CHAPTER 5 RESULTS

5.1 Climatic conditions at Esholt

The climatic conditions for the two-year sampling period, both from the Esholt weather station and the UK average, are shown in Figure 5.1. The two periods between November and January experienced the lowest solar intensity, around 20 W m^{-2} ; whilst the highest solar intensity (around 150 W m^{-2}) was experienced between May and July. There was a similar pattern to the sunshine hours for the whole of the UK.

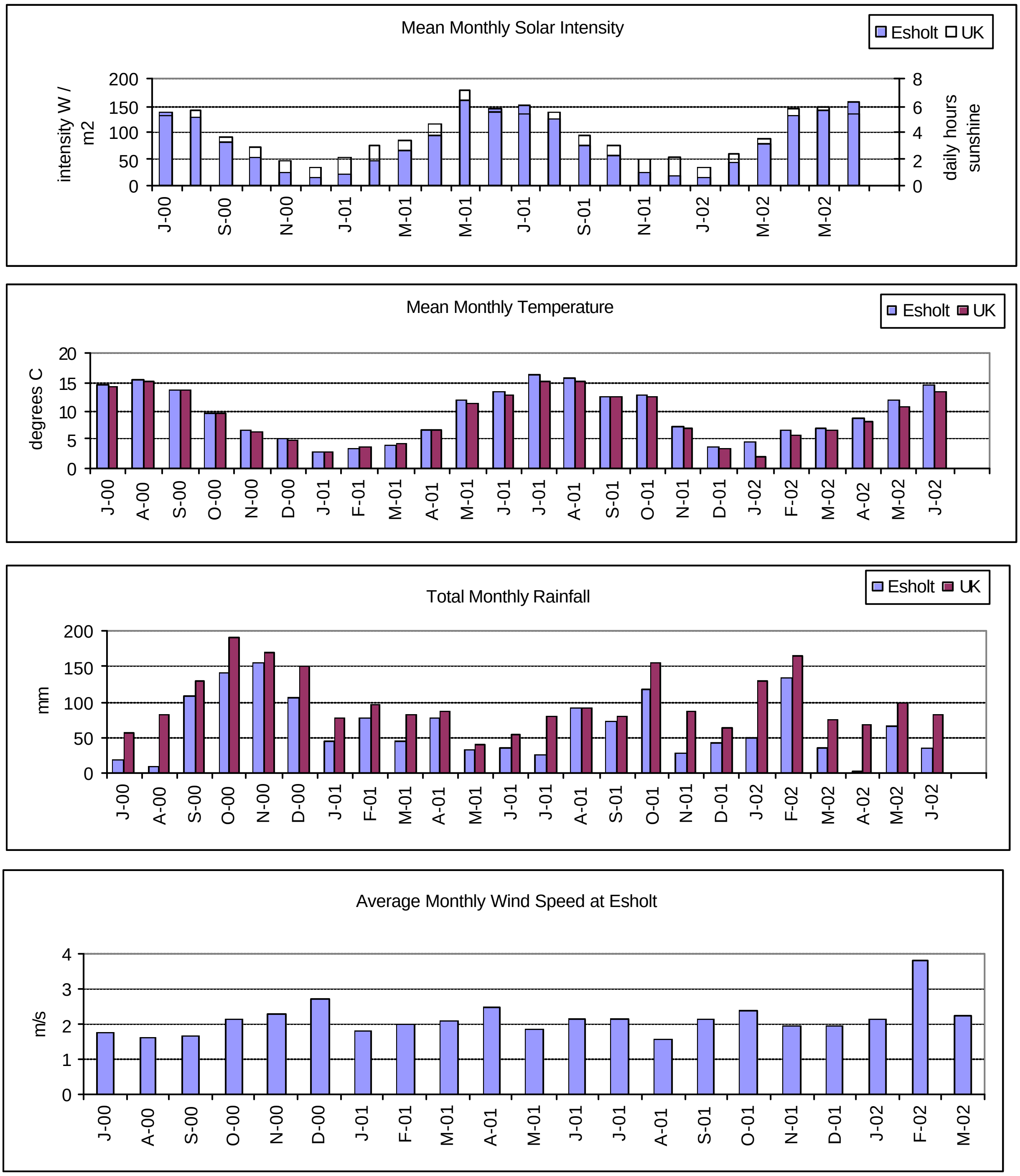
At Esholt, January-March was the coldest period, with mean monthly air temperatures around 3^{o}C; the warmest period (around 16^{o}C) was between July and August. Throughout the year, Esholt was slightly warmer than the UK average.

Esholt was also consistently drier than the UK average: rainfall was higher during the first autumn and then appeared to be independent of season, though the driest period was May-July 2001.

Wind speed was independent of season, usually between 1.5 and 3.0 m/s. Early spring 2002 was extremely windy, and at the end of March the anemometer was damaged in high winds of more than 8 m/s. The wind direction was predominantly from 290-300^{o} (approximately WNW). The orientation of the ponds is shown in Figure 5.1.

5.1.1 Temperature of the ponds

The mid-depth temperature of the ponds were all the same and varied about 3-20^{o}C as shown in Figure 5.2. The influent temperature was always warmer than the pond water and was 5-25^{o}C (except during start-up when it was above 30^{o}C: the tubing was exposed to the sunlight at this time, but became shaded by the long grass later on). Temperature data was logged at 0.25 m depth intervals every hour in each pond between June 2001 and July 2002. This data is given in Appendix E.



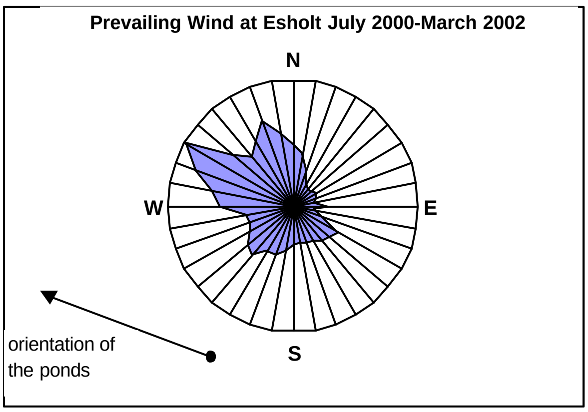
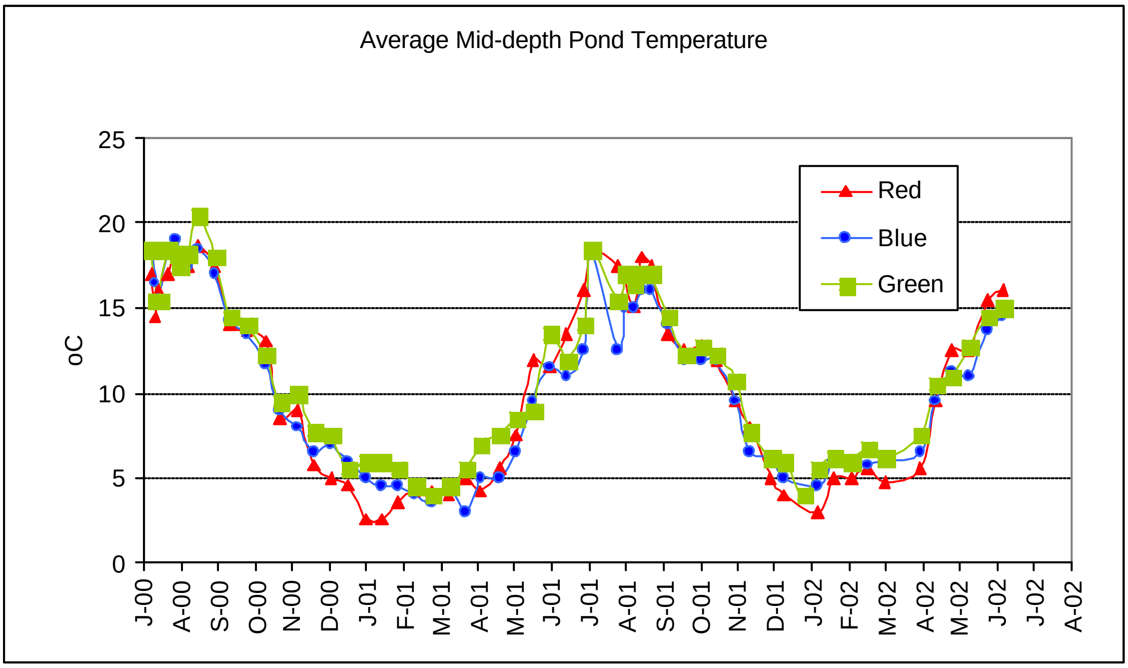


Figure 5.1 Monthly summaries of the weather data from the Esholt weather station and from the UK Met Office (2002)



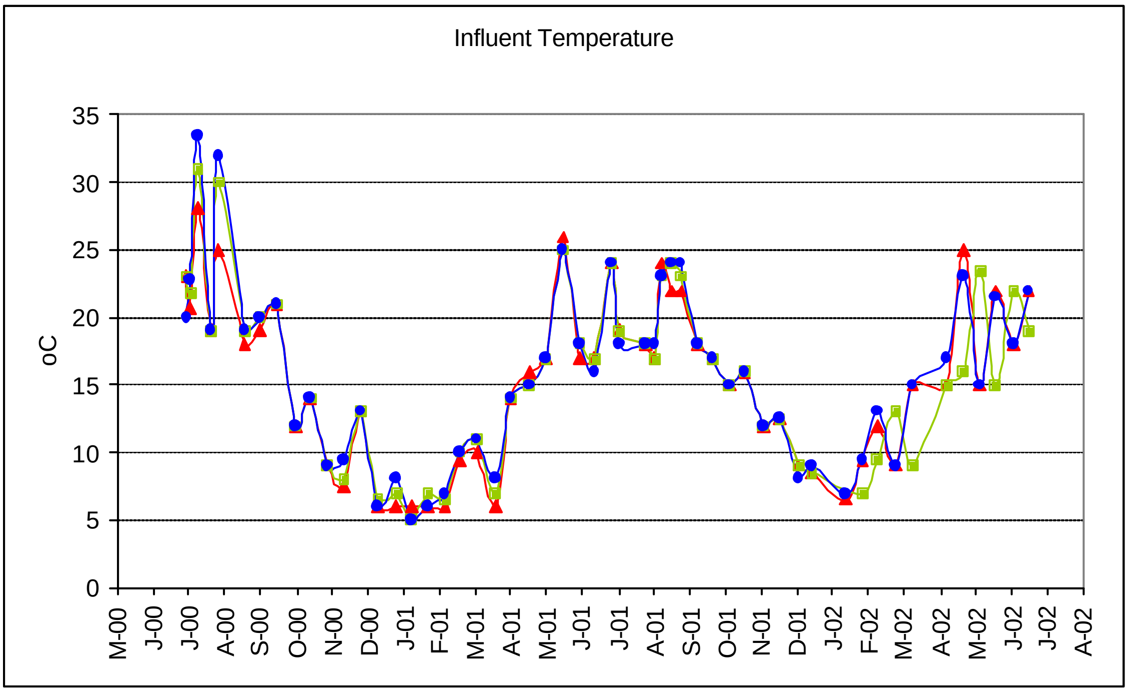


Figure 5.2 The mid-depth temperature and the influent temperature for all ponds

5.2 BOD Removal

5.2.1 The components of influent BOD to the pilot-scale facultative ponds

The BOD in the influent to all the ponds was modelled (as shown in Appendix A); the components of influent BOD are summarised in Figure 5.3. Around two thirds of the incoming BOD settled to the bottom, whilst just over one third entered the pond liquid. Only around 20 % of the incoming BOD was soluble.

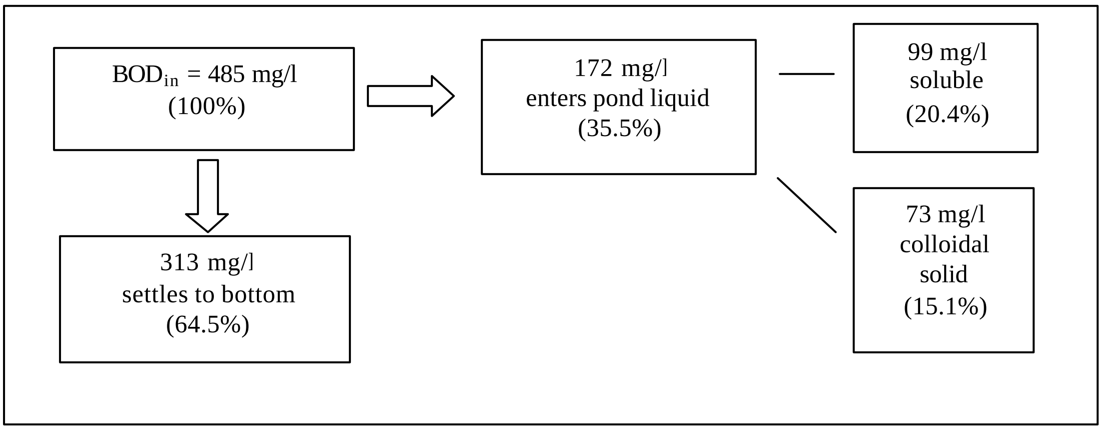


Figure 5.3 The components of the influent BOD.

In the pond liquid, 58% of incoming BOD was soluble and 42% insoluble. The proportion of soluble to insoluble BOD in the effluent of all ponds did not fluctuate seasonally and was on average 33% soluble and 67% insoluble.

5.2.2 Total BOD removal and effluent quality

A graph of the monthly average BOD effluent concentration from all the ponds is shown in Figure 5.4. There appears to be a relationship between surface BOD load and effluent concentration as the Blue pond effluent was usually higher than the other two and the Green pond was usually higher than the Red. For all ponds higher BOD effluent concentrations were experienced in summer than winter. The average concentrations for each experimental phase are shown in Table 5.1.

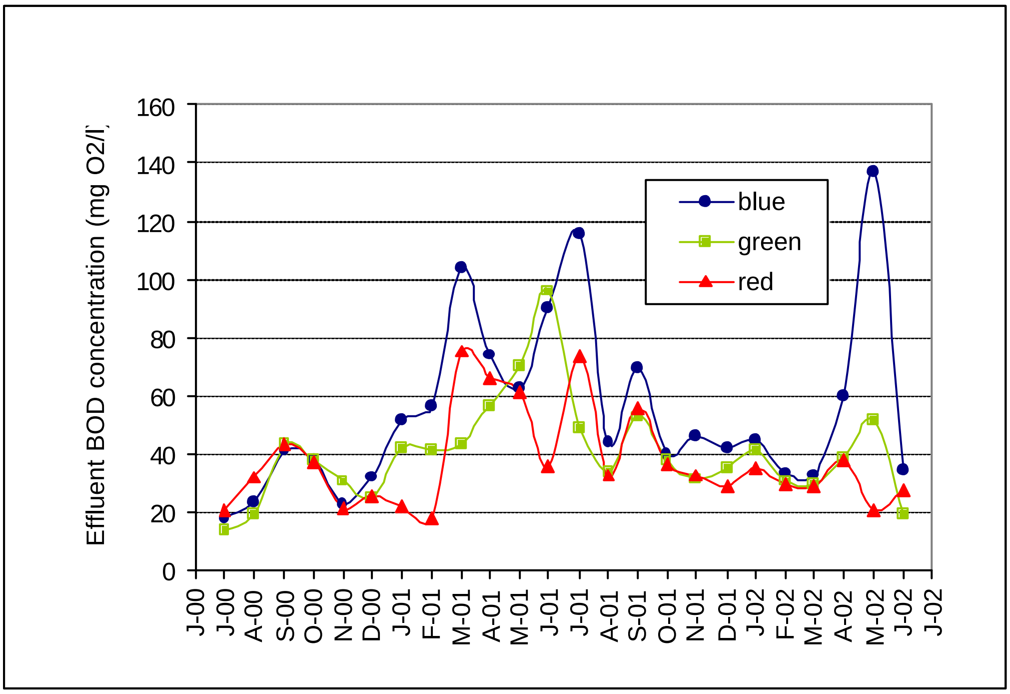


Figure 5.4 Monthly effluent total BOD concentration for all ponds

Table 5.1 The mean total BOD effluent concentration (mg O_2 /l) for each pond in each phase

Phase	λ_s (kg BOD /ha.d)	BOD concentration (mg O_2/l)	(95% CI)	n	ANOVA p=
1 July-Sept 2000	51	25.9	(±15.9)	8	0.687
	62	23.4	(±12.6)	8	
	63	30.5	(±12.5)	8	
2 Sept 2000-March 2001	169	46.1	(±17.2)	11	0.053
	116	36.0	(±9.3)	11	
	63	26.4	(±8.9)	12	
3 March -July 2001	117	89.1	(±24.3)	9	0.043
	116	70.9	(±16.8)	9	
	63	54.7	(±21.0)	9	
4 July 2001 – June 2002	107	54.4	(±13.3)	24	0.009
	82	37.3	(±4.7)	24	
	63	36.6	(±7.8)	25	

After Phase 1, there was marginal evidence of an effect of loading on effluent concentration (and hence concentration removal). A linear regression analysis of the effect of load on total effluent BOD concentration gave p = 0.08[16], with 20% of variance accounted for. This weak correlation is illustrated by the plot shown in Figure 5.5.

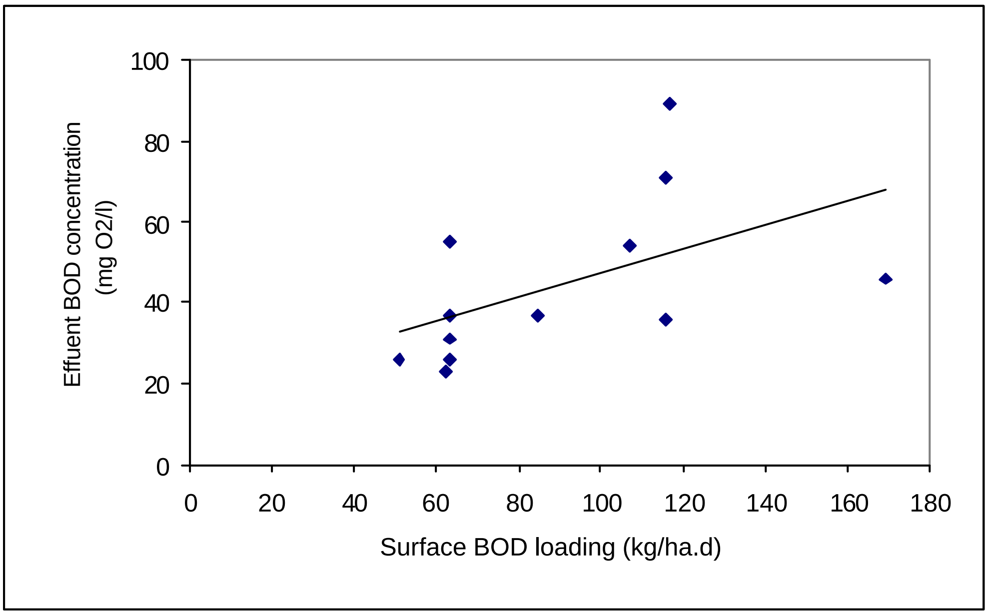


Figure 5.5 Scatterplot of average effluent total BOD concentration against surface loading

With the addition of chlorophyll-a concentration to the model the fit became much better: p=0.002[16] and 68% of the variance was accounted for. The resulting model is given in equation 5.1 (chlorophyll-a and load were not correlated (p= 0.534)).

$$C_e = 0.3738\,\lambda_s + 0.0584\,\text{Chl-a} - 8.1 \qquad (5.1)$$

where

C_e = effluent total BOD concentration (mg O_2 /l)
λ_s = surface BOD loading applied to the ponds (kg/ha.d)
Chl-a = chlorophyll-a concentration in the effluent (µg/l)

[16] null hypothesis: slope= 0 (H_0: β=0)

The model suggests that the effect of algae in the effluent has a significant impact on the effluent BOD concentration and explains the poor correlation with load alone. However, 32% of the variability remains unaccounted for. The incorporation of temperature to the model led to no improvement in the fit (68% variance accounted for).

The effluent concentration of the pilot-ponds had a linear relationship with the percentage concentration removal due to the influent BOD concentration being fixed at 485 mg/l. Therefore, for percentage removal equation 5.1 becomes:

$$\% \text{ removal} = 101.71 - 0.0754\,\lambda_s - 0.01227\ \text{Chl-a} \qquad (5.2)$$

As the relationship is linear across the range of test loadings (51-169 kg/ha.d), it is reasonable to assume that the optimum surface BOD load for BOD removal is >169 kg/ha.d.

The fitted removals at various loadings and chlorophyll-a values are given in Table 5.2, which shows that when the chlorophyll-a concentration is zero, a loading of 150 kg/ha.d gives a BOD removal of around 90%. Table 5.2 also shows that the impact of algae on unfiltered BOD removal is quite considerable, thus emphasising the need for algal removal facilities. The remaining variation may be due to other solids entering the effluent such as protozoa, fly larvae, rotifers and sludge feedback solids (see Sections 5.5.4 and 6.4). The filtered BOD removal should give a clearer picture of the effect of loading in the absence of the effect of all these solids.

Table 5.2 Fitted values of % BOD removal from equation 5.2 at various loadings and chlorophyll-a concentrations.

λ_s (kg/ha.d)	Chlorophyll-a concentration (µg/l)		
	0	500	1000
50	97.9	91.8	85.7
100	94.2	88.0	81.9
150	90.4	84.3	78.1

5.2.3 Filtered BOD removal and effluent quality

A graph of the average monthly BOD concentration of filtered effluent samples from all ponds is given as Figure 5.6. The separation between the different loadings is clearer than in Figure 5.4, particularly during Phase 2 when the loadings were 167, 116 and 63 kg/ha.d. The loading of 169 kg/ha.d applied to the blue pond appeared to cause a steady decrease in quality throughout Phase 2 and did not recover until the loading was reduced in March 2001. The loading of 116 kg/ha.d, applied to the Green pond to July 2001, generally gave a worse quality effluent than from July 2001 when the loading was reduced to 82 kg/ha.d. During Phase 4 (from July 2001 onwards), the loading range was narrower (63-107 kg/ha.d), and the difference in quality also became less. The average concentrations for each phase are summarised in Table 5.3.

