Appendix A

A1. Source term functions of *E. coli*, BOD removals and the spatial residence time distribution in the CFD model of waste stabilization ponds with isothermal conditions

The source term functions of *E. coli*, BOD removals and the spatial residence time distribution were written in C programming language using the *user defined function* facility that is available in FLUENT software. The computer code was added to FLUENT solver to modify the 3D scalar transport equation 2.29 for the simulation of *E. coli*, BOD removals and spatial residence time distribution in the waste stabilization pond. The pond temperature was assumed constant at all points in the pond to simulate effects of isothermal conditions. The computer code was written as:

```
#include "udf.h"
#define isotherm_temp 287                    /* assumed pond temperature*/

DEFINE_ADJUST (my_isothermo_temp, domain)  /* isothermal condition
function*/
{
        thread *t;
        real x[ND_ND];
        cell_t c;
        real my_temp;
        real y;
        thread_loop_c(t,domain)

                {
                        begin_c_loop(c, t)
                        {
                        C_CENTROID(x, c, t);
                        y = x [1];
                        if  y < 1.65;
```

```
                C_T(c, t) = isotherm_temp;
                end_c_loop(c, t)
                }
        }
}

DEFINE_PROPERTY (my_density, c, t)     /* the wastewater density function,
equation 6.7*/
{
        real my_rho;
        real my_temp;
        my_temp = C_T(c, t);
        my_rho = -0.0000006*pow ((my_temp-273), 4) + 0.00009*pow ((my_temp-
        273), 3) - 0.0095*pow ((my_temp-273), 2) + 0.0817*my_temp+999.82;
        return my_rho;
}

DEFINE_SOURCE (feacaldecay_source, c, t, ds, eqn) /* the source term function of
E. coli removal*/
{
        int i;
        real source;
        real KT, KTT, my_temperature;
        real rho = C_R(c, t);
        i=0;
        my_temperature = C_T(c, t);
        KTT = 2.6*pow (1.19, ((my_temperature-273)-20.0)); /* Marais' equation*/
        KT = rho*KTT/86400.00;
        ds [eqn] = -KT;
        source = -KT*C_UDSI(c, t, i);
        return source;
}
```

```
DEFINE_SOURCE (bodremoval_source, c, t, ds, eqn) /*the source term function of
BOD removal*/
{
        int i;
        real source;
        real BKT, BKTT, my_temperature;
        real rho = C_R(c, t);
        i = 0;
        my_temperature = C_T(c, t);
        BKTT = 0.3*pow (1.05, ((my_temperature-273)-20.0)); /*Mara’s equation*/
        BKT = rho*BKTT/86400.00;
        ds [eqn] =-BKT;
        source = -BKT*C_UDSI(c, t, i);
        return source;
}

DEFINE_SOURCE (myretention_source, c, t, ds, eqn) /* the source term function of
the spatial residence time at all points in the pond*/
{
        real source;
        real rho = C_R(c, t);
        source = rho;
        ds [eqn] = 0.0;
        return source;
}
```

A2. Source term functions of *E. coli*, BOD removals and the spatial residence time distribution in the CFD model of waste stabilization ponds with thermo-stratification conditions

