5. RESULTS AND DISCUSSION: MATURATION POND PERFORMANCE AND NITROGEN REMOVAL EFFICIENCY

The pilot-scale WSP system was sampled on a weekly basis in order to monitor the performance of the two maturation ponds in series under study, as described previously in section 3.3. The monitoring programme aimed to determine the seasonal pattern of total nitrogen and ammonium concentrations in the pond influents and effluents. Relevant operational parameters were also monitored (e.g., pH, DO, temperature, alkalinity, VSS, chlorophyll-*a*, etc.), in order to asses the seasonal variation of environmental and operational indicators which were very useful in placing in context the various nitrogen transformations and removal mechanisms occurring in the ponds. Laboratory analytical results are also important to understand how maturations ponds work in the UK and to estimate their potential as a reliable technology for tertiary treatment in domestic wastewater treatment, including nitrogen control. This information may be also useful to beneficiaries such as UK water authorities and companies, researchers, wastewater engineers and environmental regulators.

5.1 Environmental Conditions

Environmental related parameters both inside and outside maturation ponds create specific conditions which promote some nitrogen transformations and removal mechanisms over others. Such parameters are water temperature, air temperature, number of hours of sunlight per day, pH, oxidation reduction potential (ORP) and dissolved oxygen (DO), among others. In this section, a succinct description of these parameters is reported over the experimental timeframe.

5.1.1 Temperature

Temperature plays a major role in any biochemical process and domestic wastewater treatment by WSP is no exception. Monthly mean water temperature values calculated from readings collected every hour, along with monthly maximum and minimum temperature values from the maturation ponds M1 and M2, are shown in Figure 5.1; corresponding air temperature values (obtained from a weather station located in Bradford, West Yorkshire (Location 4149E 4352N); Met Office UK, 2008) are also given thereon.

A statistical analysis (the *t*-test) of monthly mean values showed that there was no significant difference between in-pond water temperature and air temperature values (p >0.05). Considering that for design purposes water temperature values are not always available, mean air temperature values from local weather stations could be used instead as they fairly represent the water temperature pattern (Abis and Mara, 2006).

