Research Monograph No. 5

Development of a new approach to waste stabilization pond design

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Preface to Series

I am very pleased to introduce this series of *Research Monographs in Tropical Public Health Engineering*. Each Monograph is an edited version of a research report or PhD thesis on a topic of tropical public health engineering, and we hope that through this Monograph form it will reach a much wider audience, especially in the developing world. Dissemination of research results is as important as the research itself, yet all too often neglected or done ineffectively. These Monographs will, we hope, redress this imbalance.

This series of *Research Monographs in Tropical Public Health Engineering* was financed by the former Overseas Development Administration (now the Department for International Development) of the United Kingdom Government, and we are especially grateful to Mr A Wray of ODA's Engineering Division for his support for the series.

Professor Duncan Mara
Series Editor

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Abstract

The objective of this study was to investigate the performance of waste stabilization pond (WSP) systems with short retention times and shallow maturation ponds, in order to determine whether such low-cost systems could produce high quality effluents. Our global experience of WSP systems, particularly in relation to our understanding of their microbiological behaviour indicates that such systems could be highly efficient and would result in considerable savings in both land and cost. In this Monograph we present the results of a study on this innovative approach to WSP design, which also included a comparison with a more conventional WSP series.

Experimental WSP

The experimental pond complex, comprising the two main systems described below, was constructed at the Catingueira wastewater treatment plant located 10 km from the centre of the city of Campina Grande in the State of Paraíba, northeast Brazil (latitude 7° 13' 11", longitude 35° 52' 31" W, altitude 550 m). Raw municipal wastewater was pumped to a constant level tank in a pumphouse immediately above the experimental WSP. From here the wastewater was pumped into the first ponds of the complex.

Series of ten WSP

A series of ten small WSP was constructed which comprised an anaerobic pond and nine subsequent ponds, of which the first was nominally facultative and the remaining eight nominally maturation ponds.

In experiment 1 the retention times were 1 day in the anaerobic pond and 2 days in the others. In experiment 2 these were altered to 1.5 days and 3 days, respectively.

Innovative WSP

The "innovative" WSP system comprised anaerobic, facultative and maturation ponds as follows:

(a) two anaerobic ponds in parallel; their effluents were mixed together to feed:

(b) five facultative ponds in parallel; four of which had length-to-breadth ratios of 6 to 1 and the other was square; depths varied from 1 to 2 m; their effluents were mixed and discharged into:

(c) a single primary maturation pond; its effluent was split equally to feed five secondary maturation ponds (see (d) below) and three rock filters (see (f) below):

(d) five secondary maturation ponds in parallel, with depths of 0.39-0.90 m, the effluents from three of them were mixed together to feed:

(e) four tertiary maturation ponds in parallel, with depths of 0.60 m, one was baffled to give a length-to-breadth ratio of 143 to 1, one was planted with floating macrophyte *Pistia stratiotes*, and one was seeded with the microcrustacean *Daphnia magna*; and

(f) three rock filters containing rocks of size 19, 25 and 38 mm.

Retention times and organic (BOD) loadings were as follows:

	Experiment 1	*Experiment 2*
Anaerobic ponds:	1 day 187 g/m^3 d	0.5 day 413 g/m^3 d
Facultative ponds:	3 – 6 days 230 kg/had	1.5 – 3 days 697 kg/had
Primary maturation pond:	3.8 days 73 kg/had	1.9 days 267 kg/had
Secondary maturation ponds:	1 – 7 days 24-70 kg/had	0.5 – 3.5 days 105-309 kg/had
Tertiary maturation ponds:	4.2 – 5 days 28 – 31 kg/had	2.1 – 2.5 days 65 – 72 kg/had

Conclusions

From the findings of the research reported herein, the following conclusions can be drawn:

1. Anaerobic ponds are essential not only for high removals of BOD, COD and suspended solids but also, due to their high sulphide concentrations, for the efficient removal of *Vibrio cholerae* O1.

2. The loading regimes used in this study suggest that maximum design volumetric loadings for anaerobic ponds can be increased to 350 g/m^3 day at 25°C, rather than restricting it to 300 g/m^3 day at all temperatures above 20°C. The results also show that some operational loss in anaerobic pond efficiency occurs at retention times less than 1 day, although the ponds systems did not fail or cause odour problems.

3. At an in-pond temperature of 25°C the effluent from a 1-day, 2.5 m deep anaerobic pond and a 3-day, 1 m deep facultative pond complies with the EU effluent requirement of $\leq$ 25 mg filtered BOD_5 per litre and $\leq$ 50 mg suspended solids per litre, and also with the WHO limit for crop irrigation of $\leq$ 1 intestinal nematode egg per litre.

4. At temperatures above 20°C the filtered BOD in the effluent from a series of short retention time anaerobic facultative ponds may be tentatively estimated from the equations:

$$L_{e(filt)(fac)} = L_i/(1 + k_{1(T)}\theta_a)(1 + k_{1(T)}\theta_f)$$

$$k_{1(T)} = 1.1\ (1.05)^{T-20}$$

5. The performance of and effluent quality from secondary facultative ponds are independent of pond geometry, at least within the range of length-to-breadth ratios of 1 to 1 and 1 to 6 and within the depth range of 1 to 2 m. This finding validates the use of surface BOD_5 loading for the design of these ponds in preference to other approaches based on retention time (for example, first order kinetics) or those incorporating hydraulic dispersion, and also permits the design engineer greater freedom to shape ponds to make the best use of available land, especially on awkwardly shaped sites. Surface BOD_5 loading rates twice those recommended by the design equations did lead to some loss in BOD removal efficiency in the combined operation of anaerobic and facultative ponds, and chlorophyll levels indicated that the facultative ponds were operating at the very limit of their capacity. They did not, however, produce any noticeable odour.

6. Doubling the maximum design organic loading and thus concomitantly halving the retention time still produced an acceptable BOD_5 in the final effluent, but the bacteriological quality just failed to meet WHO guidelines for unrestricted irrigation, except when a baffled tertiary maturation pond was included. This suggests that all final maturation ponds should be baffled as part of the basic physical design criteria. Shallow maturation ponds are more efficient at faecal coliform removal than deeper ones (i.e. those > 1 m), and therefore deepening maturation ponds, to increase the retention time, will not improve the microbiological quality of the final effluent.

7. Excessive organic loading of a WSP system reduces nutrient removal efficiency to a greater extent than either BOD or bacterial removal. Whereas the bulk of organic carbon removal occurs in the anaerobic ponds, most nutrient (both N and P) removal occurs in the maturation ponds and is dependent on high pH levels in the pond water column. These pond systems were capable of > 90% ammonia removal, > 70% TKN removal and > 40% total P removal at optimal pond loadings.

8. At temperatures above 20°C ammoniacal nitrogen removal in facultative and maturation ponds may be estimated from the equation:

$$C_{(Amm.N)_e} = C_{(Amm.N)_i} / [1 + 8.65x10^{-3} (A / Q)e^{1.727(ph\ -6.6)}]$$

9. Faecal bacterial and viral removal is more efficient in shallow, rather than deep, facultative and maturation ponds, at least within the depth ranges of 1 to 2 m for facultative ponds and 0.4 to 1.5 m for maturation ponds. Thus increasing pond depths to achieve, for the same pond area, increased retention times for insertion into the Marais equation to obtain improved FC removals, is not a valid process design strategy, since the predicted design performance will be less than the actual performance.

10. At temperatures above 20°C k_T values for FC removal in shallow, short retention time facultative and maturation ponds may be tentatively estimated from the equation:

$$k_T = 2.6\ (1.15)^{T-20}$$

This equation gives slightly lower values than the Marais equation as the value of k_T changes with temperature by 15 percent per degC rather than by 19 percent.

11. The incorporation of the floating macrophyte *Pistia stratiotes* on a tertiary maturation pond achieves only a slight increase in physicochemical effluent quality, but a decrease in microbiological effluent quality; its use therefore appears unwarranted.

12. The presence of the microcrustacean *Daphnia magna* in a tertiary maturation pond is difficult to sustain due to predation by larger aquatic invertebrates. Thus *Daphnia* ponds are not yet a feasible design option.

13. Baffled tertiary maturation ponds are more efficient than unbaffled ponds, in terms of both microbiological and physicochemical effluent quality.

14. Short-retention-time rock filters receiving primary maturation pond effluent should be loaded at 1 m^3 of gross rock filter volume per day. They achieve only a small reduction in BOD and COD but can achieve SS concentrations < 30 mg/l. FC and FS removal is nearly an order of magnitude, and rotavirus removal approximately half an order of magnitude. No difference in performance due to rock size within the range 19-38 mm was found.

Acknowledgements

We wish, first of all, to express our gratitude to the former Overseas Development Administration of the United Kingdom Government, for financing this four-year research programme from April 1991 to May 1995. We are also greatly indebted to the Universidade Federal da Paraíba-UFPB, and the Companhia de Água e Esgotos da Paraíba-CAGEPA, for the provision of research facilities at EXTRABES and Catingueira.

Almost all the academic, technical, clerical and maintenance staff at EXTRABES were involved in one way or another with this research project. Indeed without them and their unstinting devotion the project would never have drawn to a successful conclusion. We are very pleased to thank them all, especially Dr Rui de Oliveira and Dr José Soares and our own three field assistants who worked such long hours so cheerfully and so efficiently: Lenimar de Andrade Oliveira, José Wanderley do Nascimento Silva, and Antônio Minervino da Silva, to whom we say a heartfelt *muitíssimo obrigado*.

1. Introduction

Waste stabilization ponds (WSP) are now regarded as the method of first choice for the treatment of wastewater in many parts of the world. In Europe, for example, especially France and Germany (Boutin *et al.,* 1987; Bucksteeg, 1987), WSP are very widely used for small rural communities (generally up to 2000 population, but larger systems exist in Mediterranean France, and also in Spain and Portugal). In the United States one third of all wastewater treatment plants are WSP, usually serving populations up to 5000 (EPA, 1983). However in warmer climates (the Middle East, Africa, Asia and Latin America) ponds are commonly used for large populations (up to around 1 million) and, although sufficient land is often available at reasonable cost, this is not always the case, especially when the production of a high quality effluent is required for agricultural or aquacultural reuse.

The objective of this study was to investigate the performance of WSP systems with short retention times and shallow depths, in order to determine whether such lower cost systems could produce high quality effluents. Our global experience of WSP systems, particularly in relation to our understanding of their microbiological behaviour (see Pearson *et al.,* 1988), indicates that such systems could be highly efficient and would result in considerable savings in both land and cost. In this Research Monograph we present the results of a study on this innovative approach to WSP design, which also included a comparison with a more conventional WSP series.

Section 2 describes our two experimental WSP systems, and in Section 3 we give brief details of our sampling regimes and experimental methods and materials. In Sections 4 and 5 we present the results from the more conventional WSP (the series of 10 ponds) and the "innovative" WSP system, respectively. The results are discussed, together with kinetic analyses, in Section 6 and conclusions drawn in Section 7.

2. Experimental WSP

2.1 Location

The experimental pond complex, comprising the two main systems described in Sections 2.2 and 2.3 below, was constructed at the Catingueira wastewater treatment plant located 10 km from the centre of the city of Campina Grande in the State of Paraíba, northeast Brazil (latitude 7° 13' 11", longitude 35° 52' 31"W, altitude 550 m). Raw municipal wastewater was pumped from the wastewater channel downstream of the grit removal channels by means of a submersible pump (1.2 hp, 3380 rpm, manufactured by Dynapac Equipamentos Industriais Ltd, São Paulo) to a constant level tank in a pumphouse immediately above the experimental WSP. From here the wastewater was pumped by variable speed centrifugal pumps (model NE30A, Netzsch do Brasil, Pomerode, Santa Catarina) into the three anaerobic ponds (one in the series of 10 ponds (Section 2.2) and two in the "innovative" WSP system (Section 2.3)).
Figure 2.1 shows schematically the whole complex of the 27 experimental WSP.

2.2 Series of ten WSP

A series of ten small WSP was constructed which comprised (Figure 2.2) an anaerobic pond (coded A11) and nine subsequent ponds, of which the first was nominally facultative (F26) and the remaining eight nominally maturation ponds (M25-M32). Their dimensions (length, breadth, depth) were:

A11	1.80 × 1.20×1.50 m
Others	3.60×1.20×1.50 m

In experiment 1 the flow of raw municipal wastewater into pond A11 was 3.24 m^3/day (135 litres/hour), such that the retention time in the anaerobic pond was 1 day and in the other ponds 2 days. In experiment 2 the flow was 2.16 m^3/day (90 litres/hour) with retention times of 1.5 days in the anaerobic pond and 3 days in the others.

2.3 Innovative WSP

The "innovative" WSP system comprised anaerobic, facultative and maturation ponds as follows:

(a) two anaerobic ponds (A9 and A10 in parallel), the effluents of which were mixed together to feed:

(b) five facultative ponds (F21-F25) (Figure 2.3), the effluents of which were mixed and discharged into:

(c) a single primary maturation pond (M15) (Figure 2.1), the effluent of which was split equally into eight streams of 5 m^3/day to feed five secondary maturation ponds (see (d) below) and three rock filters (see (f) below):

(d) five secondary maturation ponds (M16-M20) (Figure 2.4); the effluents from three of them (M16, M17 and M18) were mixed together and split equally into four streams to feed:

(e) four tertiary maturation ponds (M21-M24) (Figures 2.5 and 2.6); and

(f) three rock filters (RF2-RF4) (Figure 2.7), each of which received effluent from the primary maturation pond M15. The rock sizes used were 19-38 mm.

The dimensions of the experimental WSP are given in Table 2.1, which also gives flow rates, retention times and organic loadings during experiments 1 and 2. Table 2.2 gives the dimensions of the experimental rock filters, and Table 2.3 gives the flow rates and retention times in the two experiments.

The effluents from two of the secondary maturation ponds (M19 and M20), the four tertiary maturation ponds and the three rock filters were discharged to waste in the main raw wastewater channel downstream of the submersible pump feeding the experimental WSP.

Rationale for the innovative WSP

Anaerobic Ponds. The two identical anaerobic ponds were operated in parallel for several months in experiment 1 to determine whether they were producing effluents of essentially the same helminthological quality. One of them (A10) was then fitted with an "egg deflector" plate made from 15 mm PVC sheet (dimensions: 0.9 m wide and 1 m long; and angled at 17.5º to the vertical) located under its outlet in order to determine whether this was a useful strategy.

Facultative ponds. Four of the five secondary facultative ponds had the same length-to-breadth ratio of 6 to 1, but different depths (1, 1.33, 1.67 and 2m), so that their retention times were 3, 4, 5 and 6 days in experiment 1; and 1.5, 2, 2.5 and 3 days in experiment 2. The fifth secondary facultative pond was square with a depth of 2 m and had a retention time of 6 days in experiment 1 and 3 days in experiment 2. Thus it was possible to investigate a range of retention times and compare two geometric configurations.

Maturation ponds. The primary maturation pond was common to the five secondary facultative ponds. It had a length-to-breadth ratio of 2 to 1, a depth of 1 m and a retention time of 3.8 days. The four secondary maturation ponds had the same area and length-to-breadth ratio of 2.8 to 1, but had different depths (0.39, 0.64 and 0.90 m) and retention times (3, 3, 5 and 7 days in experiment 1, and 1.5, 1.5, 2.5, and 3.5 days in experiment 2; two were identical, to act as an internal control). Thus it was possible to investigate a range of depths and retention times. The tertiary maturation ponds were identical (0.6 m deep, 5 days retention time in experiment 1 and 2.5 days in experiment 2) to permit investigations into the use of aquatic macrophytes, *Daphnia* and baffles (the latter yielded an effective length-to-breadth ratio of 14.3 to 1 in pond M24, compared with 2.3 to 1 in the other three).

Rock filters. The three rock filters (receiving effluent from the primary maturation pond) were identical in reactor geometry, but different in rock size. Small rock sizes were chosen (19-38 mm) as these were more readily available in Brazil than the larger sizes (100 mm or more) used in rock filters in the United States (Middlebrooks, 1988).