The source term functions of *E. coli*, BOD removals and the spatial residence time distributions were again written to assess the treatment performance of waste stabilization ponds under the effects of thermo-stratification. The computer program calculates the temperature of five different wastewater layers that were defined for thermo stratification conditions in the pilot-scale pond. The wastewater density of the individual wastewater layer was calculated using the density equation that was developed in Section B2 of Appendix B. Five different first-order rate constants removal of *E. coli* and BOD were calculated using the temperature data that was obtained from the pilot-scale pond. Again, the computer code was added to FLUENT solver to modify the CFD scalar transport equation and the flow equations for the simulation of *E. coli*, BOD removals and the hydraulic flow patterns in the waste stabilization pond. The computer code is presented as:

```
#include "udf.h"

DEFINE_ADJUST (my_stratification, domain)
{
        thread *t;
        real x[ND_ND];
        cell_t c;
        real my_temp;
        real y;

        thread_loop_c (t, domain)
                {
                        begin_c_loop(c, t) /* definition of the five wastewater layers
                        and assignment of temperature profile in the pond*/
                        {
                        C_CENTROID (x, c, t);
                        Y = x [1];
                        if y < 0.3
                        C_T(c, t) = 283;
                        elseif y < 0.6
                        C_T(c, t) = 285;
                        elseif y < 0.9
                        C_T(c, t) = 287;
                        elseif y < 1.2
```

```
            C_T(c, t) = 289;
            elseif y < 1.5
            C_T(c, t) = 291;
            end_c_loop(c, t)
            }
        }
}

DEFINE_PROPERTY (my_density, c, t) /* the wastewater density function, equation
6.7*/
{
    real my_rho;
    real my_temp;
    my_temp = C_T(c, t);
    my_rho = -0.0000006*pow ((my_temp-273), 4) + 0.00009*pow ((my_temp-
    273), 3)-0.0095*pow ((my_temp-273), 2) + 0.0817*my_temp+999.82;
    return my_rho;
}

DEFINE_SOURCE (feacaldecay_source, c, t, ds, eqn) /* the source term function of
E. coli decay*/
{
    int i;
    real source;
    real KT, KTT, my_temperature;
    real rho = C_R(c, t);
    i=0;
    my_temperature = C_T(c, t);
    KTT = 2.6*pow (1.19, ((my_temperature - 273) -20.0));
    KT = rho*KTT/86400.00;
    ds [eqn] = - KT;
    source = -KT*C_UDSI(c, t, i);
    return source;
}
```

```
DEFINE_SOURCE (bodremoval_source, c, t, ds, eqn) /* the source term function of
BOD removal*/
{
        int i;
        real source;
        real BKT, BKTT, my_temperature;
        real rho = C_R(c, t);
        i = 0;
        my_temperature = C_T(c, t);
        BKTT = 0.3*pow (1.05, ((my_temperature - 273) - 20.0));
        BKT = rho*BKTT/86400.00;
        ds [eqn] =-BKT;
        source = -BKT*C_UDSI(c, t, i);
        return source;
}

DEFINE_SOURCE (myretention_source, c, t, ds, eqn) /* the source term function of
the spatial residence time distribution*/
{
        real source;
        real rho = C_R(c, t);
        source = rho;
        ds [eqn] = 0.0;
        return source;
}
```

Appendix B

B1. The average design flow in the pilot-scale ponds

Figure B1 presents the weekly flow of wastewater and freshwater in the pilot-scale primary facultative ponds. The operation of the pilot-scale ponds was based on the average freshwater flow of 800 ml per minute and the wastewater flow of 470 ml per minute to achieve the 30-days hydraulic retention time. It can be seen from Figure B1 that there was significant variation of the weekly design flow during the operational period of the pilot-scale ponds. This could have been attributed to the fluctuation of the freshwater flow as this was supplied by gravity to the pond inlet from the water tank. It was difficult to maintain the constant energy head of water in the tank due to the fluctuation of pressure at the tap. In addition, there was continuous deposition of sludge in the 15.9-mm diameter flexible tubing that carried the raw sewage from the inlet works and this reduced the cross sectional area of the tubing and hence the wastewater flow.

