The reasons behind the performance superiority of a high rate algal pond over three facultative ponds in series

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Abstract Results from a tracer study were used to determine and to compare actual and standard ($k_{20°C}$) first order reaction rate constants for COD removal in a High Rate Algal Pond (HRAP) and in 3 facultative ponds (FP) in series. An annual average $k_{20°C}$ of 0.123 day^{-1} was found for the HRAP while the values of 0.097 , 0.025 and 0.003 d^{-1} were found for facultative ponds 1, 2 and 3 respectively. Also, comparing nominal and tracer study hydraulic retention times showed large differences for the FP but not for the HRAP indicating that the former were suffering from severe short-circuiting. Loading rate within the range of operation exhibited a positive correlation with $k_{20°C}$ for the HRAP but did not show such a relationship for any of the FP. Optimal chlorophyll-a concentration was found to be 3 mg/l for the HRAP and only 1.1 mg/l for the FP. Pollutant specific removal rates (SRR), that translate the hydrodynamic efficiency and the rate of COD biodegradation into pond performance per m^2 and per day were calculated. They show that the adoption of the HRAP in place of a series of 3 FP reduces the net land area requirement (LAR) by at least 40%.

Keywords Area of land requirement; first-order reaction rate constant; high-rate algal pond; WSP

Introduction

Many developing countries have a massive need for investment in the water sanitation sector, for which the local economies do not have the necessary financial capacity. Also, experience shows that mechanised systems are not affordable at the present time. WSP, which has been identified as a suitable technology for these countries could represent a provisional solution (Arthur, 1983). However, the LAR of WSP is large due to inefficient hydrodynamics in FP where short-circuiting and thermal stratification are often reported to occur (Llorens *et al.*, 1992; Herrera and Castillo, 2000; Shilton *et al.*, 2000). This is why the shallow and mixed High Rate Algal Pond (HRAP) developed by Oswald in California, USA (Oswald and Gotaas, 1957) is often presented as an alternative to minimize the LAR.

A tracer study was performed on the HRAP and on the FP compared in this paper by Vasel and his coworkers (Nameche and Vasel, 1998) to determine their hydrodynamics. The result of this study was used in this paper to determine the first order rate constant, k, for COD removal and to analyse the factors that govern the superiority of the HRAP over the FP. Pollutant Specific Removal Rates (SRR) were then calculated to show that the HRAP superiority could be translated into a substantial LAR saving and consequently to a significant reduction of earthwork and construction cost.

Materials and methods

Climate of the city of Ouarzazate

The city of Ouarzazate is located 600 km south of the capital Rabat (Morocco). Its latitude is 30°56’N and its average altitude is 1,160 m. The climate of Ouarzazate is typical North Saharan, with a cool winter. The average temperature is about 19°C with a minimum of 6.4°C and a maximum average of 31.2°C. The air humidity is 21% in July and 57% in December. Average annual rain is 109 mm.

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Wastewater treatment facilities

Three pond trains were constructed (concrete structure) on the same site. They received the same sewage and shared the same preliminary treatment unit. They were tested for two consecutive years, 1995 and 1996. The preliminary treatment unit included grit, sand and oil/grease removal. The compared trains consisted of two WSP trains (WSP no 1 and no 2) and one HRAP train. The design details of these trains are given in Figure 1 and in Tables 1 and 2. The anaerobic pond, An_1 placed at the head of the two WSP trains received 345 m^3/day of sewage. At its outlet, the flow was divided into two equal parts of 172.8 m^3/day that were feeding WSP no 1 and WSP no 2 (Figure 1). The HRAP train, which starts with the anaerobic pond, An_2, received 345 m^3/day of sewage. In order to mitigate the effect of odour emanation in the anaerobic stage in the hot season, part of the effluent of the HRAP train was recycled at a rate of 86.4 m^3/day to each of the two anaerobic ponds. Since the recycling was done using the same rate and the same effluent, this operation did not affect the comparison. Surface loading rates applied during the comparison are shown in Table 3.

A slight difference in the surface areas of WSP trains no 1 and no 2 existed, particularly in their respective FP units with 2,076 and 2,627 m^2 (a difference of approximately 20%). But the depth of the ponds was changed so that overall hydraulic retention times in the FP units were the same. The 3 FP (F_{11}, F_{12} and F_{13}) of WSP no 1 were all identical and did have a similar area while those of the WSP no 2 (F_{21}, F_{22} and F_{23}) were occupying different areas with F_{21} having an area similar to that of F_{12} from WSP no 1 (see Table 1). Only the facultative F_{12} and the HRAP were subjected to the tracer study. But the values obtained were used for F_{11} and F_{13} from WSP no 1 and for F_{21} from WSP train no 2 because these ponds were identical in their shape, dimensions, lining material and in the way their inlet and outlet pipes were placed. During the follow-up period, WSP no 1 experienced the "red water phenomenon" in the summer indicating a dysfunction of the system. This phenomenon originates from an intensive development of purple sulphur-reducing bacteria concomitant with a decline of the population of green, useful algae in the pond (Pinheiro *et al.*, 1987). Such a dysfunction did not affect WSP no 2, this is why comparison between the HRAP and the series of 3 FP was based on the performance of WSP no 2.