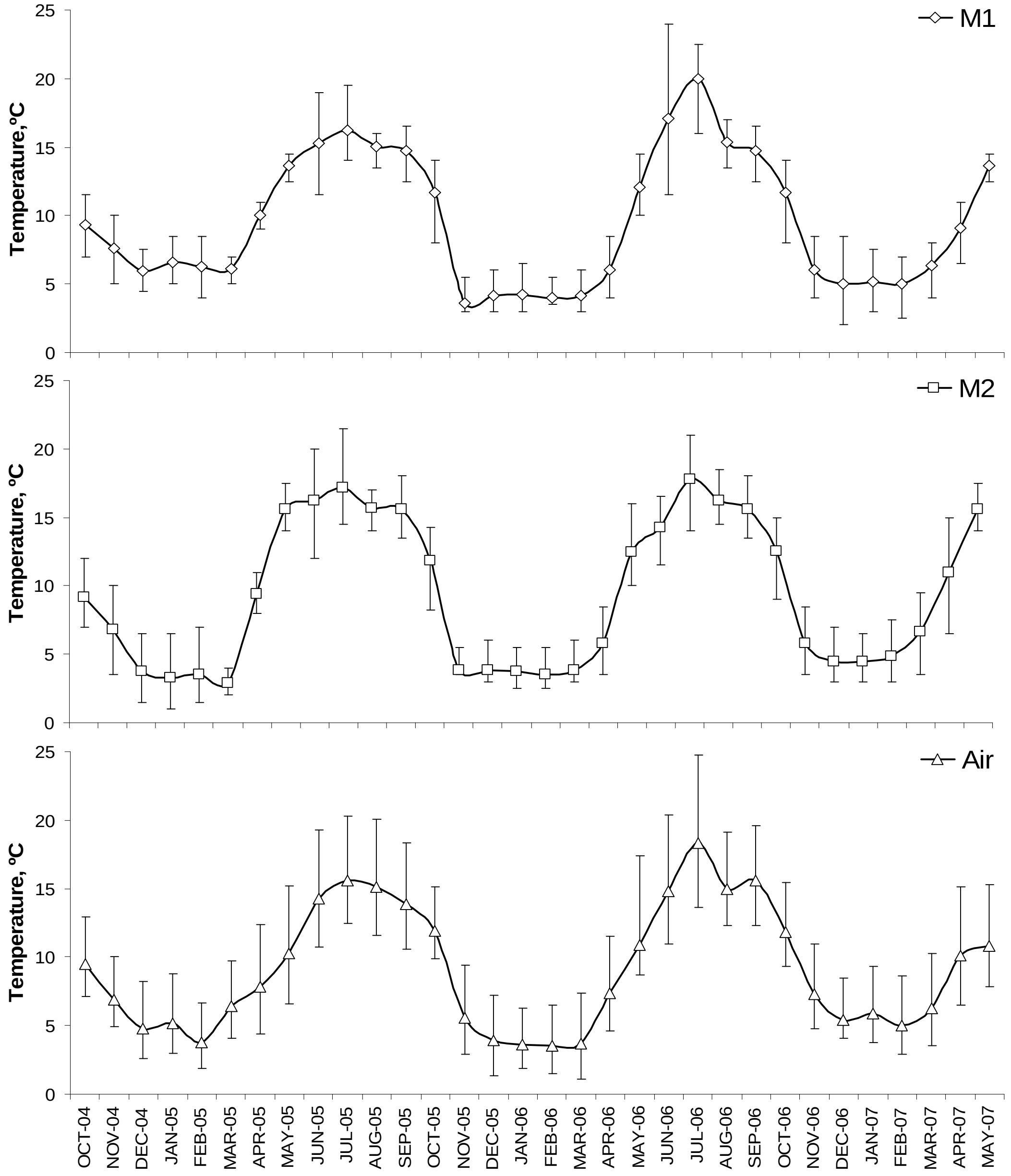


Figure 5.1 Monthly mean temperatures for air and in-pond water in M1 and M2

From the data given in Figure 5.1, it is clear that the maturation ponds M1 and M2 were operating under three temperature intervals over the year: (a) warm conditions (June, July, August, September), with in-pond water temperatures ranging from 13.3 to 18.8ºC; (b) intermediate conditions (May and October), 10.1 to 14.7ºC; and (c) cold conditions (November, December, January, February, March, April), 3.7 to 7.7ºC. Average water temperature figures for each period were 16.1, 12.5 and 5.5ºC, respectively. The monthly mean air temperature for the months corresponding to the interval of cold temperatures in the north of England is 4.7ºC (for the period 1971 to 2000; Met Office, 2008). That figure could be used for the design of WSP in Yorkshire and Humber (UK) when a temperature value is required to calculate kinetic constants or loading rates.

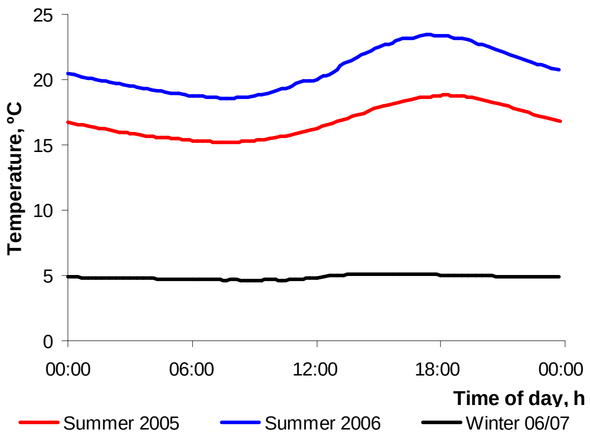


Figure 5.2 Hourly mean water temperatures for M1 effluent

In-pond water temperatures for the two pilot-scale maturation ponds also showed a diurnal variation, but no thermal stratification within pond depth as reported by Abis and Mara (2006) in primary facultative ponds under similar weather conditions; that was probably due to the maturation ponds under study being shallower (0.88m at the deepest point) and the fact that vertical mixing was well induced by wind speed. Diurnal temperature variation in the M1 pond effluent is shown in Figure 5.2; data were collected during the tracer experiments with Rhodamine WT (see Chapter 4). It is important to note that, although air temperature may vary in a broader range (e.g., 11.6–20.3ºC, summer 2005; 12.3–24.8ºC, summer 2006; 3.8–9.3ºC, winter 2006/2007), in-pond water temperature may not.

5.1.2 pH, dissolved oxygen and ORP

In maturation ponds, pH, DO and ORP are strongly related to algal activity. Algal metabolism interferes to a great extent with the chemical equilibrium of bicarbonates, carbonates and hydroxides and hence the pH varies as a result of photosynthetic activity (CO_2 consumption and production during photosynthesis and respiration, respectively). Therefore the pH increases during the daytime and declines over night; a similar pattern should be expected for dissolved oxygen concentrations in maturation ponds, as the highest pH values are usually reported when photosynthetic activity reaches its maximum.