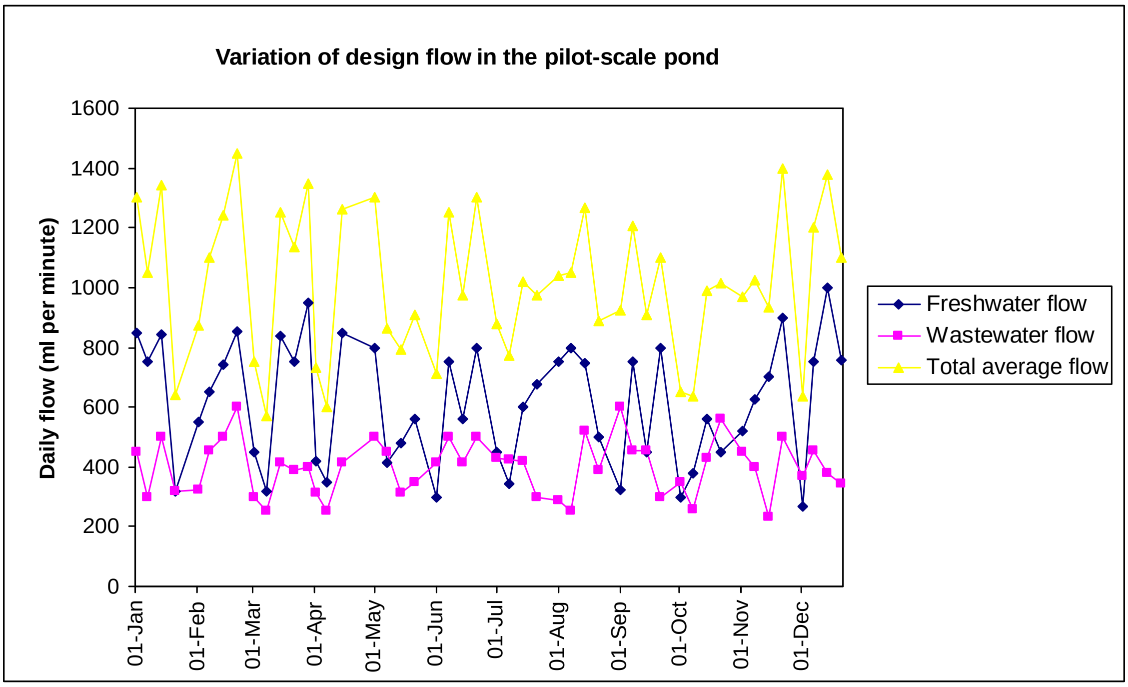


Figure B1 The weekly wastewater flow in the pilot-scale ponds

Table B1 Summary statistics of the design flow in the pilot-scale ponds.

Statistical variable	Flow (ml per minute)
Mean	1015
Standard error	35
Minimum	570
Maximum	1451

Based on the pond volume of $55m^3$ and the average hydraulic retention time of 30 days, the design flow in the three pilot-scale primary facultative ponds was 1273 ml per minute. However, the experimental data from Table B1 shows that this was not achieved during the operation of the pilot-scale ponds. The observed average flow rate (1015 ml per minute) in the pilot-scale pond was lower by 25% compared with the theoretical flow rate (1273 ml per minute). The weekly variation of the influent flow could have played a significant role in influencing the hydraulic flow patterns in the pilot-scale ponds.

B2. The empirical equation of the wastewater density function

Simulation of thermo-stratification effects in the CFD model of the pilot-scale pond was achieved by developing an empirical equation of the wastewater density function that depended on the temperature of the wastewater. A polynomial curve was fitted to the temperature data of Perry and Green (1984). The average temperatures for five different wastewater layers that were defined for thermo-stratification in the pilot-scale pond (12^oC, 14^oC, 15^oC, 16^oC and 17^oC) were used to calculate the density of the individual wastewater layer.

The computer code of the wastewater density function for the polynomial curve was written in C programming language and was added to FLUENT solver. This enabled the accurate simulation of the hydraulic flow patterns and the removal of *E. coli* and BOD in the pilot-scale pond model under the effects of thermo-stratification. Examination of the CFD equations (2.21 – 2.29) shows that the wastewater density is significant in CFD models of waste stabilization ponds. Figure B2 presents the correlation data of temperature and the wastewater density that was used to develop the empirical equation of the wastewater density that is indicated in Figure B2.

The polynomial curve has a high correlation coefficient of (R^2 =1) and this suggests that the equation is more precise in calculating the density of wastewater in the CFD model.