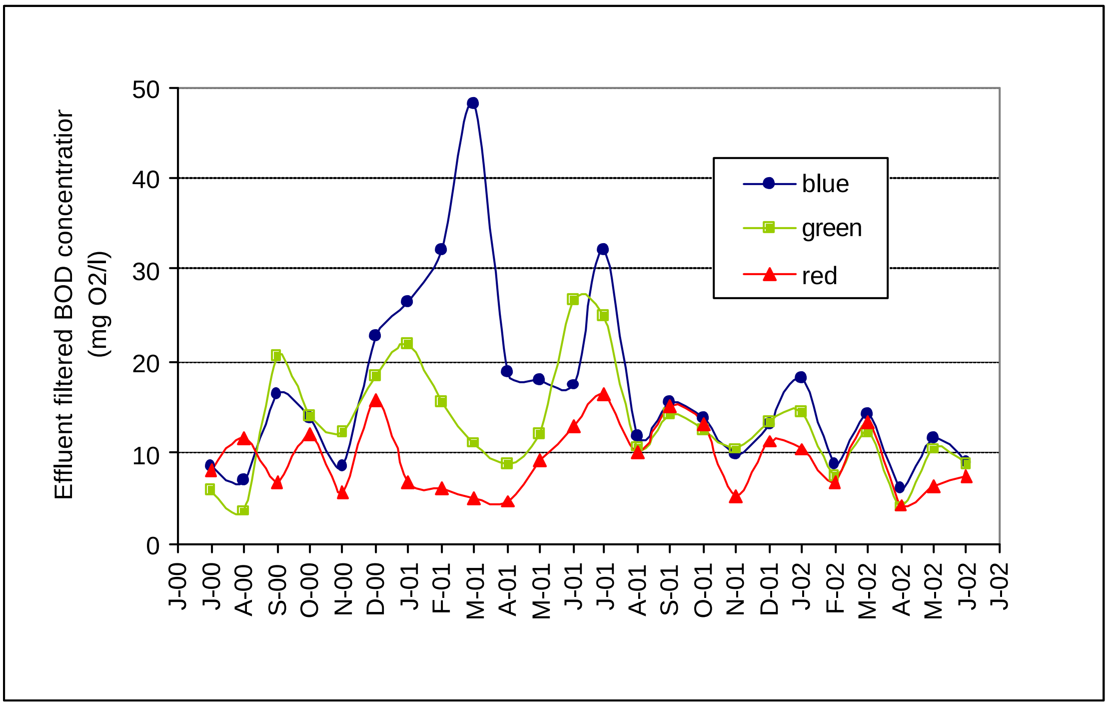


Figure 5.6 Monthly BOD filtered effluent concentration

Table 5.3 The mean filtered effluent BOD concentration (mg O_2 /l) for each pond in each phase

Phase	λ_s (kg BOD /ha.d)	Filtered BOD concentration (mg O_2/l) (95% CI)	n	ANOVA p=
1 July-Sept 2000	51	10.6 (±5.5)	6	0.863
	62	10.1 (±8.7)	6	
	63	8.8 (±3.4)	6	
2 Sept 2000-March 2001	169	23.4 (±10.1)	11	0.008
	116	16.6 (±5.6)	11	
	63	8.2 (±4.3)	11	
3 March -July 2001	117	21.4 (±7.3)	9	0.016
	116	17.9 (±7.3)	9	
	63	9.8 (±3.0)	9	
4 July 2001 – June 2002	107	14.1 (±3.4)	24	0.076
	82	11.7 (±2.5)	24	
	63	10.1 (±1.8)	25	

Table 5.3 shows strong evidence of an effect of loading on effluent concentration in Phases 2 and 3. The effect became marginal in Phase 4 when all the loadings were below 107 kg/ha.d. Regression analysis on the effect of surface BOD loading on the filtered effluent concentration gave an excellent fit with 86% of the variance accounted for and p <0.001; the scatterplot is shown in Figure 5.7. This gives strong evidence that the BOD surface load is the principal variable for the determination of effluent concentration and thus concentration removal efficiency of BOD, when the effects of effluent solids are removed. The fitted line is given in equation 5.3.

$$C_{e(filt)} = 0.1321\ \lambda_s + 1.76 \qquad (5.3)$$

where $C_{e(filt)}$ = filtered effluent BOD concentration.

The equivalent equation for removal efficiency is given by:

$$\%\ \text{removal} = 99.642 - 0.0273\ \lambda_s \qquad (5.4)$$

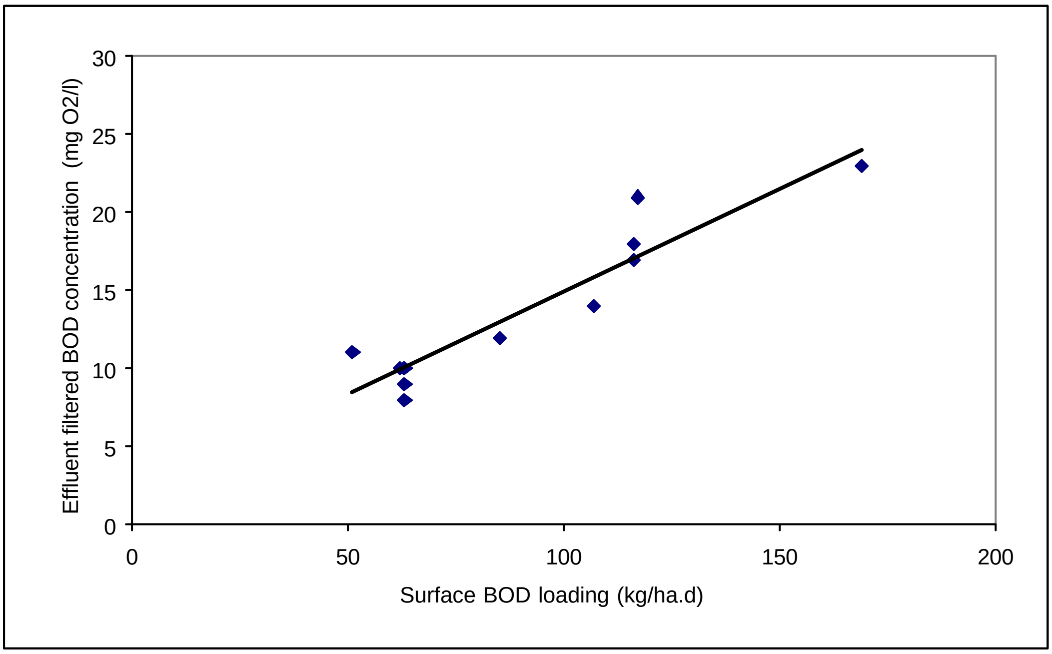


Figure 5.7 Average filtered effluent BOD concentration against surface loading

Again the relationship is linear across the range of loadings, but the decline in performance experienced at 169 kg/ha.d (as shown in Figure 5.6) suggests that had this loading been continued, the significant loss in performance could have affected the model. It should also be noted also that the lower loadings, associated with better performance, were clustered around the start-up period in Phase 1. Start-up conditions were expected to be more conducive to better performance as the full loading was not reached and there was no sludge accumulation.

5.2.4 BOD load removal

The base flow into each pond was set by the speed of the associated pump. It was assumed that the only other source of inflow was direct rainfall, and only this and evaporation could materially affect the outflow. The relative contribution of rainfall/evaporation affected the inflow by up to 30% and depended on the surface areas of the ponds (blue>red>green) and the inflow rates from the pumps (blue>green>red).

Outflow was assumed as:

Outflow (m^3/d) = Inflow (m^3/d) + direct rainfall - direct evaporation from pond surface (m^3/d)

Hence, the load removal (g BOD/d) could potentially differ from the concentration removal, due to the effects of rainfall and evaporation, by up to 30%. After the application of regression analysis to the load removal (%), a similar pattern emerged to the concentration removal. Total BOD removal had a significant relationship with surface BOD loading and chlorophyll-a (the relationship is shown in equation 5.5) and filtered BOD load removal (%) had a significant relationship with surface BOD loading only (equation 5.6).

$$\% \text{ total BOD load removal} = 99.39 - 0.067\ \lambda_s - 0.01\ \text{Chl-a} \qquad (5.5)$$

$$\% \text{ filtered BOD load removal} = 99.31 - 0.025\ \lambda_s \qquad (5.6)$$

These models give statistically similar removal efficiencies to the concentration removal models ($p=0.571$ and $p= 0.758$ respectively).

5.2.5 The effect of hydraulic retention time on BOD removal

BOD surface load and hydraulic retention time were both determined by the inflow rate, consequently, the two parameters were highly correlated ($p<0.001$). An experiment to partition these parameters by applying different dilutions to the influent wastewater and then applying the same flow rate to each pond was planned for the summer of 2002, but was not possible due to equipment and time constraints. Inevitably, therefore, with the available data, BOD effluent concentration was also significantly correlated with hydraulic retention time. The relationships are shown in equations 5.7 and 5.8.

$$C_e = 69.9 - 0.528\ R + 0.0565\ \text{Chl-a} \quad (68.1\% \text{ variance; } p = 0.002) \qquad (5.7)$$

$C_{e(filt)} = 28.7 – 0.176$ R (75.4% variance; $p < 0.001$) (5.8)

where R = hydraulic retention time (days)

These models are not as useful for prediction most likely due to the long hydraulic retention times applied to the ponds (38 – 110 days) which were not fixed. A lower percentage variance is accounted for by equation 5.8 than by equation 5.3. This is the only evidence available to suggest that surface loading is the key variable for BOD removal, rather than hydraulic retention time, over the test range.

5.2.6 BOD removal: comparison with McGarry and Pescod (1970)

The model of McGarry and Pescod (1970) for BOD removal as described in Section 2.61 is repeated in equation 5.9.

$$\lambda_r = 10.75 + 0.725\ \lambda_s \qquad (5.9)$$

where λ_r = surface BOD removal (kg/ha.d).

Their model infers that surface removal is dependent on surface loading and independent of other parameters. Regression analysis on the BOD data from the pilot-scale ponds showed an extremely similar relationship to that found by McGarry and Pescod:

$$\lambda_r = 5.08 + 0.8278\ \lambda_s \qquad (5.10)$$

This model, which has 98.5% of the variance accounted for and $p<0.001$, is plotted as Figure 5.8. The range of the model is 51-169 kg/ha.d, and again is linear, suggesting that the optimum loading is more than 169 kg/ha.d. The model infers that load and area are important, yet application of a similar model to load (g BOD /d) only gives a similar fit:

BOD $load_{rem}$ (g/d) = 0.885 BOD load (g/d) (98.6 % variance; $p<0.001$) (5.10a)

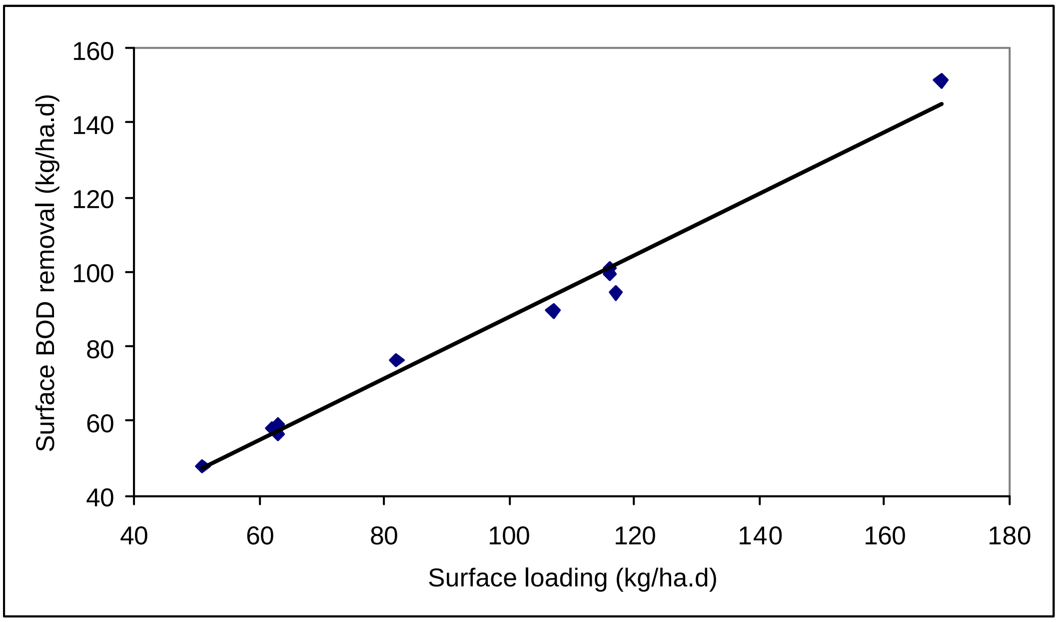


Figure 5.8 Average surface removal against surface loading (as McGarry and Pescod)

This model reflects the very high removal efficiency over the test range and is not sensitive to relatively small changes in effluent concentration compared to the very large difference between influent and effluent concentration. If the model were taken as is, it suggests that, over the test range, BOD loading does not affect removal efficiency (it is 88.5% at all loadings). However, the previous analysis of the effluent concentration, in Section 5.2.4, shows this was not so for the pilot-pond data.

McGarry and Pescod used empirical data from 143 climatic conditions and noted that their surface loading data were not independent of temperature (higher loadings were associated with higher temperatures). The pilot-pond data were all collected at the same site, thus providing evidence in support of the McGarry and Pescod model in the absence of this uncertainty.

5.2.7 BOD removal: comparison with Marais and Shaw (1961)

The Marais and Shaw model was described in Section 2.5.4; for a single pond equation 2.7 may be expressed as:

$$\frac{C_o}{C_n} - 1 = k_c R \tag{5.11}$$

This model uses temperature and hydraulic retention time as the key variables for BOD removal. A plot of (C_o / C_n)-1 against R for the pilot-pond data is given in Figure 5.9. The model has a fit of 37.9% ($p<0.001$), the estimate for k_c is 0.1414 d^{-1} (±0.0262 95% confidence interval). This is evidence that Marais and Shaw's model has some validity in this case, though loading and hydraulic retention time were not partitioned in the pilot-scale experiments.

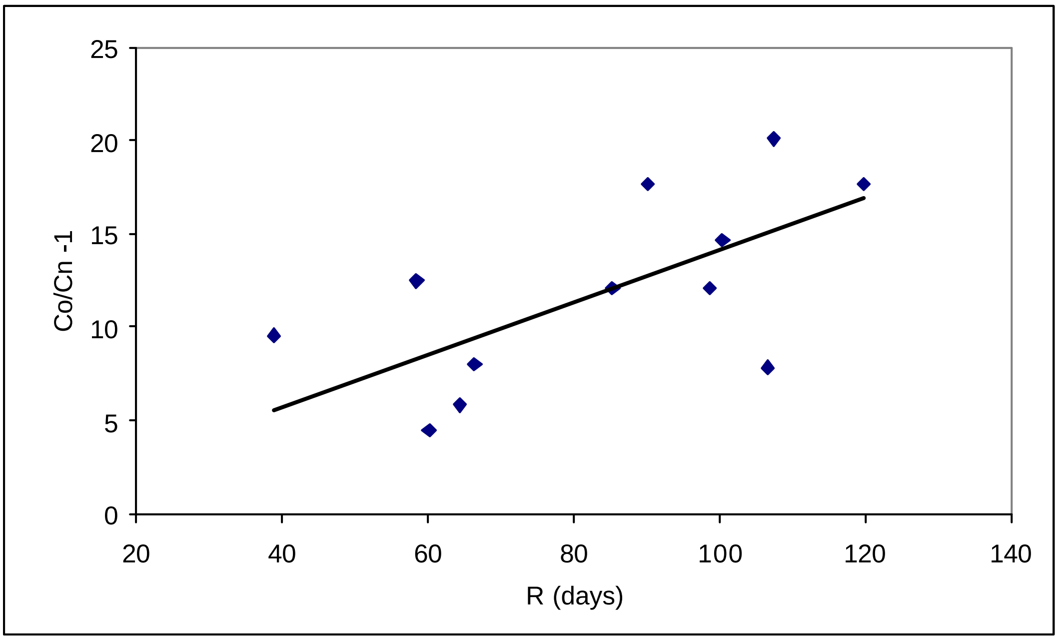


Figure 5.9 Modelling of pilot-pond data as Marais and Shaw

5.3 Suspended solids removal

Suspended solids removal is a complex issue in primary facultative ponds due to the capacity of the system to produce solids in the form of biological (mainly algal) cells. This internal production complicates the calculation of the non-algal suspended solids removal as the algal cells cannot be readily distinguished from other suspended solids using standard laboratory techniques. The mean concentration of suspended solids in the influent wastewater (as detailed in Appendix A) was 1078 mg/l. The mean concentration of suspended solids in the supernatant of the settleable solids test was 187.5 mg/l, thus it is assumed that 83% of the suspended solids settled to form sludge and 17% directly entered the pond liquid. Of the solids entering in the sludge, a proportion of this feeds back to the water column, so a direct 83% reduction in SS by sedimentation cannot be assumed.

The average monthly effluent SS concentrations for all the ponds are shown in Figure 5.10. There appears to be a seasonal effect (generally higher concentrations in summer than winter), though no obvious overall difference between the ponds (and hence loading). The average concentration for each experimental phase is given in Table 5.4. This supports the assertion that surface BOD load is possibly not an important parameter for SS effluent concentration.

Table 5.4 The mean effluent SS concentration (mg /l) for each pond in each phase

Phase	λ_s (kg BOD /ha.d)	SS concentration (95% CI)	n	ANOVA p=
1 July-Sept 2000	51	46.6 (±21.8)	8	0.410
	62	40.2 (±15.3)	8	
	63	56.5 (±22.3)	8	
2 Sept 2000-March 2001	169	39.1 (±10.9)	11	0.060
	116	25.0 (±6.8)	11	
	63	25.2 (±11.6)	12	
3 March -July 2001	117	79.5 (±22.7)	9	0.948
	116	75.2 (±15.1)	9	
	63	75.3 (±32.8)	9	
4 July 2001 – June 2002	107	71.7 (±24.3)	24	0.354
	82	51.4 (±11.6)	24	
	63	71.8 (±30.2)	25	

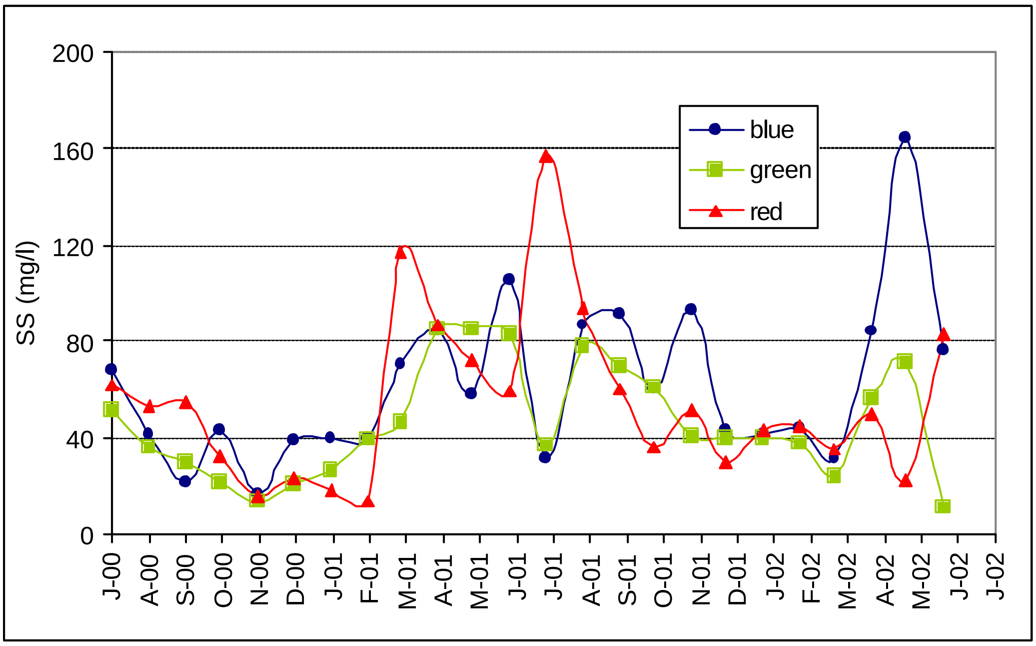


Figure 5.10 The monthly average SS concentration in the effluent (all ponds)

A marginal difference was experienced only in Phase 2; this was a winter period when the loadings were most different. Peaks in the concentration, as shown in Figure 5.10, may be attributed to algal or other cells observed in the effluent (eg. mosquito larvae, see Section 5.5.4.); with the exception of the peak in the Blue pond effluent in April 2002, which appeared, on visual inspection, to be due to sludge-feedback. Stepwise regression analysis on BOD loading, SS loading, hydraulic retention time, temperature and chlorophyll-a revealed the only significant relationship was that with chlorophyll-a. This relationship is given in equation 5.12 and shown as Figure 5.11.

$$SS_{out} = 32.88 + 0.0679 \text{ Chl-a} \quad \text{(variance 63.4 \%; p=0.001)} \qquad (5.12)$$

This outcome is not surprising due to the complex nature of SS removal in facultative ponds. This model suggests that, in the test range, effluent SS concentrations in excess of 33 mg/l are most likely due to the contribution of algal solids.

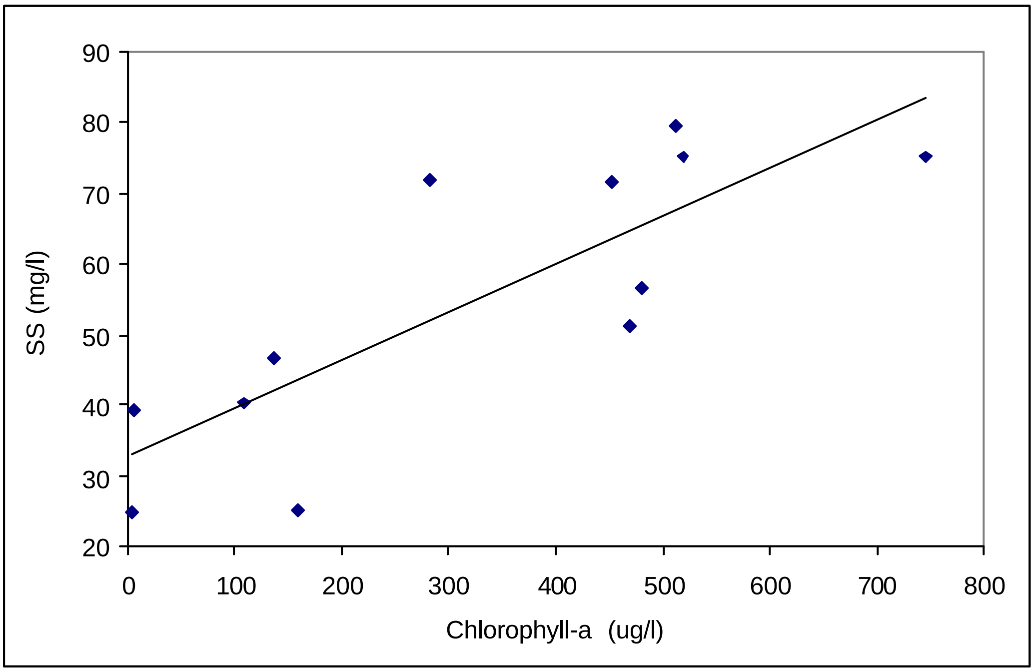


Figure 5.11 Relationship between chlorophyll-a and SS concentration in the effluent

5.4 Ammonia removal

The ammonia concentration in the influent showed seasonal fluctuations, therefore local means were calculated as detailed in Appendix A. The ammonia concentrations in the effluent for all ponds are shown in Figure 5.12; the percentage concentration removals are shown in Figure 5.13. There are three striking features of these graphs. Firstly, an effect of surface BOD load on removal is apparent up to the end of July 2001 (Phase 3), after which the removal efficiencies for all ponds became more similar. Secondly, the overall removal was much better in the first year than the second. Thirdly, there appears to be better removal in summer periods than winter periods: during January and February 2002, removal dropped to around zero.