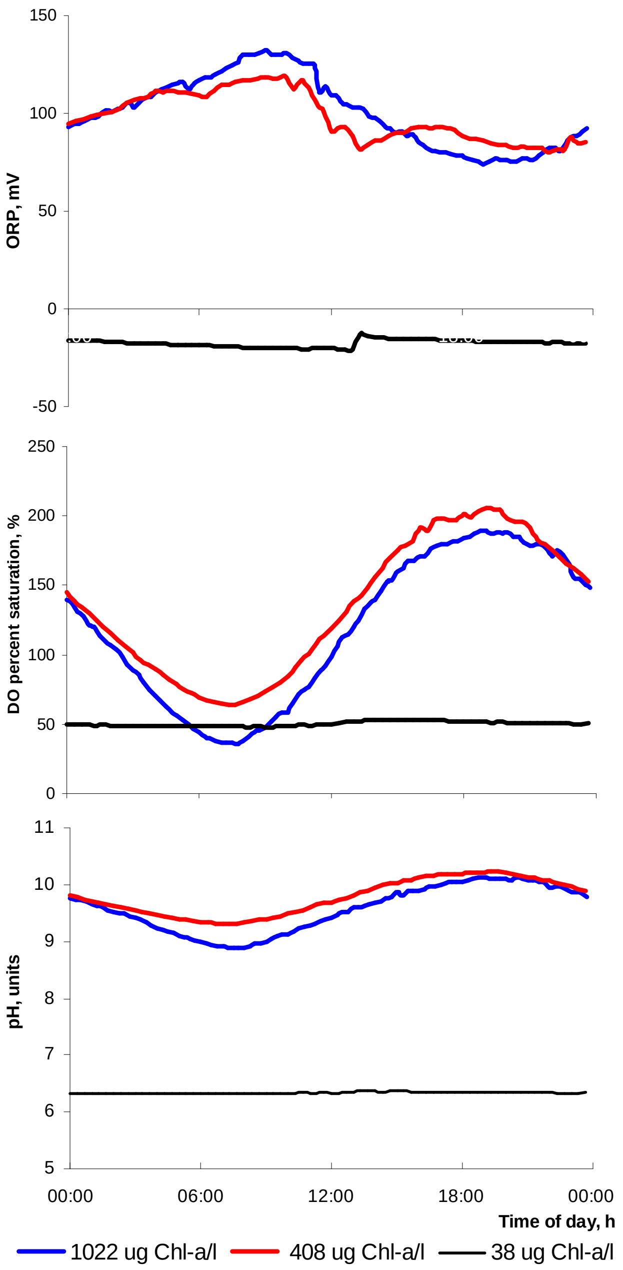


Figure 5.3 Diurnal variation of pH, DO and ORP in M1 pond effluent

Consequently, in-pond dissolved oxygen contributes, along with organic loading rates and pH, to the establishment of conditions suitable for the performance of oxidation or reduction reactions in WSP, which can be monitored with the in-pond ORP. It would be expected that under fully aerobic conditions ORP would have positive values (oxidising conditions), whilst under anaerobic or less oxic conditions it would have negative values (reducing conditions). Figure 5.3 shows the diurnal variation of pH, DO and ORP in the

M1 pond effluent under three different levels of in-pond algal biomass concentrations: (a) high (1022 μg Chl-*a*/l – summer 2005); (b) medium (408μg Chl-*a*/l – summer 2006); and (c) low (38 μg Chl-*a*/l; winter 2006/2007). Dissolved oxygen concentrations are reported in Figure 5.3 as percentages of saturation as this allows a straight comparison between DO readings taken at different water temperatures.

Under conditions with low algal biomass concentrations there was no major diurnal variations of pH, DO and ORP, and it seems that environmental in-pond conditions were more favourable for reducing reactions. However, when the chlorophyll-*a* concentration increased during warmer conditions, diurnal variation was very clear and a positive correlation between pH, DO and ORP was also observed. This can be straightforwardly explained by increasing pond water temperatures increase phytoplanktonic activity, and consequently in-pond algal growth would have a major influence on the pH, DO and ORP diurnal variations, and this made the maturation ponds under study suitable for oxidising reactions during that particular period of time.

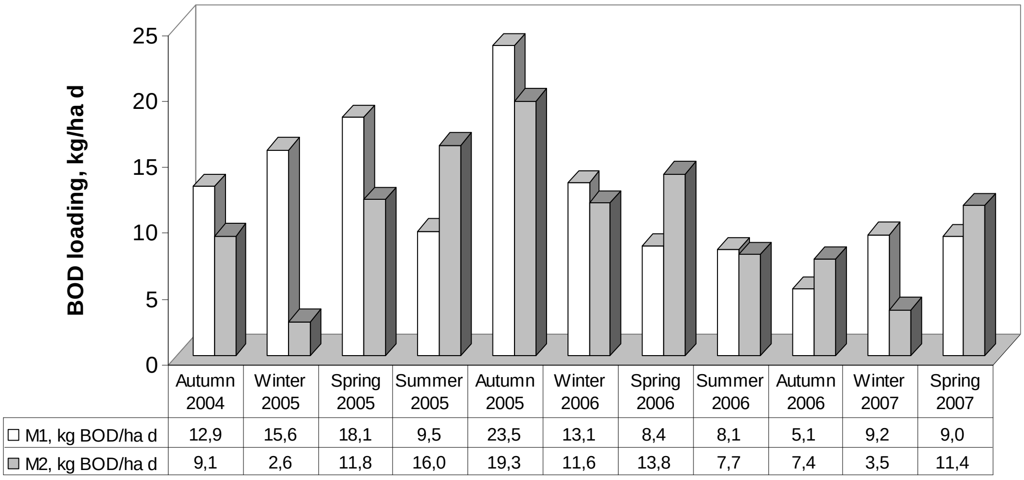
5.2 Operational Conditions

5.2.1 Organic and nitrogen loading rates

The maturation pond M1 was fed with the effluent of the primary facultative pond PFP1, which was fed with screened wastewater at average loading rates of 80 kg BOD_5/ha d and 8 kg N/ha d. The average nominal retention time (θ_0) for the PFP1 was 60 days. Organic and total nitrogen loadings for the maturation ponds M1 and M2 are shown in Figures 5.4 and 5.5, respectively.