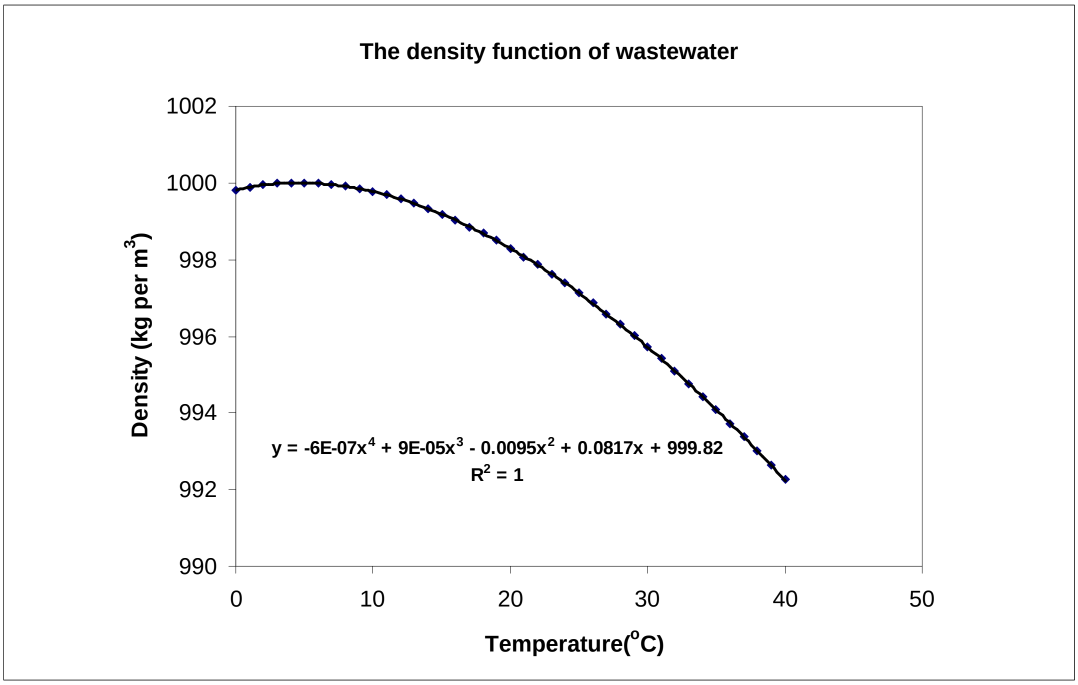


Figure B2 The density-temperature dependent function of wastewater

Appendix C

C1. The influent wastewater characteristics

The concentration of BOD, *E. coli*, ammonia, total nitrogen and suspended solids in the influent varied considerably over the two-year operation of the pilot-scale ponds. Table C1 presents the summary statistics of these pollutants in the pond influent.

Table C1 Summary statistics of BOD, *E. coli*, ammonia, total nitrogen and suspended solids in the influent

Influent parameter	Mean	Standard error	Range
BOD (mg/l)	387	±25	116- 826
E. coli count per 100 ml	1.0×10^{7}	$\pm1.4\times10^{6}$	1.0×10^{6}- 6.0×10^{7}
Ammonia (mg/l)	47	±4	8-106
Total nitrogen (mg/l)	68	±4	20-139
Suspended solids (mg/l)	254	±9	120-392

The standard error was calculated using equation c1, which is available in Microsoft Excel spreadsheet;

$$S.E. = \sqrt{\frac{\sum_{s=1}^{m} \sum_{i=1}^{n} {y_{is}}^{2}}{(n_y - 1)n_y}} \qquad \text{c1}$$

where:

s= series number

i = point number in series s

m= number of series for point “y” in chart

n=number of points in each series

y_{is}=data value of series “s” and ith point

n_y= total number of data values in all series

It can be seen from Table C1 that there was significant fluctuation of pollutants concentration in the influent wastewater. This could have been attributed due to the dilution of the wastewater by the storm water (UK sewerage system carries both wastewater and storm water). In addition, the high concentration of the industrial wastewater that was discharged at the inlet channel where the raw wastewater for the pilot-scale ponds was pumped could also play a significant role in influencing the variation of the influent concentration. It is interesting to note that the concentration of the influent parameters compares well with the expected concentration of a typical wastewater (Mara, 2004; Tchobanoglous *et al.,* 2003).