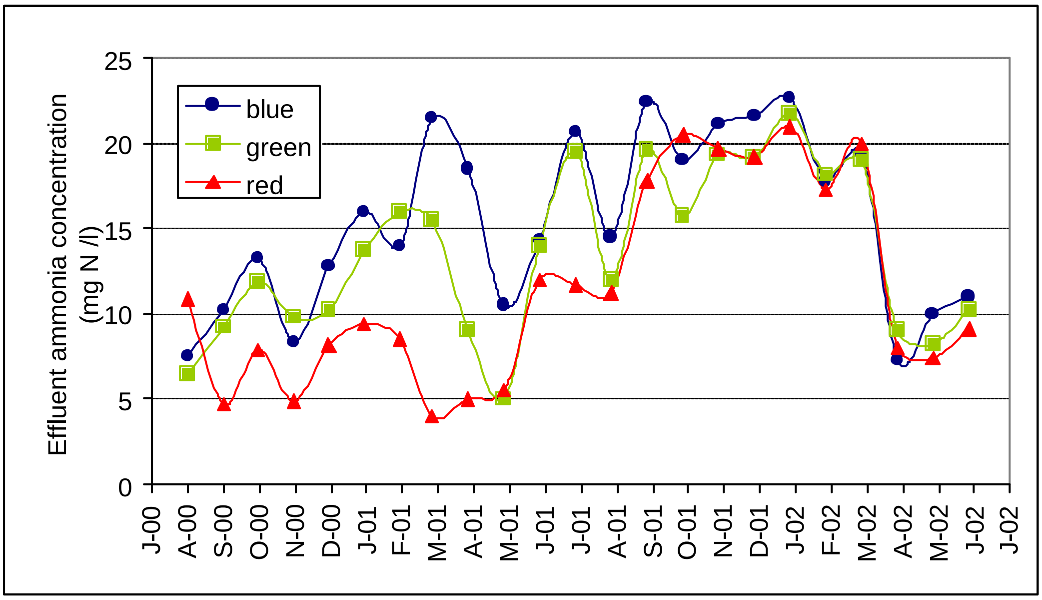


Figure 5.12 Ammonia concentration in the effluent all ponds

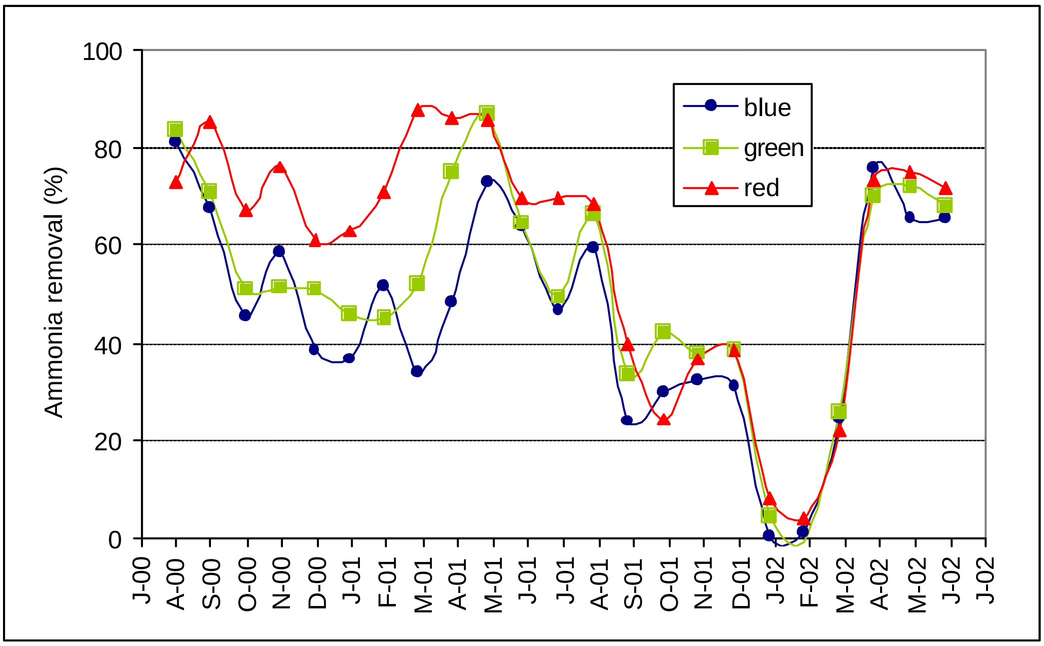


Figure 5.13 Ammonia concentration removal all ponds

5.4.1 Ammonia removal: the effect of surface BOD load

The average concentration removals for each experimental phase are shown in Table 5.5. The ANOVA significance probabilities suggest that surface BOD loading had a relationship with ammonia removal in Phases 2 and 3, but not in Phase 4; this may be due to the narrowing of the loading range in Phase 4. A simple linear regression analysis (as shown in Figure 5.14) revealed that ammonia removal was only marginally correlated with surface BOD loading ($p=0.062$; variance accounted for 23.7%). When the data were partitioned for phase (as shown in Figure 5.14a) it is becomes clear that the data were not distributed randomly, supporting the suggestion that other factors such as season or year were important. This is because Phase 2 was during a winter period, Phase 3 was during a short summer period and Phase 4 was during the whole of the second year.

Table 5.5 The mean ammonia removal efficiency (%) for each pond in each phase

Phase	λ_s (kg BOD /ha.d)	Ammonia-N removal (95% CI)	n	ANOVA p=
1 July-Sept 2000	51	75.8 (±12.2)	5	0.919
	62	78.6 (±9.9)	5	
	63	77.8 (±18.2)	5	
2 Sept 2000- March 2001	169	44.2 (±9.0)	11	<0.001
	116	48.3 (±4.5)	11	
	63	68.4 (±6.2)	12	
3 March -July 2001	117	59.3 (±10.1)	9	0.005
	116	70.1 (±9.9)	9	
	63	79.7 (±7.46)	9	
4 July 2001 – June 2002	107	35.6 (±10.7)	24	0.494
	82	41.9 (±11.2)	24	
	63	44.4 (±11.3)	25	

There was a strong correlation between surface ammonia removal ($g/m^2.d$) and surface ammonia loading ($g/m^2.d$) ($p<0.001$; 48.9%), but not as strong as the BOD equivalent as detailed in Section 5.2.6. Surface ammonia loading was also strongly correlated with surface BOD loading ($p<0.001$), so it is not certain which of these was a key explanatory variable.

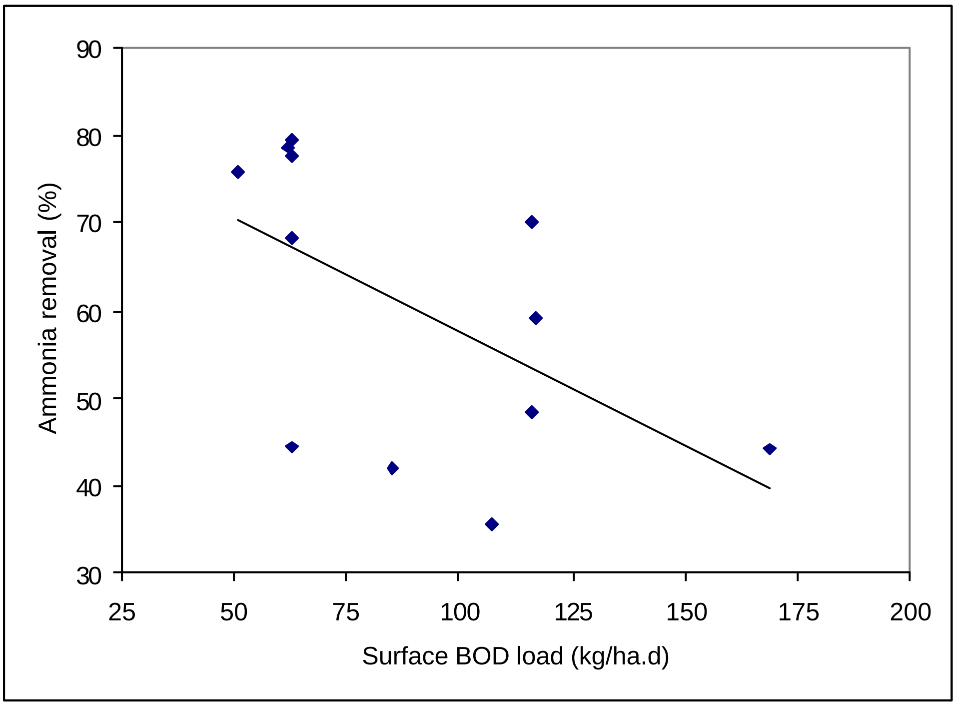


Figure 5.14 Average ammonia removal against surface BOD load

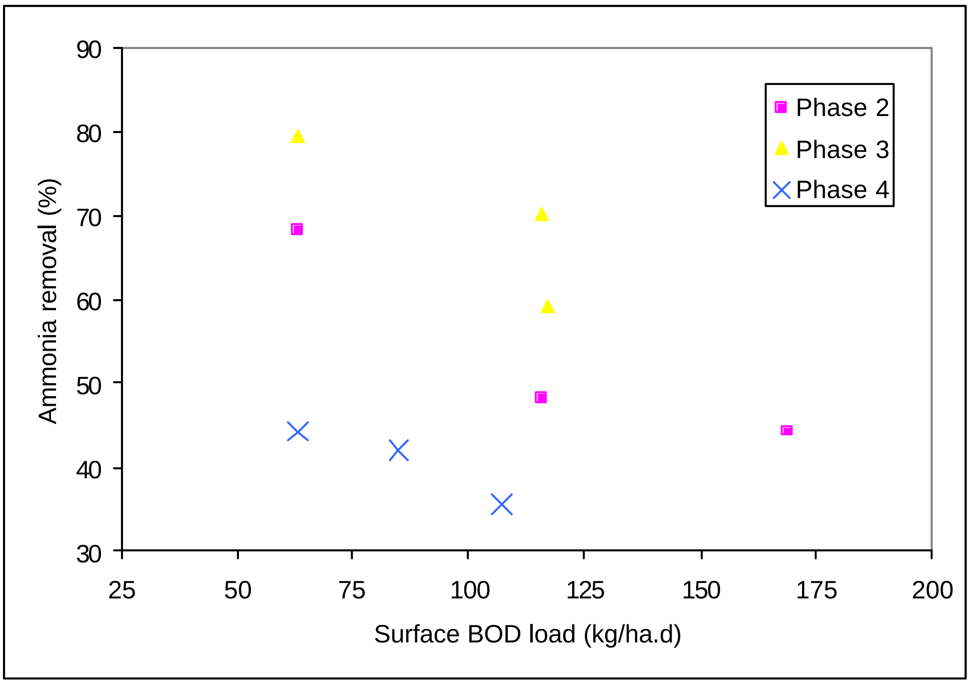


Figure 5.14a Ammonia removal against surface BOD load partitioned for phase

5.4.2 Ammonia removal: the effect of year of operation and season

The ammonia concentrations in the effluent from all ponds were significantly ($p<0.001$) higher in the second year than the first. Figure 5.15 shows that 75% of the values from the second year were above the median value for the first year. Not only were the effluent concentrations different between the two years, but also the relationship between the effluent ammonia concentrations and surface ammonia loadings was also different (Figure 5.16).

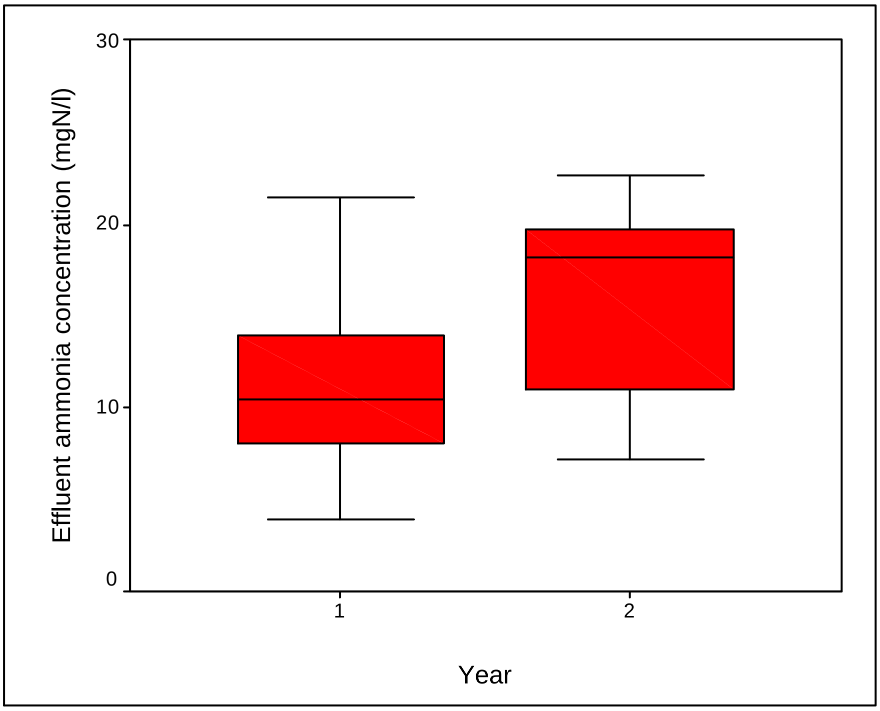


Figure 5.15 Boxplot of effluent ammonia concentration from all ponds; comparison of Years 1 and 2

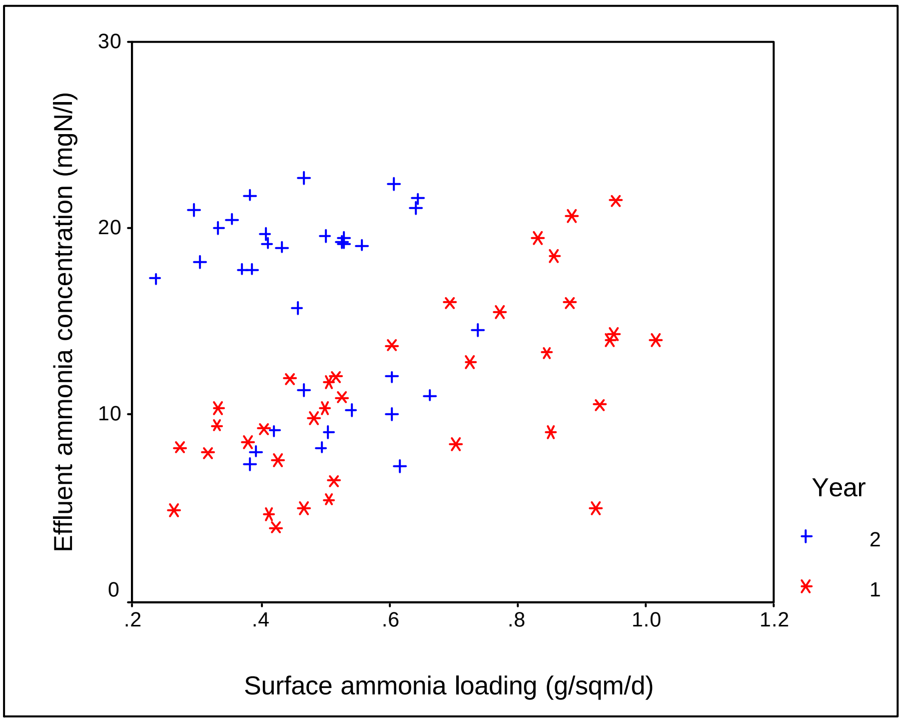


Figure 5.16 A scatterplot of effluent concentration against ammonia loading partitioned for year

Figure 5.17 shows the monthly variation in surface ammonia removal for both years. The surface removal for April – August appeared to be consistently above the overall mean, while for January-March and September-December, most values appeared to be below the overall mean. Therefore, to examine seasonal effects, the data for months between April and August were assigned "summer" and for other months "winter". Figures 5.18 and 5.19 show the relationships between surface ammonia loading and effluent concentration partitioned for season: Figure 5.18 is for the second year and Figure 5.19 is for the first year. In the second year, the seasonal effect is very marked with much higher effluent concentrations in winter than in summer for the same surface loading. In the first year of operation, there does not appear to be an effect of season, with summer and winter values well mixed; note that the loading range here is wider than the second year. This difference in seasonality between the two years may be due to the evolution of the pond over time: perhaps during the first year of operation insufficient sludge had accumulated to feedback significant quantities of ammonia into the pond water. Also, the pilot-scale ponds experienced a duckweed infestation (see Appendix B) during the first winter which had the potential to take up ammonia. A third year's data would be useful to confirm this. Because the second year was not affected by duckweed and had an established sludge layer, it is sensible to assume that this year's data give a better prediction of pond performance for ammonia removal.

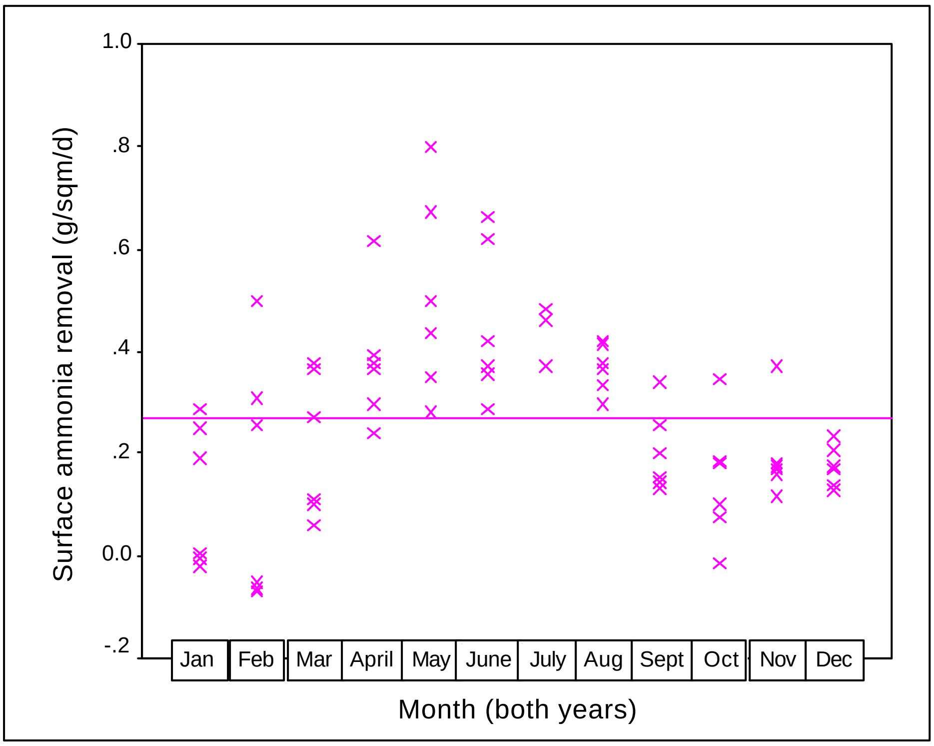


Figure 5.17 Monthly surface ammonia removal (both years) with overall mean line

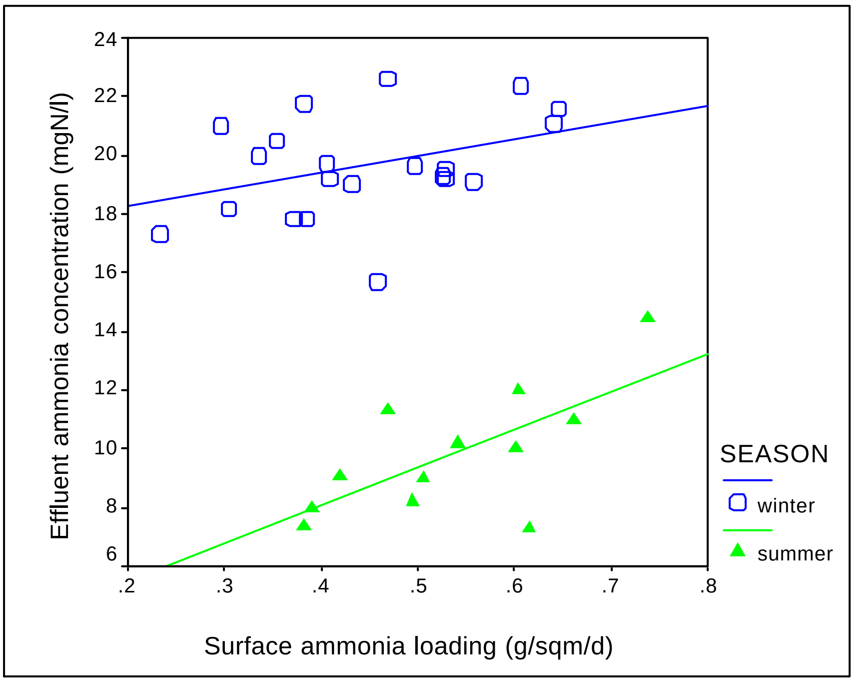


Figure 5.18 The relationship between ammonia surface loading and effluent concentration in Year 2 partitioned for season

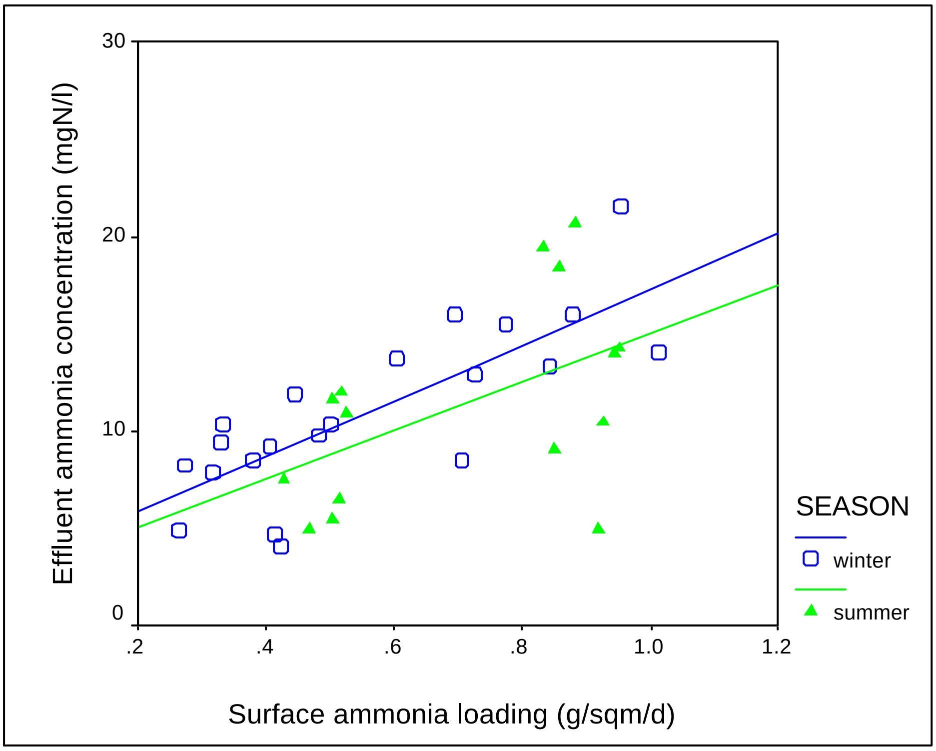


Figure 5.19 The relationship between ammonia surface loading and effluent concentration in Year 1 partitioned for season

5.4.3 Ammonia removal: key parameters

Using the data from the second year, there appeared to be a strong correlation between the surface ammonia removal (g / m^2 /d) and the pH and surface temperature as shown in Figures 5.20 and 5.21. In both cases $p<0.001$ and the variance accounted for was 55.9% and 55.5% respectively. Thus the data provide evidence in support of the volatilisation model for ammonia removal. As the pH and surface temperature were also strongly correlated ($p<0.001$), it is not possible to tell which was the key parameter. Ammonia removal was also correlated ($p< 0.001$) with the chlorophyll-a concentration as shown in Figure 5.22 providing evidence in support of the algal uptake model; though the fit was not as close as for pH and temperature: the variance accounted for was 39.6%. The effect of hydraulic retention time on the ammonia effluent concentration as shown in Figure 5.23 suggests there was only a relationship during the summer. This may be because ammonia removal processes only occurred during the summer months, thus the retention time in winter had no effect. The effluent concentration was used in Figure 5.23 because the surface removal already had a relationship with the hydraulic retention time as the latter was not partitioned with surface loading.