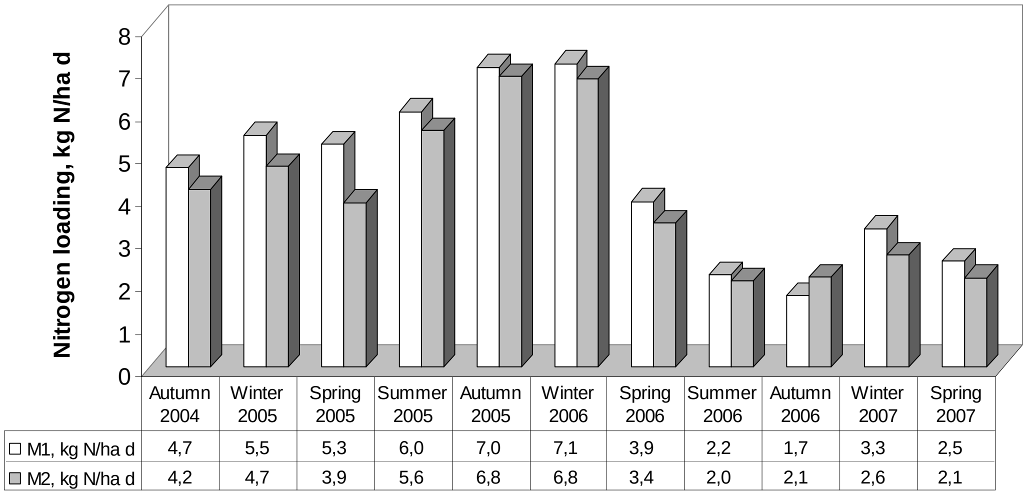
The mean organic loading rates over the experimental timeframe for M1 and M2 were 12 and 10 kg BOD/ha d, respectively. M1 received BOD loading rates according to the performance of PFP1, whereas the quality of the M2 influent was affected by the performance of the M1 pond. Therefore, organic loading rates in M1 and M2 were affected by algal activity (i.e., CO_2 fixation rates) and sludge feedback occurring in the preceding pond. Thus organic loading rates on M2 pond were sometimes higher than the organic load on M1 (e.g., in autumn 2006).

In terms of total nitrogen loading rates, M1 and M2 were loaded on average at 4.5 and 4.0 kg N/ha d, respectively. Nitrogen loading rates on M2 were consistently lower than those on M1 during the experimental timeframe, with the exception of autumn 2006 when sludge feedback affecting M1 increased the nitrogen concentration in the influent to M2. This pattern would suggest that there was no biological nitrogen fixation from the atmosphere and the only nitrogen input came from the pond influents. M2 was also affected by sludge feedback in summer and autumn 2006.



	Autumn 2004	Winter 2005	Spring 2005	Summer 2005	Autumn 2005	Winter 2006	Spring 2006	Summer 2006	Autumn 2006	Winter 2007	Spring 2007
☐ M1, kg BOD/ha d	12,9	15,6	18,1	9,5	23,5	13,1	8,4	8,1	5,1	9,2	9,0
▨ M2, kg BOD/ha d	9,1	2,6	11,8	16,0	19,3	11,6	13,8	7,7	7,4	3,5	11,4

Figure 5.4 BOD loading rates for the maturation ponds M1 and M2



	Autumn 2004	Winter 2005	Spring 2005	Summer 2005	Autumn 2005	Winter 2006	Spring 2006	Summer 2006	Autumn 2006	Winter 2007	Spring 2007
☐ M1, kg N/ha d	4,7	5,5	5,3	6,0	7,0	7,1	3,9	2,2	1,7	3,3	2,5
▨ M2, kg N/ha d	4,2	4,7	3,9	5,6	6,8	6,8	3,4	2,0	2,1	2,6	2,1

Figure 5.5 Total nitrogen loading rates for the maturation ponds M1 and M2

The maturation ponds under study were operated at low BOD loading rates which guaranteed a predominance of aerobic conditions even during the cold winter months. The nutrient ratio (BOD/N/P) in the pond influent was 81/30/1 for M1 and 67/27/1 for M2, which was sufficient to maintain microbiological activity in both maturation ponds. For aerobic wastewater treatment a minimum of 1 mg P/l and 5 mg N/l is required for the treatment of a liquid waste with 100 mg BOD/l (i.e., a 100/5/1 ratio) (Metcalf and Eddy Inc., 1991).