Least retention time. The series of ponds in the innovative system with the least retention times in experiment 1 were:

(a) A9 (or A10) (1 day), F21 (3 days), M15 (3.8 days), M18 (3 days) and M21 (or M22,M23, M24) (5 days), to give an overall retention time of 15.8 days;

(b) A9 (or A10), F21, M15 and M20 (1 day), to give an overall retention time of 8.8 days; and

(c) A9 (or A10), F21, M15 and RF1 (or RF2, RF3) (1 day), also to give an overall retention time of 8.8 days.

Table 2.1: Details of the physical and operational characteristics of the experimental "innovative" pond system

Pond	Dimensions (m)			Flow Rate (m^3/d)		HRT* (d)		λ_v (g BOD/m^3d)		λ_s (kgBOD_5/ha d)	
	Length	Width	Depth	Expt. 1	Expt. 2	Expt. 1	Expt. 2	Expt. 1	Expt. 2	Expt. 1	Expt. 2
A9	4.90	1.65	2.50	20.0	40.0	1.0	0.5	187	413		
A10	4.90	1.65	2.50	20.0	40.0	1.0	0.5	187	413		
F21	12.90	2.00	1.00	8.0	16.0	3.0	1.5	19	77	230	697
F22	12.90	2.00	1.33	8.0	16.0	4.0	2.0	1419	5877	230	697
F23	12.90	2.00	1.67	8.0	16.0	5.0	2.5	11	46	230	697
F24	12.90	2.00	2.00	8.0	16.0	6.0	3.0	10	38	230	697
F25	4.90	4.90	2.00	8.0	16.0	6.0	3.0	10	38	247	697
M15	17.35	8.80	1.00	40.0	80.0	3.8	1.9	6	27	73	267
M16	10.40	3.75	0.90	5.0	10.0	7.0	3.5	2	12	24	105
M17	10.40	3.75	0.64	5.0	10.0	5.0	2.5	3	16	24	105
M18	10.40	3.75	0.39	5.0	10.0	3.0	1.5	5	27	24	105
M19	10.40	3.75	0.39	5.0	10.0	3.0	1.5	5	27	24	105
M20	10.40	1.30	0.39	5.0	10.0	1.0	0.5	14	78	70	309
M21	8.45	3.70	0.60	3.75	7.5	5.0	2.5	4	12	28	65
M22	8.45	3.70	0.60	3.75	7.5	5.0	2.5	4	12	28	65
M23	8.45	3.70	0.60	3.75	7.5	5.0	2.5	4	12	28	65
M24**	64.0	0.44	0.60	3.75	7.5	4.2	2.1	4	12	31	72

* HRT: hydraulic retention time (d); λ_v: volumetric organic loading; λ_s: surface organic loading.
** baffled pond.

Table 2.2 Physical characteristics of the pilot-scale rock filters.

Rock filter	RF2	RF3	RF4
Length (m)	5.00	5.00	5.00
Width (m)	1.00	1.00	1.00
Depth (m)	1.40	1.40	1.40
Rock layer thickness (m)	1.15	1.15	1.15
Water column (m)	1.00	1.00	1.00
Crushed rock mean diameter (mm)	38	15	19
Rock layer volume (m^3)	5.75	5.75	5.75
Immersed rock layer volume (m^3)	5.00	5.00	5.00
Voids (%)	41	39	32

Table 2.3 Operational characteristics of the pilot-scale rock filters.

Experiment	1	2	1	2	1	2
Flow rate (m^3/d)	5.0	10.0	5.0	10.0	5.0	10.0
Hydraulic retention time (hour)	9.8	4.9	9.5	4.8	7.7	3.9
Organic loading (g BOD_5/m^3 d) *	59	137	62	144	75	175

* based on the void space volume.

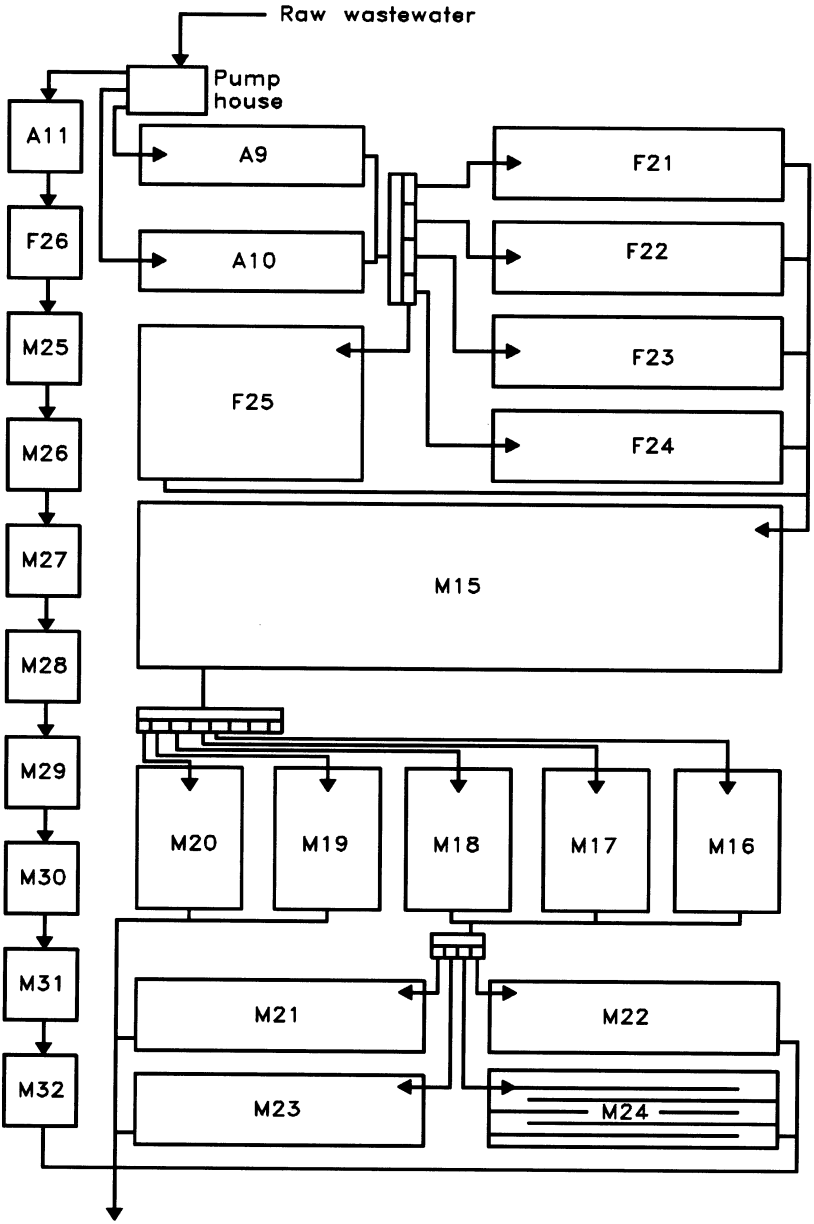

Figure 2.1: Layout of experimental WSP at Catingueira, northeast Brazil.

Figure 2.2: Series of ten WSP at Catingueira.

Figure 2.3: Anaerobic (bottom left) and secondary facultative ponds at Catingueira.

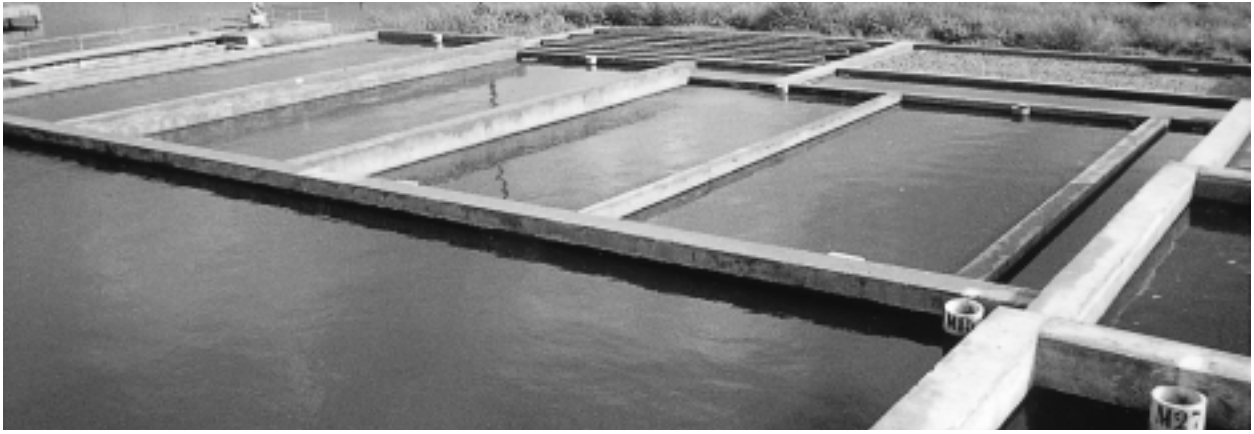

*Figure 2.4: Primary maturation (*foreground*) and secondary maturation ponds at Catingueira.*

Figure 2.5: Tertiary maturation ponds at Catingueira, including one baffled (M24) and one with Pistia stratiotes *(M23).*

Figure 2.6: Tertiary maturation pond baffled to give a length-to-breadth ratio of 143 to 1.

Figure 2.7: Experimental rock filters receiving effluent from the primary maturation pond.

3. Experimental methods and materials

3.1 Sampling

Routine monitoring. Twenty-four hour composite samples of raw wastewater were taken twice weekly from the constant level tank in the pumphouse by means of a refrigerated automatic sampler. For the innovative WSP weekly column samples (Pearson *et al.,* 1987*a*) were taken from each pond adjacent to its outlet; these served as estimates of the mean daily effluent quality from each pond (Figure 3.1). For the series of ten WSP grab samples of the effluent of each pond and effluent column samples were taken in alternate weeks.

Profiles. Once (occasionally twice) a week 24-hour physicochemical and microbiological depth profiles were obtained on the following ponds (Pearson *et al*., 1987*b*): (a) in the innovative WSP system – ponds F21, F24, F25, M15, M16, M20, M23 and M24; and (b) in the series of 10 WSP – ponds M26, M31 and M32. The depths at which samples were taken depended on the depth of the pond being sampled: a surface (3-6 cm) sample was always taken, and the remaining depths are evident from the profile graphs obtained (Section 5).

In the case of the baffled tertiary maturation pond (M24) a "horizontal" profile was also undertaken: column samples were taken at the end of each baffle wall, making a total of ten samples along its 64 m effective length.

A 24-hour diurnal study of the effluent quality from the last pond (M32) in the series of 10 WSP was also undertaken; samples were taken every four hours.

3.2 Physicochemical analyses

Wherever possible samples were analysed for physicochemical parameters according to the recommendations in *Standard Methods for the Examination of Water and Wastewater* (APHA, 1989). In the list below reference is made to the method number given in the 17th (1989) edition of *Standard Methods*, unless otherwise stated:

BOD	Method 5210 B (dissolved oxygen measured by a YSI BOD electrode)
COD	Method 5220 C
Suspended solids	Method 2540 D

Volatile suspended solids	Method 2540 E
Ammonia	Method 4500-NH_3 C
Nitrate	Method 418 D (15th edition, 1980)
Total kjeldahl	Method 4500-N_{org} B nitrogen
Total phosphorus	Method 4500-P B (persulphate digestion) and E
Soluble phosphorus	Method 4500-P E
Sulphate	Method 4500-SO_4 E
Sulphide	Method 4500-S D
Chloride	Method 4500-Cl B
pH	Method 4500-H B
Alkalinity	Method 2320 B
Dissolved oxygen	Method 4500-0 G
Temperature	Method 2550 B

Mean daily temperatures of the raw wastewater and the ponds were obtained from maximum-and-minimum thermometers suspended in the constant level tank in the pumphouse and in each pond at mid-depth.

3.3 Microbiological analyses

Viruses. Rotavirus numbers were determined by the method of Oragui and Mara (1989).

Bacteria. Faecal coliforms, faecal streptococci and *Clostridium perfringens* were enumerated by membrane filtration according to the methods given in *Report 71* (Department of the Environment, 1983). Numbers of salmonellae, *Vibrio cholerae* O1 and pathogenic campylobacters were determined by the most probable number (MPN) techniques described by Oragui *et al.* (1993*a*), Oragui *et al.* (1993*b*) and Oragui *et al.* (1987), respectively.

Helminth eggs. The numbers of human intestinal nematode eggs were determined by the method of Mara and Silva (1986).

Algae. Chlorophyll *a* was determined by the method of Pearson *et al*. (1987*a*), and algal speciation according to the recommendations given in Mara *et al*. (1992).

In-pond V. cholerae *batch-culture studies.* Studies were done to determine the survival of *V. cholerae* O1 seeded into samples of raw wastewater, pond effluents (A9, F21 and M15) and $^1/_4$ strength Ringer's solution. The strain of *V. cholerae* O1 used in these experiments was isolated from raw wastewater at Catingueira. The procedure was as follows:

1. Stock cultures of the *V. cholerae* isolate were maintained on Nutrient Agar slopes at 4°C.

2. When required for experimentation, a stock culture was inoculated into ten 10-litre bottles of Nutrient Broth and incubated at 37°C for 24 hours. These cultures were then centrifuged at 3500 rpm for 20 minutes. The pellets were resuspended in Ringer's solution and recentrifuged; this washing procedure was repeated three times. The pellets were then pooled and made up to 100 ml with Ringer's solution. The number of *V. cholerae* in this 100 ml solution was then determined by surface plate counts on Nutrient Agar with incubation at 37°C for 24 hours. The culture was then stored overnight at 4°C.

3. The following day 5-litre volumes of raw wastewater, effluents from ponds A9, F21 and M15, and Ringer's solution were inoculated with the *V. cholerae* culture to give 10^8-10^9 cells per 100 ml. These volumes were then transferred to 10-litre plastic buckets and suspended in the appropriate ponds (raw wastewater and A9 effluent in pond A9; Ringer's solution and F21 effluent in pond F21; and M15 effluent in pond M15) such that the liquid surface in the bucket was at the same level as the liquid surface in the pond. The initial sulphide concentrations in the samples were also determined.

4. Samples were then withdrawn from the buckets daily for 13 days and the numbers of *V. cholerae* determined.

3.4 Meteorological data

Data on temperature, rainfall, evaporation and solar radiation were obtained from the EMBRAPA meteorological station at Centenário in Campina Grande (10 km from Catingueira).

4. Experimental results from the series of ten WSP

4.1 Experiment 1

The operational retention times were 1 day in the anaerobic pond and 2 days in the other nine (in experiment 2 this was changed to 1.5 and 3 days, respectively).

4.1.1 Physicochemical results

Data for BOD (filtered and unfiltered), COD, suspended and volatile suspended solids (SS and VSS), ammonia and nitrate, total and soluble phosphorus, sulphate and sulphide, alkalinity, chloride, chlorophyll *a* and pH are given in Tables 4.1 – 4.3 as arithmetic means and ranges (maximum and minimum values determined).

The data show that after the first four ponds an effluent was achieved with an unfiltered BOD_5 of 10 mg/l and a filtered BOD_5 of 5.5 mg/l, with (as expected) most of the reduction occurring in the anaerobic pond (66 percent for unfiltered BOD). The remaining six ponds achieved little, if any, further reduction, and this pattern was followed for all the other parameters, except pH and chlorphyll *a* which showed a gradual increase throughout the series of 10 ponds, and except alkalinity and chloride which (as would be expected) remained essentially constant throughout the series.

These physicochemical results are, given the very short retention times of the ponds, excellent: if physicochemical quality were the only criterion for effluent quality (that is, if its microbiological quality were unimportant), then only two ponds (A11 and F27, with an overall retention time of just three days) are needed to achieve the maximum permissible effluent BOD and SS concentrations stipulated for pond effluents in the EU Directive on Urban Waste Water Treatment (Council of the European Communities, 1991), i.e. a filtered $BOD_5 < 25$ mg/l and a suspended solids concentration < 150 mg/l.

4.1.2 Microbiological results

Data for faecal coliforms (FC), faecal streptococci (FS), *Clostridium perfringens*, salmonellae, campylobacters, *Vibrio cholerae* O1 and rotaviruses are given in Tables 4.4 and 4.5, and for helminth eggs in Table 4.6.