It was noted that the influent BOD_5 and *E. coli* numbers varied significantly during winter and summer seasons. The average values of these parameters were calculated statistically to improve the prediction of the CFD model when isothermal and thermo-stratification conditions developed in the pilot-scale pond (Section 6.6.1.3). Figure C2 presents summary statistics of BOD_5 concentration and *E. coli* counts that were observed during winter and summer seasons respectively.

Table C2 Summary statistics of BOD_5 concentration and *E. coli* counts in the influent during winter and summer seasons

Influent parameter	Mean	Standard error	Range
BOD (mg/l)	286	±38	116- 717
E. coli count per 100 ml	5.4×10^{6}	$\pm1.2\times10^{6}$	1.0×10^{6}- 2.0×10^{7}
BOD (mg/l)	457*	±42*	150- 826*
E. coli count per 100 ml	$1.5\times10^{7*}$	$\pm4.5\times10^{6*}$	4.1×10^{6}- $6.0\times10^{7*}$

Note: * BOD_5 and *E. coli* counts in the summer season

Appendix D

D1. Chlorophyll-a concentration in the two-baffle and four-baffle pilot-scale primary facultative ponds

The assessment of BOD overloading conditions in the two-baffle pilot-scale pond and four-baffle pilot-scale pond was carried out by measuring the concentration of chlorophyll. Details of the tests are explained in Chapter 4. In overloaded facultative ponds, the concentration of chlorophyll is significantly reduced due to the increased loading of ammonia and sulphide that are toxic to the pond algae (Mara, 2004; Pearson *et al.* 1987b). Figure D1 presents the concentration of chlorophyll that was monitored in the two-baffle and four-baffle pilot-scale primary facultative ponds.

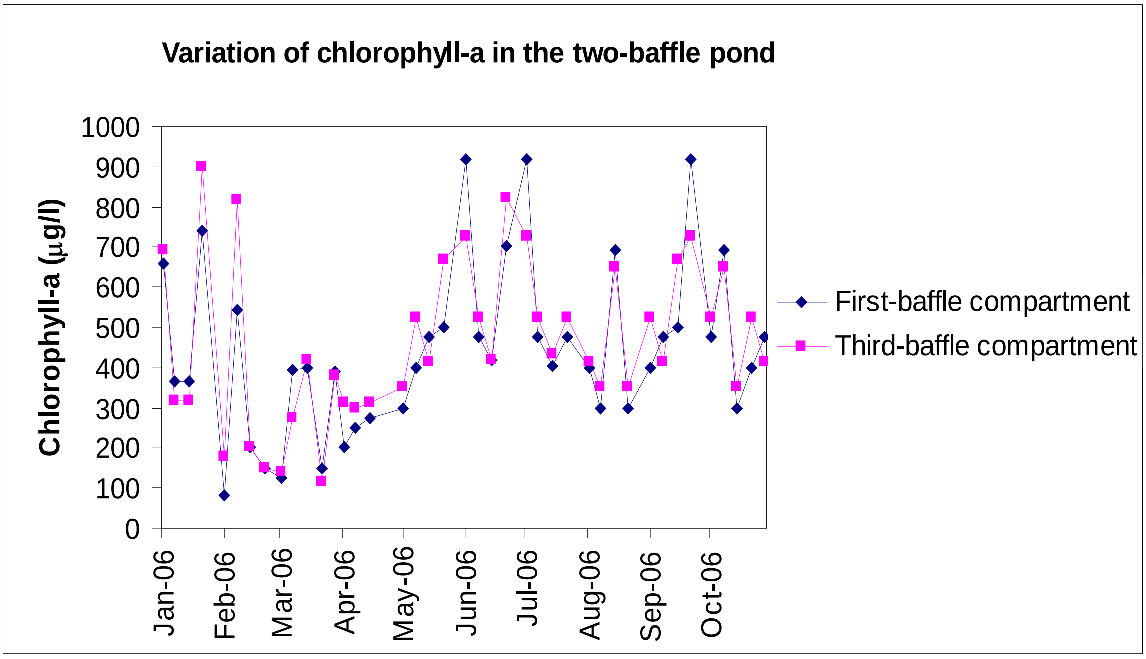


Figure D1 The chlorophyll concentration in the two-baffle pilot-scale primary facultative pond

