THE PERFORMANCE OF PILOT-SCALE PRIMARY-FACULTATIVE WASTE-STABILISATION PONDS IN THE UK

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ABSTRACT

Three pilot-scale primary-facultative waste stabilisation ponds were constructed at Esholt sewage-treatment works, Bradford. Each pond received screened sewage at different BOD loading rates over a two-year period. Concentrations of BOD, SS, amm. N and chlorophyll-a were measured weekly in summer and bi-weekly in winter, and sludge accumulation was measured after 3, 9, 15 and 20 months. BOD and SS removals were consistently high, although they were lower in summer than in winter due to high levels of algae. The removal of amm. N was generally much better in summer than in winter – the removal mechanism being most likely related to algal activities. Sludge accumulation rates were very low.

Key words: ***Facultative pond; performance; sludge accumulation; waste stabilisation ponds.***

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INTRODUCTION

Waste stabilisation ponds (WSPs) are an environmentally sustainable technology for either full or partial treatment of domestic sewage. Basically, they are constructed impoundments into which sewage enters and flows out after a specified retention period. Treatment occurs as a result of natural purification processes which take place at their own natural rates. In the UK, WSPs are suitable for small treatment works serving less than about 2000 population equivalent (p.e.).

Mara *et al* [1] reported on the potential benefits that WSPs could bring to small communities in the UK, and noted their widespread use in France, Germany and the USA. During the period 1989-2000, forty full-scale WSP systems were commissioned in the UK, serving populations of 2-1000 people[2]. Approximately 50% of the systems receive domestic sewage directly, and the rest are preceded by a septic tank. These UK pond systems were designed according to the recommendations of other countries which have a similar climate to the UK, although there is disagreement between these recommendations, e.g. the recommended area for the first (facultative) pond in France is 6 m^2/person[3] (84 kg BOD/ha. d); in northern Germany the area is 3 m^2/person[4] (167 kg BOD/ha. d); and in the USA the recommended loading is approximately 50 kg BOD /ha. d (for an average air temperature of 2-4^{0}C during the coldest month)[5]. Ponds are also popular in New Zealand where the recommended loading on the facultative pond is 84 kg/ha. d[6]. If the facultative pond receives crude sewage, it is known as a primary facultative pond. If it is preceded by a septic tank or an anaerobic pond, it is known as a secondary facultative pond.

In order to establish the correct design loading for primary facultative ponds in the UK climate, three pilot-scale facultative ponds were constructed at Yorkshire Water's Esholt sewage-treatment works, Bradford, West Yorkshire. Also on this site are two maturation ponds, five rock filters and a reed-bed channel. This paper reports on the performance of the facultative ponds, operated at different loadings, during a two-year period (July 2000 - June 2002).

PILOT-SCALE FACULTATIVE PONDS

The three facultative ponds (Fig. 1) were constructed in Spring 2000, each pond being about 40 m^2 in area, 2 m deep and lined with a 1 mm high-density polyethylene liner. The ponds were filled with Esholt works' final effluent, giving a water depth of 1.5 m (Fig. 2). The ponds were operated in parallel, each receiving screened sewage via a Watson Marlow peristaltic pump (model 604S/R). Sewage entered each pond at a depth of 1 m and effluent was withdrawn at 100 mm below the surface.