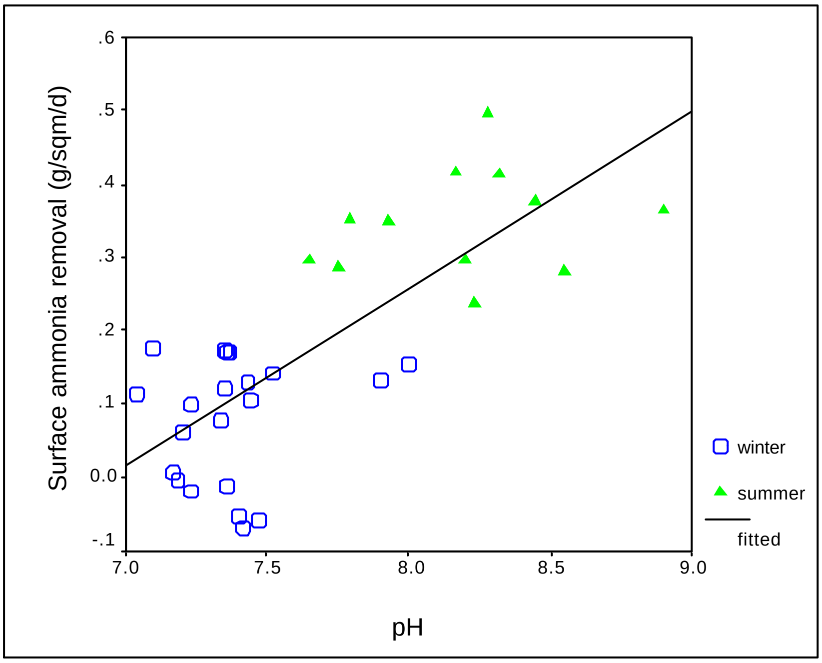


Figure 5.20 The relationship between surface ammonia removal and pH

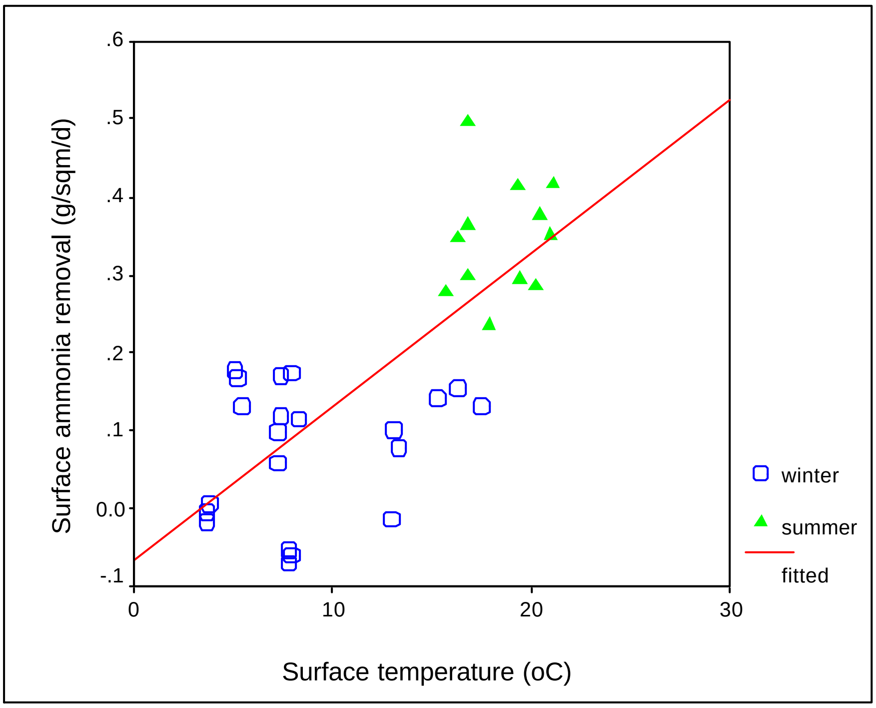


Figure 5.21 The relationship between surface ammonia removal and surface temperature

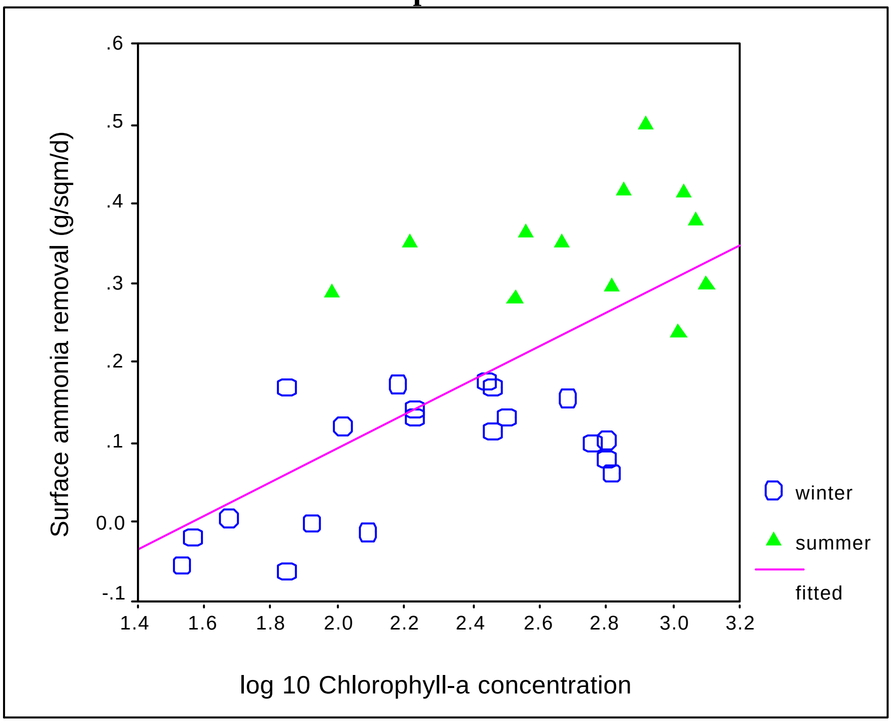


Figure 5.22 The relationship between surface ammonia removal and the chlorophyll-a concentration

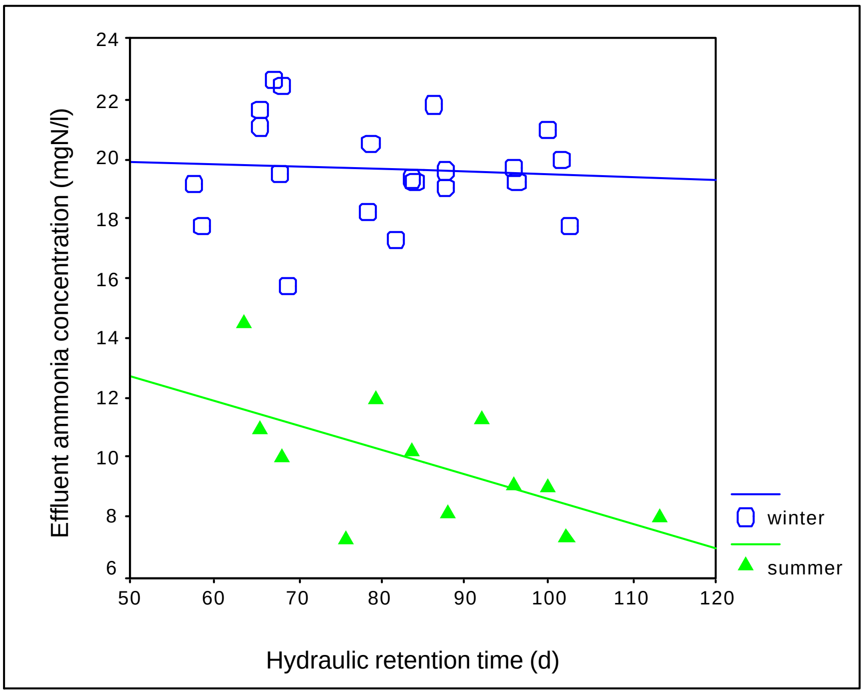


Figure 5.23 The relationship between effluent ammonia concentration and the hydraulic retention time

5.4.4 Ammonia removal: comparison with Pano and Middlebrooks (1982)

The model for ammonia removal in facultative ponds as proposed by Pano and Middlebrooks (1982) was given as equation 2.2 in Section 2.4.9.1 and is repeated here:

$$C_e = C_o / \{1 + [(A/Q)(0.0038 + 0.000134\,T).\exp((1.041 + .044T)(pH - 6.6))]\} \qquad (2.2)$$

Plots of actual ammonia effluent concentrations measured in the pilot-ponds against those predicted by Pano and Middlebrooks are given as Figures 5.24 and 5.25 for Years 1 and 2, respectively. In Year 1, although there was good correlation (p=0.001), most measured values were much lower than predicted by the model. The fit in Year 2 was much closer than the first year. The summer-fitted line suggests that the summer effluent ammonia concentrations in the pilot-ponds were lower than predicted, but that the winter concentrations were about the same as predicted by the Pano and Middlebrooks model.

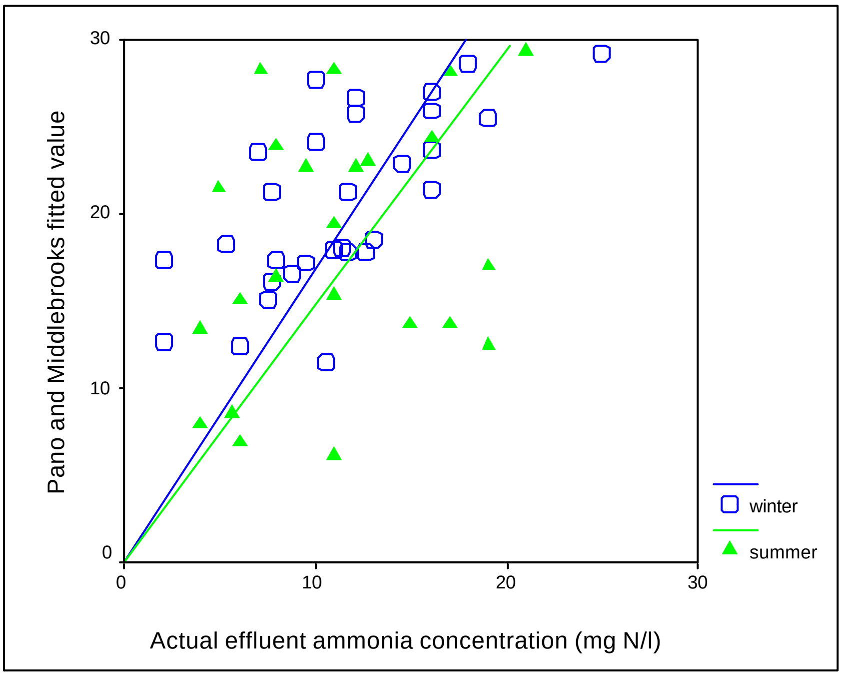


Figure 5.24 Scatterplot of ammonia effluent concentration against Pano and Middlebrooks predicted value Ce for first year (all ponds; partitioned for season)

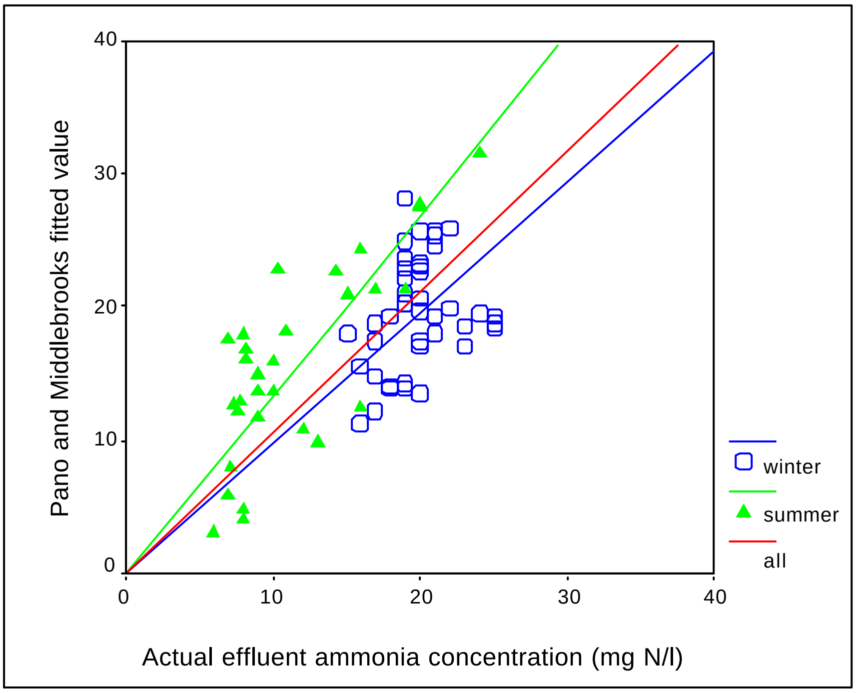


Figure 5.25 Scatterplot of ammonia effluent concentration against Pano and Middlebrooks predicted value Ce for second year (all ponds; partitioned for season)

5.4.5 Ammonia removal by nitrification

The effluent concentrations of nitrate and ammonia are shown in Figure 5.26. The effluent nitrate concentration was consistently less than 0.7 mg N/l and effluent nitrite concentration (not shown) was less than 0.01 mg N/l. Thus the data gave no evidence of nitrification for the removal of ammonia in the pilot-scale facultative ponds during the first two years of operation.

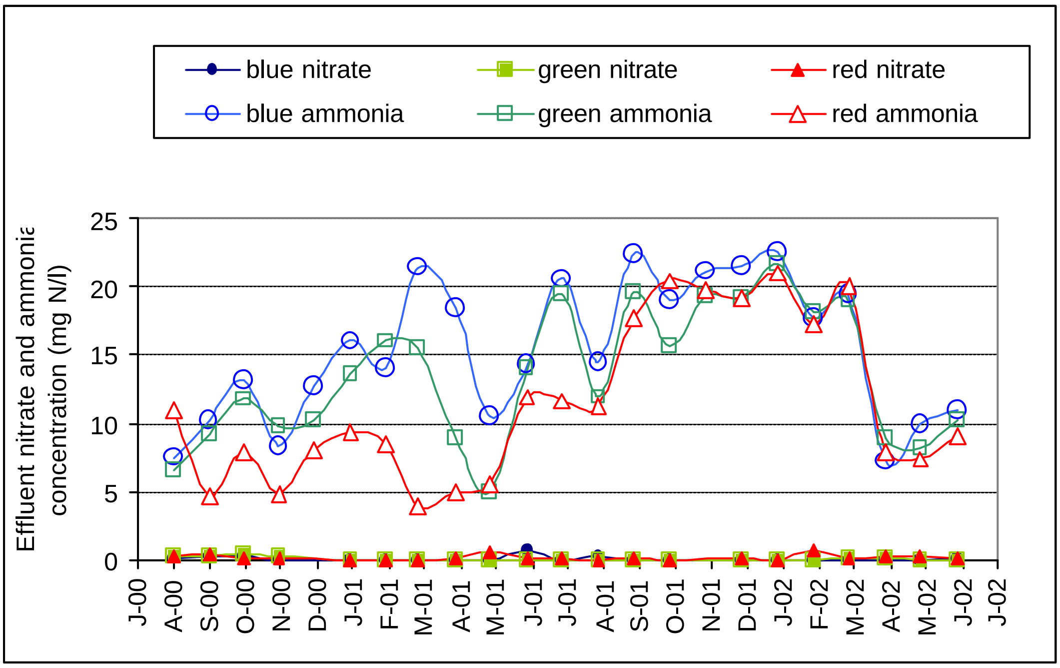


Figure 5.26 Nitrate and ammonia effluent concentrations (all ponds)

5.5 Facultative conditions

5.5.1 The chlorophyll-a concentration

A description of facultative conditions was given in Section 2.4; in Section 2.4.5 it was suggested that failure conditions could be identified by changes in biology and Pearson (1996) suggested that a steady chlorophyll-a concentration of less than 300 µg/l in the pond liquid indicated failure conditions. Figure 5.27 shows that the pilot-scale ponds experienced failure according to this criterion during the winter months; the length of this winter failure varied between the ponds. The winter failure for the first year started in November for the Red pond, September for the Blue pond and August for the Green pond. This initial failure was due to the duckweed infestation as described in Appendix B. The duckweed was removed in November 2000, by which time the chlorophyll-a concentrations were very low and winter conditions prevailed; recovery did not occur until the following spring. The Red pond (with the lowest loading) recovered first, followed by Green and then Blue. This suggests that surface BOD loading affects the rate of recovery for the same environmental conditions. Recovery was accompanied by a very sharp increase in the algal populations. After the initial peak, the concentrations of chlorophyll-a in the Green pond generally declined; but the Blue pond concentrations were generally high all summer, declining from August. The summer fluctuations were more pronounced in the Red pond and the onset of winter failure occurred in September 2001. The second winter failure periods were shorter (3-4 month's duration); they were unhampered by duckweed and at lower surface BOD loadings than the first winter.

After the winter failure, the algal populations in all ponds in both years tended to recover between the end of February and the end of April, depending on the loading. The actual dates when the measured chlorophyll-a concentration in the column samples dropped below and rose above 300 μg/l are given in Table 5.6.

Table 5.6. The dates of failure and recovery (as identified by column chlorophyll-a concentrations) from spring 2001 onwards.

	Red pond	Green pond	Blue pond
1st Spring (recovery)	12th March 2001 63 kg/ha.d	9th April 2001 116 kg/ha.d	24th April 2001 117kg/ha.d
Winter failure	12th September 2001 63 kg/ha.d	18th December 2001 82 kg/ha.d	6th November 2001 107 kg/ha.d
2nd Spring (recovery)	19th March 2002 63 kg/ha.d	19th March 2002 82 kg/ha.d	26th March 2002 107 kg/ha.d

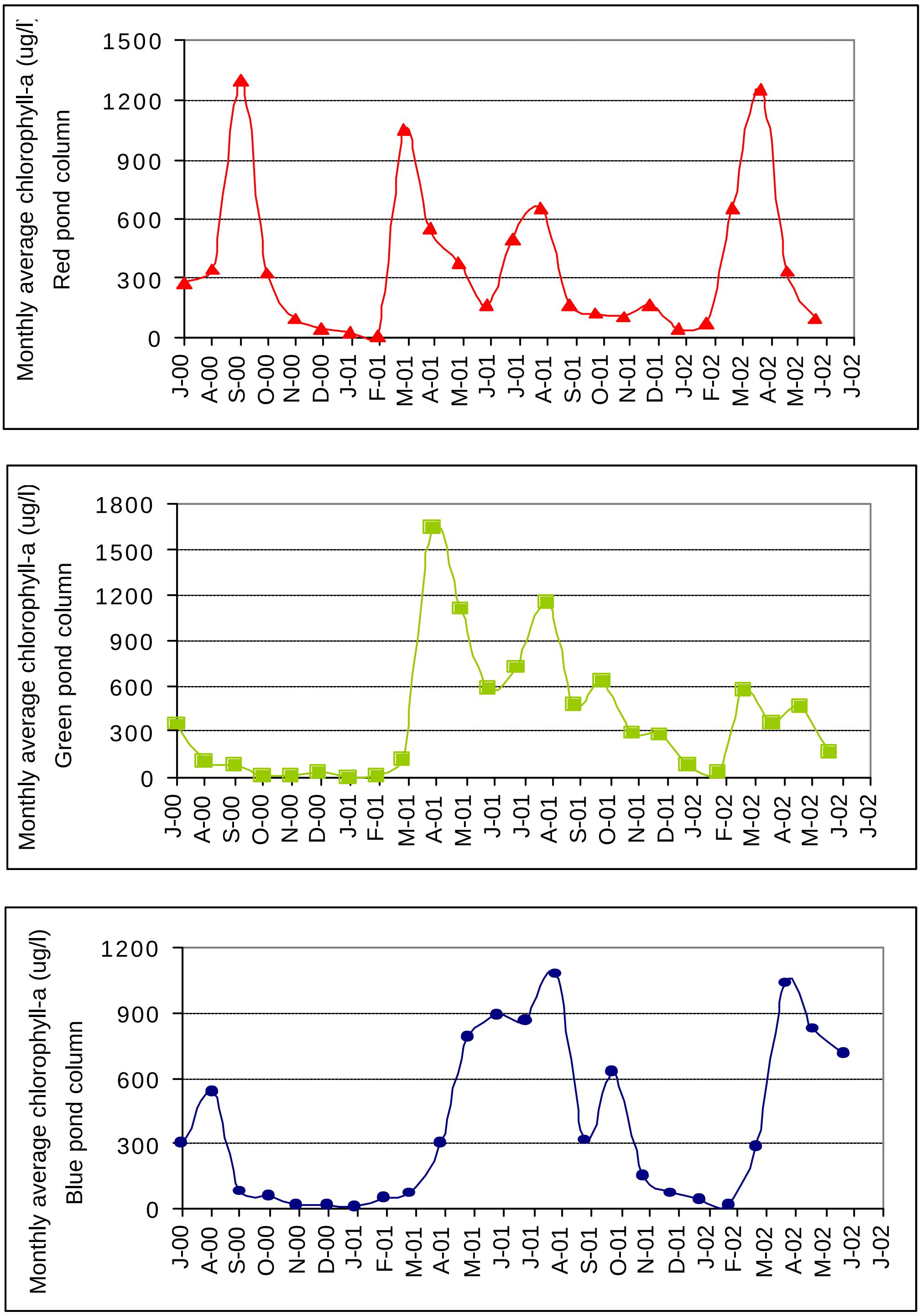


Figure 5.27 The average monthly chlorophyll-a column concentration for each pond

The Red pond recovered at almost at the same time during both springs and was subject to the same loading at both times. In the second spring, all ponds recovered within a week of each other at the loading range for Phase 4, but failed at different times in the autumn or winter. The pilot-scale experiment suggests that at the given loadings, primary facultative ponds in the UK climate will have a chlorophyll-a concentration of less than 300 μg/l during the winter for at least three months. It is uncertain, with the data available, if lower surface loadings would sustain a sufficient algal population during the winter as the onset of failure in the Red pond, on the 12th September, was earlier than the other two.

5.5.2 Dissolved oxygen concentration

Facultative conditions are accompanied by an oxygenated surface layer in the pond. Apart from algal photosynthesis, surface aeration and rainfall were identified as other sources of dissolved oxygen in Section 2.4.4. Therefore, the failure intervals may also be defined by the presence of dissolved oxygen at the surface. The DO concentration threshold is not clear, as it depends on the relative oxygen uptake rate of the system. Although the DO concentration takes into account non-algal sources, it is very variable from hour to hour and so the pilot-pond data, being taken from spot measurements, must be interpreted with more caution than the chlorophyll-a data.