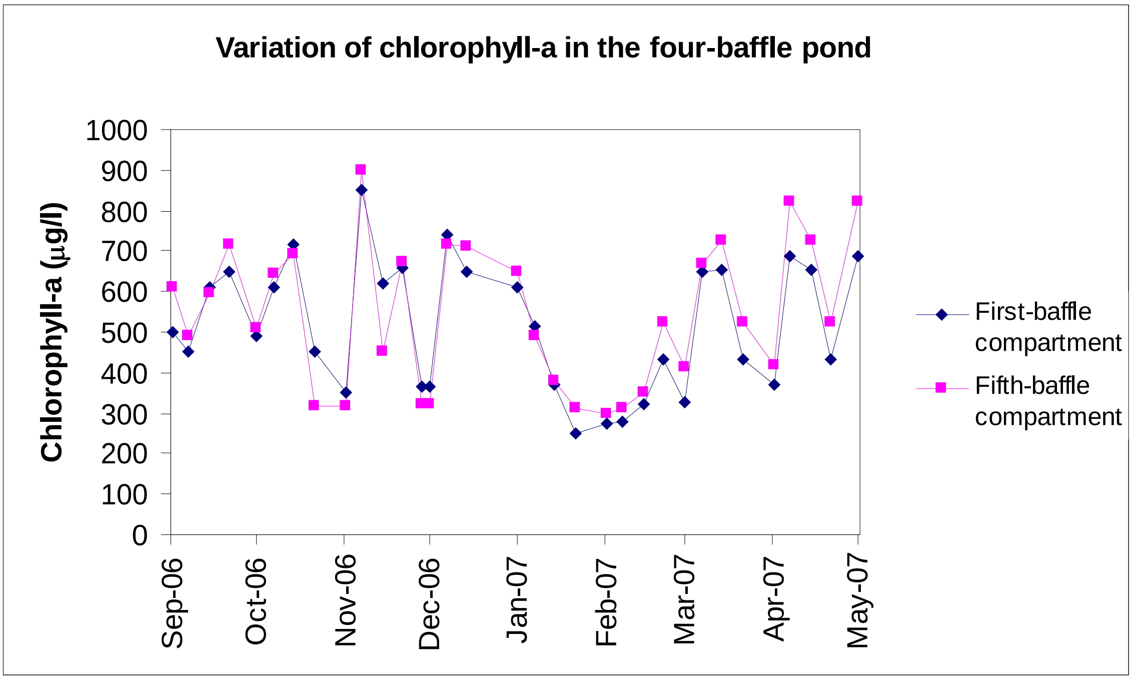


Figure D2 The chlorophyll concentration in the four-baffle pilot-scale primary facultative pond

It can be seen from Figure D1 and D2 that the concentration of chlorophyll in the baffled pilot-scale ponds varied considerably over the operational period of the pond. This could have been influenced by the variation of the influent BOD loading, sunshine intensity and temperature as these factors are thought to affect the algal population in the pond (Pearson *et al.* 1987b; 1987c; Mara, 2004). The pattern of the chlorophyll variation in the first baffle compartment where BOD loading is high is not significantly different to that in the last baffle compartment where BOD loading is low. It should be noted that the concentration of chlorophyll was low during the spring season when the population of algae predators was high.