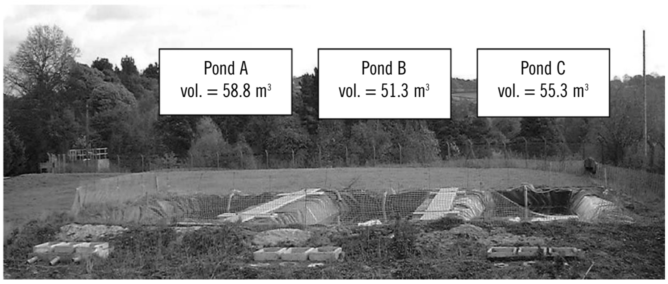

Fig. 1. Pilot-scale facultative ponds

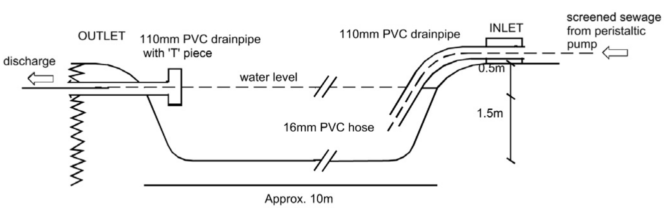

Fig. 2. Facultative pond: side view

During the two years of operation, different sewage flowrates were applied to the ponds over four phases (Table 1), to give different BOD surface loadings. Phase I was a start-up phase when all the ponds received the same low loading of 50–60 kg BOD/ha. d. During Phase II (winter period), the ponds were fully loaded at 60–170 kg BOD/ha. d. Phase III was the same as Phase II, except that the loading on Pond A was reduced to 120 kg BOD/ha. d, because it had become anaerobic at the 170 kg BOD/ha. d loading. Based upon the experience of the first year's data, in July 2001 the overall loading range was reduced to 60–110 kg BOD/ha. d. This loading range was applied to the ponds during Phase IV, which comprised the whole of the second annual cycle.

Table 1. Loading regimes on primary facultative ponds

Parameter	Pond	Phase I 7/00-9/00	Phase II 9/00-3/01	Phase III 3/01-7/01	Phase IV 7/01-6/02
Surface BOD loading (kg/ha. d)	A	50	170	120	110
	B	60	120	120	80
	C	60	60	60	60
Inflow rate (m^3/d)[a]	A	0.431	1.412	0.976	0.894
	B	0.430	0.801	0.801	0.565
	C	0.516	0.516	0.516	0.516
Hydraulic retention period (d)	A	110	40	60	60
	B	110	60	60	80
	C	95	85	100	95

[a] *From influent screened sewage (excludes direct rainfall)*

SAMPLING AND ANALYSIS

Influent samples were collected as 2.5 l 'grab' samples and as 24-h samples taken at 2-h intervals, using a Bühler Montec Xian 1100 autosampler attached to the influent tubing via a stainless steel T-piece. 'Grab' samples of effluent were collected bi-weekly in winter and weekly in summer. This sampling regime proved to be satisfactory because there was little variation in effluent quality from week to week during the winter, and effluent-quality variations occurred during the summer due solely to fluctuations in algal concentration. Ammonia and chlorophyll-*a* analyses were carried out within 2 h of collection. The concentration of amm. N was measured according to standard method 4500-NH_3[7], and chlorophyll-*a* was determined using the methanol-extraction method as described by Pearson *et al*[8]. Settleable solids were measured using standard method 2540F, but allowed to settle for 5 h rather than 1 h. BOD and SS were measured (after overnight refrigeration) on influent samples, supernatant from the settleable solids test, effluent and filtered effluent samples, by standard methods 5210B and 2540D, respectively. Concentrations in the supernatant from the settleable solids test were interpreted as non-settleable BOD and SS. Filtered effluent BOD was determined because this excludes the contribution of algal solids to the BOD. Depth profiles of DO, pH and temperature were taken on each pond at bi-weekly intervals in winter and weekly intervals in summer, using a YSI 6820 sonde probe. Sludge accumulation was measured at six-monthly intervals, from October 2000 to March 2002, using the white-towel test of Malan[9].

RESULTS

Influent Quality

Table 2 gives the analysis of typical influent quality. The main difference between the influent to the pilot-scale ponds and a typical sewage was the high concentration of settleable solids in the influent, which occasionally exceeded 200 ml/l. These solids originated from intermittent sludge wastage upstream from the pond influent-abstraction point. Therefore, the influent BOD and SS were normally higher than expected and periodically subject to high peak values, and geometric mean values were calculated to reduce the impact of these peak values. BOD and SS were non-seasonal, fluctuating around the mean at all times of the year. To achieve the desired surface loadings (given the high influent BOD), low flowrates were applied to the ponds - resulting in long retention periods (Table 1). The concentration of amm. N in the influent was within the range of a normal sewage, but was higher in summer than in winter.

Table 2. Typical influent quality

Parameter	Mean	Max	Min	No. samples
BOD (mg/l)	485 [b]	2150	30	164
SS (mg/l)	1057 [b]	6081	52	164
Amm. N (mg/l)	18-40 [c]	53	3	156
Settleable solids (ml/l)	33 [b]	240	2	158

[b] *Geometric mean*

[c] *Seasonal*

BOD Removal

Total BOD removal in all the ponds at all loadings was consistently high (Table 3) and at the upper end of those for facultative ponds elsewhere[10]. BOD removal was slightly lower in summer due to higher concentrations of algal solids in the effluent. With the algal solids removed, i.e. removal based on filtered effluent samples, the removal was the same in summer and winter. It is likely that the high influent BOD (due to the high settleable solids) contributed to the high BOD removals. BOD removal due to solids sedimentation in the ponds was estimated to be about 65%, whereas a typical primary sedimentation tank removes only 25-40% BOD[11].