5.2.2 Algal activity

Algal activity can be monitored by chlorophyll *a* as a surrogate parameter for algal biomass concentration. Chlorophyll-*a* analyses were carried out in water column samples collected from M1 and M2 within the weekly performance monitoring programme. Mean monthly chlorophyll-*a* values are reported in Figure 5.6. It is important to mention that the algae grew well even at low temperatures; however, natural predators (e.g., *Daphnia*), short photoperiods (e.g., winter months) and few sun hours per day were definitely the most influencing factors for the low chlorophyll concentrations observed during a few months.

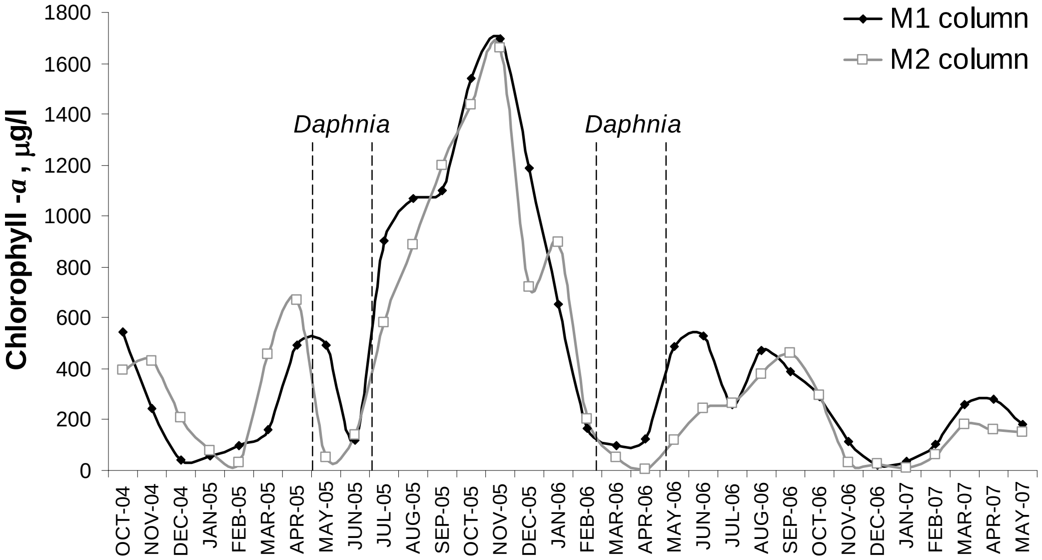


Figure 5.6 Mean monthly chlorophyll-*a* in water column samples

Microscopic examination of samples collected from the water columns in M1 and M2 revealed mainly the presence of the following algal species: *Chlorella*, *Scenedesmus*, *Cryptomonas, Trachelomonas, Polytoma* and *Chlamydomonas*.

5.3 Suspended Solids Removal

Generally speaking, suspended solid removal was very poor in both M1 and M2; however, low concentrations of SS were observed when there was a *Daphnia* infestation as SS concentrations in maturation pond effluents are strongly dependent on algal activity (see chapter 7). The increment of SS in maturation ponds is not a novel fact − it has been widely reported in the literature; it has been mainly attributed to algal activity and sludge feedback (Walmsley and Shilton, 2005). Figure 5.7 shows the percentage of SS remaining in M1 and M2 effluents in comparison with the content of SS in the effluent of the primary facultative pond PFP1.