The results for FC show that they were removed by around half an order of magnitude in each pond, with an overall reduction of five $\log_{10}$ units. The World Health Organization guideline level of $\nless 1000$ FC per 100 ml for unrestricted irrigation (WHO, 1989) was achieved by the first

six ponds, after an overall retention time of only eleven days, by which time FS and *C. perfringens* numbers were also low (< 500 per 100 ml). The removals of bacterial and viral pathogens were also very good: only small numbers of salmonellae (< 1 per 100 ml) were present after 13 days; the numbers of *V.cholerae* and campylobacters were too low to be evaluated. Rotavirus numbers reached zero after 19 days, a five $\log_{10}$ unit reduction.

Helminth egg removal was very good as well (Table 4.6): most were removed in the anaerobic and facultative pond, and the World Health Organization guideline value for crop irrigation (both restricted and unrestricted) of $\not>1$ egg per litre was achieved after the first four ponds, i.e. after an overall retention time of only seven days.

Detailed pond profile results (parameter variation with depth over 24 hours) are presented in Mara *et al*. (1994). Figure 4.1 shows, as a typical example, the diurnal variation of COD, SS, pH, chlorophyll *a* and FC in the effluent of pond M32 (the final pond in the series) on 17-18 March 1993 during experiment 1. The algal (chlorophyll *a*) peak at 4 pm coincides with the COD, SS and pH peaks at this time and also with the minimum FC level, thus confirming the importance of high algal-induced pH in the removal of FC in maturation ponds (see Pearson *et al.,*1987*c*).

4.2 Experiment 2

In experiment 2 the hydraulic retention times were 1.5 days in the anaerobic pond and 3 days in the other nine, i.e. 50% higher than in experiment 1. Table 4.7 shows the main results obtained in both experiments, from which it can be seen that no advantage was obtained by increasing the retention times in experiment 2. Despite the 2–d retention times in the facultative and maturation ponds during experiment 1 being less than the minimum value of 3 days recommended by Marais (1974), the ponds performed well and the results clearly indicate that such a series is a highly effective method of reducing the land area requirements of WSP systems at temperatures of around 25ºC.

Table 4.1 Physicochemical results (arithmetic mean and range) for the series of ten WSP in experiment 1

Pond	Unfiltered BOD (mg/l)	Filtered BOD (mg/l)	Unfiltered COD (mg/l)	SS (mg/l)	VSS (mg/l)
RW*	181 (98-274)	63 (33-98)	523 (270-860)	280 (167-643)	208 (143-444)
A11	62 (18-108)	40 (20-98)	377 (117-1801)	137 (13-451)	119 (13-631)
F26	29 (12-81)	14 (3-24)	178 (102-581)	82 (23-469)	65 (26-311)
M25	18 (1-54)	8 (3-17)	132 (71-242)	53 (14-172)	43 (8-118)
M26	10 (1-32)	5.5 (1-19)	109 (72-217)	40 (11-66)	32 (8-54)
M27	9 (0-23)	5.1 (1-14)	105 (60-173)	39 (9-146)	29 (9-76)
M28	7 (3-18)	4.4 (1-11)	103 (61-176)	33 (8-88)	28 (7-67)
M29	8 (0-17)	4.8 (2-10)	108 (64-188)	39 (1-131)	32 (1-113)
M30	10 (0-23)	5.76 (2-13)	107 (63-199)	33 (4-61)	29 (4-56)
M31	9 (1-15)	5.1 (2-12)	106 (47-153)	39 (9-127)	30 (9-61)
M32	11 (2-18)	5.0 (2-12)	101 (58-179)	39 (16-70)	33 (8-70)

*RW: raw wastewater.

Table 4.2 Physicochemical results (arithmetic mean and range) for the series of ten WSP in experiment 1

Pond	Ammonia (mg N/l)	Nitrate (mg N/l)	Total P (mg/l)	Soluble P (mg/l)	Sulphate (mg SO_4/l)	Sulphide (mg/S/l)
RW*	28.0 (10.0-52.8)	0.55 (0.10-1.73)	5.60 (3.0-7.4)	2.32 (0.4-3.4)	16.84 (3.4-37.0)	0.55 (0.10-1.73)
A11	34.1 (21-53.5)	0.48 (0.01-1.25)	5.96 (3.0-13.1)	3.52 (1.8-5.0)	10.81 (0.0-20.4)	11.31 (0.16-35.29)
F22	34.6 (19.20-51.70)	0.49 (0.03-1.12)	5.22 (1.9-8.7)	2.84 (0.5-4.4)	12.26 (0.0-25.4)	1.75 (0.00-8.33)
M25	31.5 (7.0-44.9)	0.53 (0.13-1.12)	4.99 (1.5-10.2)	2.31 (0.0-4.2)	13.51 (0.0-22.4)	0.27 (0.00-1.99)
M26	24.3 (13.9-46.7)	0.67 (0.11-1.69)	4.71 2.6-10.4)	2.38 (0.0-4.6)	16.01 (0.0-32.0)	0.09 (0.00-0.65)
M27	19.3 (7.6-42.7)	0.67 (0.10-1.71)	4.82 (3.5-10.7)	2.64 (0.6-5.5)	15.25 (3.0-26.0)	0.02 (0.00-0.26)
M28	19.7 (2.2-39.0)	0.72 (0.10-1.76)	5.08 (2.6-11.0)	3.39 (1.3-5.2)	13.97 (3.4-24.0)	0.02 (0.00-0.13)
M29	15.7 (0.0-35.1)	0.85 (0.31-2.21)	4.94 (2.7-10.8)	3.35 (1.5-5.3)	12.27 (3.0-19.8)	0.03 (0.00-0.38)
M30	12.3 (0.0-34.2)	0.98 (0.41-3.40)	4.72 (1.8-11.2)	3.26 (1.1-5.9)	12.36 (8.8-21.0)	0.01 (0.00-0.08)
M31	9.3 (0.0-30.6)	0.93 (0.41-2.97)	4.59 (1.4-11.7)	3.15 (0.9-6.6)	12.41 (3.0-19.8)	0.00 (0.00-0.03)
M32	6.3 (0.0-22.5)	0.86 (0.29-2.27)	4.43 (1.4-11.7)	3.02 (0.8-5.8)	12.04 (0.0-19.8)	0.00 (0.00-0.04)

*RW: raw wastewater.

Table 4.3 Physicochemical results (arithmetic mean and range) for the series of ten WSP in experiment 1

Pond	Chlorophyll (μg/l)	pH	Alkalinity (mg $CaCO_3$/l)	Chloride (mg/l)
RW*	-	7.34 (7.0-7.6)	317 (248-373)	362 (308-412)
A11	-	7.26 (7.1-7.30)	377 (330-439)	354 (312-424)
F26	252 25-419	7.49 (6.8-7.8)	377 (314-416)	364 (298-439)
M25	196 (16-477)	7.65 (7.0-7.9)	367 (313-409)	354 (322-409)
M26	137 (24-355)	7.71 (7.0-8.0)	342 (264-405)	335 (316-518)
M27	169 (53-305)	7.77 (7.4-8.0)	322 (247-401)	341 (314-467)
M28	169 (38-558)	7.79 (7.3-8.3)	325 (227-397)	363 (307-518)
M29	180 (25-544)	7.92 (7.0-8.6)	320 (247-461)	370 (316-444)
M30	211 (2-524)	8.13 (7.3-8.8)	308 (229-428)	374 (308-461)
M31	191 (14-425)	8.17 (7.5-8.8)	296 (238-369)	392 (330-506)
M32	230 (15-472)	8.32 (7.6-9.0)	293 (238-344)	384 (322-447)

*RW: raw wastewater.

Table 4.4 Microbiological results (geometric mean and range) for the series of ten WSP in experiment 1

Pond	Faecal coliforms (per 100 ml)	Faecal streptococci (per 100 ml)	*Clostridium perfringens* (per 100 ml)
RW*	2.75×10^7 (6.10×10^6-5.50×10^7)	4.07×10^6 (1.77×10^6-9.3×10^6)	9.12×10^3 (5.0×10^2-1.37×10^5)
A11	7.41×10^6 (1.13×10^6-1.53×10^7)	9.33×10^5 (2.60×10^5-3.15×10^6)	6.92×10^3 (8.5×10^2-9.38×10^4)
F26	2.69×10^6 (8.15×10^4-8.0×10^6)	3.09×10^5 (5.35×10^4-2.7×10^6)	2.57×10^3 (5.0×10^2-4.7×10^4)
M25	4.47×10^5 (5.5×10^3-2.5×10^6)	6.03×10^4 (2.85×10^3-2.73×10^6)	1.62×10^3 (2.0×10^2-1.59×10^4)
M26	1.05×10^5 (3.85×10^3-2.04×10^6)	8.7×10^3 (6.5×10^2 – 6.45×10^4)	4.07×10^2 (50-9.10×10^3)
M27	1.05×10^4 (1.65×10^2-2.85×10^5)	1.74×10^3 (3.3×10^2-8.8×10^3)	2.29×10^2 (30-2.72×10^3)
M28	1.0×10^3 (14-6.35×10^4)	4.9×10^2 (52-1.75×10^4)	1.35×10^2 (10-1.2×10^3)
M29	$3.98\times10^{2)}$ (15-1.26×10^4)	1.48×10^2 (15-1.34×10^4)	49 (10-8.25×10^2)
M30	1.91×10^2 (17-2.2×10^3)	6.61×10^2 (15-7.03×10^4)	38 (6-2.3×10^2)
M31	95 (15-9.28×10^2)	3.39×10^2 (15-5.29×10^3)	50 (8-1.57×10^3)
M32	5.01×10^2** (33-2.53×10^4)	4.47×10^2 (35-9.55×10^3)	45 (5-1.35×10^3)

* RW: raw wastewater.
**Mostly *Klebsiella pneumoniae* (as determined by API 20E strips).

Table 4.5 Microbiological results (geometric mean and range) for the series of ten WSP in experiment 1

Pond	Salmonellae (per 100 ml)	Campylobacters (per 100 ml)	*Vibrio cholerae* (per 100 ml)	Rotaviruses (per litre)
RW*	1.28×10^{2} ($4\text{-}1.8\times10^{3}$)	9 (6-17)	4 (0-13)	1.35×10^{5} ($3.55\times10^{4}\text{-}7.83\times10^{5}$)
A11	70 ($5\text{-}1.6\times10^{3}$)	10 (9-14)	1 (0-6)	3.80×10^{4} ($2.1\times10^{4}\text{-}8.66\times10^{4}$)
F26	72 ($5\text{-}1.8\times10^{3}$)	0.86 (5-14)	1 (0-6)	2.21×10^{4} ($9.77\times10^{3}\text{-}7.5\times10^{4}$)
M25	31 ($1\text{-}3.5\times10^{2}$)	5.4 (0-161)	0 (0-1)	1.24×10^{4} ($6.3\times10^{3}\text{-}3.76\times10^{4}$)
M26	8 ($0\text{-}2.8\times10^{2}$)	3 (2-5)	0	9.08×10^{3} ($4.10\times10^{3}\text{-}1.13\times10^{4}$)
M27	3 ($0\text{-}1.61\times10^{2}$)	2 (0-6)	0	6.17×10^{3} ($4.05\times10^{3}\text{-}8.32\times10^{3}$)
M28	2 (0-35)	0 (0-1)	0	2.38×10^{3} ($1.56\times10^{3}\text{-}4.0\times10^{3}$)
M29	0 (0-1)	0	0	2.40×10^{3} ($1.75\times10^{3}\text{-}3.69\times10^{3}$)
M30	1 (0-3)	0	0	6.96×10^{2} ($2.5\times10^{2}\text{-}1.25\times10^{3}$)
M31	1 (0-3)	0	0	2.17×10^{2} ($0\text{-}2.4\times10^{2}$)
M32	0	0	0	0

*RW: raw wastewater.

Table 4.6 Helminthological results (arithmetic mean and range) for the series of ten WSP in experiment 1

Pond	*Ascaris* eggs (per litre)	*Trichuris* eggs (per litre)	Hookworm eggs (per litre)
RW*	442 (0-2333)	8 (0-100)	27 (0-267)
A11	256 (0-833)	4 (0-67)	18 (0-167)
F26	3 (0-10)	0	0
M25	0	0	0
M26	1 (0-10)	0	1 (1-20)
M27	0	0	0
M28	0	0	0
M29	0	0	0
M30	0	0	0
M31	0	0	0
M32	0	0	0

*RW: raw wastewater.

Table 4.7 Mean physicochemical and microbiological results for the pilot-scale series of ten ponds from January to December 1992 (experiment 1) and from November 1993 to September 1994 (experiment 2)

Sample	T* (°C)	pH	Dissolved oxygen (mg/l)	BOD_5 (mg/l)	COD (mg/l)	SS (mg/l)	Chlorophyll *a* (µg/l)	Faecal coliforms (per 100ml)	Helminth eggs (per litre)
Experiment 1									
CRS*	-	7.3	0.2	181	523	280	-	2.72E7	477
A11	23	7.3	0.2	62	376	137	-	9.21E6	278
F26	22	7.5	0.8	29	178	82	282	2.37E6	3
M25	22	7.7	2.1	18	132	53	93	5.90E5	0
M26	22	7.7	2.7	13	117	40	76	8.90E4	1
M27	22	7.8	3.9	9	106	39	117	1.20E4	0
M28	22	7.8	4.5	7	101	33	111	2.50E3	0
M29	22	7.9	4.4	8	108	39	115	6.90E2	0
M30	22	8.1	5.4	10	107	33	109	1.94E2	0
M31	22	8.2	6.0	9	106	39	138	1.10E2	0
M32	22	8.3	7.5	11	101	39	166	2.84E2	0
Experiment 2									
CRS	-	7.6	0.2	279	569	312	-	4.46E7	n.d*
A11	24	7.4	0.1	91	240	74	-	1.07E7	
F26	23	7.6	0.4	52	190	71	247	3.88E6	
M25	23	7.8	1.0	37	154	60	232	8.00E5	
M26	23	7.9	0.9	22	119	39	121	1.06E5	
M27	23	7.9	1.5	15	116	31	111	1.33E4	
M28	23	7.9	1.7	14	101	30	98	1.39E3	
M29	23	8.0	2.3	13	101	28	118	2.55E2	
M30	23	8.2	3.1	13	114	30	144	6.99E1	
M31	23	8.4	3.6	12	112	32	139	4.85E1	
M32	23	8.6	4.7	12	103	32	108	1.07E2	

*T – Temperature; CRS – composite raw sewage; n.d. – not determined.

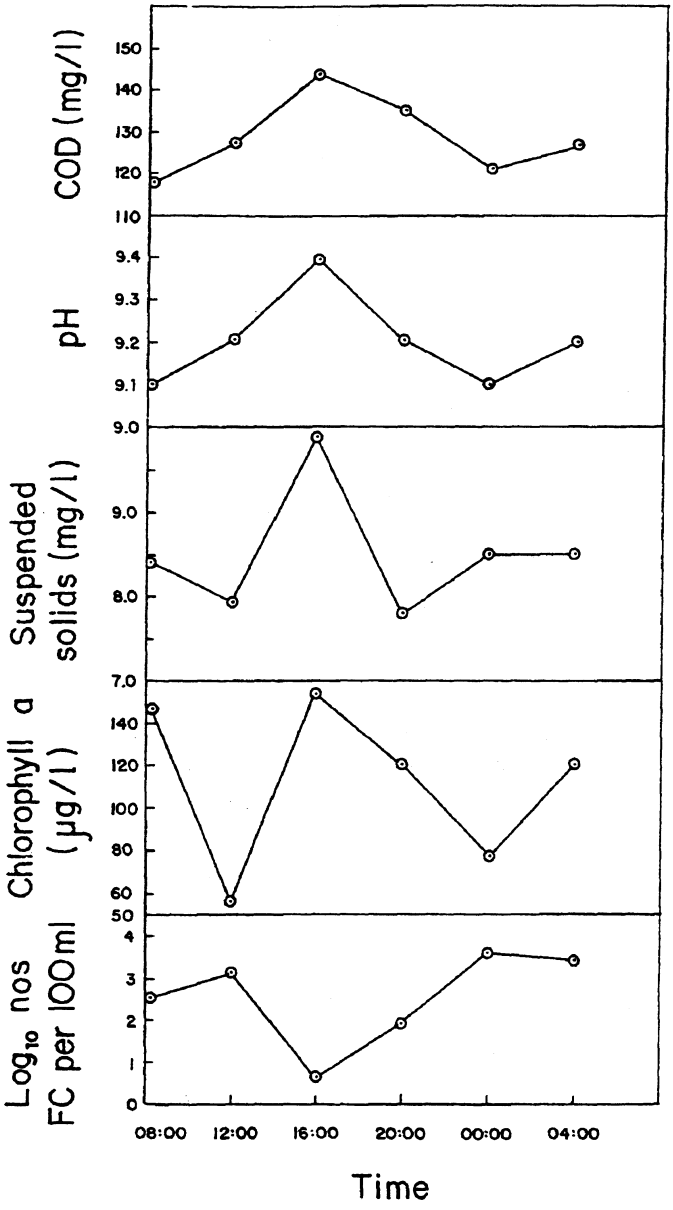

Figure 4.1: Diurnal variation of COD, SS, pH, chlorophyll a and faecal coliforms in the effluent of pond M32 (the last pond in the series) on 17-18 March 1993 during experiment 1.