The average monthly DO at the surface for each pond is given in Figure 5.28. The DO in all the ponds declined steadily from start-up, until November 2000. The winter concentration remained below 2 mg/l in the Red pond for two months, 2-4 months in the Green pond and 5 months in the Blue pond. The recovery in the Blue pond occurred sometime after the surface BOD loading was reduced from 169 kg/ha.d to 117 kg/ha.d on the 12 March 2001. The concentrations in all ponds fluctuated during the summer, sometimes reaching supersaturation; but the Green and Blue ponds "crashed" in July 2001. During the second winter, the duration of low concentrations was similar to those during the first (except in the case of the Red pond). Interestingly, the DO only dropped below 1 mg/l in the Red and Green ponds between 10 November and 18 December 2000

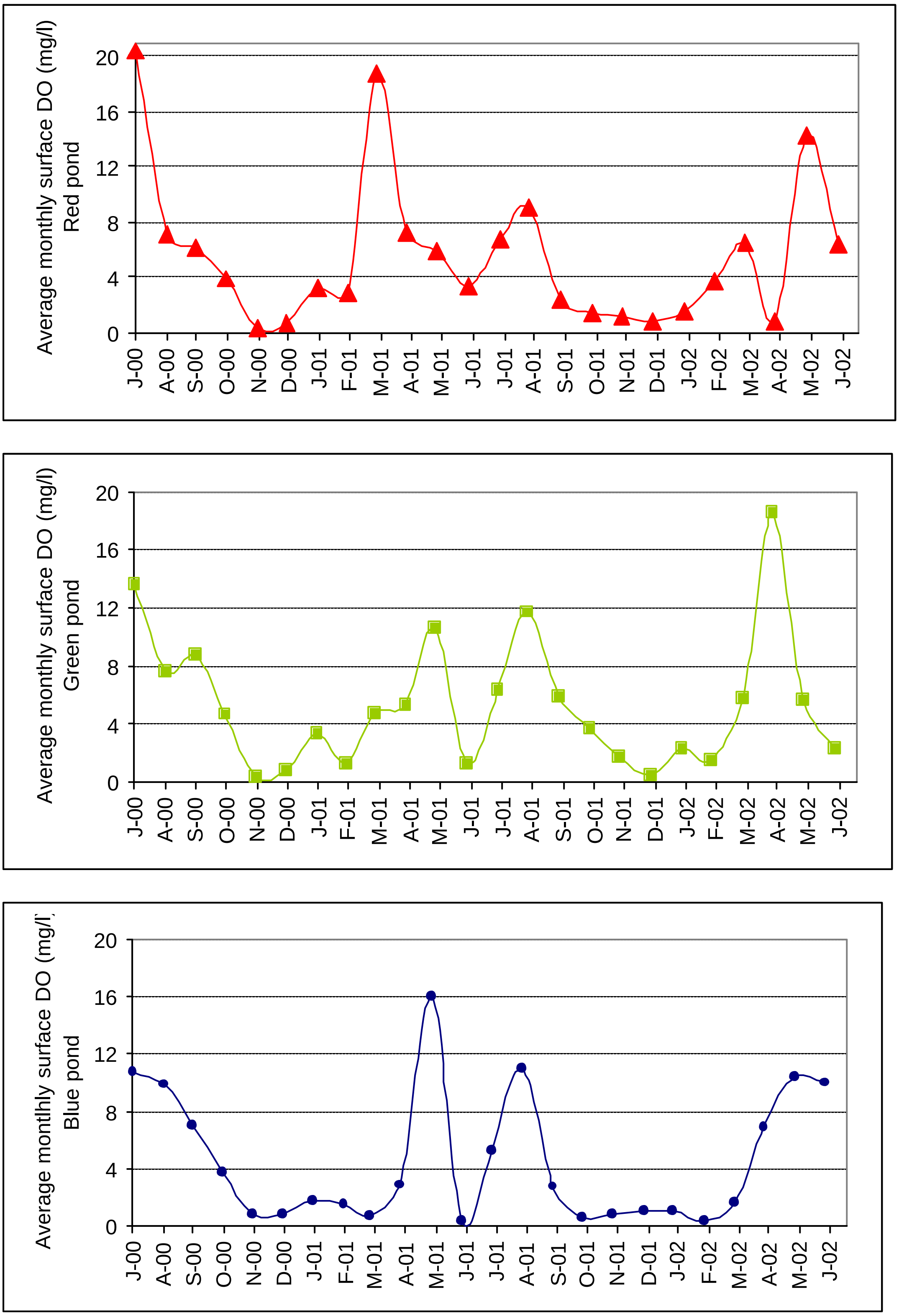


Figure 5.28 Average monthly DO concentration at the surface all ponds

and between 4 and 18 December 2001 respectively; however it was less than 1 mg/l in the Blue pond between 10 November 2000 and 18 April 2001. This suggests that, at loadings less than 100 kg/ha.d, non-algal sources of DO, combined with the higher solubility of oxygen at lower temperatures, and low uptake rates, are able to maintain DO concentrations of > 1 mg/l at the surface during much of the winter. However, during winter this layer of DO was usually less than 10 cm in depth.

The penetration of oxygen into the pond was measured by depth profiling as described in Section 4.5.4. The results of the DO % saturation profiles are given in Figures 5.29-5.34. Figures 5.29 and 5.30 are for the Red pond and suggest that during the first year of operation, the pond usually had low DO below 0.5 m depth at all seasons while the surface DO fluctuated between 3 % in November 2000 and 155% on the 12 March 2001. The profiles changed during spring 2002 when there were signs of DO penetration below 0.5 m, and on 7 May 2002 there was penetration to 1.0 m depth. By June 2002, the familiar shape of the profile from the previous year had returned.

Figures 5.31 and 5.32 are for the Green pond. They show a very similar picture to the Red pond profiles, but with higher DO in the second winter and lower DO during the second summer.

The Blue pond profiles are shown in Figures 5.33 and 5.34 and show a different picture to the other two, most noticeably that the pond appeared to be better mixed: DO penetrating deeper when present. The mid-winter profiles show that the whole pond could become devoid of oxygen, but this could also occur in mid-summer (see 5 June 2001, Figure 5.33.). Generally, DO concentrations were lower in the Blue pond than the other two during the first year, and much closer during the second year.

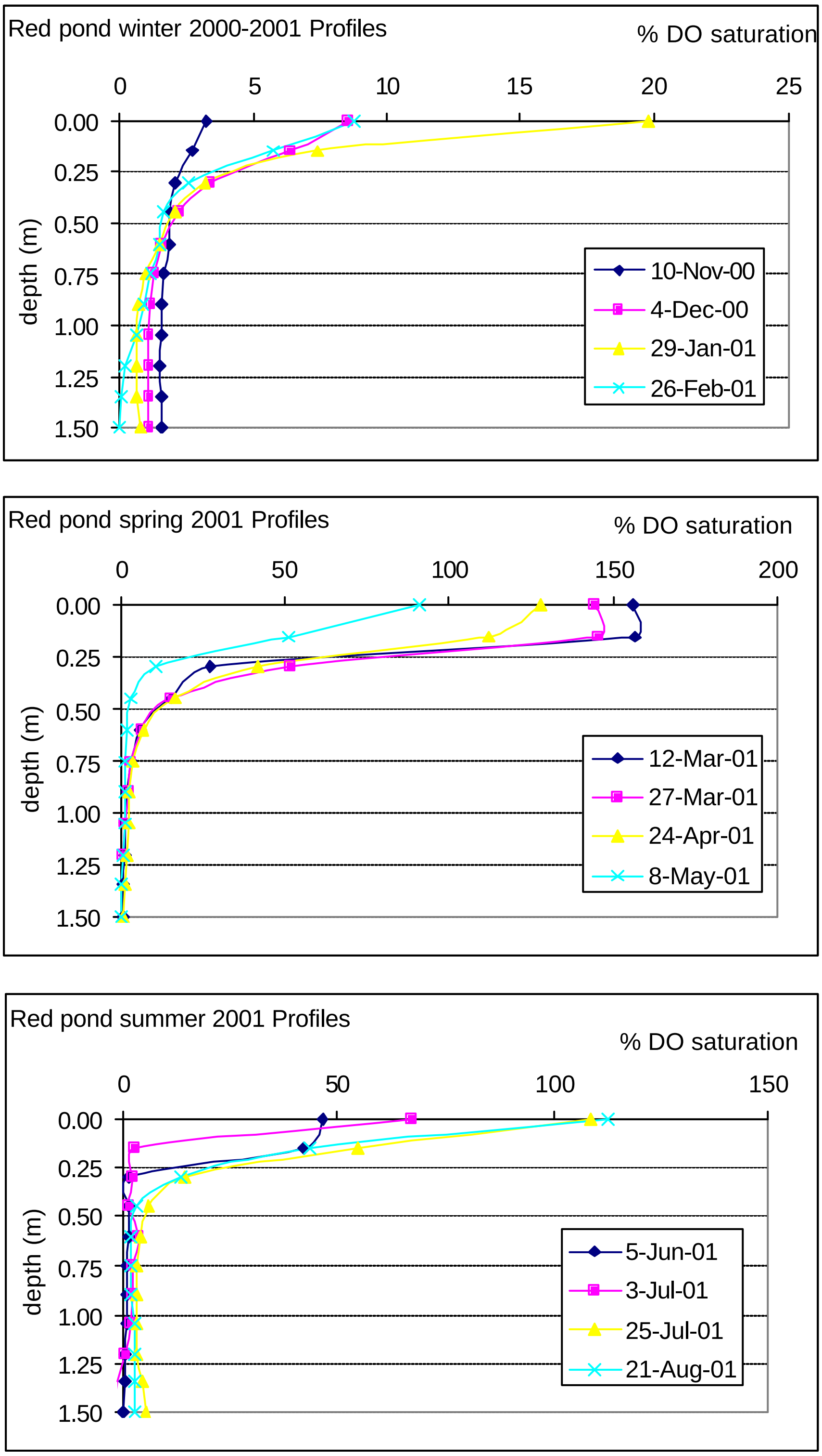


Figure 5.29 DO profiles for the Red pond (Nov 2000-Aug 2001)

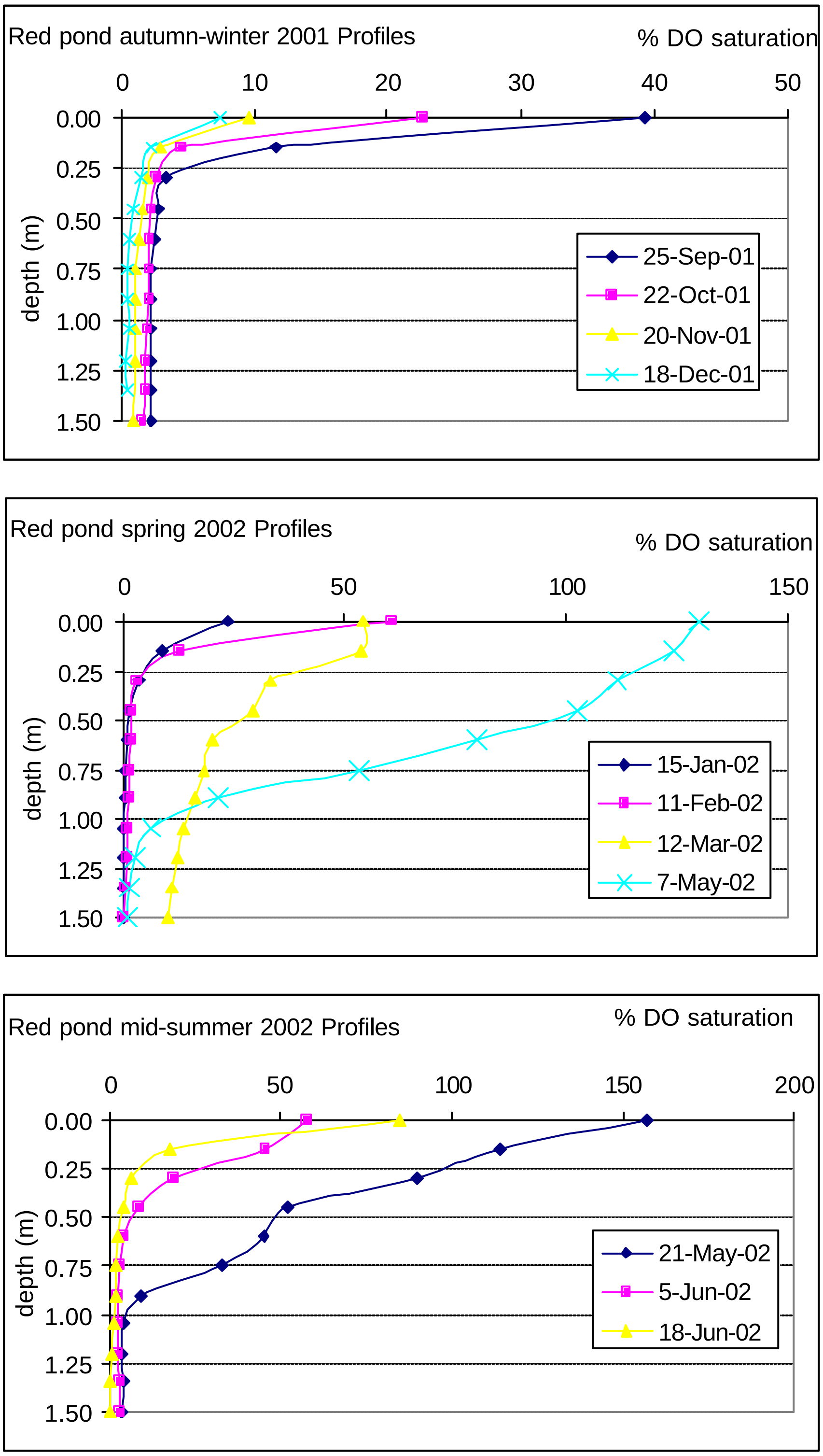
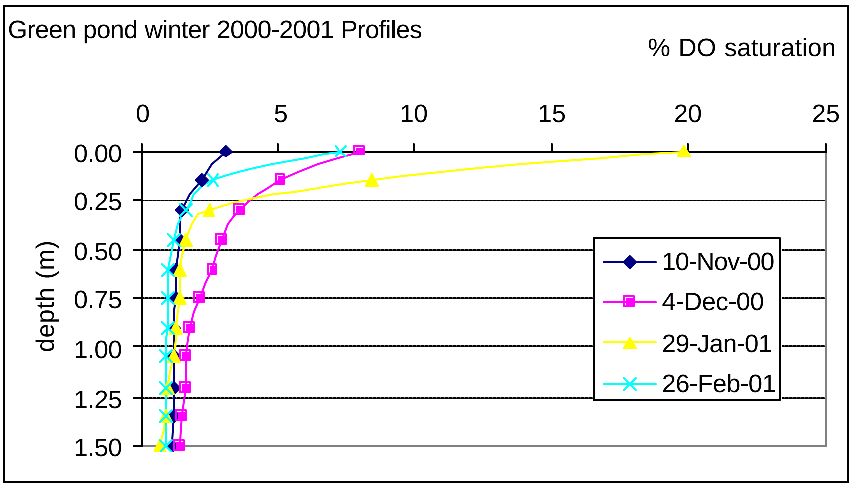
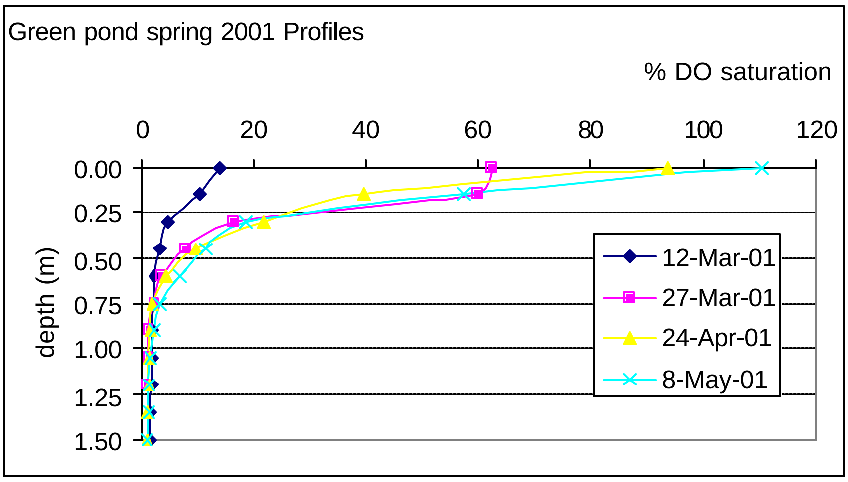


Figure 5.30 DO profiles for the Red pond (Sept 2001-Jun 2002)





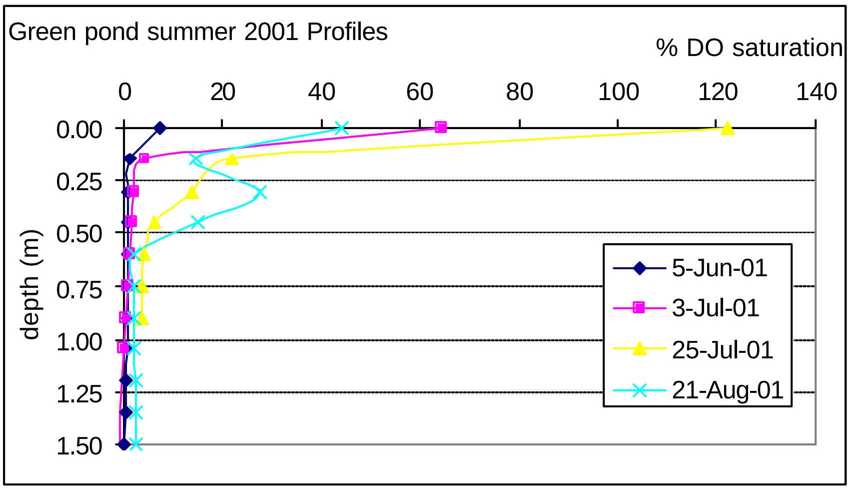


Figure 5.31 DO profiles for the Green pond (Nov 2000-Aug 2001)

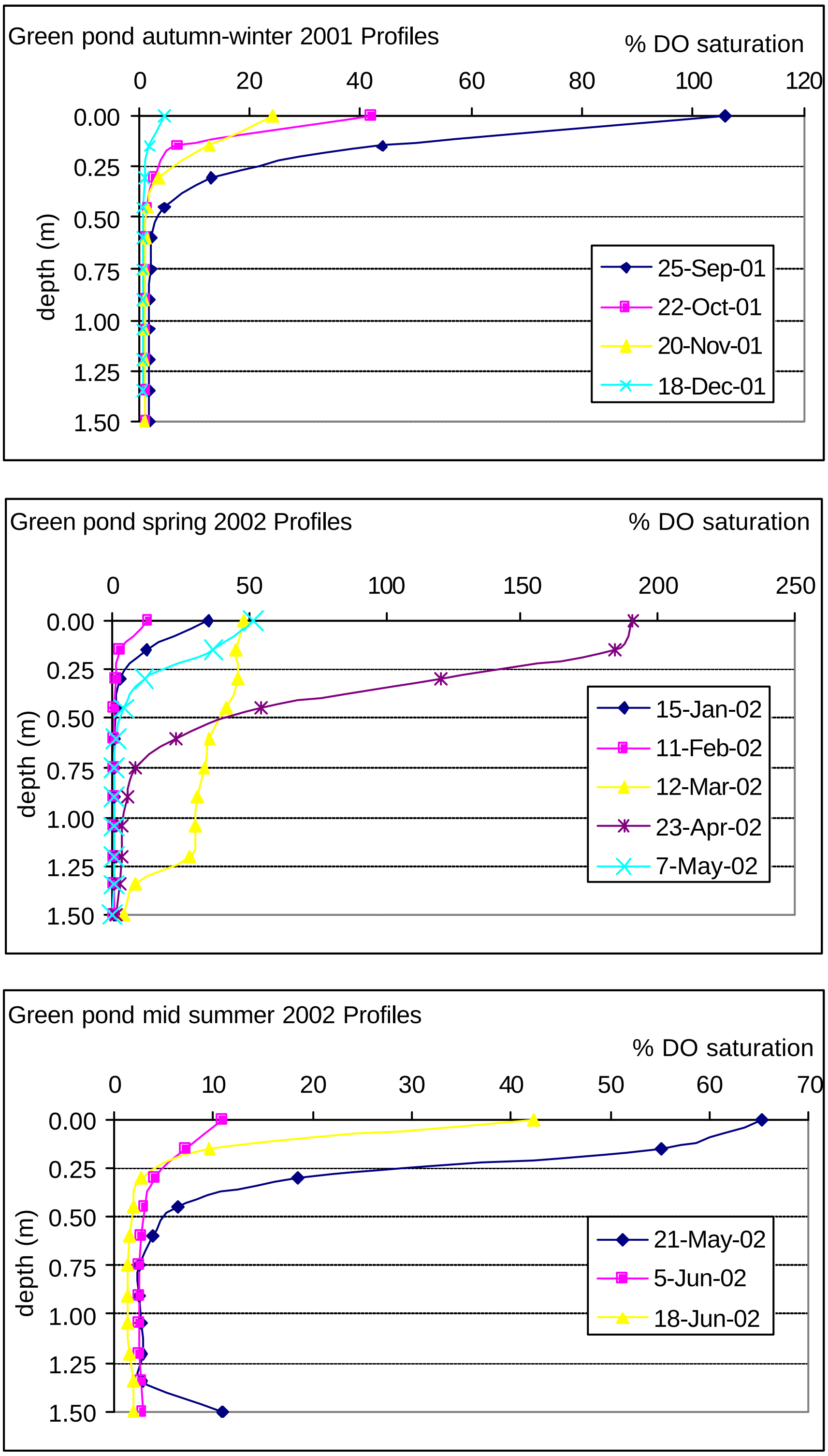
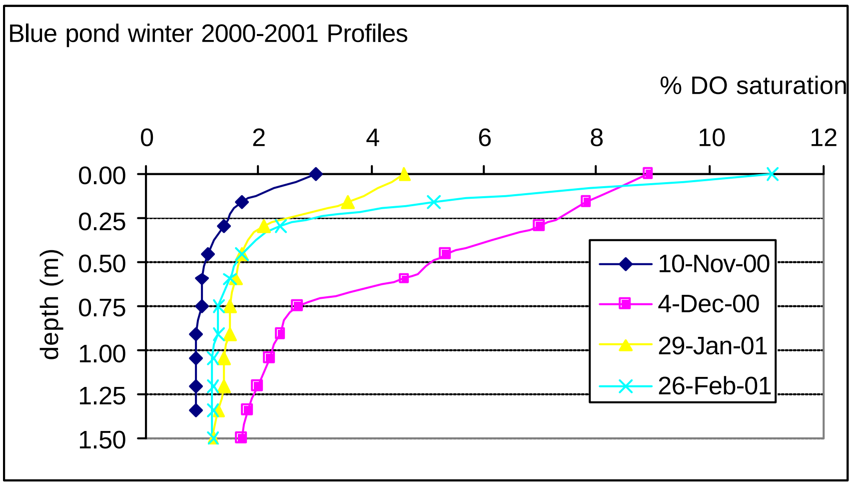
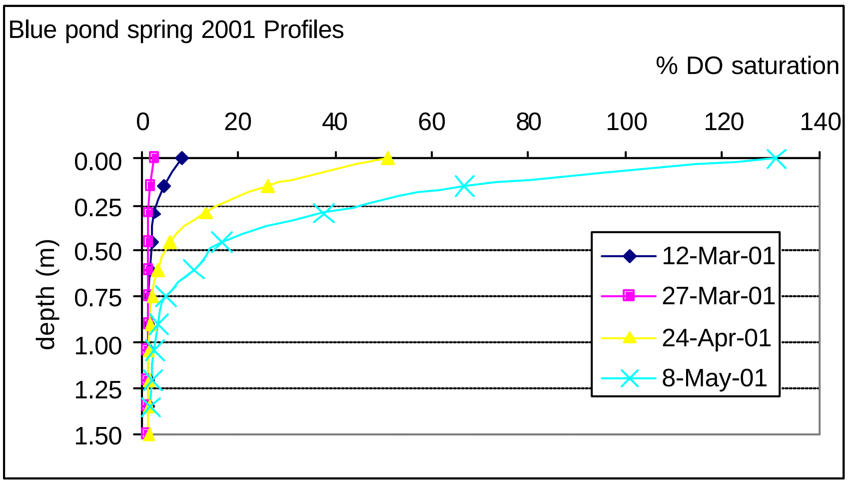


Figure 5.32 DO profiles for the Green pond (Sept 2001-Jun 2002)





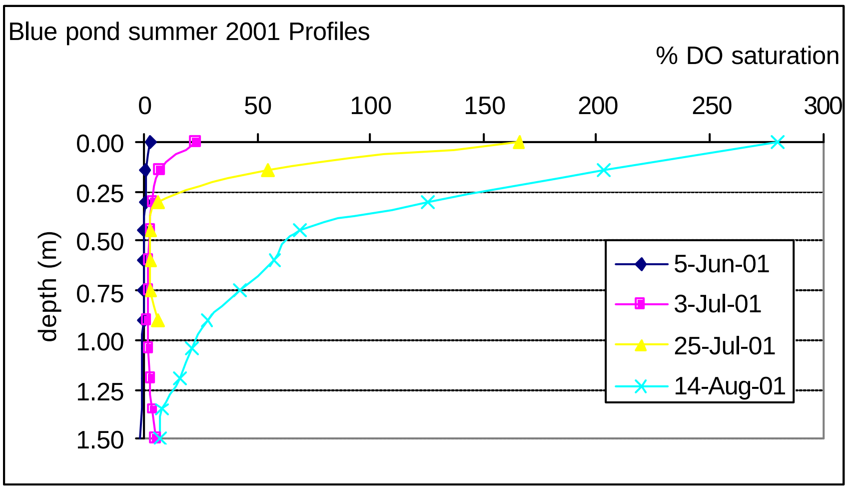


Figure 5.33 DO profiles for the Blue pond (Nov 2000-Aug 2001)