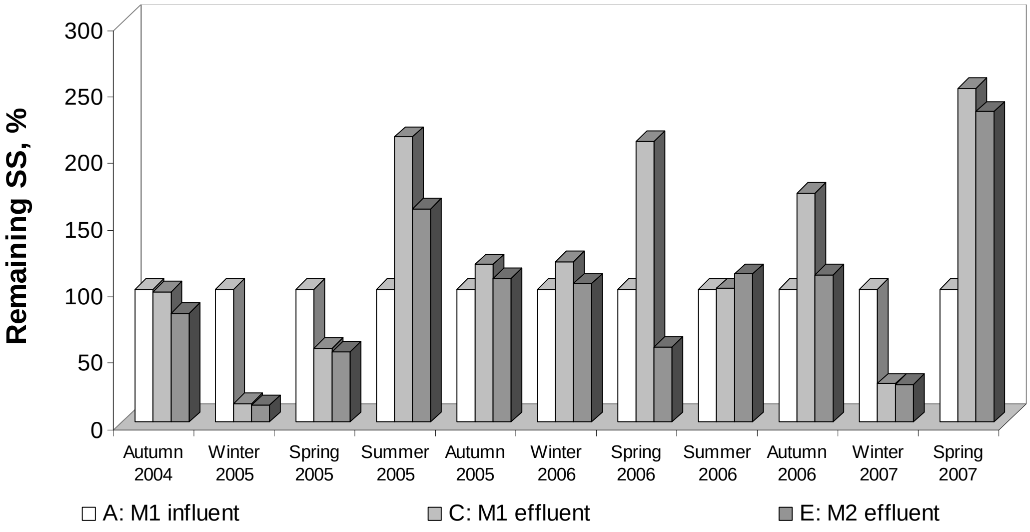


Figure 5.7 Percentage of SS remaining in M1 and M2 effluents per season

95-percentile values for SS in M1 influent (A), M1 effluent (C) and M2 effluent (E) were 101, 138 and 115 mg/l respectively; therefore, the PFP1effluent would not need tertiary treatment (maturation ponds) to meet the UWWTD requirement of ≤150 mg SS/l for the final effluent of WSP systems. In the view of the UK environmental regulators, conventional maturation ponds would not contribute substantially to improve the quality of facultative pond effluents, as M2 effluent would not be able to meet current UK discharge standards which are much stricter then those in the UWWTD (e.g., ≤15 mg SS/l, as a 95-percentile value).

5.4 Organic Matter Removal

Seasonal variations of BOD and soluble BOD concentrations in M1 and M2 effluents are shown in Table 5.1. From this information the PFP1 effluent would not meet the UWWTD requirement for BOD discharge (≤25 mg filtered BOD/l) as its mean effluent BOD was 33 mg/L. Maturation ponds may be able to upgrade the quality of the primary facultative pond effluent in terms of organic matter removal, considering that mean effluent BOD values in M1 and M2 were 25 and 23 mg/l, respectively. 95-percentile values for BOD in M1 influent (A), M1 effluent (C) and M2 effluent (E) were 78, 53 and 61 mg/l respectively, so the pilot-scale WSP system would not meet UK environmental standards related to organic matter discharges (e.g., ≤40 mg BOD/l, as a 95-percentile value).

Table 5.1 Seasonal variation of mean BOD and soluble BOD in M1 and M2

Season	BOD, mg/l			Soluble BOD, mg/l		
	A	**C**	**E**	**A**	**C**	**E**
Autumn 2004	36	23	23	9	4	3
Winter 2005	43	7	7	8	4	2
Spring 2005	49	30	23	11	7	4
Summer 2005	27	43	45	12	4	7
Autumn 2005	65	49	49	12	5	4
Winter 2006	35	29	24	19	6	2
Spring 2006	21	32	13	11	5	7
Summer 2006	22	21	23	8	5	5
Autumn 2006	13	17	15	7	6	14
Winter 2007	24	8	9	6	4	5
Spring 2007	23	28	27	10	8	5

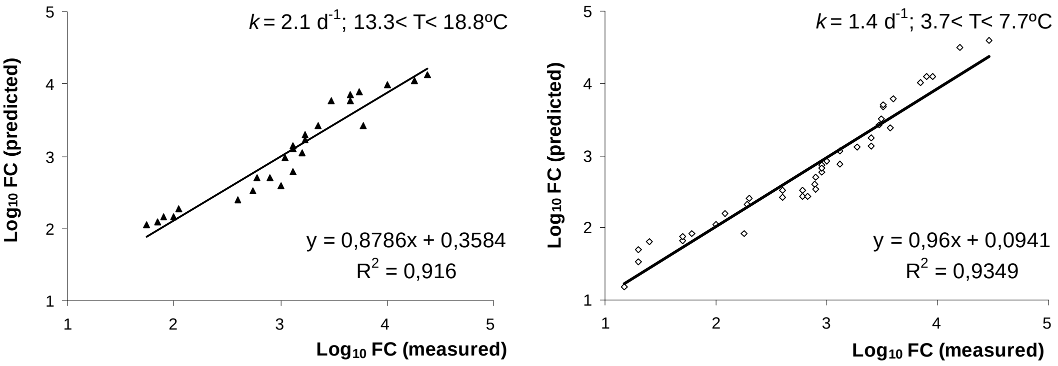
A= M1 influent; C= M1 effluent; E= M2 effluent

High organic matter removals are particularly difficult to achieve in maturation ponds, mainly because carbon fixation during photosynthesis and the accumulation of recalcitrant soluble organic matter along the treatment train. That tendency could be observed by using the COD/BOD ratio, which was on average 3.4, 4.1 and 4.2 for unfiltered samples collected from sampling points A, C and E, respectively. The corresponding values for filtered samples were 5.0, 8.0 and 8.5.

5.5 Faecal Indicator Bacteria Removal

Faecal coliforms bacteria (*E. coli*) were monitored from samples collected from sampling points A (M1 influent), C (M1 effluent) and E (M2 effluent); mean $\log_{10}$ *E.coli* values were 4, 3 and 2, respectively. Therefore, the maturation ponds contributed to remove faecal bacteria indicators at suitable levels for the reuse of treated wastewater for unrestricted irrigation and aquacultural reuse (<1000 cfu/100 ml; WHO, 2006). The overall performance of the maturation ponds M1 and M2 for faecal coliforms removal was according to its original design (Johnson and Mara 2002).

