispersion number was 84% for unbaffled pilot-scale pond, 77% for two-baffle pilot-scale pond and 88% for four-baffle pilot-scale pond.

It has been shown that CFD models do not give predictions that are identical to measurements of the hydraulic performance of the three pilot-scale primary facultative ponds. There are many possibilities why this may be the case, for example the discrepancies could be attributed to the diurnal variation of the influent flow (Appendix B), wastewater density, temperature difference and wind velocity as these factors are thought to affect significantly tracer experiments that are conducted in field waste stabilization ponds (Shilton and Harrison, 2003a; Fredrick and Lloyd, 1996; Brissaud *et al.*, 2000, 2003). Despite the clear differences it can be concluded that the CFD *has* satisfactorily simulated the tracer experiments in the three pilot-scale primary facultative ponds noting the small difference of the hydraulic retention time and dispersion number that was observed in the CFD and the three pilot-scale primary facultative ponds.

6.7 Summary of the chapter

The chapter has shown that the treatment performance of the four-baffle pilot-scale pond and two-baffle pilot-scale pond was relatively higher than that of the unbaffled pilot-scale pond in removing *E. coli*, BOD_5, ammonia and the total nitrogen at any cumulative percentile. The results of the tracer experiment showed that the hydraulic performance of the four-baffle pilot-scale pond and two-baffle pilot-scale pond is again higher than that of the unbaffled pilot-scale pond. The increase in the treatment and hydraulic performance of the baffled pilot-scale ponds could have been attributed due to the installation of the 70% pond-width baffles. These could have reduced the hydraulic short-circuiting that usually diminishes the treatment performance of waste stabilization ponds.

Facultative conditions were sustained satisfactorily in the two-baffle pilot-scale pond and four-baffle pilot-scale pond due to the high concentration of dissolved oxygen and pH in the aerobic zone. The results indicate that BOD overloading was not initiated in the baffled pilot-scale primary facultative ponds despite the installation of baffles that increase the BOD loading in the baffle compartments. It can be concluded that baffled primary facultative ponds with two and four baffle configurations could be designed using the Mara’s (1987) surface BOD equation.

Thermo-stratification and isothermal conditions developed in the three pilot-scale primary facultative ponds during winter and summer seasons. The experimental data showed that the treatment performance of the pilot-scale primary facultative ponds during winter and summer seasons was not significantly different from each other. This could have been attributed due to the use of the long hydraulic retention time (30 days).

The CFD has been well validated by the experimental data from the three pilot-scale primary facultative ponds. Simulations of *E. coli* removal, BOD_5 removal and tracer experiment were estimated satisfactorily in the CFD as the model results were not significantly different to the experimental results that were carried out in the three pilot-scale primary facultative ponds. The significance of the CFD validation is that regulators and designers can use CFD confidently both as a reactor model and as a hydraulic tool to assessing realistically the treatment efficiency of baffled facultative ponds.