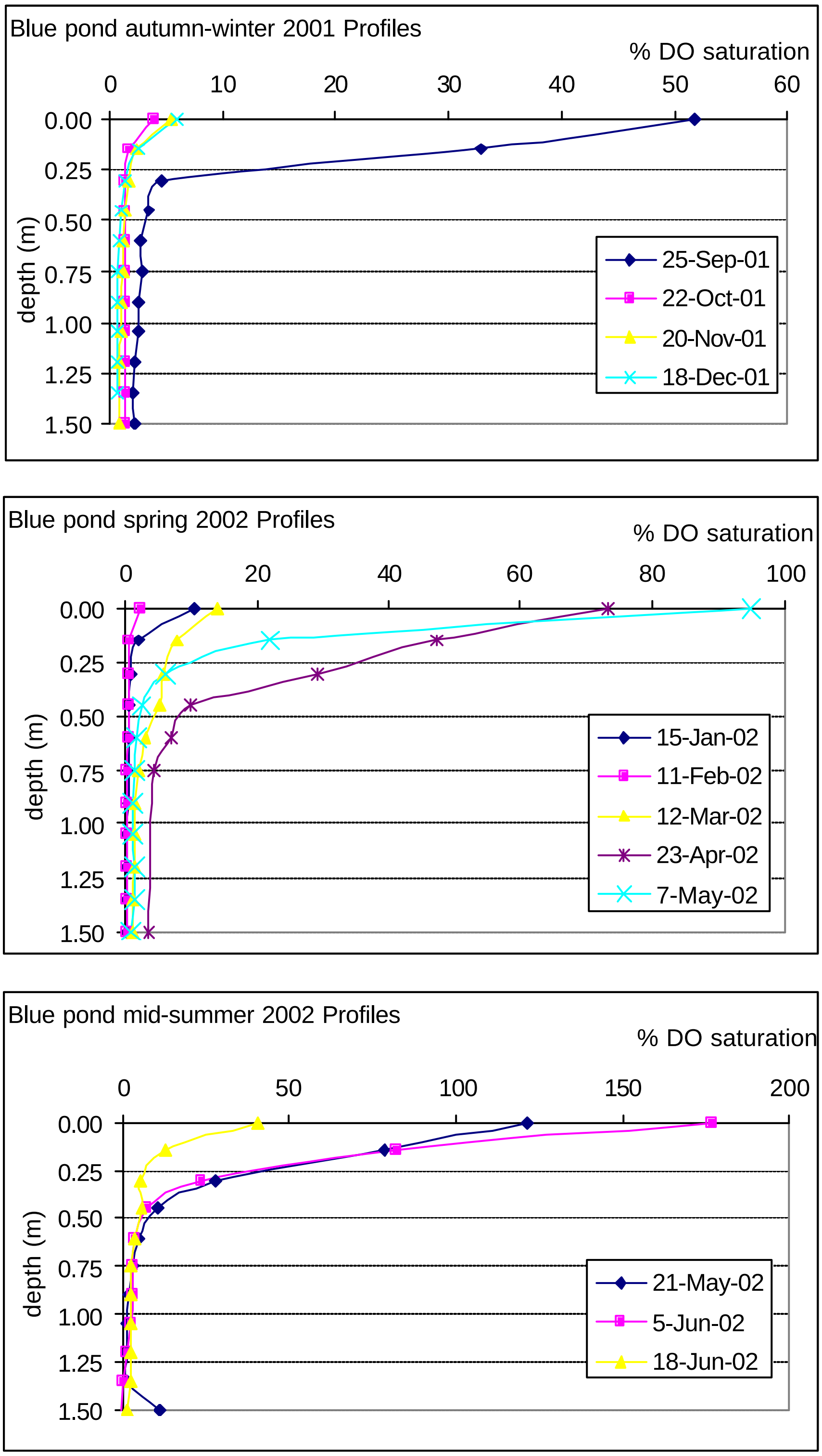


Figure 5.34 DO profiles for the Blue pond (Sept 2001-Jun 2002)

5.5.3 Site observations

During failure, the degree of anoxia or anaerobic conditions may be determined by the redox potential (mV). These readings were taken as part of the depth profile but were discarded because the poisoning of the probe in the pond water led to unreliable readings. On all site visits a visual record was kept of the colouration of the ponds together with observations of odour. The site records for the first and second winter periods are given in Tables 5.7 and 5.8 respectively; records are only included where a change had occurred between visits.

The observations recorded in Table 5.7 suggest that after the removal of the duckweed, the ponds were devoid of algae; but the Red pond was a purple colour and the other two were black. This suggests that the Red pond was anoxic whilst the other two were anaerobic. In fact, at no time during the two years of operation, did the Red pond become black: only grey or purple. This suggests that at 63 kg/ha.d, the pond will never become fully anaerobic. Odour was only observed at loadings above 100 kg BOD/ha.d; however, all observations were made during daylight hours so it is not known if there was any odour during the night at lower loadings.

Although all ponds failed during the winter, the data suggest that at a loading of 82 kg/ha.d, the pond will possibly become anaerobic at the surface immediately after the ice has melted and this may last a few weeks. At loadings of 107 kg/ha.d and above there is a definite risk of odour even before ice cover conditions.

Table 5.7 Observations of all the ponds: November 2000-May 2001

Date	**Red pond 63 kg/ha.d**	**Green pond 116 kg/ha.d**	**Blue pond 169 kg/ha.d**
6 November 2000	pink (under duckweed)	black (under duckweed)	black solids in water (under duckweed)
<< duckweed removed >>			
14 November	sulphur on surface	sulphur on surface	sulphur on surface
20 November			odour
7 December	purple colour	black no solids	black no odour sulphur on surface solids in water
3 January 2001 - 13 February	frozen		
26 February	dark green	black sulphur on surface	black odour
1 March	frozen	frozen	frozen
12 March	green	grey/green	black odour
27 March	green		**117 kg/ha.d** black, odour
9 April	green	green	black
18 April	clear	green	black
24 April	green	green	grey/green
1 May	clear	green	green

Table 5.8 Observations of all the ponds : November 2001-March 2002

Date	**Red pond 63 kg/ha.d**	**Green pond 82 kg/ha.d**	**Blue pond 107 kg/ha.d**
6 November 2001	purple	green	black
20 November	green	green	green
4 December	grey/green	green	grey sulphur on surface odour
18 December	clear grey	green	black odour
3 January 2002	frozen		
15 January	grey sulphur on surface	black sulphur on surface	grey sulphur on surface
28 January	clear	dark grey	dark grey
26 February	sludge solids	clear	clear
12 March	green	green	brown clear
19 March	green	green	green

5.5.4 Changes in pond biology

Between April 2001 and June 2002, observations of pond microbiology were made as described in Section 4.6.6. The organisms were categorised according to whether they were purple bacteria, algae or algal predators. Typical purple bacteria were *Chromatium*, *Rhodopseudomonas* and *Rhodospirillum*; typical algae were *Chlamdymonas*, *Chlorella* and *Euglena*; typical algal predators were rotifers, *Paramecium* and *Culex* larvae. The most abundant organism type for each sampling interval are shown in Figure 5.35 for effluent samples and Figure 5.36 for column samples. Figure 5.35 gives a picture of what was happening on the surface, whilst Figure 5.36 shows the water column to 0.75 m depth. Appendix C contains more detailed versions of these figures together with photographs.

Figure 5.35 indicates that the Red pond was dominated by algal predators more often than the other two, and that the Blue pond was more likely to be dominated by purple bacteria. The dominance of purple bacteria indicates anoxic conditions on the surface, and thus there is evidence that a loading of 107 kg/ha.d may be too high. The Green pond was dominated in this way between mid January and mid February and the Red pond in mid January. The evidence suggests that Red pond loading of 63 kg/ha.d led to conditions which allowed algal predators to dominate and wipe out the algal communities on the surface. This explains the early failure in September 2001 as shown in Table 5.5. The loading of 82 kg/ha.d overall led to algal dominance throughout the year, whilst the Blue pond loading led to purple bacterial dominance during the winter. Visual inspection of the pond water supports this. Figure 5.36 takes into account the water column and was less likely to include the effect of algal predators which inhabited the surface, than those of the algae and bacteria who lived deeper in the column. This figure shows that algae dominated the Green and Red ponds, and purple bacteria dominated the Blue pond in winter.

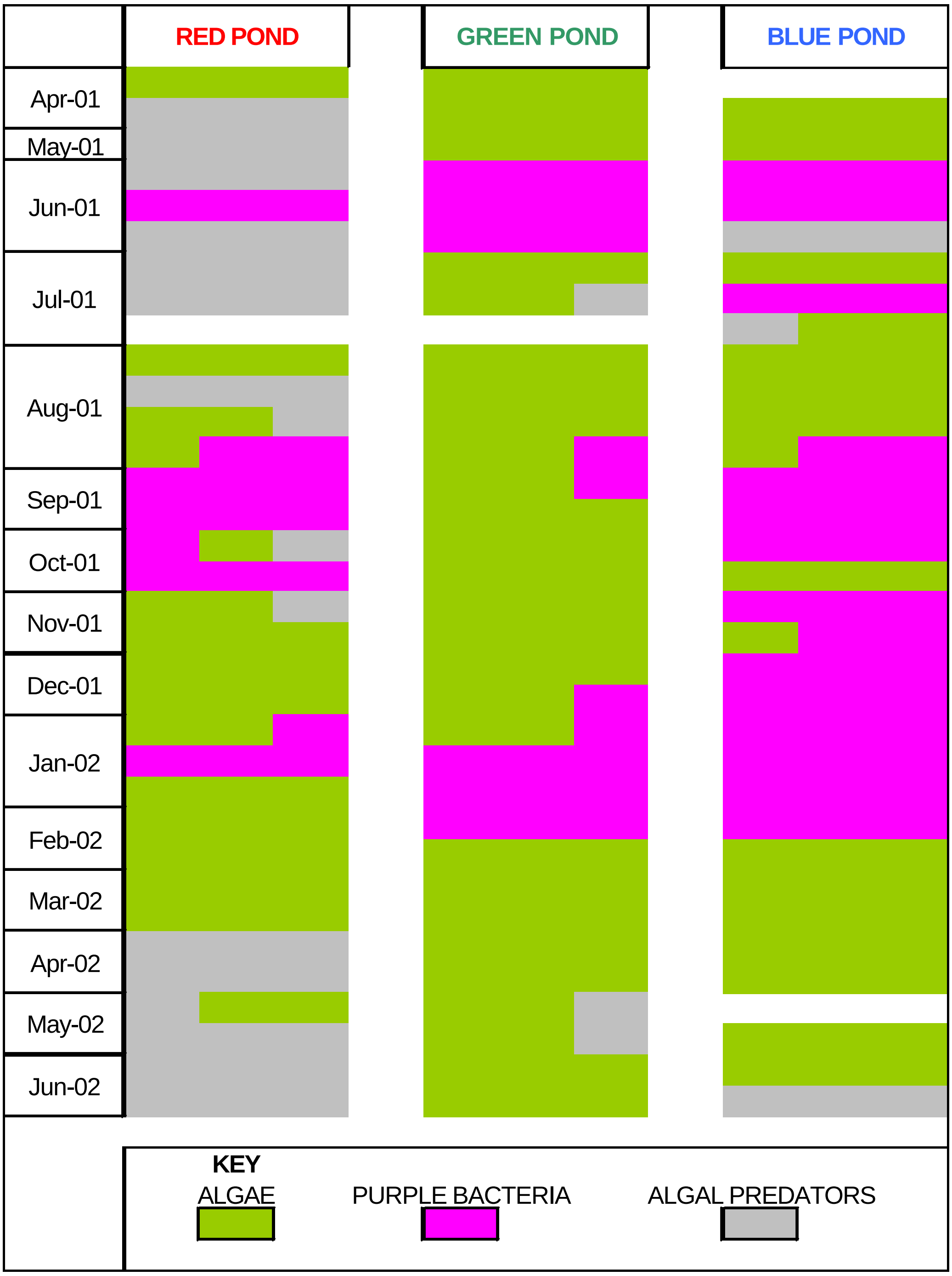


Figure 5.35 Dominant organisms found in the effluent samples from all ponds

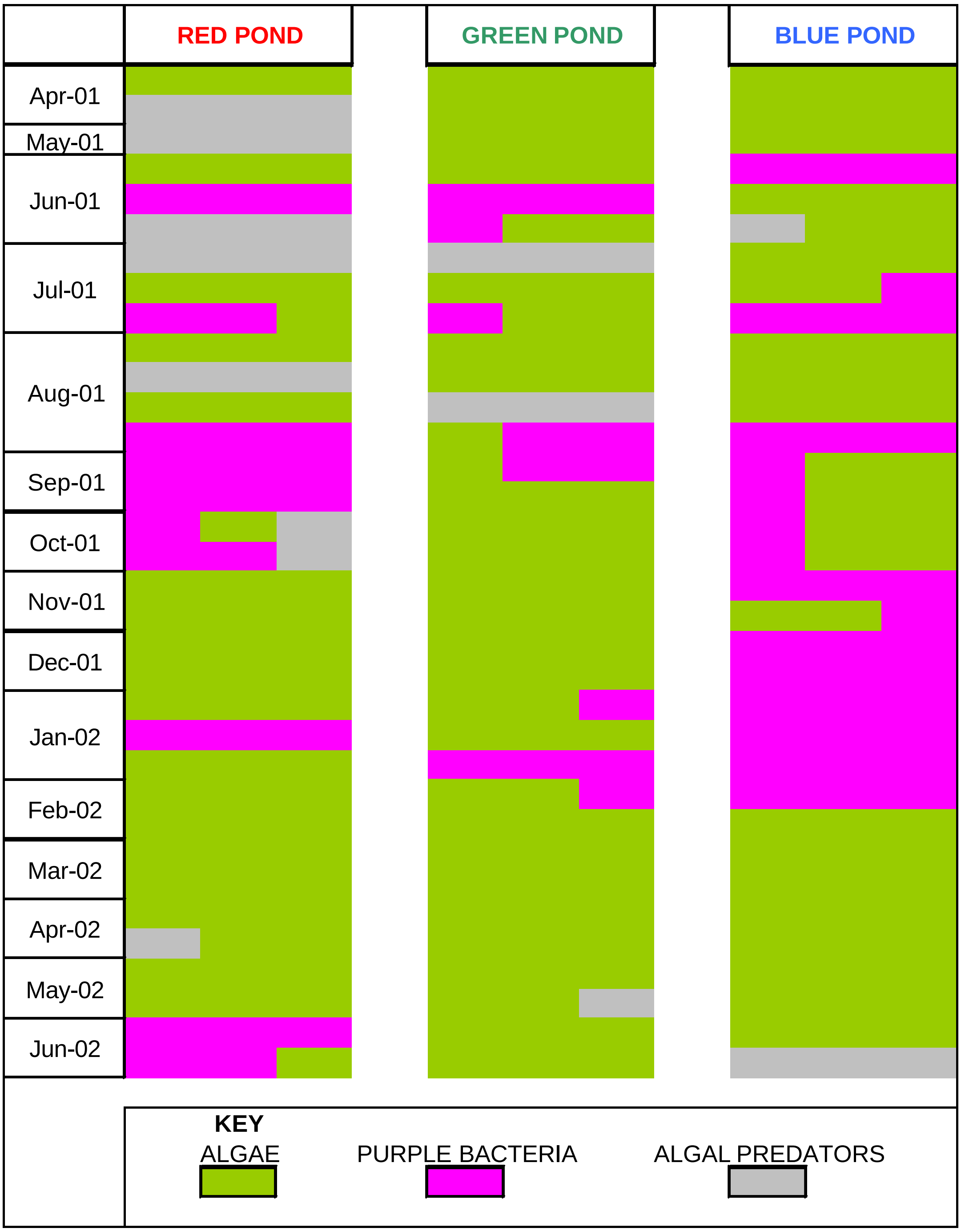


Figure 5.36 Dominant organisms found in the column samples from all ponds

One of the algal predators was a mosquito, *Culex* sp. These larvae populated the Red pond during both summers from mid June to mid August summer 2001 and from mid April to the end of sampling in June 2002. Although the ponds were adjacent to each other, the mosquitoes appeared to flourish in the Red pond only (see Figure 5.37). This suggests that surface BOD loading may have an effect on mosquito breeding.

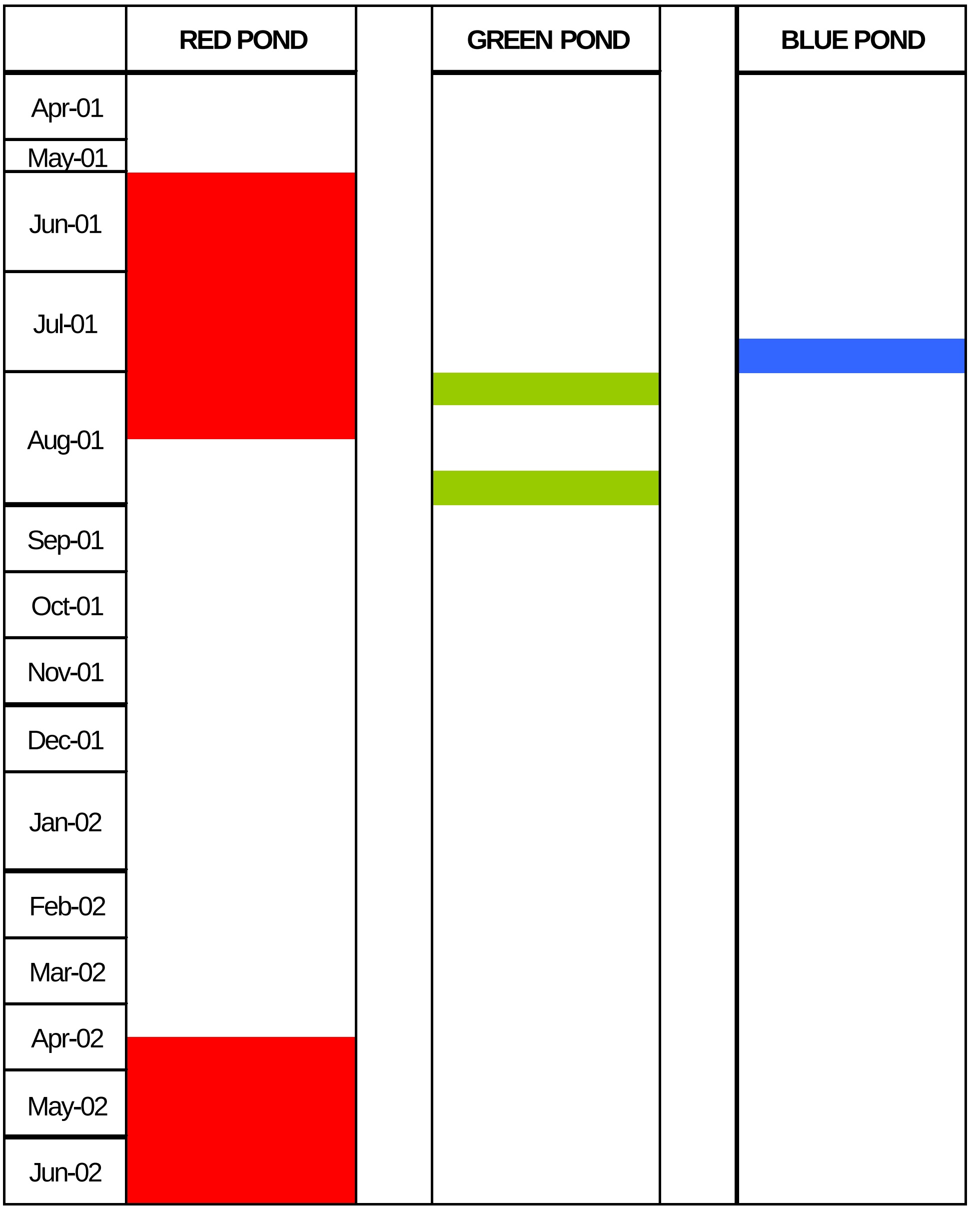


Figure 5.37 Observations of *Culex* sp. in the pond effluent

5.5.4.1 Changes in biology: fluctuations of chlorophyll-a

The algal populations in facultative ponds fluctuate due to many parameters as described in Section 2.4.5. Figure 5.38 shows how the monthly average chlorophyll-a concentration in the column samples for all ponds fluctuated with solar intensity, predation and competition effects. The effects of the duckweed (competition for light) are evident on the chlorophyll-a concentrations in all ponds during the autumn of 2000: they were at a low level and independent of solar intensity. After the removal of the duckweed, the Blue pond did not experience large populations of algal predators and the chlorophyll-a concentration appeared to fluctuate with solar intensity. The Green pond graph has a similar pattern, except during the *Paramecium* blooms in June and November, and with rotifers in May 2002. The Red pond was strongly affected by algal predators and after early spring the chlorophyll-a concentrations appeared to fluctuate in response to the main predators: rotifers in May, followed by *Culex* and then *Paramecium* in the autumn.

The fluctuations of chlorophyll-a with average air temperature for all ponds are shown in Figure 5.39 and have a similar pattern as shown on Figure 5.38. This is not surprising as changes in solar intensity and air temperature are strongly related; however, as solar intensity is highly dependent on day-length, it changed more steadily and rapidly than temperature. A first glance at both figures suggests the recovery of the algal populations in the pilot-scale ponds after winter possibly responds to changes in solar intensity, rather than temperature.

Evidence from the pilot-scale ponds suggests therefore that chlorophyll-a concentration in facultative ponds in the UK is affected by availability of light or low temperatures in the winter and predation effects in summer. The extent of the predation effects appears to be related to surface BOD loading.