5. Experimental results from the innovative WSP

5.1 Experiment 1

The retention times in experiment 1 were 1 day in the anaerobic ponds, 3-6 days in the facultative ponds, 3.8 days in the primary maturation pond, 1-5 days in the secondary maturation ponds, and 5 days in the tertiary maturation ponds (4.2 days in the baffled pond). These values were halved in experiment 2.

5.1.1 Physicochemical results

Data for BOD (filtered and unfiltered), COD, suspended and volatile suspended solids (SS and VSS), total kjeldahl nitrogen (TKN), ammonia, nitrite and nitrate, total and soluble phosphorus, alkalinity, pH, chloride and chlorophyll *a* are given in Tables 5.1-5.4 as arithmetic means and ranges (maximum and minimum values determined).

These results are fully discussed in Section 6, but it may be noted here that the EU pond effluent standard of < 25 mg filtered BOD per litre and < 150 mg SS per litre was achieved after pond F21, that is after an overall retention time of 4 days.

5.1.2 Microbiological results

Data for faecal coliforms (FC), faecal streptococci (FS), *C. perfringens*, salmonellae, campylobacters, *V. cholerae* and rotaviruses are given in Tables 5.5 and 5.6, and for helminth eggs in Table 5.7. These results are fully discussed in Section 6, but it may be noted here that the WHO guideline value of ≤ 1 helminth egg per litre was achieved by ponds A9 (or A10) and F21, after an overall retention time of 4 days; and that the WHO guideline of ≤ 1000 FC per 100 ml achieved by the series A9 (or A10), F21, M15 and M19, after an overall retention time of 11 days (although including M20 rather than M19 would be just acceptable, so the overall retention time would be 9 days).

V. cholerae *survival studies*

The results of the *V.cholerae* survival studies are shown in Figure 5.1. The times for *V. cholerae* numbers to reach zero and the initial sulphide concentrations were:

Ringer's solution	5 days	0 mg S l^{-1}
Raw wastewater	5	3.0
A9 effluent	10	8.0
F21 effluent	> 13	0.2
M15 effluent	> 13	0

The presence of high sulphide levels appears to accelerate the removal of *V. cholerae*. This is confirmed by the data on *V. cholerae* removal in anaerobic ponds in Tables 4.5 and 5.6: 50-75 percent removal at sulphide levels of 11.3 mg/l, and Oragui *et al*. (1993*b*) report a reduction of *V. cholerae* numbers in pond A11 from 485 per litre to 28 per litre (94 percent removal). Thus anaerobic ponds are important for the removal of *V. cholerae*.

5.1.3 Floating macrophyte pond

The tertiary maturation pond M23 was covered with the floating macrophyte *Pistia stratiotes*. From the results in Tables 5.1-5.6 it can be seen that this achieved only small increases in physicochemical performance (mainly nutrient removal), but that microbiological efficiency was reduced compared with the normal algal pond M21.

5.1.4 Microcrustacean pond

The tertiary maturation pond M22 was seeded with *Daphnia magna*, but it was found to be impossible to sustain viable *Daphnia* populations due to predation by higher aquatic invertebrates. Further work is needed to determine strategies to prevent such predation, such as the provision of underwater refuges.

5.2 Experiment 2

The retention times in experiment 2 were 0.5 days in the anaerobic ponds, 1.5-3 days in the facultative ponds, 1.9 days in the primary maturation pond, 0.5-2.5 days in the secondary maturation ponds, and 2.5 days in the tertiary maturation ponds (2.1 days in the baffled pond), i.e. half the values in experiment 1.

5.2.1 Physicochemical results

The volumetric loading on the anaerobic ponds (A9 and A10) of 413 g BOD_5/m^3 d was 38% higher than the maximum recommended value of 300 g BOD/m^3 d for temperatures above 20ºC. It was, however, less than the value of 500 $BOD_5/m^3/d$ which would be obtained from the equation 20T-200 (where T in this case = 25ºC) normally applied to design situations between 10-20ºC. At this volumetric loading, which gave a HRT in the anaerobic pond of 12 h, one would predict a 60% removal of BOD_5. The results (Table 5.8) show that the A9 effluent quality of 121 mg BOD/1 falls short of this prediction with a removal efficiency of only 44%, whereas A10 with an effluent quality of 88 mg BOD/1 for the same volumetric loading had a removal efficiency of 59%, almost equal to the predicted level. These results suggest that the maximum loading on anaerobic ponds at 25ºC approaches 400 g/m^3 d. When the sewage is stronger than the relatively weak concentration of 215 mg/1 in this experiment (Table 5.8), there would be the added bonus of a higher hydraulic time (closer to 1 day), rather than the very short 12 h period used here, and this would also aid BOD_5 removal efficiency. It is clear from these studies that the 20T-200 equation is not applicable above 20ºC (see Mara and Pearson, 1986).

The surface BOD_5 loading on the secondary facultative ponds of 697 kg/ha d was close to double that which would be applied at 25ºC using conventional design equations (Table 2.1).

Nevertheless BOD_5 removals were high in these secondary facultative ponds, ranging from 49% (F21 and F22) to 56% (F23). The combined removal efficiency of 75-79% of the anaerobic and secondary facultative ponds is still good, but slightly lower than the predicted 80-90% for combined BOD_5 removal in anaerobic and facultative ponds in series (Mara *et al*., 1992), and lower than the value of 82-87% obtained in experiment 1. The BOD_5 of the final effluent from the system (*i.e.* the effluents from the tertiary maturation ponds) in experiment 2 were comparable to those obtained in experiment 1, despite the greatly increased volumetric and surface loadings.

The excessively high organic surface loadings on the secondary facultative ponds reduced chlorophyll *a* concentrations to the low levels of 288 – 518 μg Chl *a*/m^2 (equivalent to 288-310 μg Chl *a*/l), which are close to the value of 300 mg Chl *a*/l predicted to be the minimum required for the algal population to sustain aerobic conditions in the surface layers of the facultative ponds (Pearson and König, 1986). The relative impact of increased organic loadings on the dissolved oxygen concentrations in the ponds can be seen in Table 5.9, which shows the mean dissolved oxygen for the entire water column samples taken at 08.00 h. Clearly, disturbing the water column samples affects the oxygen values, and the actual O_2 concentration varies with depth and time of day. However, these measurements give a good relative picture of the impact of increased organic loadings: they serve to show that in experiment 2 the secondary facultative ponds were virtually anoxic and at the very limit of their operational tolerance.

As one would predict, BOD removal largely occurred in the anaerobic and facultative ponds, although in experiment 2 there was a shift down the pond series. This emphasises the advantage of 3 and 4 pond series even for BOD_5 removal at high organic loads.

The high organic loadings in experiment 2 adversely affected the relative dissolved oxygen concentrations in the maturation ponds, and also suppressed their pH levels (see below).

The differences in depth, HRT and geometry of the facultative ponds did not apparently affect pond performance (as was also found in experiment 1). This emphasizes the importance of surface organic loading as the key parameter in facultative pond design.

5.2.2 Microbiological results

The increased organic loadings on the innovative pond system in experiment 2 and the concomitant shortening of the HRT reduced the microbiological quality of the final effluent (Tables 5.10 and 5.11). However, the reduction in the mean total HRT from 20 days in experiment 1 to 10 days in experiment 2 still provided a final effluent in the range $2.65\text{-}6.06\times10^3$ FC/100 ml from the tertiary maturation ponds M21-23 which only just fails to meet the WHO guidelines for unrestricted irrigation. However, most significant was the result for experiment 2 with a 5-pond series with a total HRT of 9.2 days which included the baffled tertiary maturation pond (M24): effluent quality was 727 FC per 100 ml (Table 5.10) suitable for unrestricted irrigation. When pond disinfection efficiency is compared on the basis of k_T values (43.6 day^{-1} for pond M24), it is clear that highly baffled maturation ponds are more efficient at faecal coliform removal than unbaffled ponds.

In experiment 1 k_T values for the maturation ponds were highest in the secondary maturation ponds (M17-20), but that they fell again in the tertiary maturation ponds (except for the baffled pond M24). This drop in efficiency between ponds of comparable geometry (M17 compared to M21 and 22) was attributed to the low numbers of bacteria being treated at this tertiary maturation stage, and the fact that this remaining FC population was probably less sensitive to the natural disinfection processes. In experiment 2 with high loads and shorter HRT this situation was reversed, with the tertiary maturation ponds now giving the best disinfection rates and highest k_T values.

This general trend of bacterial disinfection efficiency being higher later in the pond series as the organic loading rates on the ponds decreases, is also true for faecal streptococci and salmonellae, but not for the anaerobic spore-forming *Clostridium perfringens* (Table 5.11).

The increased faecal coliform removal rates also coincided with the outset of the highest mean pH and dissolved oxygen values in the series (Table 5.9). No clear statistical correlation existed between the efficiency of biological disinfection in the algal ponds and either the surface BOD_5 loading values or the BOD_5 concentration in the pond water column. However k_T values did not usually reach or exceed predictable levels (*i.e.* 6.20 day^{-1} at 25ºC) until BOD_5 surface loadings on the maturation ponds were below 75 kg/ha d and in-pond BOD_5 concentrations were < 25 mg/l.

No helminth eggs were found in the effluents of any of the facultative ponds or maturation ponds.

5.3 Nutrient removal

Ammonia nitrogen and total Kjeldahl nitrogen

The innovative WSP system showed ammonia removal efficiencies of 87-92% for the 5-pond series. (Table 5.12), with the bulk of the removal occurring in the secondary and tertiary maturation ponds where mean pond pH values were high (> 8.7). This supports the hypothesis of ammonia loss being predominantly due to volatilisation in pond systems. In experiment 2, with its elevated organic loading rates and reduced hydraulic retention times, ammonia removal efficiency for the 5-pond series was reduced to 72-79%, and individual ammonia removal efficiencies were greatest in the tertiary maturation ponds where the mean pH values were the highest in the series.

In the facultative ponds some of the ammonia loss due to volatilisation is masked by the ammonification process which releases ammonia from organic nitrogen compounds. This is supported by the results which show higher ammonia levels in the facultative ponds in both experiments 1 and 2, but lower total nitrogen (TKN) concentrations, than in the preceding anaerobic ponds. Generally speaking in these experiments, doubling the organic load on the system and halving the total HRT reduced ammonia removal efficiencies by approximately 20% (i.e. from 90% to 70%) and total N removal by 10% (i.e. from 75% to 65%). This could be attributed to less efficient ammonia volatilisation from the maturation ponds.

The N removal efficiencies were not affected by depth (at least within the range studied), nor by retention times of 3-7 days; but at a retention time of 1 day the efficiency was much less, even in shallow ponds (39 cm) (M18 and M19).

Orthophosphate and total phosphorus

Orthophosphate removal in the 5-pond series was highly variable in both experiments, with ranges of 29%-62% in experiment 1 and 12-38% in experiment 2 (Table 5.12). Total phosphorus removals were also variable: 43-56% in experiment 1 and 0-36% in experiment 2. Again phosphate and total phosphorus removal appeared to be a function of high pH with phosphate precipitation, rather than assimilation by the pond algae, being the principal mechanism involved. As with nitrogen, variations in pond geometry had little effect on phosphorus removal efficiencies, and nor did retention times of 3-7 days, although at a 1-day retention time the removal efficiency was reduced even in shallow ponds.

5.4 Rock filters

The mean results obtained within the experimental rock filters during experiments 1 and 2 are given in Table 5.13. Rock size (at least within the range used, 19-38 mm) had no significant influence on the results obtained.

Mean dissolved oxygen concentrations decreased from 5.9 mg/l (experiment 1) and 1.5 mg/l (experiment 2) in the effluent of maturation pond M15 down to 0.2 mg/1 in the effluents of rock filters. The pH was 7.6-7.7 in both experiments. The anoxic conditions within the rock layer caused sulphate to be reduced from more than 8 mg S/1 down to near 2.5 mg S/1 (experiment 1) and 4 mg S/1 (experiment 2), and the sulphide to be increaed from 0.03 mg S/1 (experiment 1) and from 0.75 mg S/1 (experiment 2) up to the range 5.35 – 5.88 mg S/1 (experiment 1) and to around 8.6 mg S/1 (experiment 2) due to biochemical sulphate reduction.

Ammonia concentrations increased slightly in the rock filters due to anaerobic degradation of organic matter and to the inhibition of ammonia removal mechanisms such as volatilization, assimiliation and nitrification. The higher mean values observed during experiment 2 were due to the higher organic loadings applied.

BOD_5, COD, chlorophyll *a* and SS were reduced (Table 5.14) as a consequence of particle deposition within the rock interstices and subsequent anaerobic digestion. During experiment 1 BOD_5 was reduced from 24 mg/1 in the effluent of pond M15 to 13 mg/1, and SS from 65 mg/1 to less than 25 mg/1. During experiment 2 effluent quality was decreased as a consequence of the higher hydraulic and organic loadings applied to the rock filters: BOD_5 was reduced from 28 mg/1 (M15) to only 24 mg/1 and SS from 64 mg/1 (M15) to 30 mg/1.

Rock filters are an effective means of reducing the BOD and SS concentrations in pond effluents. With the small rock sizes used herein (19-38 mm, these being chosen as they are commonly available as aggregrate for concrete), rather than the larger size of 100 mm recommended by Middlebrooks (1988), a hydraulic loading of 1 m^3 per m^3 of rock filter volume per day was found to be more appropriate than one of 2 m^3/m^3 d.

Table 5.1 Physicochemical results (arithmetic mean and range) for the innovative WSP in experiment 1

Pond	Unfiltered BOD (mg/l)	Filtered BOD (mg/l)	COD (mg/l)	SS (mg/l)	VSS (mg/l)
RW*	181 (50-388)	58 (17-119)	528 (197-897)	285 (78-584)	212 (62-419)
A9	73 (17-313)	33 (19-54)	274 (85-916)	121 (18-484)	91 (18-383)
A10	75 (19-191)	ND	345 (79-1119)	442 (9-938)	124 (4-546)
F21	32 (2-112)	13 (5-29)	205 (121-398)	81 (17-238)	65 (17-183)
F22	29 (4-96)	ND	211 (110-843)	77 (9-122)	67 (9-110)
F23	28 (1-107)	ND	183 (85-355)	67 (5-208)	56 (5-167)
F24	24 (3-107)	11 (3-26)	171 (84-314)	63 (1-151)	54 (1-126)
F25	25 (2-96)	ND	179 (97-354)	69 (7-220)	59 (5-203)
M15	19 (0-63)	7.8 (2-18)	156 (62-293)	53 (2-165)	46 (2-144)
M16	22 (4-52)	5.7 (2-16)	188 (78-516)	74 (8-140)	65 (8-120)
M17	21 (6-41)	7 (2-17)	191 (97-310)	73 (16-140)	63 (14-125)
M18	25 (5-56)	6 (1-17)	228 (86-471)	115 (4-397)	96 (4-274)
M19	26 (6-62)	ND	232 (68-350)	118 (39-222)	99 (17-179)
M20	25 (0-110)	ND	216 (3-440)	103 (5-314)	89 (5-273)
M21	24 (0-52)	14.5 (7-22)	219 (121-328)	101 (31-293)	89 (30-161)
M22	26 (4-62)	5.1 (2-17)	208 (135-318)	89 (2-205)	77 (2-175)
M23	20 (2-50)	5.9 (2-16)	201 (89-312)	94 (19-187)	83 (19-170)
M24	17 (1-42)	4.85 (1-16)	196 (51-391)	107 (19-321)	83 (16-240)

*RW: raw wastewater; ND: not determined.