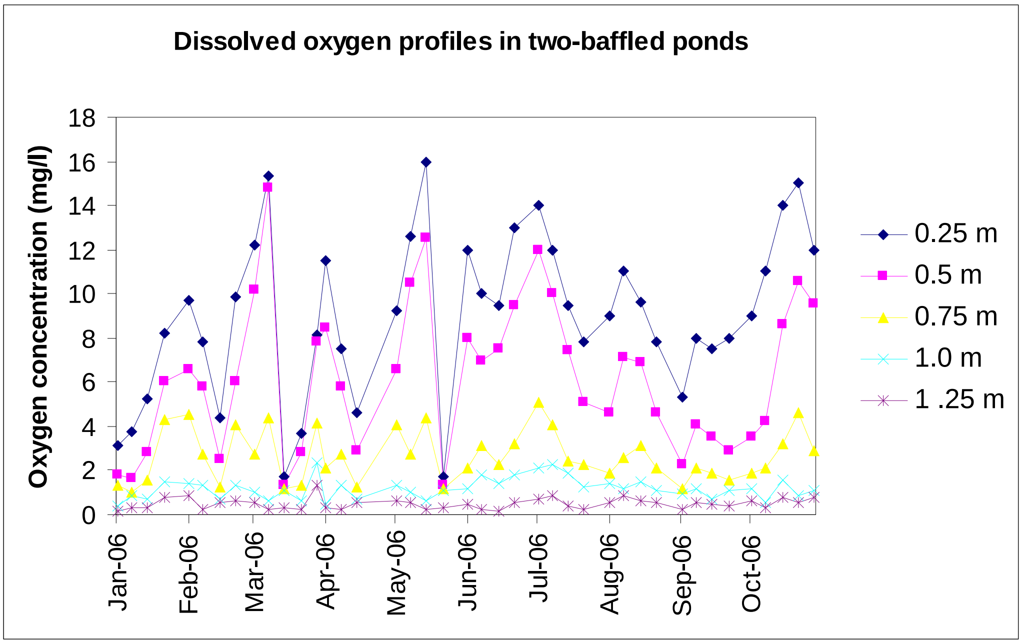
Table D1 presents summary statistics of chlorophyll concentration in the two-baffle pilot-scale pond and the four-baffle pilot-scale pond. It can be seen from Table D1 that the average concentration of chlorophyll in the baffled pilot-scale ponds was above the minimum (300ug/l) found in a healthy facultative pond (Mara, 2004). The experimental data confirms that BOD overloading was not initiated in the baffled pilot-scale primary facultative ponds despite the installation of baffles.

Table D1 Summary statistics of chlorophyll-a concentration in the two-baffle and four-baffle pilot-scale primary facultative ponds

Baffle compartment	Mean (µg/l)	Standard error (µg/l)	Range(µg/l)
First-baffle compartment (two-baffle pond)	515	±29	150-920
Third-baffle compartment (two-baffle pond)	537	±27	250-900
First-baffle compartment (four-baffle pond)	441	±32	200-850
Fifth-baffle compartment (four-baffle pond)	464	±31	195-905

D2. Dissolved oxygen and pH profiles in the two-baffle and four-baffle pilot-scale primary facultative ponds

Facultative conditions in the two-baffle pilot-scale pond and four-baffle pilot-scale pond was assessed by monitoring profiles of dissolved oxygen concentration and pH in the aerobic and anaerobic zones (Chapter 4). The experimental data of dissolved oxygen and pH profiles shown in Figures D3 and D4 show that facultative conditions were sustained satisfactory in the aerobic zone represented by layers (0 .25 m, 0.5 m and 0.75 m) near the surface of the pond at a BOD loading of 80 kg per ha per day. The concentration of dissolved oxygen in the aerobic zone was always higher compared with that of the anaerobic zone near the bottom level of the pond. It is also interesting to note that the pH values in the aerobic zone was above 8 and this is vital in killing the excreted pathogens (Mara, 2004).