Table 3. BOD removal and effluent concentrations

Parameter	Pond	Phase I summer 7/00-9/00	Phase II winter 9/00-3/01	Phase III early summer 3/01-7/01	Phase IV all year 7/01-6/02
Total BOD mass removal including solids sedimentation (%)[d]	A	93	90	81	89
	B	94	91	86	92
	C	93	93	88	92
BOD mass removal with algae removed from effluent (%)[d]	A	97	95	95	97
	B	97	96	97	97
	C	98	98	98	98
BOD mass removal excluding solids sedimentation (%)[d]	A	81	71	47	69
	B	82	75	61	76
	C	78	81	65	77
Mean effluent concentration value and range (mg /l)	A	20 (7-38)	48 (14-107)	89 (52-158)	54 (24-154)
	B	19 (8-30)	38 (15-57)	71 (43-104)	37 (14-58)
	C	28 (9-46)	28 (14-61)	55 (25-104)	37 (15-109)
Mean effluent concentration filtered samples and range (mg /l)	A	11 (3-18)	23 (5-50)	21 (15-46)	14 (6-45)
	B	10 (2-21)	17 (8-34)	18 (6-33)	12 (4-25)
	C	9 (6-15)	8 (3-12)	10 (4-15)	10 (3-19)

[d] *(100 – (g out/g in)) x 100*

In order to calculate BOD removal without the effect of sewage-solids sedimentation, the BOD of the supernatant from the settleable-solids test (carried out on influent samples) was used in the calculation. The calculated average removal (Table 3) was in excess of 70% during winter (Phase II) and 69-77% all year (Phase IV). In the absence of algal populations, the effluents were typically clear, with a BOD of 20-50 mg/l; concentrations in excess of 50 mg/l were invariably due to the presence of algae. The average BOD of the filtered-effluent samples is also given in Table 3.

The Urban Waste Water Treatment Directive[12] allows WSP effluents to be filtered before the application of discharge standards. The facultative ponds, although only a primary/secondary system, almost achieved this standard of ≤20 mg/l filtered BOD, particularly at loadings of 80 kg BOD/ha. d or less. The filtered-effluent analysis showed that surface BOD loading had an effect on effluent concentration, but it was not sufficient to impact on the overall efficiency.

SS Removal

The SS removal data (Table 4) show a similar pattern to BOD removal, i.e. consistently high, although slightly worse during summer. However, unlike the BOD data, there was no obvious difference in performance between the ponds, despite their different loadings; again, the high removal could be due to the high influent concentration. A primary sedimentation tank is expected to remove 50-70% SS[10] whereas, in the pilot-scale ponds, 83% SS was estimated to be removed by sedimentation (based upon the SS in the supernatant from the settleable-solids test). However, a proportion of the settled solids fed back to the water column; therefore a direct 83% reduction by sedimentation should not be assumed. Table 4 shows that, even in the absence of sedimentation processes, significant SS removal occurred.

Table 4. Suspended-solids removal and effluent concentrations

Parameter	Pond	Phase I summer 7/00-9/00	Phase II winter 9/00-3/01	Phase III early summer 3/01-7/01	Phase IV all year 7/01-6/02
SS removal inc. sedimentation of sewage settleable solids (%)	A	95	96	93	93
	B	96	97	93	95
	C	95	97	92	94
SS removal excl. sedimentation of sewage settleable solids (%)	A	77	78	58	57
	B	78	84	60	69
	C	71	82	56	68
Mean effluent conc. and range (mg/l)	A	47 (17-101)	39 (9-70)	80 (43-130)	72 (31-152)
	B	40 (21-68)	25 (10-43)	75 (38-97)	51 (8-139)
	C	57 (30-98)	25 (9-77)	75 (24-157)	72 (11-196)

Effluent-quality data are also given in Table 4. During the summer, SS frequently exceeded 100 mg/l due to the presence of algae. The production of algal cells complicates the calculation of SS removal in facultative WSPs, because standard laboratory techniques do not readily distinguish algae from other suspended solids. When the effluent was free of algae, i.e. when the effluent chlorophyll-*a* concentration was less than 1 μg/l, effluent SS concentrations did not normally exceed 35 mg/l.