Table 5.2 Physicochemical results (arithmetic mean and range) for the innovative WSP in experiment 1

Pond	TKN (mg N/l)	Ammonia (mg N/l)	Nitrite (mg N/l)	Nitrate (mg N/l)
RW*	53.9 (22.2-95.5)	33.3 (11.70-280.00)	37 (0-96)	0.47 (0.00-1.10)
A9	50.0 (17.1-78.4)	33.6 (14.3-48.34)	35 (0-96)	0.41 (0-1.18)
A10	51.6 (17.3-83.3)	33.8 (16.20-44.04)	30 (0-85)	0.41 (0-1.11)
F21	46.6 (16.3-75.6)	29.9 (12.60-45.0)	58 (0-449)	0.49 (0-1.26)
F22	45.9 (14.9-72.7)	28.8 (3.60-43.5)	38 (0-77)	0.51 (0-1.24)
F23	43.5 (12.8-72.1)	28.8 (4.50-41.8)	34 (0-77)	0.52 (0-1.36)
F24	43.2 (15.7-70.0)	28.4 (5.2-40.2)	29 (0-69)	0.51 (0-1.11)
F25	42.8 (16.6-73.7)	27.6 (3.4-42.3)	40 (0-76)	0.47 (0-1.10)
M15	31.8 (3.3-74.8)	16.9 (0-31.89)	176 (0-470)	0.59 (0.03-1.31)
M16	15.3 (0-32.5)	5.4 (0-27.68)	107 (0-330)	0.53 (0-1.34)
M17	16.0 (0-30.7)	5.4 (0-18.4)	86 (0-494)	0.52 (0-1.17)
M18	20.6 (2.0-43.2)	6.2 (0-25.3)	60 (0-173)	0.51 (0-1.61)
M19	21.0 (0-40.2)	6.2 (0-24.79)	76 (1-179)	0.48 (0-1.25)
M20	29.7 (0-75.7)	14.1 (0-30.58)	114 (17-288)	0.51 (0-1.00)
M21	15.0 (0.6-34.2)	1.8 (0-28.2)	53 (0-127)	0.48 (0-1.65)
M22	11.6 (1.0-20.1)	1.3 (0-27.1)	46 (0-114)	0.48 (0-1.71)
M23	12.4 (0-21.1)	1.8 (0-24.2)	42 (3-77)	0.51 (0-1.65)
M24	12.6 (1.5-23.6)	1.0 (0-24.3)	47 (0-150)	0.45 (0-1.54)

* RW: raw wastewater.

Table 5.3 Physicochemical results (arithmetic mean and range) for the innovative WSP in experiment 1

Pond	Total P (mg/l)	Soluble P (mg/l)	Sulphate (mg SO_4/l)	Sulphide (mg S/l)
RW*	5.49	2.24	17.7	0.52
	(2.9-9.1)	(0.4.8)	(5.0-26.0)	(0-1.16)
A9	5.12	3.60	10.7	11.95
	(2.24-8.24)	(0.71-6.20)	(0-18.4)	(1.05-21.71)
A10	5.48	3.70	10.3	12.29
	(2.40-11.46)	(0.71-6.80)	(0-18.4)	(1.19-35.01)
F21	5.40	3.78	12.59	1.06
	(3.15-7.7)	(1.00-5.5)	(1.0-18.4)	(0-5.16)
F22	5.25	3.60	12.5	1.10
	(3.1-8.0)	(1.5-5.2)	(0-19.0)	(0-8.00)
F23	5.11	3.65	12.1	1.02
	(2.96-8.5)	(0.99-8.5)	(1.0-21.6)	(0-5.01)
F24	5.1	3.2	12.5	0.81
	(2.92-7.36)	(0.4-5.2)	(3.4-18.4)	(0-6.36)
F25	5.2	3.3	12.9	0.83
	(3.76-7.99)	(0.12-4.7)	(3.0-17.6)	(0.4.20)
M15	4.81	2.9	14.0	0.04
	(2.7-8.54)	(0.41-4.7)	(3.4-21.0)	(0-0.45)
M16	3.60	1.84	14.8	0.02
	(1.1-8.4)	(0-4.27)	(3.40-24.0)	(0-0.09)
M17	3.76	1.89	14.1	0.01
	(1.5-7.8)	(0-5.8)	(4.6-24.4)	(0-0.06)
M18	4.46	1.90	13.8	0.02
	(2.3-7.3)	(0-3.6)	(3.4-23.2)	(0-0.07)
M19	4.91	1.82	13.9	0.01
	(1.77-10.6)	(0.2-3.4)	(0-26.0)	(0-0.08)
M20	5.66	2.88	15.0	0.02
	(3.01-8.5)	(0.6-5.6)	(6.0-25.4)	(0-015)
M21	3.04	1.06	14.7	0.10
	(1.5-7.7)	(0.18-4.9)	(6.0-23.8)	(0-1.53)
M22	2.5	0.88	14.3	0.07
	(1.26-6.8)	(0-4.3)	(3.4-23.2)	(0-1.89)
M23	3.11	1.57	14.2	0-12
	(1.6-7.5)	(0.2-5.7)	(0-23.8)	(0-3.35)
M24	3.07	1.34	14.0	0.10
	(1.4-6.7)	(0.2-4.0)	(3.0-22.4)	(0-1.69)

* RW: raw wastewater.

Table 5.4 Physicochemical results (arithmetic mean and range) for the innovative WSP in experiment 1

Pond	Chlorophyll *a* (μg/l)	pH	Alkalinity (mg $CaCO_3$/l)	Chloride (mg/l)
RW*	-	7.3 (6.6-7.9)	311 (245-386)	360 (9-489)
A9	-	7.2 (6.5-7.7)	368 (307-415)	365 (277-444)
A10	-	7.2 (6.5-7.8)	371 (261-417)	353 (295-474)
F21	435 (15-1165)	7.5 (6.8-8.3)	362 (293-424)	347 (308-398)
F22	543 (33-2138)	7.5 (7.0-8.6)	359 (287-410)	367 (304-444)
F23	392 (21-1321)	7.5 (6.9-8.3)	366 (283-429)	352 (308-396)
F24	358 (9-940)	7.6 (7.1-8.6)	366 (301-422)	343 (263-406)
F25	353 (11-797)	7.6 (7.0-8.5)	363 (301-420)	338 (280-414)
M15	369 (70-1133)	8.0 (7.3-8.9)	320 (245-410)	369 (321-421)
M16	497 (54-2205)	8.7 (7.5-10.0)	279 (181-352)	382 (316-446
M17	612 (97-2271)	8.7 (7.5-10)	273 (170-356)	378 (326-444)
M18	901 (186-2641)	8.6 (7.8-10)	273 (153-349)	382 (270-466)
M19	925 (112-2800)	8.7 (7.3-9.7)	271 (149-370)	376 (316-439)
M20	518 (67-1739)	8.0 (7.3-8.9)	314 (218-392)	365 (319-432)
M21	658 (195-2041)	9.11 (8.2-10.0)	248 (155-321)	384 (283-465)
M22	547 (139-1557)	9.2 (8.2-9.8)	245 (147-336)	408 (336-482)
M23	480 (93-1073)	8.7 (7.0-9.7)	249 (155-360)	417 (334-534)
M24	663 (62-2036)	9.1 (8.1-9.7)	240 (160-328)	394 (336-452)

*RW: raw wastewater.

Table 5.5 Microbiological results (geometric mean and range) for the innovative WSP in experiment 1

Pond	Faecal coliforms (per 100 ml)	Faecal streptococci (per 100 ml)	*Clostridium perfringens* (per 100 ml)
RW*	2.57×10^7 (15×10^5-1.86×10^8)	3.72×10^6 (1.1×10^5-8.6×10^6)	4.07×10^4 (2.4×10^3-5.30×10^5)
A9	7.08×10^6 (1.22×10^6-1.91×10^7)	1.02×10^6 (9.0×10^3-7.55×10^6)	145×10^4 (6.00×10^2-$1.95\times10^{5)}$
A10	5.89×10^6 (2.00×10^4-4.05×10^7)	9.12×10^5 (9.50×10^4-2.7×10^6)	1.55×10^4 (3.5×10^2-2.76×10^5)
F21	9.55×10^5 (9.50×10^3-1.22×10^7)	8.13×10^4 (1.90×10^3-$1.15\times10^{6)}$	3.47×10^3 (2.0×10^2-4.55×10^4)
F22	8.71×10^5 (2.10×10^4-7.85×10^6)	5.89×10^4 (5.00×10^2-1.17×10^6)	3.39×10^3 1.8×10^2-4.55×10^4
F23	9.33×10^5 (5.00×10^4-9.80×10^6)	5.1×10^4 (1.80×10^3-8.10×10^5)	2.45×10^3 (1.00×10^2-2.83×10^4)
F24	6.61×10^5 (3.7×10^4-5.85×10^6)	4.47×10^4 (1.00×10^2-6.05×10^5)	2.19×10^3 (1.00×10^2-2.87×10^4)
F25	5.50×10^5 (1.05×10^3-4.7×10^6)	5.62×10^4 (5.0×10^2-1.71×10^6)	2.57×10^3 (1.8×10^2-7.1×10^4)
M15	2.57×10^4 (1.4×10^2-1.07×10^2)	3.63×10^3 (2.1×10^2-1.18×10^5)	2.95×10^2 (75-6.26×10^3)
M16	7.41×10^2 (12-6.40×10^4)	6.61×10^2) (10-2.19×10^4)	1.44×10^2 (0-8.30×10^3)
M17	7.43×10^2 (0-3.43×10^4)	8.13×10^2 (28-1.30×10^4)	2.34×10^2 (6-8.0×10^3)
M18	1.10×10^3 (18-2.26×10^5)	1.32×10^3 (18-6.9×10^4)	1.74×10^2 (0-5.15×10^3)
M19	7.41×10^2 (0-4.70×10^4)	8.71×10^2 (28-1.36×10^4)	2.34×10^2 (23-3.30×10^3)
M20	2.24×10^3 (1-4.61×10^5)	1.32×10^3 (1.7×10^2 – 2.62×10^4)	2.29×10^2 (3-1.26×10^4)
M21	40 (0-3.50×10^3)	4.90×10^2 (6-2.47×10^4)	78 (4-4.18×10^3)
M22	46 (0-1.1×10^3)	4.07×10^2 (11-1.33×10^4)	87 (6-2.9×10^3)
M23	89 (0-1.30×10^4)	3.63×10^2 (8-4.87×10^3)	1.15×10^2 (5-1.17×10^4)
M24	30 (0-1.62×10^4)	4.10×10^2 (36-755×10^3)	1.38×10^2 (17-1.42×10^4)

*RW, raw wastewater

Table 5.6 Microbiological results (geometric mean and range) for the "innovative" WSP as in experiment 1

Pond	Salmonellae (per 100 ml)	Campylobacter (per 100 ml)	*Vibrio cholerae* (per 100 ml)	Rotaviruses (per litre)
RW*	4.68×10^2 ($8\text{-}9.2\times10^3$)	27 ($7\text{-}3.5\times10^2$)	4 (1-20)	5.13×10^4 ($3.50\times10^4\text{-}9.92\times10^4$)
A9	3.63×10^2 ($11\text{-}1.6\times10^4$)	10 ($0\text{-}1.61\times10^2$)	2 (0-16)	1.70×10^4 ($4.8\times10^3\text{-}4.86\times10^4$)
A10	3.55×10^2 ($0.00\text{->}1.8\times10^4$)	1.3 ($3\text{-}1.61\times10^2$)	2 (0-8)	1.70×10^4 ($5.0\text{x}10\text{-}3.6\times10^4$)
F21	38 ($2\text{-}9.2\times10^2$)	4 (0-33)	2 (0-2)	(8.13×10^3) ($2.25\times10^3\text{-}3.48\times10^4$)
F22	59 ($0\text{-}1\times10^3$)	11 ($0\text{-}2.4\times10^2$)	1 (0-2)	1.02×10^4 ($3.18\times10^3\text{-}3.21\times10^4$)
F23	22 ($1\text{-}5.40\times10^2$)	3 (0-20)	0	6.92×10^3 ($2.74\times10^3\text{-}2.62\times10^4$)
F24	19 ($0\text{-}1.6\times10^3$)	4 (0-63)	0 (0-1)	5.50×10^3 ($1.25\times10^3\text{-}1.73\times10^4$)
F25	37 ($2\text{-}1.60\times10^3$)	5 ($0\text{-}4.3\times10^2$)	1 (0-4)	4.68×10^3 ($1.89\times10^3\text{-}1.92\times10^4$)
M15	5 (0.170×10^2)	2 (0-17)	0	4.57×10^3 ($8.4\times10^2\text{-}1.46\times10^4$)
M16	13 (0-7)	0 (0-1)	0	1.12×10^3 ($1.88\times10^2\text{-}2.51\times10^3$)
M17	1.2 (0-3)	1.3 (0-16)	0	1.48×10^3 ($5.25\times10^2\text{-}3.58\times10^3$)
M18	1.5 (0-6)	1.1 (0-1)	0	1.95×10^3 ($7.4\times10^2\text{-}4.97\times10^3$)
M19	1.3 (0-9)	0	0	2.04×10^3 ($6.8\times10^2\text{-}4.76\times10^3$)
M20	1.9 0-22	1.1 0-4	0	8.13×10^2 ($0\text{-}5.25\times10^3$)
M21	1.02 (0-1)	0	0	1 ($0\text{-}7.3\times10^2$)
M22	1.02 (0-2)	0	0	4 ($0\text{-}5.8\times10^2$)
M23	1.5 (0-16)	0	0	0
M24	1.1 (0-2)	0	0	2 ($0\text{-}4.0\times10^2$)

* RW, raw wastewater

Table 5.7 Helminthological results (arithmetic mean and range) for the innovative WSP as in experiment 1

Pond	*Ascaris* eggs (per litre)	*Trichuris* eggs (per litre)	Hookworm eggs (per litre)
RW*	145 (0-500)	0	10 (0-100)
A9	129 (0-1200)	0	15 (0-150)
A10	222 (0-1667)	1 (1-12)	14 (0-133)
F21	1 (0-25)	0	0
F22	1 (0-25)	0	0
F23	1 (0-20)	0	0
F24	0	0	0
F25	1 (0-10)	0	0
M15	0	0	0
M16	0	0	0
M17	1 (0-10)	0	0
M18	0	0	0
M19	0	0	0
M20	8 (0-230)	0	0
M21	1 (0-3)	0	0
M22	1 (0-1)	0	0
M23	1 (0-300)	0	0
M24	0	0	0

*RW, raw wastewater

Table 5.8 Mean values of BOD_5, COD, suspended solids and chlorophyll *a* for each pond of the innovative system in experiments 1 and 2