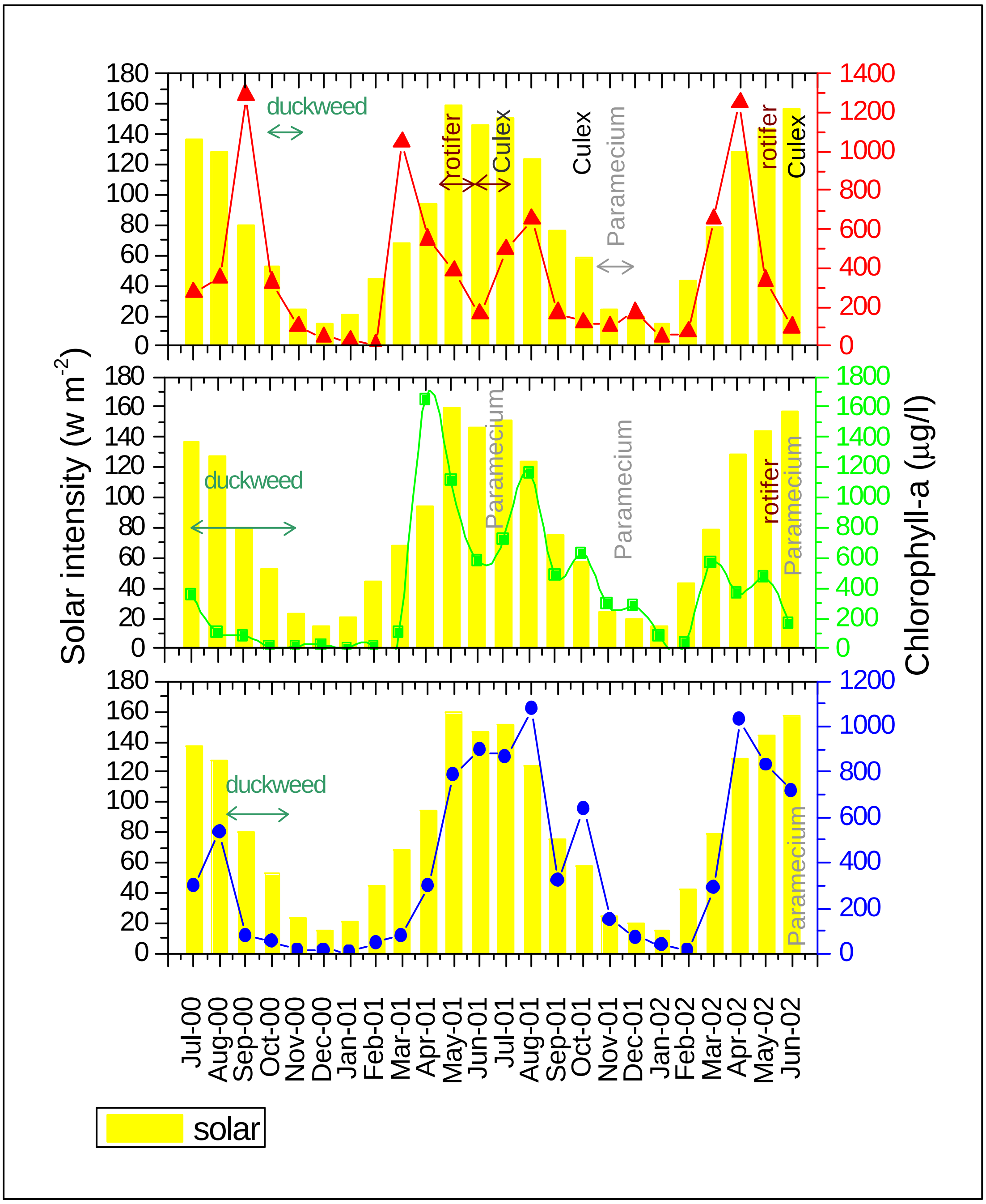


Figure 5.38 Fluctuations in chlorophyll-a with changes in solar radiation, predation and competition effects

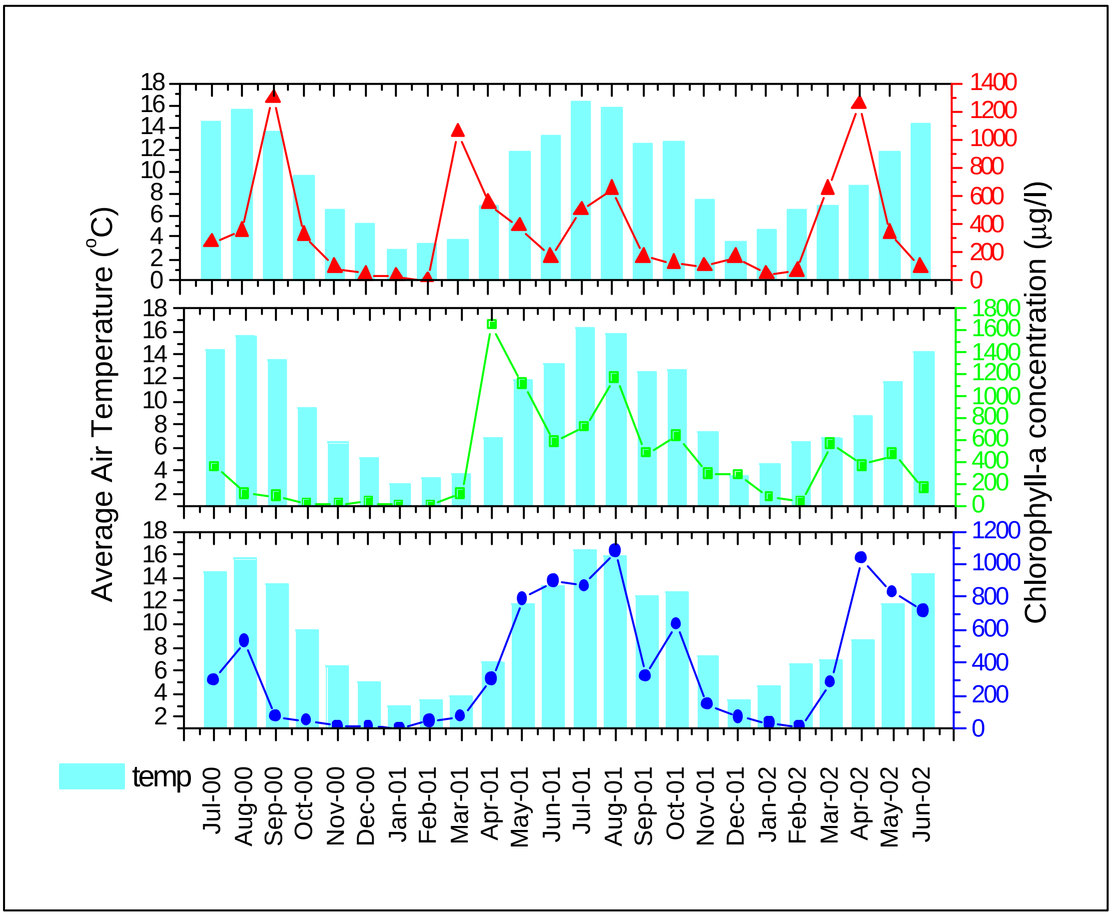


Figure 5.39 Fluctuations in chlorophyll-a concentration with changes in air temperature

5.5.5 The contribution of chlorophyll-a to the dissolved oxygen concentration

A scatterplot of chlorophyll-a against dissolved oxygen concentration is given in Figure 5.40 together with line graphs with the chlorophyll-a and dissolved oxygen concentration overlaid for each pond. The scatterplot shows there is no clear relationship between the two parameters for the pilot-pond data. The line graphs suggest that there is a relationship, which is closest for the Red pond, followed by Green, then Blue. This may be due to the difference in dissolved oxygen uptake rate of each pond which is related to BOD loading. Most noticeably, the DO may drop during mid summer whilst the chlorophyll-a is still high. This is due to stratification effects where the algae became trapped on the surface. Tables 5.9 and 5.10 show the site observations for May-July 2001 and April-July 2002. These observations suggest that low DO during summer may be as a result of algal scum on the surface and sludge solids feeding back into the liquid.

It is likely that algae are not the only source of DO especially during the winter, therefore DO is mostly likely to be a better measurement of aerobic conditions on the surface then chlorophyll-a; however, as the DO data were spot measurements taken at midday, it is not sensible to rely upon them to establish a failure threshold. With the data available it has not been possible to establish a new criterion for pond failure based on chlorophyll-a concentration nor surface DO. Therefore, the criterion suggested by Pearson (1996) (i.e. chlorophyll-a < 300 µg/l) will be adopted.

Table 5.9 Site observations May-July 2001

Date	**Red pond** **63 kg/ha.d**	**Green pond** **116 kg/ha.d**	**Blue pond** **117 kg/ha.d**
1 May 2001	murky	very green	very green
8 May	algal bloom surface	algal bloom	algal bloom
22 May	clear: rotifer bloom	very green	very green
5 June	algal scum on surface	algal scum on surface	algal scum on surface
12 June	purple	algal scum on surface	algal scum on surface
19 June	purple	very green	murky
3 July	clear, Culex larvae	pale green	pale green

Table 5.10 Site observations April-July 2002

Date	**Red pond** **63 kg/ha.d**	**Green pond** **82 kg/ha.d**	**Blue pond** **107 kg/ha.d**
23 April 2002	clear green	very green	green turbid
30 April	brown	green	dark green
21 May	clear	green turbid (sludge solids)	green turbid (sludge solids)
5 June	brown	pale green	green
18 June	pale green	dark green	dark green
25 June	very green	dark green	algal scum
3 July	green	very green	murky green

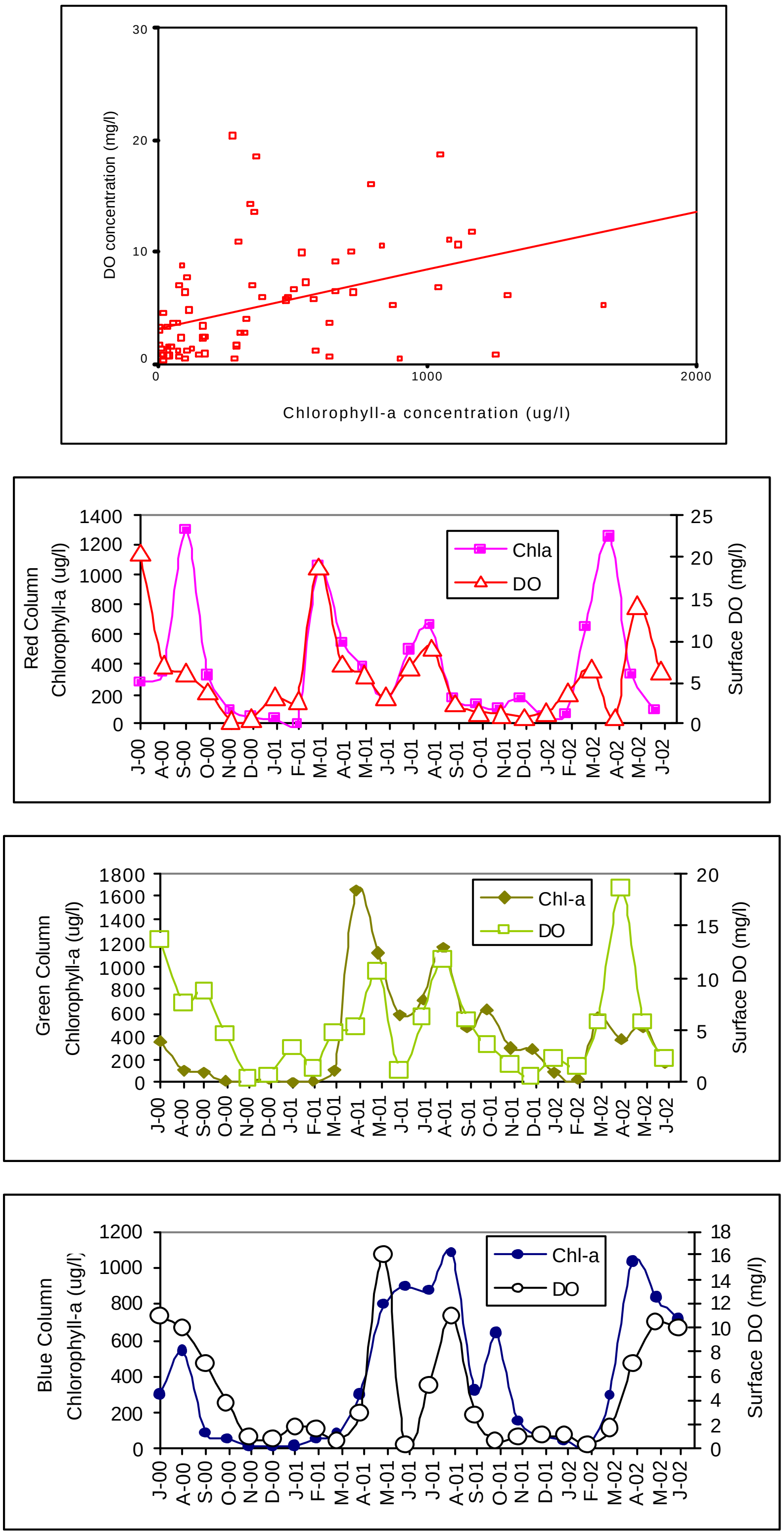


Figure 5.40 Relationship between the DO concentration at the pond surface and the column chlorophyll-a concentration

5.5.6 Failure: comparison with McGarry and Pescod's "Envelope of Failure" (1970)

The model given in Section 2.6.2 for McGarry and Pescod's Envelope of Failure is repeated below:

$$\lambda_s = 60\ (1.099)^T \qquad (2.14b)$$

where T is the average air temperature of the (coldest or measurement) month. The dates of failure and recovery for the pilot-scale ponds according to the 300 µg/l chlorophyll-a concentration were detailed in Table 5.5. The only exception is the winter failure for the Red pond, when the chlorophyll-a concentration dropped below 300 µg/l in September due to predation effects. For this point, a criterion of 200 µg/l was used which gives a failure date of 3rd January 2002. The average air temperature during the preceding 30 days before the failure or recovery date was used for "T" in equation 2.14b; the calculated loading was plotted against the actual surface loading applied to the ponds as shown in Figure 5.41.

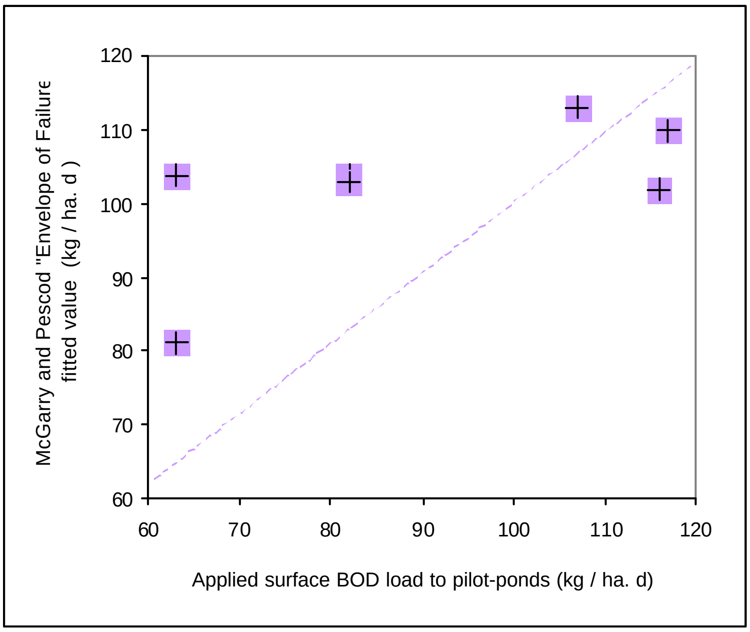


Figure 5.41 Comparison of pilot-scale ponds failure threshold with McGarry and Pescod's Envelope of Failure

Figure 5.41 shows that the pilot-pond data underestimate McGarry and Pescod's values at loadings below 100 kg/ha.d, ie, the pilot ponds failed at lower loadings than predicted by the model. However, at loadings above 100kg/ha.d the fit appears better with the two points at more than 110 kg/ha.d over-estimating the model. In general, the pilot-scale pond data tend not to agree with McGarry and Pescod, almost forming an independent relationship, especially if the Red pond data point (63,81) is removed. McGarry and Pescod's definition of failure was anaerobic conditions throughout the pond liquid all day rather than the chlorophyll-a concentration used here. McGarry and Pescod's data also tended to be based on data from a number of full-scale pond systems which were consistently either facultative or anaerobic.

5.5.7 Failure: comparison with Mara's global design equation (1987)

Mara's global design equation for facultative ponds was given in Section 2.6.3 and repeated below:

$$\lambda_s = 350\,(1.107 - 0.002T)^{T-25} \qquad (2.15)$$

A plot of the fitted values from the pilot-pond data is shown in Figure 5.42. Equation (2.15) is for temperatures over 8^{o}C, and below this temperature a loading of 80 kg/ha.d is recommended; this line is also shown on Figure 5.42. All the failure temperatures for the pilot-pond data were below 8^{o}C. The pilot-ponds consistently failed at higher loadings than predicted by Mara's equation, suggesting that the global design equation may be too generous for the pilot-pond conditions. Again, the equation is for consistent design loading and is not based on threshold values. However, all the ponds failed at some point during the winter even at the lowest loading of 63 kg/ha.d, suggesting that a flat loading rate of 80 kg/ha.d for temperatures below 8^{o}C may not be appropriate.

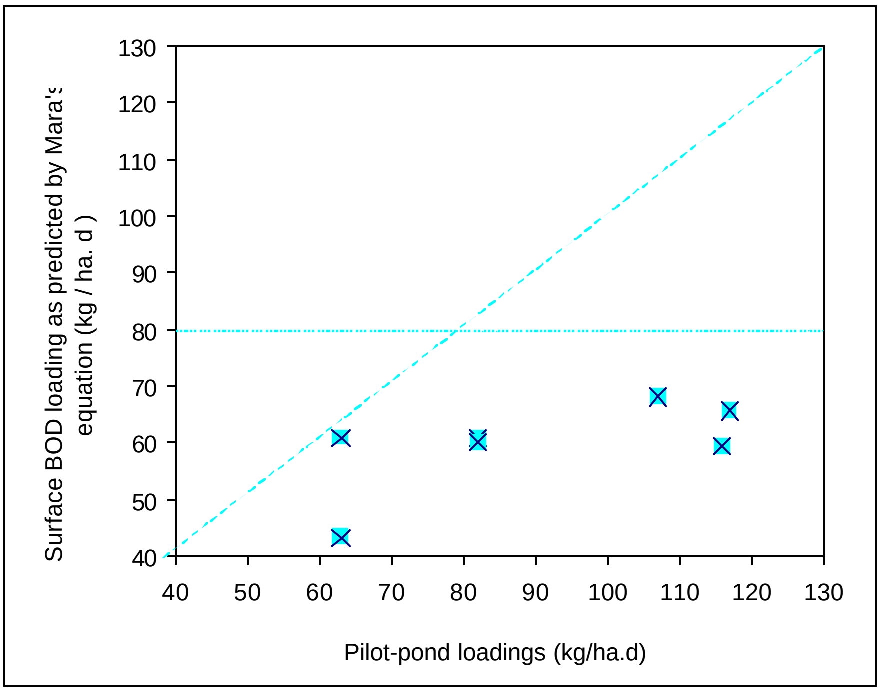


Figure 5.42 Comparison of pilot-scale ponds failure threshold with Mara's global design equation

5.5.8 Pilot-pond failure and recovery thresholds

The pilot-pond data used in Sections 5.5.6 and 5.5.7 did not distinguish between failure and recovery events. Figure 5.43 shows the temperature thresholds partitioned for recovery and failure. This suggests that failure may be more temperature dependent than recovery. Generally the ponds recovered at temperatures of 5-6^{o}C, but the temperature of failure was dependent on surface loading. Figure 5.44 is a similar plot, but with solar radiation instead of temperature. This suggests that failure and recovery are very different phenomena: the solar radiation required to bring about recovery is much higher than that leading to failure. This figure suggests that an average monthly solar radiation of at least 57 W/m^2 is required for recovery at any surface loading, whilst it may drop below 20 W/m^2 before failure takes place at loadings of 80 kg/ha.d or less. The model of McGarry and Pescod assumes that solar radiation is taken into account by average temperature. Figures 5.43 and 5.44 suggest this is possibly not the case for the UK climate.

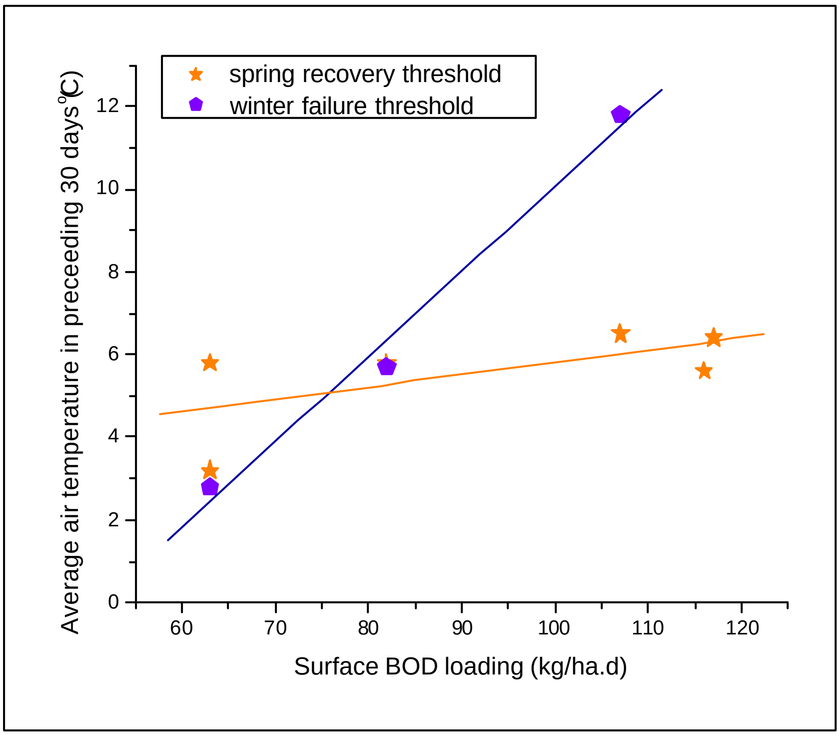


Figure 5.43 Temperature thresholds for failure and recovery of pilot-scale ponds

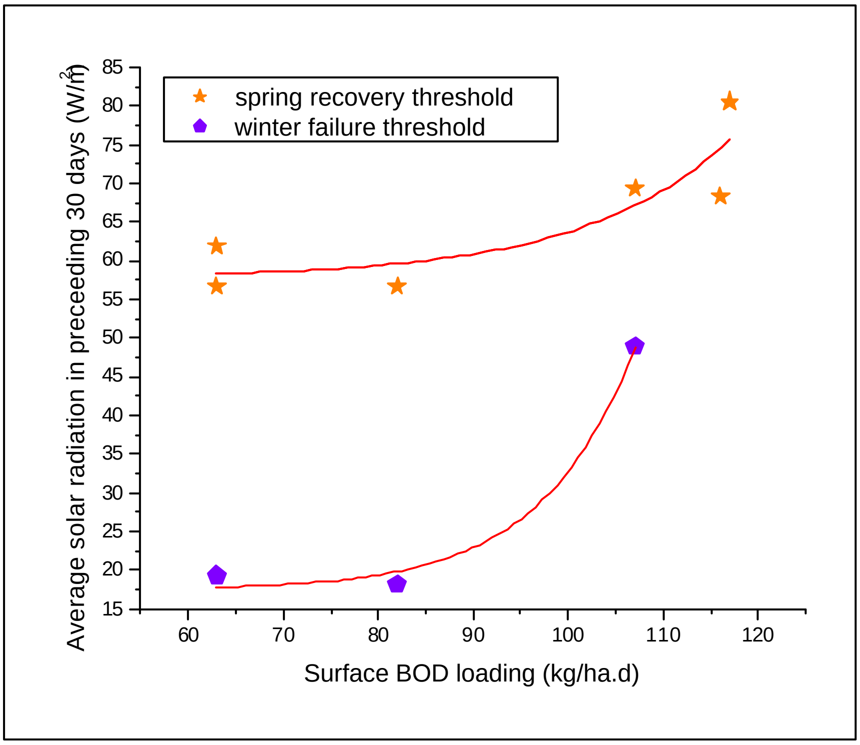


Figure 5.44 Solar radiation thresholds for failure and recovery of pilot-scale ponds

The failure plots on each figure have only three points, representing the three ponds in the second winter (the first winter data cannot be used due to the duckweed problem). During this second winter, the Red pond failure is uncertain due to the predation effects, therefore it is not reasonable to construct a model here without further data. Figure 5.44 suggests that below a surface loading of 80 kg/ha.d, changes in loading become less important and the ponds may fail at a solar intensity of around 18 W/m^2 and will recover around 57 W/m^2. If this is the case, then primary ponds will theoretically fail at any organic loading during the UK winter due to light limitation.