Ammonia Removal

Ammonia removal from the facultative ponds was seasonal (Table 5), and this effect was most marked during Phase IV when it averaged 60-71% in summer, but only 19-24% in winter. This seasonal effect also occurred during Phases II and III when the influent amm. N concentration was higher during the summer. The data support the evidence from other WSPs in temperate climates, where ammonia-removal efficiency in summer is much better than in winter[3,4,13].

Table 5. Ammonia removal and effluent concentration

Parameter	Pond	Phase I summer 7/00-9/00	Phase II winter 9/00-3/01	Phase III early summer 3/01-7/01	Phase IV summer 7-8/01 & 4-6/02	Phase IV winter 9/01-3/02
Ammonia removal (%)	A	76	44	59	60	19
	B	79	48	70	67	24
	C	78	68	80	71	24
Mean effluent conc. value and range (mg/l)	A	9 (6-13)	14 (5-25)	15 (6-21)	14 (7-24)	21 (17-25)
	B	8 (5-10)	13 (8-19)	11 (4-19)	11 (6-20)	19 (15-24)
	C	8.4 (4-19)	7.8 (2-11)	7.8 (2-19)	10 (7-16)	19 (16-26)

The removal of amm. N correlated with the chlorophyll-*a* concentration, pH and temperature – all of which were higher in summer than in winter and correlated with each other. During January and February 2002, the concentration of chlorophyll-*a* decreased to less than 1 μg/l, and the effluent amm. N concentration equalled the influent concentration. Although the ammonia-removal mechanism is uncertain, it is most likely related to algal activities (either algal uptake, volatilisation or a combination of the two). There was no evidence of nitrification, because the concentration of nitrate in both the influent and effluent was always low (less than 0.7 mg N/l).

Facultative ponds are not designed for nutrient removal. Therefore, although effluent amm. N concentrations of less than 10 mg/l were common during the summer months, consistently low concentrations were not achieved at any time of the year. Further ammonia removal occurs later in the pond system (in the maturation ponds and reed-beds).

Sludge Accumulation

Table 6 shows that the total volume of sludge accumulated over 20 months was almost the same in all the ponds, thus being apparently independent of the total volume of incoming settleable solids. The theoretical accumulation was based on the total volume of incoming settleable solids. After 20 months' operation, only 10-20% of the volume remained; this was probably due to the continuous compression, anaerobic degradation and feedback processes occurring in the sludge layer[14]. Sludge solids feeding back to the pond are degraded further; therefore primary facultative ponds have a degree of integrated sludge treatment. It is estimated that, at the rate of accumulation observed after 20 months, the pilot-scale ponds will require desludging after 7-10 years of operation – a frequency similar to that found for French facultative ponds[15]. The pilot-scale ponds were of uniform depth; if the inlet zone had been of greater depth, the desludging interval would have been longer.

Facultative Conditions: Maintenance of Algal Layer

Part of facultative-pond operation is the presence of an algal layer at the surface of the pond; this is because algae are the principal source of dissolved oxygen (DO) for aerobic degradation. Mean monthly algal concentrations (as chlorophyll-*a*) for Phase IV are shown in Fig. 3. In all the ponds, algal concentrations decreased to a minimum during