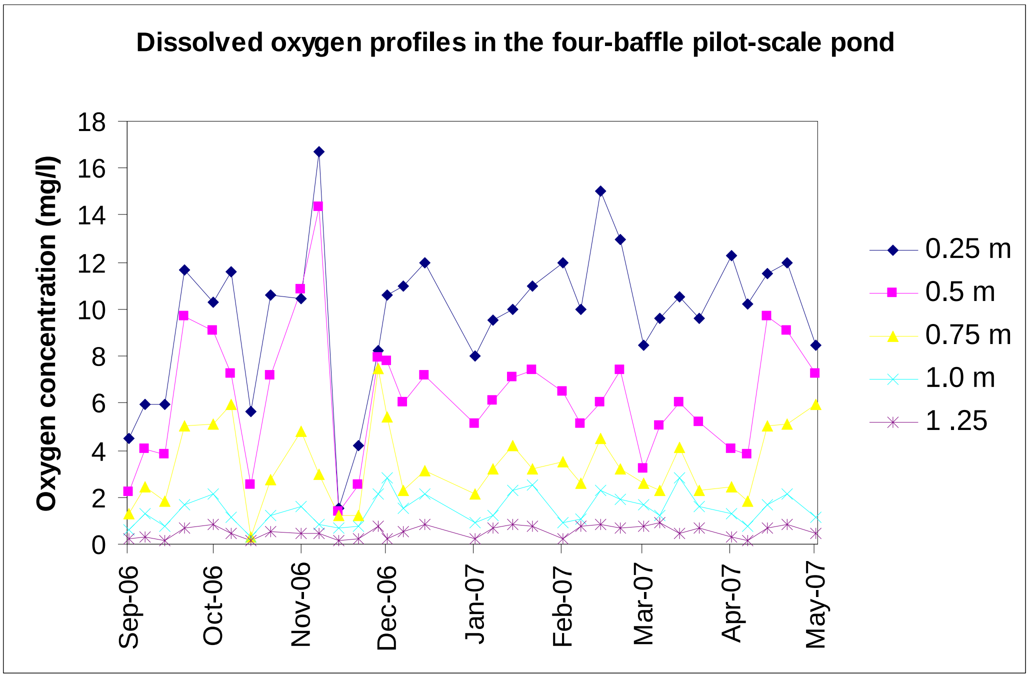


Figure D3 Dissolved oxygen concentration profiles in the two-baffle and four-baffle pilot-scale primary facultative ponds

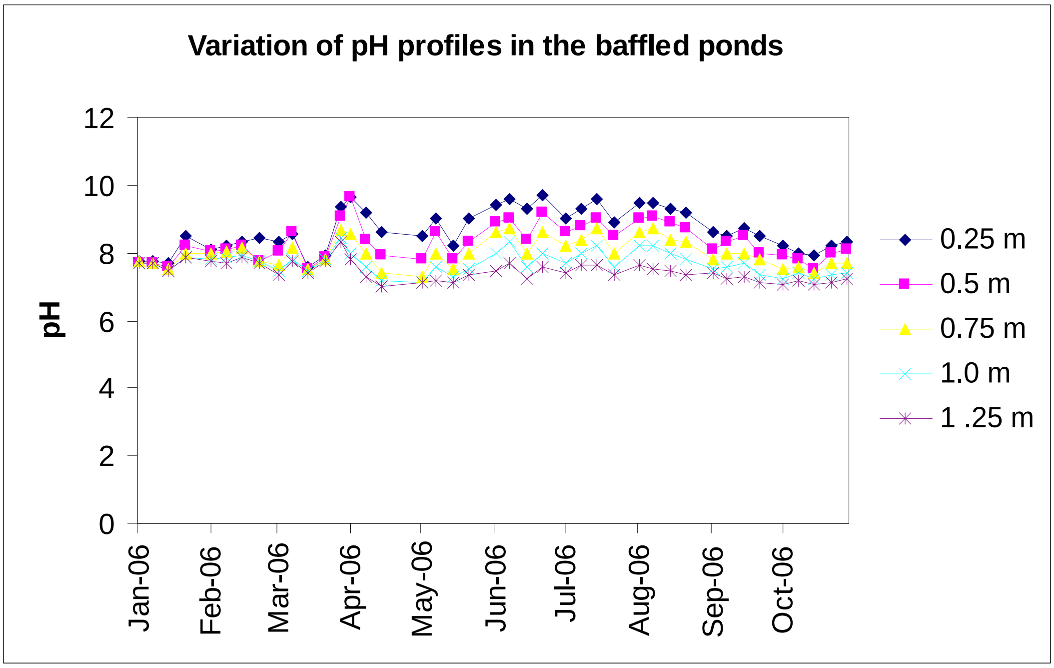


Figure D4 pH profiles in the two-baffle and four-baffle pilot-scale primary facultative ponds