Based on the model reported by Thirumurthi (1969) (equation 2.22) and results from the hydraulic characteristics of M1 and M2 (section 4.2.2), kinetic constants for *E. coli* decay were calculated for warm and cold water temperature conditions (Figure 5.8). For the mean water temperature for the warm conditions (13.3< T< 18.8ºC), the average faecal coliform removal rate was 2.1 d^{-1} for the maturation ponds M1 and M2; the corresponding value for the cold conditions (3.7< T< 7.7ºC) was 1.4 d^{-1}. These results are in agreement with von Sperling's method as reported by Mara (2004).



(a) Warm temperature conditions

(b) Cold temperature conditions

Figure 5.8 FC removal rates for M1 and M2 calculated from a dispersion model

5.6 Nitrogen Removal

Comparison of influent and effluent concentrations may mask the real ability of WSP systems to reduce the mass of nitrogen discharged rather than the concentration discharged; particularly when long retention times and weather conditions (e.g., rainfall, evaporation) remove the direct dependence between influent and effluent concentrations (Ferrara and Avci, 1982). Therefore, nitrogen removals in M1 and M2 were calculated in terms of the reduction of nitrogen load by comparing the average nitrogen mass flux from inlet (*Mo*, g N/d) and outlet (*Me*) over each season as follows:

$$Mo = Qo \times Co \tag{5.1}$$

$$Me = Qe \times Ce \tag{5.2}$$

$$N\ removal,\ \% = \left(\frac{Mo - Me}{Mo} \right) \times 100 \tag{5.3}$$

$$N\ remained,\ \% = \left(\frac{Me}{Mo} \right) \times 100 \tag{5.4}$$

In equations 5.1 to 5.4, *Qo* and *Qe* are mean inlet and outlet pond flow rates (m^3/d), respectively; and *Co* and *Ce* are mean nitrogen concentrations (mg N/l) from pond influent and effluent, respectively.

5.6.1 Ammonium removal

Ammonium was removed efficiently during the warm summer months (e.g., up to 91%; summer 2005), but poorly in the cold winter months. High ammonium removals also coincided with periods of high algal activity. An increase in the ammonium concentrations in M1 and M2 effluents was observed during the months in which sludge feedback occurred. Ammonia removals are shown in Figure 5.9.

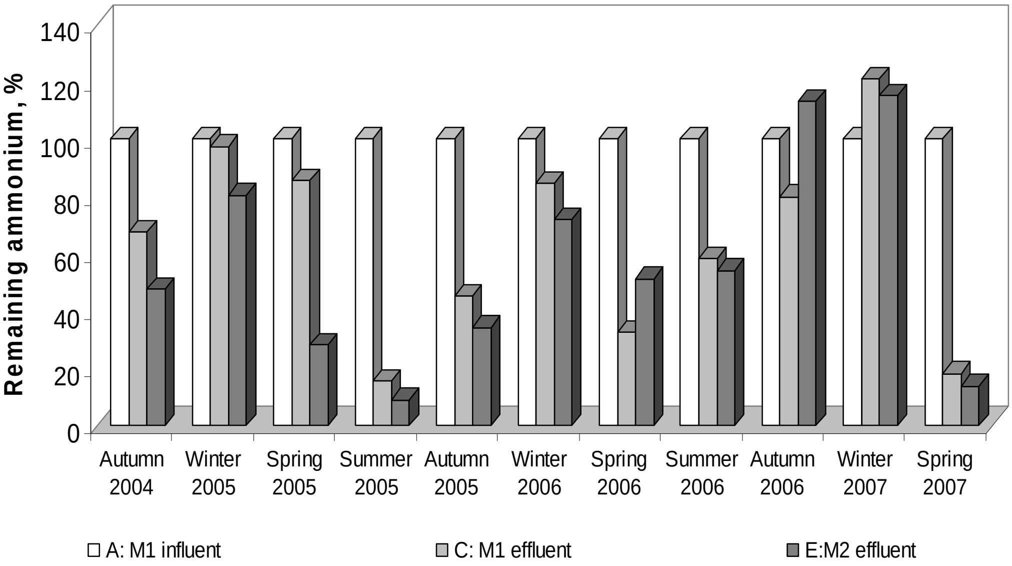


Figure 5.9 Percentage of ammonium remaining in M1 and M2 effluents per season

The Pano and Middlebrooks model (equation 2.34) is one of the most accepted models to predict ammonia removal in WSP. It was used to predict the ammonium concentrations in M1 and M2 effluents (Figure 5.10). The linear regression coefficient ($R^2 = 0.7548$) and the slope of the graph (0.7348) showed a good linear correlation (Pearson correlation coefficient = 0.869) between actual ammonium values and those predicted by values the Pano and Middlebrooks model. However, the accuracy to predict ammonium concentration in the pilot-scale maturation ponds was poor and the estimated error varied from –327 to 90 percent. Therefore, ammonium removal in the maturation ponds M1 and M2 has a good statistical relation with pH, water temperature and flow loading rate.