Sample	BOD_5 (mg/l)		COD (mg/l)		S.S (mg/l)		Chlorophyll *a* (mg/m^2)	
	Expt. 1	Expt. 2	Expt. 1.	Expt. 2	Expt. 1	Expt. 2	Expt. 1	Expt.2
CRS*	181	215	528	514	285	297	ND	ND
A9	73	121	274	383	121	208	ND	ND
A10	75	88	345	498	442	365	ND	ND
F21	32	54	205	236	81	94	435	288
F22	29	54	211	216	77	78	722	380
F23	28	46	183	200	67	76	655	518
F24	24	52	171	188	63	68	716	502
F25	25	49	179	224	69	104	706	422
M15	19	41	156	173	53	72	369	305
M16	22	22	188	174	74	82	447	245
M17	21	28	191	234	73	139	392	166
M18	25	31	228	513	115	443	351	162
M19	26	37	232	609	118	603	361	176
M20	25	48	216	545	103	429	201	202
M21	24	19	219	159	101	78	395	164
M22	26	18	208	178	89	101	328	232
M23	20	22	201	239	81	197	338	221
M24	17	19	196	230	107	173	398	157

***** CRS: composite raw sewage.

Table 5.9 Mean values for dissolved oxygen and pH for the 08.00 total pond water column sample for each of the ponds of the innovative system

Pond	Dissolved oxygen concentrations (mg/l)		pH	
	Expt. 1	Expt. 2	Expt. 1	Expt. 2
A9	0.2	0.2	7.3	7.4
A10	0.2	0.2	7.3	7.4
F21	1.7	0.4	7.6	7.5
F22	3.4	0.6	7.7	7.5
F23	2.7	0.6	7.7	7.6
F24	2.8	0.3	7.7	7.5
F25	3.3	0.3	7.7	7.5
M15	5.5	1.3	8.1	7.8
M16	8.3	4.1	8.9	8.0
M17	10.2	2.5	8.9	8.1
M18	11.0	7.6	8.7	8.1
M19	13.2	5.0	8.9	7.9
M20	7.7	2.3	8.1	7.7
M21	12.0	5.9	9.2	8.3
M22	11.2	10.1	9.2	8.6
M23	10.5	9.9	9.1	8.5
M24	11.5	6.2	9.3	8.2

Table 5.10 Faecal coliform numbers in pond water column samples from the ponds of the innovative system operating under the different loading regimes. k_T values (day $^{-1}$) are given in parentheses

Pond	Faecal coliforms (per 100 ml)			
	Experiment 1		Experiment 2	
CRS*	2.6×510^{7}	(-)	4.46×10^{7}	(-)
A9	7.06×10^{6}	(2.76)	1.56×10^{7}	(2.86)
A10	7.15×10^{6}	(2.72)	1.56×10^{7}	(2.86)
F21	1.1×10^{6}	(1.86)	6.56×10^{6}	(0.71)
F22	9.2×10^{5}	(1.68)	5.92×10^{6}	(0.64)
F23	9.2×10^{5}	(1.35)	4.79×10^{6}	(0.73)
F24	7.8×10^{5}	(1.36)	5.04×10^{4}	(0.56)
F25	8.9×10^{5}	(1.16)	4.65×10^{6}	(0.63)
M15	2.3×10^{4}	(9.46)	7.50×10^{5}	(3.80)
M16	5.45×10^{2}	(6.04)	6.51×10^{4}	(3.20)
M17	6.81×10^{2}	(6.73)	4.24×10^{4}	(6.68)
M18	7.58×10^{2}	(10.04)	8.44×10^{4}	(5.26)
M19	6.30×10^{2}	(12.15)	1.20×10^{5}	(3.52)
M20	1.60×10^{3}	(13.15)	1.66×10^{5}	(7.04)
M21	3.49×10^{1}	(3.59)	6.06×10^{3}	(4.88)
M22	4.17×10^{1}	(2.97)	2.65×10^{3}	(11.69)
M23	2.24×10^{2}	(0.39)	2.91×10^{3}	(10.58)
M24	1.92×10^{1}	(7.96)	7.27×10^{2}	(43.60)

* CRS: composite raw sewage.

Table 5.11 *Faecal streptococci* (FS), *Clostridium perfringens* (CP) and salmonellae numbers per 100 ml in the "innovative" pond system. k_T values (day^{-1}) are given in parentheses

	FS		CP		Salmonellae	
Sample	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2
CRS*	3.92×10^6	5.29×10^6	2.07×10^4	1.22×10^5	3.29×10^2	7.06×10^2
A9	1.14×10^6 (2.44)	2.70×10^6 (1.92)	1.32×10^4 (0.57)	5.46×10^4 (2.47)	3.62×10^2 (-)	2.10×10^2 (4.62)
A10	9.50×10^5 (3.13)	1.94×10^6 (3.45)	1.60×10^4 (0.29)	9.45×10^4 (0.58)	3.66×10^2 (-)	3.33×10^2 (2.28)
F21	9.72×10^4 (3.25)	7.35×10^5 (1.44)	3.90×10^3 (0.91)	2.75×10^4 (1.14)	3.0×10^1 (4.03)	6.2×10^1 (1.09)
F22	6.10×10^4 (4.03)	6.92×10^5 (1.18)	4.31×10^3 (0.60)	2.47×10^4 (1.01)	3.1×10^1 (2.69)	1.24×10^2 (0.16)
F23	6.88×10^4 (3.05)	5.81×10^5 (1.20)	2.77×10^3 (0.85)	2.29×10^4 (0.90)	2.0×10^1 (3.49)	6.9×10^1 (0.54)
F24	5.00×10^4 (3.32)	6.36×10^5 (0.88)	2.18×10^3 (0.95)	1.61×10^4 (1.21)	1.5×10^1 (4.01)	5.6×10^1 (0.63)
F25	5.78×10^4 (2.85)	4.89×10^5 (1.25)	2.84×10^3 (0.69)	1.47×10^4 (1.36)	2.3×10^1 (2.47)	5.8×10^1 (0.61)
M15	2.77×10^3 (6.10)	4.37×10^4 (7.03)	2.95×10^2 (2.59)	5.57×10^3 (1.47)	3 (1.68)	11 (1.62)
M16	7.28×10^2 (0.40)	4.24×10^3 (2.66)	1.72×10^2 (0.10)	2.07×10^3 (0.48)	1 (0.27)	7 (0.71)
M17	8.33×10^2 (0.47)	4.89×10^3 (3.18)	2.92×10^2 (0.00)	4.00×10^3 (0.16)	1 (0.33)	10 (0.56)
M18	1.44×10^3 (0.31)	6.55×10^3 (3.78)	2.17×10^2 (0.12)	7.01×10^3 (-)	1 (0.56)	7 (0.49)
M19	9.17×10^2 (0.67)	1.19×10^4 (1.78)	2.46×10^2 (0.07)	6.63×10^3 (-)	1 (0.56)	9 (0.23)
M20	9.44×10^2 (1.93)	2.36×10^4 (1.70)	2.54×10^2 (0.16)	9.26×10^3 (-)	1 (1.29)	10 (-)
M21	7.37×10^2 (0.06)	1.26×10^3 (1.26)	7.21×10^1 (0.46)	1.16×10^3 (1.10)	1 (0.04)	6 (-)
M22	3.79×10^2 (0.31)	7.25×10^2 (2.48)	9.12×10^1 (0.32)	6.47×10^2 (2.57)	1 (0.04)	2 (0.39)
M23	3.51×10^2 (0.35)	9.56×10^2 (1.79)	8.,92×10^1 (0.33)	1.25×10^3 (1.00)	1 (-)	4 (0.40)
M24	4.03×10^2 (0.34)	8.00×10^2 (2.66)	1.21×10^2 (0.23)	1.15×10^3 (1.10)	1 (0.03)	2 (0.89)

*CRS: composite raw sewage

Table 5.12 Nutrient concentrations in the innovative pond series column samples. The values in parentheses represent the removal efficiencies (%) for NH_3 in the pond series up to this point

	NH_4 – N (mg/l)		TKN (mg N/l)		Ortho P (mg P/l)		Total P (mg P/l)	
Pond	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 1	Experiment 2
CRW	33.3	23.8	54.5	45.0	2.4	2.6	5.4	5.3
A9	41.3	32.0	50.5	40.7	3.5	3.6	5.1	5.3
A10	41.8	31.7	51.8	42.4	3.6	3.8	5.3	6.1
F21	36.9	31.4	45.9	38.0	3.7	4.0	5.3	5.7
F22	36.1	31.6	45.8	36.7	3.5	3.9	5.1	5.2
F23	35.9	30.4	43.5	36.1	3.4	3.5	5.0	5.1
F24	35.4	32.0	43.3	36.9	3.3	3.5	5.1	5.0
F25	34.7	31.0	42.8	37.4	3.3	3.4	5.1	5.1
M15	23.5 (30)	25.9 (0)	31.9	31.8	2.9	3.5	4.7	5.5
M16	6.8 (80)	14.5 (39)	15.4 (72)	20.2 (55)	1.9	3.8	3.5	5.5
M17	7.4 (78)	15.5 (35)	16.5 (70)	23.8 (47)	1.8	3.8	3.5	6.8
M18	8.4 (75)	16.0 (33)	20.7 (62)	32.9 (27)	1.8		4.6	12.3
M19	8.9 (75)	18.7 (21)	21.1 (61)	40.4 (10)	1.8	2.2	4.6	15.5
M20	16.5 (51)	22.9 (4)	29.7 (48)	44.0 (2)	2.8	3.3	5.5	8.6
M21	4.3 (87)	9.2 (61)	15.1 (72)	16.2 (64)	1.0 (58)	2.3 (12)	2.9 (46)	4.1 (23)
M22	2.8 (92)	6.7 (72)	11.6 (39)	13.8 (69)	0.9 (62)	1.6 (38)	2.5 (54)	3.4 (36)
M23	2.7 (92)	6.9 (71)	12.4 (77)	18.1 (60)	1.7 (29)	1.6 (3.8)	3.1 (43)	5.8 (0)
M24	2.7 (92)	8.0 (66)	12.7 (77)	17.3 (62)	1.4 (42)	2.0 (23)	3.1 (43)	6.3 (0)

* CRS: composite raw sewage

Table 5.13 Mean results of the parameters measured in rock filter influent (M15) and effluents during experiments 1 and 2

Reactor		M15		RF2		RF3		RF4	
Experiment		1	2	1	2	1	2	1	2
BOD_5	(mg l^{-1})	24	28	13	24	12	23	12	23
COD	(mg l^{-1})	132	147	80	99	96	112	89	110
Suspended solids	(mg $^{-1}$)	65	64	24	32	23	31	24	29
Chlorophyll *a*	(mg l^{-1})	383	327	42	140	37	115	39	125
Ammonia	(mg N l^{-1})	17.5	23.1	18.4	24.1	18.8	23.0	19.1	25.2
Sulphide	(mg S l^{-1})	0.03	0.75	5.35	8.41	5.88	8.36	5.54	8.65
Sulphate	(mg S l^{-1})	8.3	8.6	2.5	3.9	2.1	4.4	2.6	4.1
pH		7.9	7.6	7.7	7.7	7.7	7.6	7.7	7.6
Dissolved oxygen	(mg l^{-1})	5.9	1.5	0.2	0.2	0.2	0.2	0.2	0.2
Temperature (°C)		23	23	23	24	24	24	24	24
Faecal coliforms (per 100ml)		4.82E3	7.72E5	2.51E3	2.70E5	1.99E3	2.75E5	1.86E3	2.32E5

Table 5.14. Percentage removals of chlorophyll *a*, suspended solids, COD, BOD_5 and faecal coliform attained in the three rock filters during experiments 1 and 2

	RF2		RF3		RF4	
	I	2	I	2	I	2
Chlorophyll *a*	89	57	90	65	90	62
Suspended solids	63	50	65	52	63	55
COD	39	33	27	24	33	25
BOD_5	46	14	50	18	50	18
Faecal coliforms	48	65	59	64	61	70

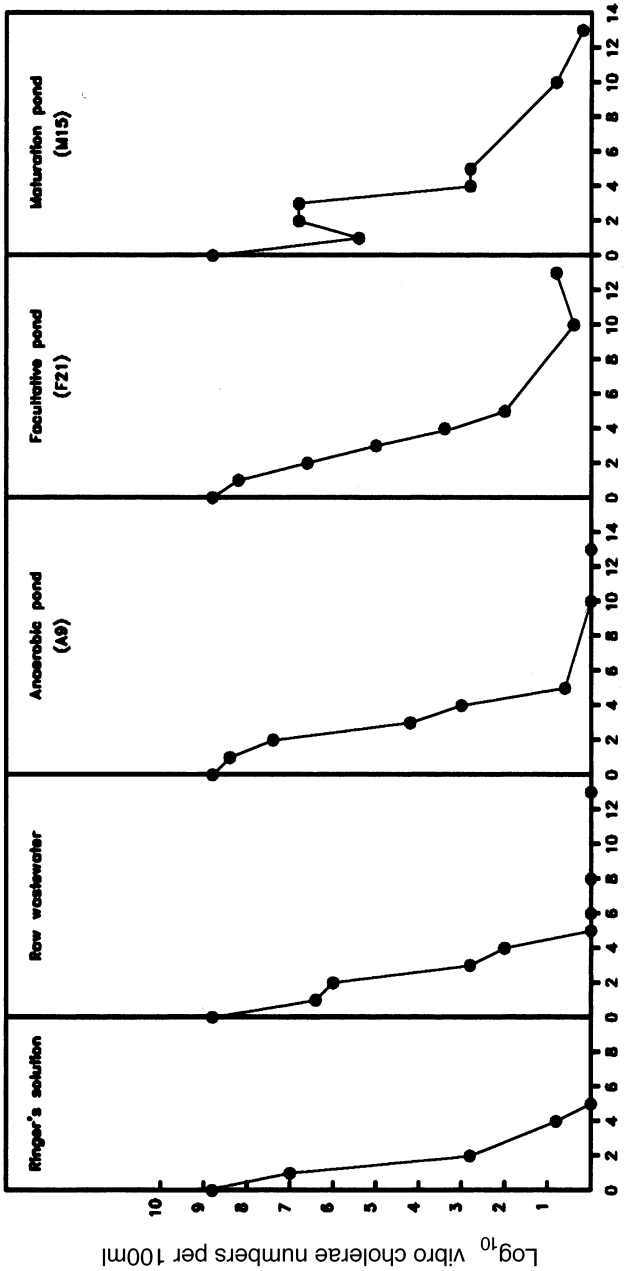

Figure 5.1 In-pond batch-culture survival of V.cholerae *O1*

6. Discussion

6.1 BOD, COD and SS removal

In both the series of ten WSP and the "innovative" ponds in experiment 1, the EU pond effluent quality of ≯ 25 mg filtered BOD_5 per litre and ≯ 150 mg SS per litre was achieved by the anaerobic and secondary facultative ponds, after a retention time of only 3 days (A11 and F26) in the series of 10 WSP and after 4 days (A9 or A10 and F21) in the "innovative" ponds. Most of the removals were achieved in the 1-day anaerobic ponds, as expected, which were loaded at 181 g BOD_5/m^3 day. This loading is less than the usual design limit of 300 g BOD/m^3 day for 20°C and above, and those on the facultative ponds (310 and 247 kg BOD_5/ha day in the series of ten ponds and the innovative ponds, respectively) were also less than the design limit of 350 kg BOD_5/ha day for 25°C, (Mara, 1987). However for wastewaters with an unfiltered BOD_5 of less than 300 mg/1 minimum retention time, rather than loading, is the more important design parameter: at 20°C and above a 1-day anaerobic pond and a 3-day facultative pond would be required to meet the EU effluent quality (and also the WHO quality of ≯ 1 intestinal nematode egg per litre for restricted irrigated: see Section 6.3).

The first order rate constant (k_1, day^{-1}) values for unfiltered and filtered BOD removal in the anaerobic and facultative ponds are given in Table 6.1. As expected, these decrease with increasing retention time. A tentative value of 1.5 day^{-1} for both unfiltered BOD removal in a 1-day anaerobic pond and filtered BOD removal in a 3-day facultative pond seems appropriate for use in the first order equation:

$$L_{e(filt)\ (fac)} = L_i/(1 + k_1\theta_a)(1 + k_1\theta_f) \qquad (6.1)$$

where $L_{e(filt)\ (fac)}$ is the filtered BOD of the facultative pond effluent, mg/l; L_i, the unfiltered BOD of the raw wastewater, mg/l; and θ_a and θ_f the retention times in the anaerobic and facultative ponds, days.