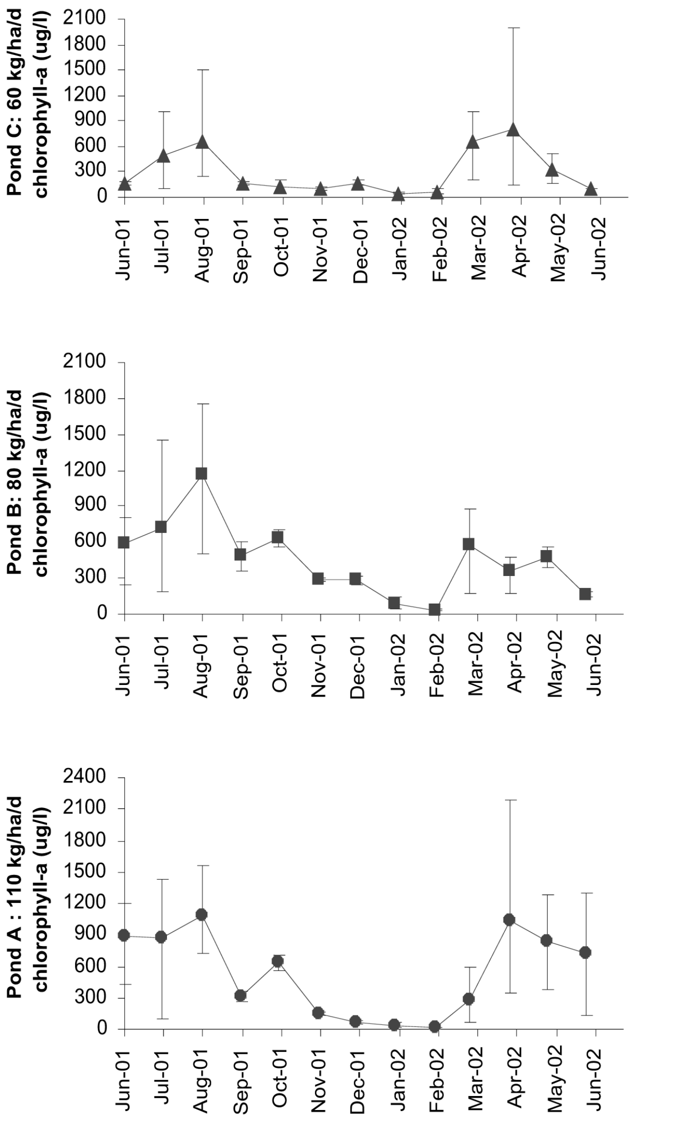

*Fig. 3. Chlorophyll-*a *in pond column samples: June 2001-June 2002.*

January and February, i.e. during and immediately after ice-cover conditions. In pond A, chlorophyll-*a* was relatively high until November and declined to a minimum in February. In pond B, the winter decline was more gradual – suggesting that higher loadings to pond A affected the ability of the algae to survive at low temperatures and light levels. In pond C, the concentration of chlorophyll-*a* was lower than in the other two ponds during most of the year, due to predation effects – mainly from rotifers and *Paramecia*; it is not certain if this was due to the lower loading.

Table 6. Sludge accumulation after 20 months

Pond	Total flow to pond (m^3)	Mean influent settleable solids (m^3/m^3) [e]	Theoretical accumulation (m^3)	Actual accumulation (m^3)
A	600	0.033	20	1.5
B	400	0.033	13	1.6
C	315	0.033	10	1.8

[e] *Geometric mean and settled for 5 h to allow compaction*

The pilot-pond data suggest that maintenance of the algal layer on primary-facultative ponds might not be possible throughout UK winters at any BOD loading. This might not be an issue, because BOD and SS removals were not affected and no odour was noted.

From the experiments, there appears to be no benefit to loading a primary-facultative pond at 60 kg BOD/ha. d rather than 80 kg BOD/ha. d. At both loadings, the performance was about the same, and the winter period (with DO concentrations of about 1 mg /l) was also about the same, i.e. two weeks during January. The pond which was loaded at 110 kg BOD/ha. d had good BOD and SS removal, but was characterised by a prolonged period in winter when the pond was devoid of algae; therefore it had very low concentrations of DO at the surface. A full-scale pond loaded at 80 kg BOD/ha. d would be 75% of the size of a pond loaded at 60 kg BOD/ha. d; thus land saving would be significant. Therefore, of the loadings tested so far, 80 kg BOD/ha.d appears to be the best.

CONCLUSIONS

1. Primary facultative ponds in the UK are capable of high BOD and SS removals at all times of the year – even when high surface loadings are applied.
2. Ammonia removal appears to be associated with algal activities. Although significant ammonia was removed during the summer when the algae were most active, the removal in winter was much reduced.
3. The pond which was loaded at 80 kg BOD/ha. d had a similar performance and operational stability to the pond loaded at 60 kg BOD/ha. d.
4. The pilot-scale ponds produced very small quantities of sludge, and it is predicted that they will require desludging after at least seven years.
5. Based upon the BOD and SS removal and sludge accumulation data, primary facultative ponds are a realistic option for primary and secondary treatment at small rural sewage-treatment works.

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