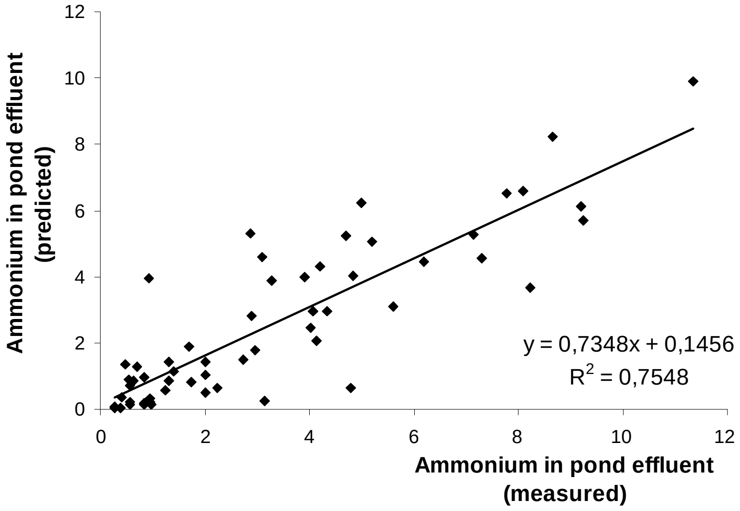


Figure 5.10 Prediction of ammonium concentration in M1 and M2 effluents

95-percentile values for ammonium in M1 influent (A), M1 effluent (C) and M2 effluent (E) were 14.0, 9.4 and 8.0 mg/l, respectively. Therefore, conventional maturation ponds in the UK would not contribute substantially to improve the quality of facultative pond effluents in terms of ammonium removal, as M2 effluent would not be able to meet current UK discharge standards (e.g., $\leq$5 mg NH_4^+-N/l as a 95-percentile value). However, it is important to note that maturation ponds would definitely contribute to improve ammonium removal from facultative pond effluents under warmer conditions that those observed during the experimental timeframe in the UK.

5.6.2 Total nitrogen removal

The maturation ponds under study reported an average total nitrogen removal of 18 percent for M1 and 14 percent for M2 during the period of study. Sludge feedback was responsible for the low total nitrogen removal during summer and autumn 2006. Figure 5.11 shows the percentage of total nitrogen remaining in M1 and M2 effluent in comparison with the content of total nitrogen in the effluent of the primary facultative pond PFP1. Based on the results reported here, conventional maturation ponds would hardly achieve a standard of 75 percent loading removal of total nitrogen, which is one of the most popular discharges standards for treated domestic wastewaters.

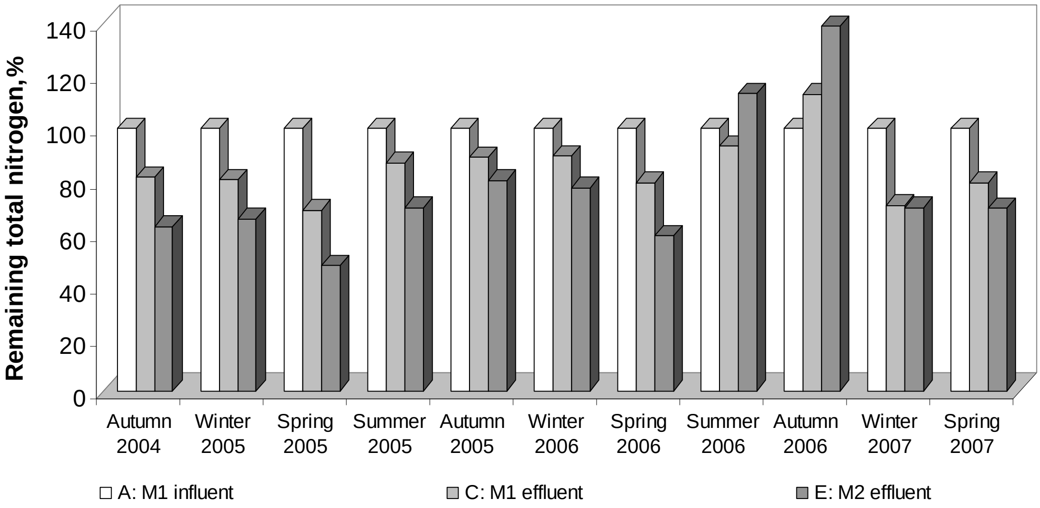


Figure 5.11 Percentage of total nitrogen remaining in M1 and M2 effluents per season

5.7 Related Publications

This research work was partially published as part of the conference proceedings of the 7th IWA Specialist Conference on Waste Stabilization Ponds held at the Asian Institute of Technology in Bangkok, 25–27 September 2006. The corresponding paper was selected for publication in *Water Science and Technology* as follows:

Johnson, M., Camargo Valero, M. A., Mara D. D. (2007). Comparison of tertiary maturation ponds and rock filters in the UK: statistical analysis of winter performance. *Water Science and Technology*, **55**(11), 135-142.