With L_i = 181 mg/l, k_1 = 1.5 day^{-1} for θ_f = 1 day and θ_f = 3 days, equation 6.1 gives $L_{e(filt)\ (fac)}$ = 13 mg/l, which is the value found (Table 5.1) for the effluent from the 3-day facultative pond F21.

With k_1 = 1.5 day^{-1} at 25°C and assuming an Arrhenius coefficient of 1.05 (Mara, 1976), a tentative design equation for $k_{1(T)}$ for T > 20°C is:

$$K_{1(T)} = 1.1(1.05)^{T-20} \qquad (6.2)$$

Equation 6.2 yields a value of 1.4 day^{-1} at 25°C, which provides a small margin of safety for use in design.

The removals of BOD, COD and SS in the maturation ponds were small in comparison with those in the anaerobic and facultative ponds but, given their main purpose is the removal of excreted pathogens, this is unimportant since the effluent quality requirements for these parameters have already been achieved in the preceding facultative ponds.

Anaerobic and facultative pond geometry

Since the BOD, COD and SS effluent quality data for all three anaerobic ponds are similar, this suggests that anaerobic pond geometry, at least within the range of length-to-breadth ratios of 1 to 1.5 (A11) and 1 to 3 (A9 and A10), which is a reasonable physical design range for anaerobic ponds, does not affect pond performance; nor does depth, at least within the range 1.5 m (A11) and 2.5 m (A9 and A10).

The data for the secondary facultative ponds also suggest that depths within the range 1 to 2 m and retention times of 2-6 days do not significantly affect either pond performance or effluent quality. Similarly, although it has frequently been suggested that pond performance should be improved by increasing length-to-breadth ratios which should favour a plug flow hydraulic regime over complete mixing, the data show that length-to-breadth ratios in the range 1 to 1 and 6 to 1, which is a realistic range for many pond sites, also have little impact on either pond performance or effluent quality.

6.2 Faecal coliform and pathogen removal

The anaerobic ponds A9, A10 and A11 and the secondary facultative ponds, F21-F25 and F26 differed little in their bacteriological, virological or helminthological effluent quality, thus confirming the finding from the physicochemical data (Section 6.1) that the geometry of anaerobic and facultative ponds (at least within the practical ranges considered) has no effect on performance. The helminth results for ponds A9 and A10 (Table 5.7) indicate that no advantage was obtained by the egg deflector plate in pond A10.

Vibrio cholerae O1 removal was highest in the anaerobic ponds. This appeared to be due to the high sulphide levels (11 mg S/l) in these ponds, a finding supported by the results of the in-pond *V. cholerae* survival studies (Figure 5.1).

The data from five secondary maturation ponds (M16-M20) showed that the shallower maturation ponds (M18, M19 and M20, all 39 cm deep) were more efficient at faecal coliform removal and were comparable in performance to the deeper maturation ponds (M16 and M17) for bacterial pathogen and rotavirus removal, even though the latter had longer retention times. Pond M20 received the same flow as the other secondary maturation ponds but had only one third the surface area, consequently it had a shorter retention time (1 day) and a higher BOD surface loading (70, rather than 24, kg BOD_5/had). It was not surprising therefore that its effluent quality was a little poorer in terms of faecal coliform numbers; however, bacterial pathogen and rotavirus numbers were comparable to those found in the other secondary maturation pond effluents.

When pond efficiency is considered however in terms of first order removal kinetics (k values), then M20 with its ultra short retention time had the highest removal constant for faecal

coliforms of any of the ponds, and also high removal rates for bacterial pathogens and rotaviruses when compared to the other secondary maturation ponds (Table 6.2). Its algal concentration, although lower than in the other ponds, was nevertheless stable and provided high pH values (>9) and supersaturated oxygen concentrations during the day.

It is also worth noting that the data for ponds M18 and M19 (which are identical in size, geometry and thus retention time) were almost identical, showing that pond performance within the complex was reproducible.

The results for the tertiary maturation ponds showed that the floating macrophyte pond (M23), although producing the best BOD effluent quality, was less efficient in terms of pathogen removal than the same sized algal ponds (M21 and M22). These latter two ponds also provided good evidence of the reproducibility of the data for ponds operating under identical conditions, except when comparing the k values for rotavirus removal which did diverge (however, this probably relates to the low number of virus particles present and the impact small changes in numbers has on k values).

In experiment 1 the tertiary maturation ponds (each 60 cm deep), with the exception of M24, appeared less efficient at faecal coliform removal than even the deeper secondary maturation ponds, but this may reflect the smaller microbial populations and the fact that those organisms still remaining viable are more resistant to the ambient conditions. However, in experiment 2 the tertiary maturation ponds were noticeably more efficient as their influent FC numbers were higher.

The baffled pond (M24), although having the same outer dimensions as the other tertiary ponds, (including the same depth of 60 cm), had a slightly reduced surface area and thus retention time, 4.2 days rather than 5 days, because of the internal baffles. These baffles also gave the pond an effective length-to-breadth ratio of 143 to 1. This pond was much more efficient at faecal coliform removal with a k value of 7.96 day^{-1} than the other tertiary ponds, although again with such small numbers in the influent the impact on actual effluent FC numbers was small. It was difficult to determine any improvement in the removal efficiencies for the bacterial pathogens because of low numbers. In experiment 2, however, the removal efficiency was much higher; again, this reflects the higher influent FC numbers.

Rotavirus removal in the tertiary maturation ponds was very good with high removal efficiencies and very few actual virus particles present in the final effluents from any of the parallel 5-pond series.

Using the equation of Marais (1974) for determining the faecal coliform die-off coefficient (k) in maturation ponds, and a temperature of 25°C, which was the mean mid-depth temperature of the ponds in the complex, gives a k value of 6.20 d^{-1}. The primary maturation pond (M15) and the five secondary maturation ponds had k values which were similar to or greatly exceeded the 6.20 value, whereas the tertiary maturation ponds, except M24 (the baffled pond), gave lower values (Table 6.2).

The actual k values for faecal coliform removal for the five secondary facultative ponds (Table 6.2) were also lower than the theoretical 6.20 value. However, this is not surprising since facultative ponds are known to be less efficient at bacterial removal than maturation ponds.

The theoretical k values for faecal coliforms calculated from the Marais equation were a poor indicator of the actual k values for salmonellae in the maturation ponds, since the latter were frequently an order of magnitude lower than the predicted 6.2 value. The actual k values for salmonellae in the secondary facultative ponds were also lower than the predicted value, but were higher than the actual k values calculated for faecal coliforms.

Actual k values calculated for rotaviruses were similar in all the secondary facultative, and the primary and secondary maturation ponds but lower than the theoretical value and the actual values obtained for faecal coliforms. In contrast very high k values were obtained for the tertiary maturation ponds, such that few or no virus particles were present in the final effluents.

The results for actual faecal coliform numbers for individual ponds were compared with two theoretical values for effluent numbers, to show the impact the disparity in k values has on predicted effluent quality. Both theoretical values were calculated using the k value of 6.20 d^{-1} for 25°C, but using either the actual influent FC values for each pond or the FC count in the raw wastewater and determining the theoretical FC count value for each pond at its position along the pond using the Marais equation. Although the theoretical value for FC numbers can be nearly an order of magnitude lower than the actual effluent values for the early ponds in the series when the former are calculated from raw wastewater FC numbers, the numbers then converge as the higher than predicted faecal coliform removal rates come into play in the secondary maturation ponds. Despite these differences in experimentally derived and theoretically determined k values, plotting log actual effluent FC numbers for each of the ponds against log theoretical effluent FC numbers using either the actual influent FC numbers (Figure 6.4) or extrapolating from the raw wastewater FC values (Figure 6.5) gave linear regressions with highly significant positive correlations (r^2) of 0.99. This would suggest there is a balancing-out effect between the pond types and that predicting effluent quality by using the Marais equation to predict effluent faecal coliforms numbers is acceptable in pond systems comprising four cells or more but is less reliable where only two ponds are in series.

This is best illustrated by considering the two series that just achieved the WHO recommended limit of $\nless$1000 FC per 100 ml for unrestricted irrigation:

(a) the first six ponds in the series of 10 ponds, and

(b) A9 (or A10), F21, M15 and M19 in the "innovative" pond complex.

The k values for each of the first six ponds in the series of ten ponds are much less than 6.20 day^{-1}. However, with the innovative ponds the k values are less than 6.20 day^{-1} only in the anaerobic and secondary facultative ponds and much higher in the maturation ponds. This can be partially explained by the difference in chlorophyll *a* values and also by the difference in retention times. In the series of ten ponds (the results from which yield an overall k value in the Marais equation of only 2.5 day^{-1}) the retention times in the facultative and maturation ponds of 2 days are too short to permit much algal biomass to develop and as a consequence faecal coliform removal is poor. In the innovative ponds, in contrast, this is not the case and the Marais equation with a k value of 6.20 day^{-1}, although not closely predicting the FC number in each individual pond in the series, yields an overall FC value for the four-pond series of 405 per 100 ml which is only slightly less than the value of 741 per 100 ml obtained. In fact the four-pond

series yields an overall k value of 5.26 day^{-1}. Marais' original equation was derived from ponds operating in the temperature range 2-21°C in which the effect of temperature was considerable:

$$k_T = 2.6\ (1.19)^{(T-20)} \tag{6.7}$$

At temperatures above this range, the effect of temperature is likely to be reduced; for example:

$$k_T = 2.6\ (1.15)^{T-20} \tag{6.8}$$

which yields a k value of 5.23 day^{-1} at 25°C.

6.3 Nitrogen removal

Nitrogen removal is a key component of nutrient removal technology and it is often imporant that waste stabilization ponds are optimised to ensure maximum nitrogen and ammonia removal. The three mechanisms for nitrogen/ammonia removal in ponds are gaseous ammonia removal or volatilization, ammonia assimilation into algal biomass and biological nitrification coupled to denitrification (Middlebrooks *et al*., 1982). The major route is considered to be via volatilization as the pH in ponds increases above 7. Several equations and models have been proposed to mathematically describe this phenomenon (Ferrara and Avci, 1982; Middlebrooks *et al*., 1982; Reed, 1985).

Organic nitrogen was 21.4 mg N/l in the raw wastewater and mean concentrations in the "innovative" ponds varied between 7.6 and 13.2 mg N/l. Reductions in the anaerobic ponds were about 50% and can be attributed to sedimentation of particulate organic material and biological degradation of both particulate and soluble organic matter. The remaining innovative ponds had organic nitrogen concentrations of < 10 mg N/l, except for the secondary maturation ponds M18 (12.4 mg N/l), M19 (12.1 mg N/l) and M20 (13.2 mg N/l), which had relatively high numbers of microcrustaceans, and the tertiary maturation pond M21 (10.8 mg N/l), which contained residues of roots from the floating macrophyte studies.

Ammonia increased from 32.5 mg N/l in the raw wastewater to nearly 42 mg N/l in the anaerobic ponds as a consequence of the biological degradation of organic compounds, such as amino acids, and urea hydrolysis by the action of the enzyme urease under anaerobic conditions (Ideliovitch and Michail, 1981). In contrast ammonia values were reduced greatly throughout the secondary facultative and maturation ponds to between 2.6 and 4.3 mg N/l in the tertiary maturation ponds. Given the mean concentration in the raw wastewater, there was a cumulative removal of 28.0% up to the primary maturation pond and this increased to 49.2% in pond M20 which was the most heavily loaded secondary maturation pond. In the other secondary maturation ponds cumulative removals reached 72.9 – 79.1 percent and in the tertiary maturation ponds reductions increased to 86.8 – 92.0 percent. Removals of ammoniacal nitrogen have been reported to vary from negligible amounts (Toms *et al*., 1975; Silva *et al.,* 1987) to values as high as 95% (Middlebrooks *et al.,* 1982), depending on the configuration of the system and the operational characteristics of the ponds. The highest removals reported by Middlebrooks *et al.* (1982), for example, were associated with very high hydraulic retention times (up to 227 d) and depths of 1.2 m in a series of ponds with influent ammonia concentrations between 7.5 and 25.5 mg N/l. Santos and Oliveira (1987) obtained an overall annual removal of 52.4 percent in a series comprising an anaerobic (3 m deep and 1.7 d retention), followed by a facultative pond (1.1 m deep and 17.3 d retention) and a maturation

pond (1.1 m deep and 9.7 d retention) at Frielas, Portugal. Silva (1982) working on a series of five 1.0 m deep ponds (1 anaerobic, 1 facultative and three maturation ponds), receiving raw wastewater with an ammonia concentration of 45 mg N/L, obtained overall removals of 32, 48 and 81% respectively for total hydraulic retention times of 8.5, 17.0 and 29.1 days. In the innovative system total hydraulic retention times from the anaerobic to the tertiary maturation ponds varied between 14 and 23 d and the higher overall removals found were due to a more rational pond series configuration combining anaerobic and secondary facultative ponds as traditionally designed but with shallow maturation ponds. This configuration promoted the development and predominance of aerobic conditions and favourable effects, such as high pH values, which enhanced ammonia removal mechanisms.

The 4-pond series culminating in M20 (30 cm deep and 1 d retention), with an overall mean retention time of 11 days, gave an overall ammonia removal of 50.8 percent compared to the concentration in the raw wastewater, and a daily ammonia removal rate in M20 of 29.8 percent (i.e. effluent over influent). The 4-pond series culminating in M18 (30 cm deep and 3 d retention), with an overall retention of 13 days, gave an overall ammonia removal of 74.5 percent, with 64.6 percent occurring in M18 representing 21.5% removal per day. The 4-pond system to M17 (64 cm deep and 5 d retention) gave an overall removal of 77.5 percent, with 68.8 percent removal in M17, but this represented a lower rate of 13.8 percent per day. The rate in the series culminating in M16 (90 cm deep and 7 d retention) gave a high 79.1 percent overall removal after 17 days, with 70.1 percent removal in M16, representing a daily removal rate of only 8.7 percent.

In the 5-pond series culminating in the tertiary maturation pond M22 (60 cm deep and 5 d retention), with an overall mean retention time of 18.8 days, the removal of ammonia was 91.4% with 62.2% removal in M22 equivalent to a removal of 12.4% per day. These latter two figures are comparable to those obtained from the secondary maturation pond M17 which was of similar depth and retention time.

Total kjeldahl nitrogen variations followed those for ammoniacal nitrogen. Its content in the raw wastewater (53.9 mg N/l) was about 60 percent ammonia and 40 percent organic nitrogen. Mean concentrations dropped a little in the anaerobic ponds (50.0-51.6 mg N/l) and decreased continuously through the pond system down to the range 11.6-15.0 mg N/l in the tertiary maturation ponds. The mean TKN concentration in the secondary maturation pond M20 (19.7 mg N/l) was as high as that in the primary maturation pond (31.8 mg N/l). This was attributed to the influence of the high organic nitrogen loading on this pond which was higher than for any of the other maturation ponds in the system, together with the high level of ammonia associated with the operation of a maturation pond with a very high organic loading. Cumulative removals increased from about 5 percent in the anaerobic ponds to about 10 percent in secondary facultative and 41 percent in pond M15. Percentage removals up to and including the secondary maturation ponds varied between 45 percent (M20) and 71.6 percent (M16), and between 72.2 percent (M21) and 78.5 percent (M22) in the tertiary maturation ponds.

Mean effluent concentrations of both ammonia and total kjeldahl nitrogen were found to be directly related to TKN surface loading (Figure 6.1). Equations 6.3 and 6.4 below represent fitted to the points (x = log N loading, y = nitrogen concentration) obtained in facultative and maturation ponds for ammonia and total kjeldahl nitrogen, respectively:

$$(1/y) = (0.60/x) - 0.24 \quad (6.3)$$

$$(1/y) = (0.189/x) - 0.0625 \quad (6.4)$$

Figure 6.2 illustrates the degree of agreement between predicted and actual mean concentrations of both ammonia and TKN.