5.6 Sludge accumulation

The sludge height was measured after 3, 9, 15 and 20 months from start-up as described in Section 2.5.7. The distribution of sludge on the bottom of each pond is shown in Figures 5.45-5.47. Figure 5.45 shows the accumulation in the Red pond up to 20 months. Most of the sludge accumulated around the inlet and there was a general increase between 3 and 9 months. Between 9 and 15 months, there was a slight decrease in the middle of the pond, but with more around the inlet; this interval was a summer period. Between 15 and 20 months (a winter period), there was a general increase and the sludge height at the inlet reached over 50 cm.

Figure 5.46 shows the accumulation in the Green pond over the 20 months. There appeared to be a steady increase in the sludge height from 3 months onwards, with the sludge tending to accumulate around the inlet and the pond sides. There is evidence of a slight reduction between 15 and 20 months (a winter period). Unlike the Red pond, the sludge height never exceeded 30 cm.

The accumulation in the Blue pond is shown in Figure 5.47, and had a similar trend to the Green pond with a steady accumulation up to 15 months and a slight decrease after. In general, the sludge was more evenly spread across the bottom than the other two ponds. Though most accumulation was near the inlet, the height never exceeded 30 cm.

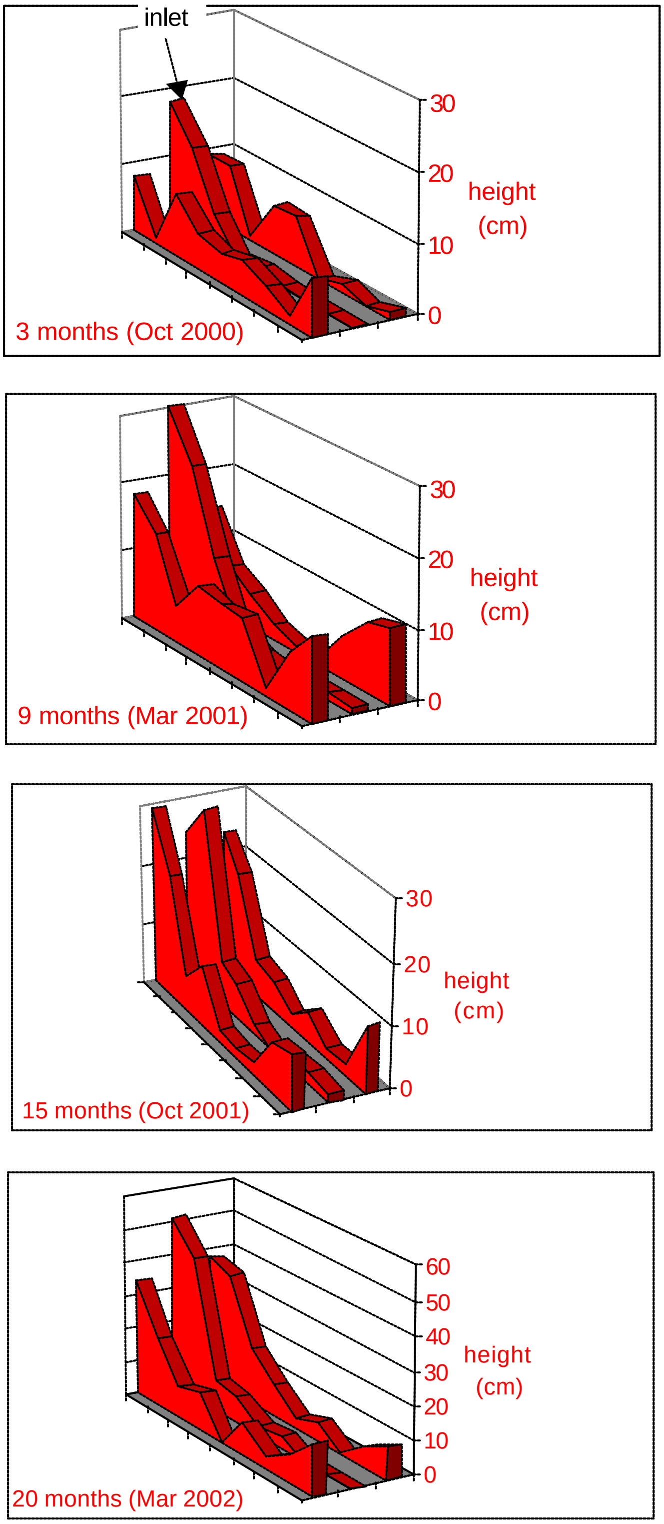


Figure 5.45 Sludge accumulation in the Red pond.

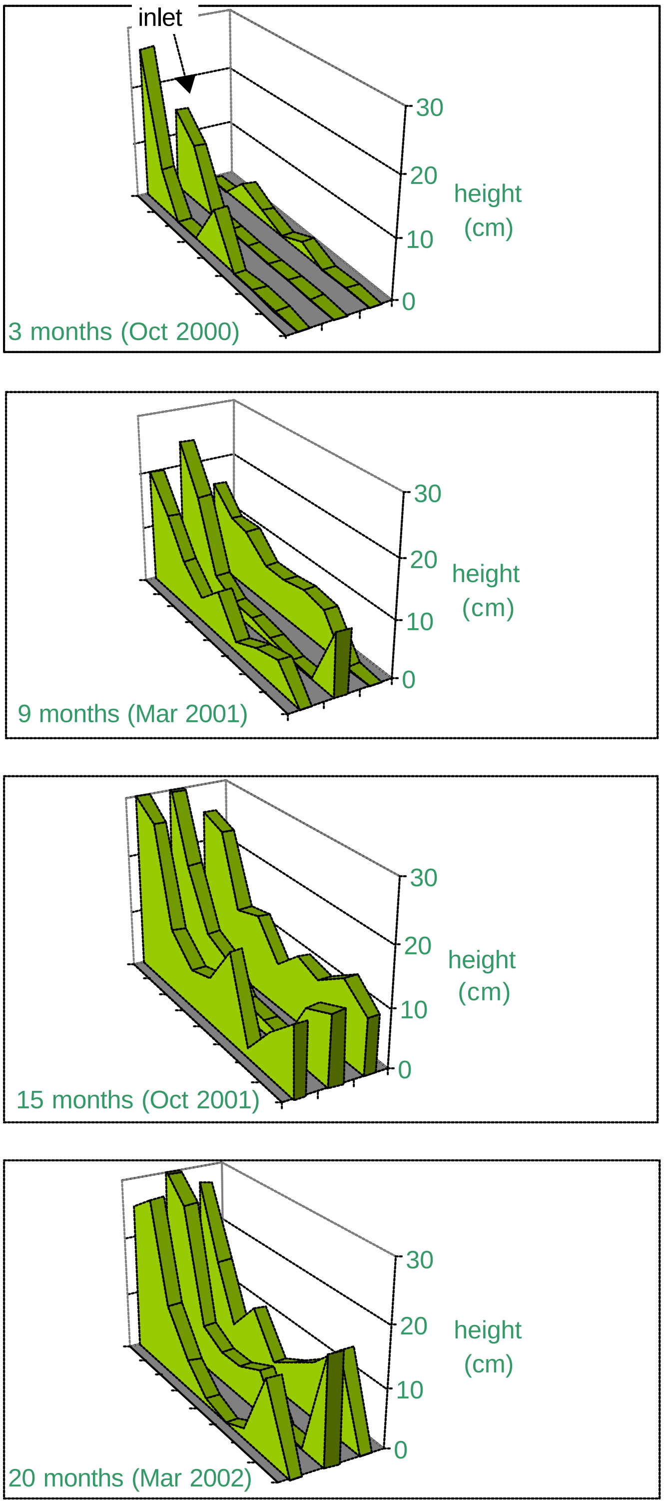


Figure 5.46 Sludge accumulation in the Green pond

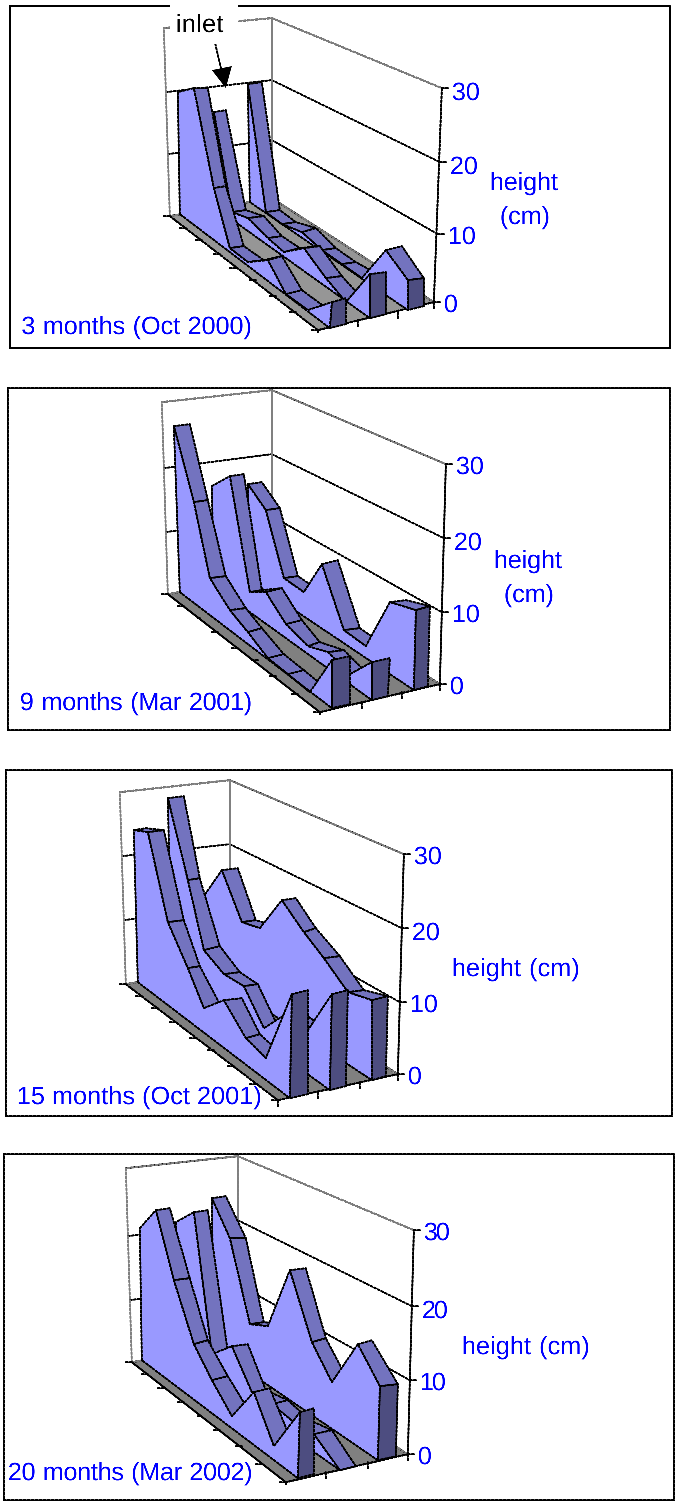


Figure 5.47 Sludge accumulation in the Blue pond

5.6.1 Total sludge accumulation compared to theoretical

The theoretical sludge volume originating from the influent was estimated from the influent settleable solids concentration as described in Appendix D. Figure 5.48 shows the total accumulation measured in each pond up to 20 months, together with the estimated sludge volume from the influent settleable solids. Total sludge accumulation appeared to be almost the same for all ponds, i.e. independent of loading. The ponds had an excellent capacity for the reduction of the incoming settleable solids, either by compaction or digestion: reaching 80-90% by 15 months of operation. This reduction figure does not include the contribution of the sedimentation of biological cells to the sludge; therefore the total reduction capacity is expected to be even greater than this. The accumulated sludge volume in each pond to 20 months was 1.46 m^3, 1.57 m^3 and 1.83 m^3 for the Blue, Green and Red ponds respectively; this is the equivalent of 0.09, 0.15 and 0.22 m^3/person/yr.

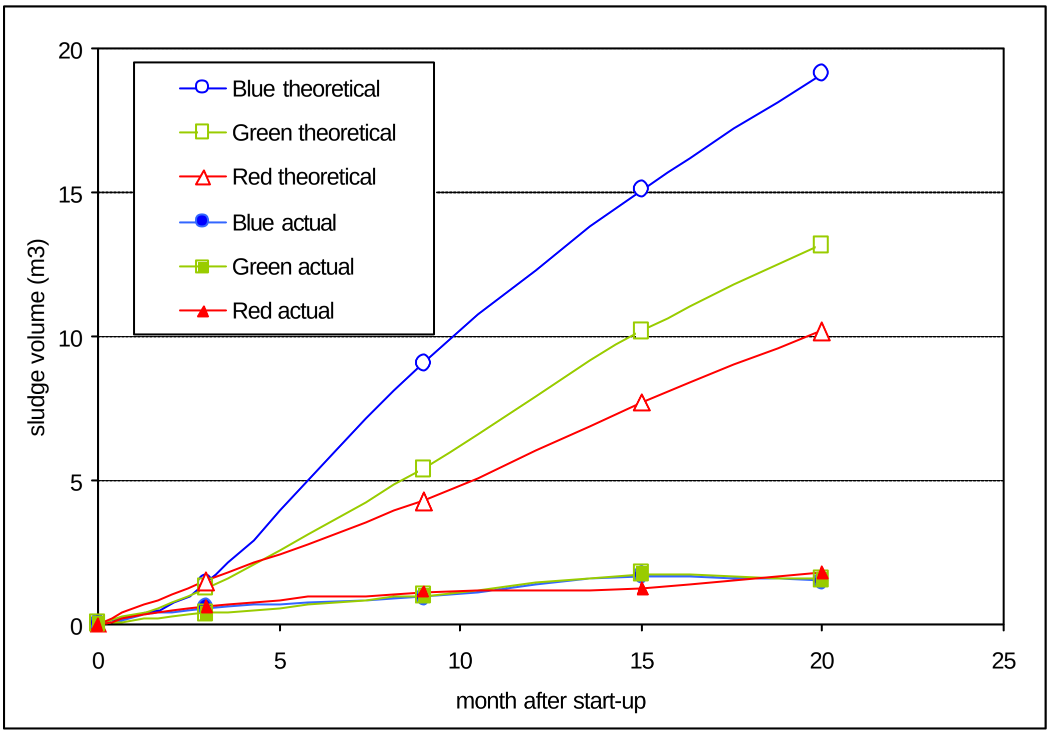


Figure 5.48 The actual volume of sludge for each pond and the theoretical volume estimated from influent settleable solids

5.6.2 Desludging interval

Figures 5.45-5.47 showed that most of the sludge accumulated around the inlets. It is sensible therefore to assume that the accumulation around this area will dictate the desludging interval. In Section 2.4.6 it was stated that desludging was usually required on French ponds when the pond was around 30% full. The prediction for the desludging intervals for the pilot-ponds as shown in Figure 5.49, is for when the height around the 2 m^2 of the inlet will reach 0.5 m (or 33% of the overall depth). The predicted intervals are: 4 years for the Red pond; approximately 7 years for the Green pond and more than 10 years for the Blue pond. These predictions are very precarious, based as they are on 20 months operation, and only four data points per pond.

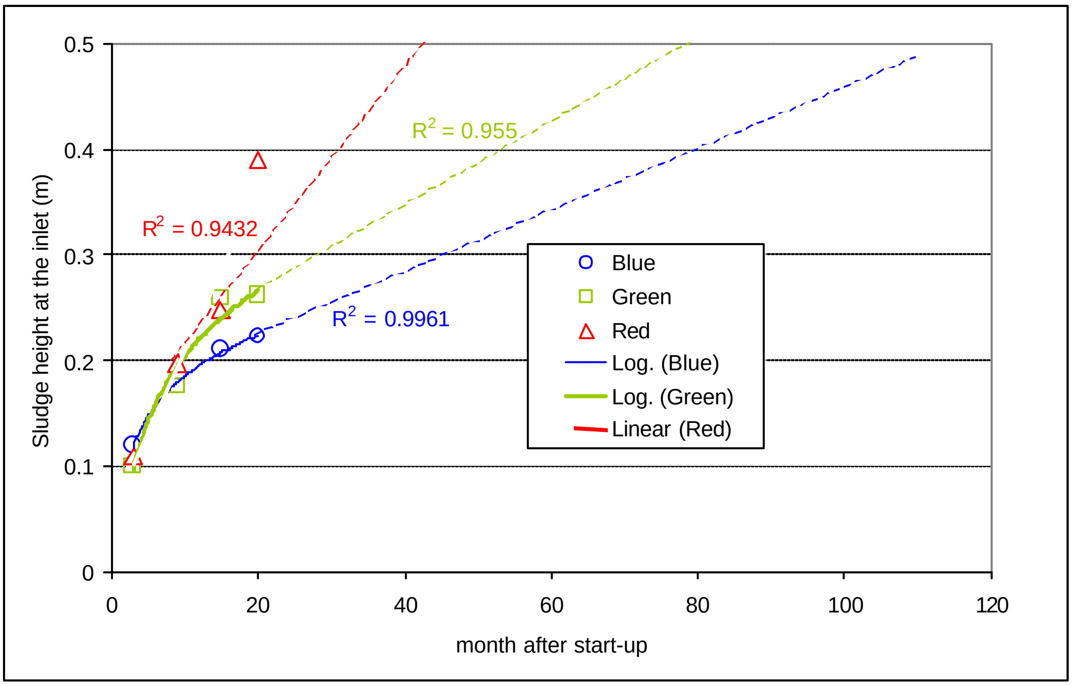


Figure 5.49 Prediction of the desludging interval based on the accumulation around the inlet to 20 months' operation

Although it appears that the desludging interval reduces with decreasing loading, this may actually be explained by the relative location of the ponds. The Red pond was located adjacent to a row of trees and received many fallen leaves in autumn. The Green pond was next to the Red and also received fallen leaves, but not as many. The Blue pond was most isolated from the trees and few fallen leaves were observed on the surface. The prevailing wind blew the leaves towards the inlets which is where the leaves settled to the sludge. Figure 5.50 shows leaves accumulating around the Red pond inlet during winter and Figure 5.51 shows leaves returning to the surface as part of sludge feedback during the following summer. These observations may account for the much higher sludge accumulated around the Red pond inlet. If this is the case, then the sludge accumulation in the Blue pond may give a better prediction of sludge accumulation in other UK facultative ponds when isolated from trees. Also, with larger (full-scale) ponds, the contribution of leaves would be less significant. Further data over time are required to predict the desludging interval more accurately.

Figure 5.50 Leaves accumulating around the inlet of the Red pond (winter 2001)

Figure 5.51 Sludge feedback bringing settled leaves back to the surface (summer 2002)

5.6.3 Sludge degradation

Three samples of the sludge were collected from each pond at the same time as the sludge height measurement as described in Section 4.5.7. On each sample, total and volatile solids analyses were performed as a measure of sludge degradation. In addition, total and volatile solids analyses were performed on the settleable solids collected from the influent samples over the 20 months.

The average percentage of VS in TS for each pond is shown in Figure 5.52, together with the average percentage of VS in TS in the influent settleable solids up to that point (it was not constant over time, see Appendix D). The graph suggests that up to 9 months after start-up, there was a net accumulation of organic matter, but after 9 months the rate of degradation exceeded the rate of accumulation. This provides evidence that degradation was an important process for the reduction of the sludge volume in the pilot-scale ponds. With the limited data available, the stabilisation effect appears to be independent of season; rather, it was a function of operation time only. Figure 5.53 shows the temperature of the sludge during this period; the range was approximately 4-16^{o}C, suggesting that sludge degradation occurs over this temperature range. Observations of the pond water support this hypothesis: gas production was observed at all times of the year, causing eruptions of solids to the surface in summer.

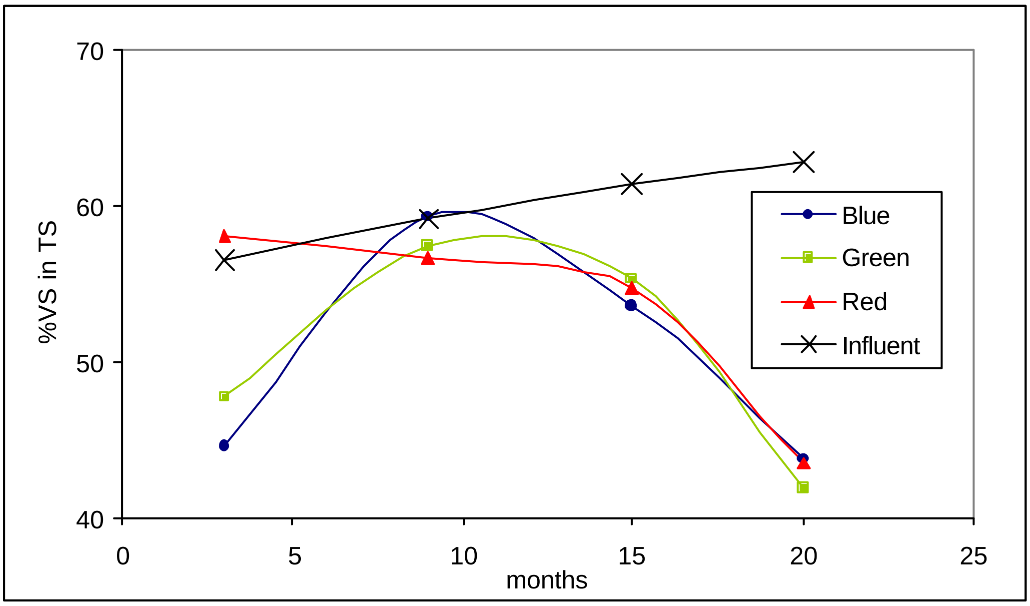


Figure 5.52 Sludge degradation over time: average percentage VS to TS all ponds and influent settleable solids

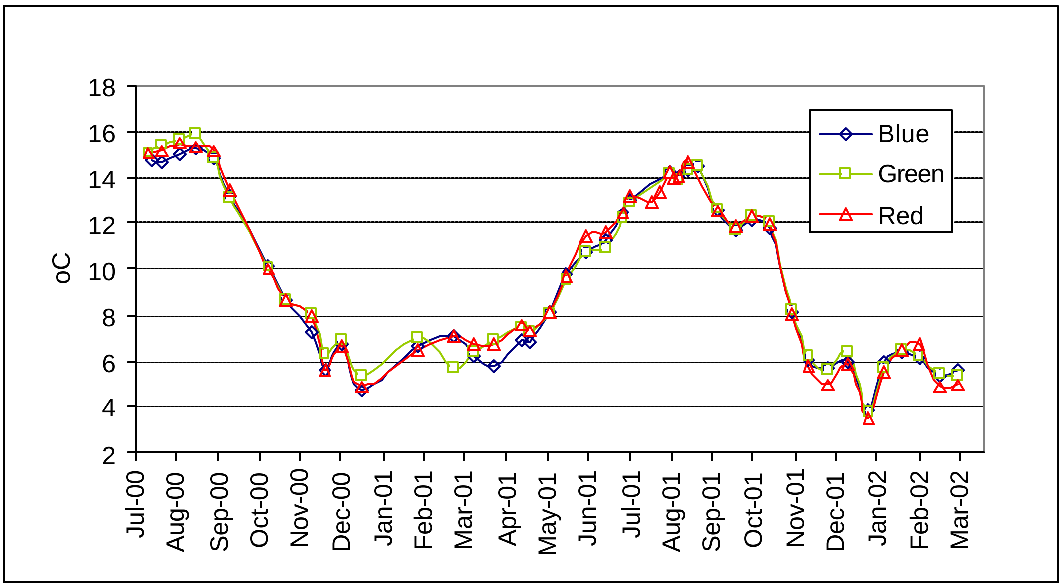


Figure 5.53 Temperature of the sludge

5.6.4 Faecal coliforms in sludge

The faecal coliform content of the sludge was measured at the request of Anglian Water plc. The range was $4.1 \times 10^4 – 1.3 \times 10^6$ CFU per gram of dry solids. From the limited data there was no evidence of a trend over time nor season, and no difference between the ponds.