A model based on the assumption that ammonia volatilization is the main mechanism of nitrogen removal, similar to that proposed by Middlebrooks *et al.* (1982), was also tested for the coordinates

$$x = [(C_i - C_e)/C_e][Q/A] \text{ and } y = [pH - 6.6]$$

where C_i and C_e are the influent and the water column nitrogen concentrations (mg N/l), respectively; Q the flow rate (m^3/d); and A the pond area (m^2). It fitted only for ammonia removal in facultative and primary and secondary maturation ponds, as follows:

$$C_e = C_i/[1 + 8.65x10^{-3}(A/Q)e^{1.727(pH-6.6)}] \quad (6.5)$$

Figure 6.3 illustrates the very good degree of agreement between the observed mean values and those predicted by both equation 6.5 and the following slightly modified form of the model:

$$C_e = C_i/[1 + 38.8x10^{-3}(A/Q)e^{1.911(pH-7.5)}] \quad (6.6)$$

Table 6.1 First order rate constants for unfiltered and filtered BOD removal in anaerobic and secondary facultative ponds

Pond	Retention time (days)	First order rate constant (day^{-1}) for removal of	
		Unfiltered BOD	Filtered BOD*
A11	1	1.92	NC**
F26	2	0.57	1.71
A9	1	1.70	NC
A10	1	1.63	NC
F21	3	0.44	1.56
F22	4	0.39	ND **
F23	5	0.33	ND
F24	6	0.35	0.95
F25	6	0.33	ND

* k_1 values for filtered BOD removal in facultative pond based on filtered BOD in facultative pond effluent but unfiltered BOD in facultative pond influent (i.e. anaerobic pond effluent), these values representing the non-algal influent and effluent BOD. $k_1 = [(L_i/L_e)-1]/\theta$.

**NC, not calculated (as not of interest); ND, not determinable (as filtered BOD not measured)

Table 6.2 First order rate constants for faecal bacterial and viral removal in the "innovative" ponds.

	First order rate constants* (day^{-1}) for				
Pond	FC	Salmonellae	Campylobacters	*V. cholerae*	Rotaviruses
A9	2.76	-0.09	1.70	1.00	2.92
A10	2.72	-0.10	1.08	1.00	2.76
F21	1.86	4.03	0.71	0	0.38
F22	1.68	2.69	0.03	0.25	0.18
F23	1.35	3.49	0.63	- **	0.30
F24	1.36	4.01	0.35	-	0.36
F25	1.16	2.47	0.25	0.17	0.33
M15	9.46	1.56	0.45	-	0.08
M16	6.04	0.27	- **	-	0.47
M17	6.73	0.33	0.11	-	0.37
M18	10.04	0.56	0.27	-	0.43
M19	12.15	0.56	-	-	0.43
M20	13.75	1.29	0.82	-	2.00
M21	3.59	0.05	-	-	24
M22	2.97	0.05	-	-	141
M23	0.39	-0.14	-	-	- **
M24	7.96	0.03	-	-	-

* $k = [(N_i/N_e) - 1]/\theta$ where k = first order rate constant (day^{-1}); N_i, N_e = numbers of microorganism per 100 ml (bacteria; per litre, rotaviruses) of pond influent and effluent, respectively; and θ = pond retention time (days).

**Not calculated as $N_e = 0$.

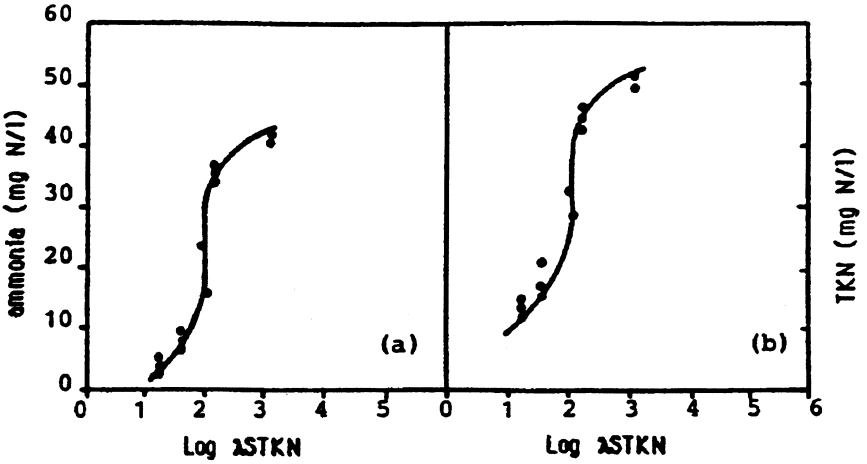

Figure 6.1: Mean pond nitrogen concentrations versus surface TKN loading: (a) ammoniacal nitrogen, (b) total kjeldahl nitrogen.

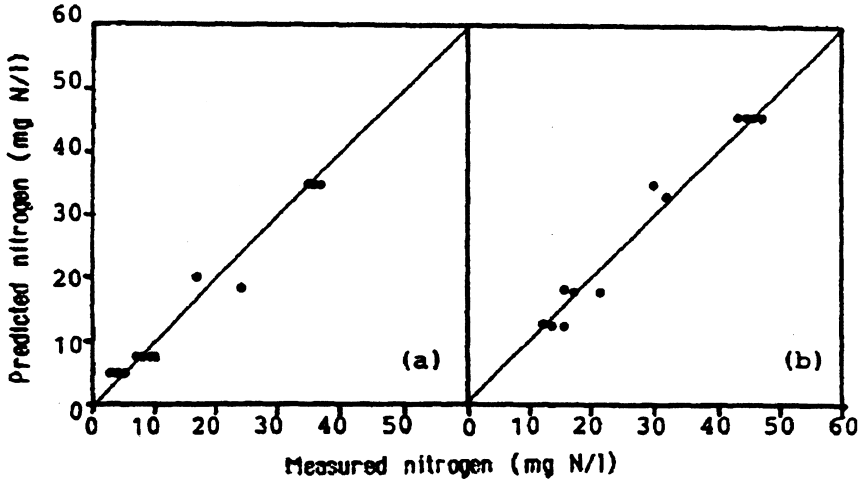

Figure 6.2: Measured versus predicted nitrogen concentrations (a) ammoniacal nitrogen (eq. 6.3), (b) total kjeldahl nitrogen (eq. 6.4).

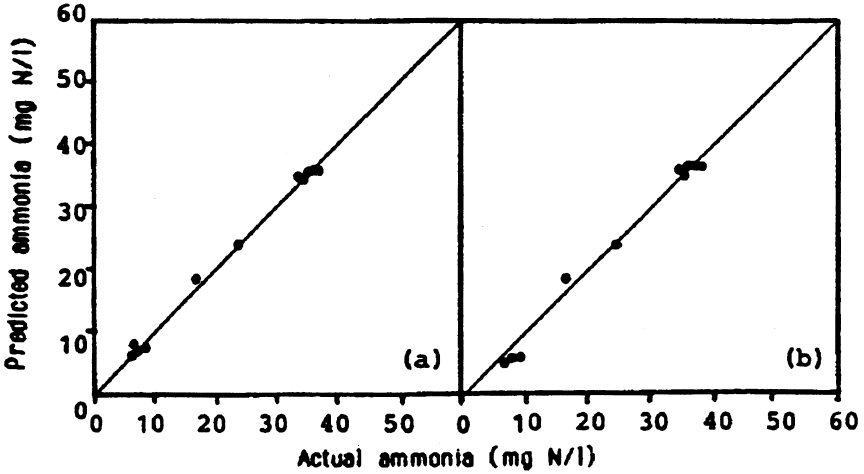

Figure 6.3: Measured versus predicted ammoniacal nitrogen concentrations: (a) equation 6.5, (b) equation 6.6.

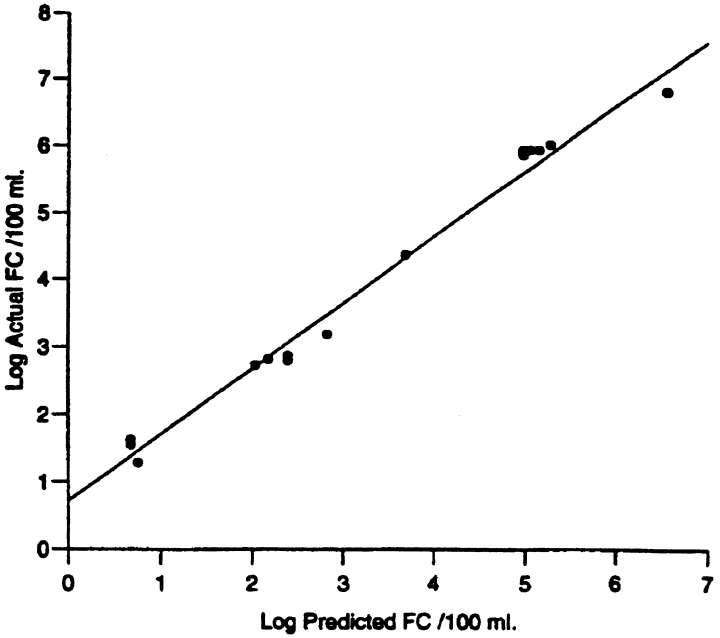

Figure 6.4: Comparison of log actual and log predicted faecal coliform numbers in individual pond effluents, based on the results of column sampling. Log predicted values were derived from actual influent values for each pond.

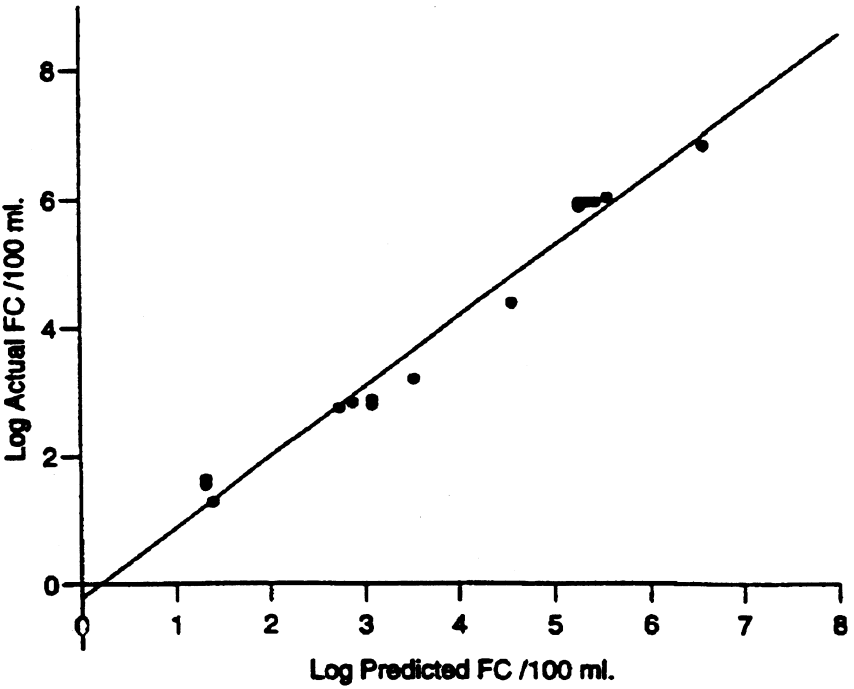

Figure 6.5: Comparison of log actual and log predicted faecal coliform numbers in pond effluents, based on the results of column sampling. Log predicted values were derived from influent values to each pond calculated from the Marais equation according to its position in the series and based on the actual FC number in the raw wastewater.

7. Conclusions

From the findings of the research reported in this Monograph (see also Mara *et al*., 1994 and 1996), the following conclusions can be drawn:

1. Anaerobic ponds are essential not only for high removals of BOD, COD and suspended solids but also, due to their high sulphide concentrations, for the efficient removal of *Vibrio cholerae* O1.

2. The loading regimes used in this study suggest that maximum design volumetric loadings for anaerobic ponds can be increased to 350 g/m^3 day at 25ºC, rather than restricting it to 300 g/m^3 day at all temperatures above 20ºC. The results also show that some operational loss in anaerobic pond efficiency occurs at retention times less than 1 day, although the ponds systems did not fail or cause odour problems.

3. At an in-pond temperature of 25°C the effluent from a 1-day, 2.5 m deep anaerobic pond and a 3-day, 1 m deep facultative pond complies with the EU effluent requirement of ≯25 mg filtered BOD_5 per litre and ≯50 mg suspended solids per litre, and also with the WHO limit for crop irrigation of ≯1 intestinal nematode egg per litre.

4. At temperatures above 20°C the filtered BOD in the effluent from a series of short retention time anaerobic and facultative ponds may be tentatively estimated from the equations:

$$L_{e(filt)(fac)} = L_i/(1 + k_{1(T)}\theta_a)(1 + k_{1(T)}\theta_f)$$

$$k_{1(T)} = 1.1\ (1.05)^{T-20}$$

5. The performance of and effluent quality from secondary facultative ponds are independent of pond geometry, at least within the range of length-to breadth ratios of 1 to 1 and 1 to 6 and within the depth range of 1 to 2 m. This finding validates the use of surface BOD_5 loading for the design of these ponds in preference to other approaches based on retention time (for example, first order kinetics) or those incorporating hydraulic dispersion, and also permits the design engineer greater freedom to shape ponds to make the best use of available land, especially on awkwardly shaped sites. Surface BOD_5 loading rates twice those recommended by the design equations did lead to some loss in BOD removal efficiency in the combined operation of anaerobic and facultative ponds, and chlorophyll levels indicated that the facultative ponds were operating at the very limit of their capacity. They did not, however, produce any noticeable odour.

6. Doubling the maximum design organic loading and thus concomitantly halving the retention time still produced an acceptable BOD_5 in the final effluent, but the bacteriological quality just failed to meet WHO guidelines for unrestricted irrigation, except when a baffled tertiary maturation pond was included. This suggests that all final maturation ponds should be baffled as part of the basic physical design criteria. Shallow maturation ponds are more efficient at faecal

coliform removal than deeper ones (i.e. those > 1 m), and therefore deepening maturation ponds, to increase the retention time, will not improve the microbiological quality of the final effluent.

7. Excessive organic loading of a WSP system reduces nutrient removal efficiency to a greater extent than either BOD or bacterial removal. Whereas the bulk of organic carbon removal occurs in the anaerobic ponds, most nutrient (both N and P) removal occurs in the maturation ponds and is dependent on high pH levels in the pond water column. These pond systems were capable of > 90% ammonia removal, > 70% TKN removal and > 40% total P removal at optimal pond loadings.

8. At temperatures above 20°C ammoniacal nitrogen removal in facultative and maturation ponds may be estimated from the equation:

$$C_{(Amm.N)_e} = C_{(Amm.N)_i} / [1 + 8.65x10^{-3} (A / Q)e^{1.727(ph\ -6.6)}]$$

9. Faecal bacterial and viral removal is more efficient in shallow, rather than deep, facultative and maturation ponds, at least within the depth ranges of 1 to 2 m for facultative ponds and 0.4 to 1.5 m for maturation ponds. Thus increasing pond depths to achieve, for the same pond area, increased retention times for insertion into the Marais equation to obtain improved FC removals, is not a valid process design strategy, since the predicted design performance will be less than the actual performance.

10. At temperatures above 20°C k_T values for FC removal in shallow, short retention time facultative and maturation ponds may be tentatively estimated from the equation:

$$k_T = 2.6\ (1.15)^{T-20}$$

This equation gives slightly lower values than the Marais equation as the value of k_T changes with temperature by 15 percent per degC rather than by 19 percent.

11. The incorporation of the floating macrophyte *Pistia stratiotes* on a tertiary maturation pond achieves only a slight increase in physicochemical effluent quality, but a decrease in microbiological effluent quality; its use therefore appears unwarranted.

12. The presence of the microcrustacean *Daphnia magna* in a tertiary maturation pond is difficult to sustain due to predation by larger aquatic invertebrates. Thus *Daphnia* ponds are not yet a feasible design option.

13. Baffled tertiary maturation ponds are more efficient than unbaffled ponds, in terms of both microbiological and physicochemical effluent quality.

14. Short-retention-time rock filters receiving primary maturation pond effluent should be loaded at 1 m^3 of gross rock filter volume per day. They achieve only a small reduction in BOD and COD but can achieve SS concentrations < 30 mg/l. FC and FS removal is nearly an order of magnitude, and rotavirus removal approximately half an order of magnitude. No difference in performance due to rock size within the range 19-38 mm was found.

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