Analytical methods

24 hour-composite samples were collected two times per month for analysis. Collected samples from the HRAP, the FP and the maturation ponds were submitted to centrifugation

Table 1 Dimensions and hydraulic retention time in WSP trains no 1 and no 2

	Area (m2)	Depth (m)	Volume (m^3)	Flow rate (m^3/day)		Retention time (day)	
				WR	R	WR	R
Anaerobic, An1	887	3	1,826	345	432	5.2	4.2
Facultative F11	700	2	1,090	173	216	6.3	5.0
Facultative F21	661	2	994	173	216	5.7	4.6
Facultative F12	690	2	1,077	173	216	6.2	5.0
Facultative F22	436	1.5	444	173	216	2.6	2.0
Facultative F13	686	2	1,087	173	216	6.3	5.0
Facultative F23	1530	2	1820	173	216	10.5	8.4
Total Facultative WSP1	2,076	–	3,258	–	–	18.8	15.0
Total Facultative WSP2	2,627	–	3,258	–	–	18.8	15.0
Maturation M11	278	1	289	173	216	1.7	1.3
Maturation M21	300	1	300	173	216	1.7	1.4
Maturation M12	318	1	311	173	216	1.8	1.4
Maturation M22	300	1	300	173	216	1.7	1.4
Total WSP no 1	3,115	–	4,771	–	–	27.5	21.9
Total WSP no 2	3,627	–	3,670	–	–	27.4	22

R: episodic recycling (hot season); WR: without recycling (cold season)

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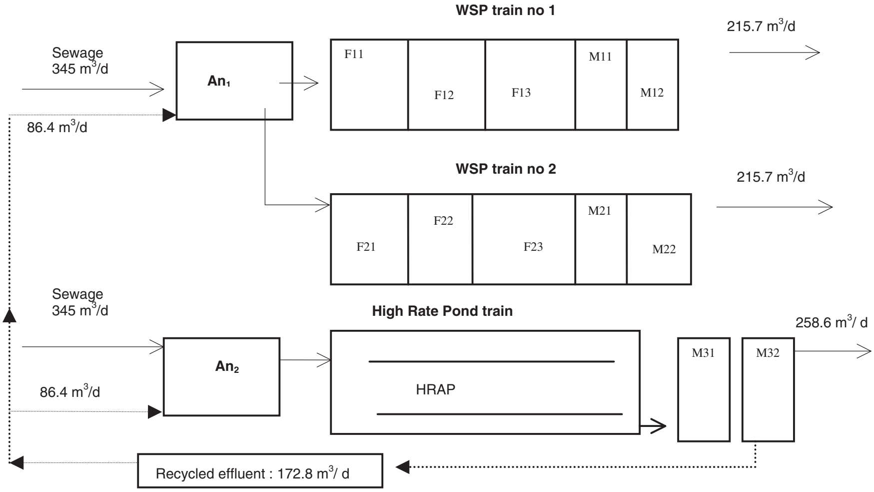

An_1 anaerobic pond 1 ; F_{11} : facultative 1 of WSP train no 1; M_{22} : maturation 2 of WSP no 2.

Figure 1 Layout of experimental wastewater treatment facilities at Ouarzazate (Morocco)

at 1,500 g for 10 minutes to remove most of the algae before performing the chemical analysis. COD, ammonia and orthophosphate were determined following *Standard Methods* (ed. 1985). Dissolved oxygen (DO) and pH were monitored on the site using portable meters. The values reported for DO were the average of values obtained at 3:00 PM for three consecutive days. Chlorophyll a was determined after extraction in hot 90% methanol (Pearson *et al*., 1987).

Bacteriological and parasitological analysis

Grab samples were taken around 11:00 am. For faecal coliforms (FC) counting, ELSAB (Enriched Lauryl Sulphate Aniline Blue) was used according to Wright (1984). Helminth eggs were counted on 24 hour-composite samples after a flotation step using sucrose according to Arther *et al*. (1981).

Results

First-order reaction rate constant, *k*

Pond efficiency for BOD (or COD) removal is expected to be within the limits of kinetics described by complete mixing from one side and plug flow from the other. Within these limits and provided the dispersion number, d, is known, biodegradation kinetics may be described by the Wehner-Wilhelm Eq. (1) (Thirumurthi, 1974).

Table 2 Dimensions and hydraulic retention time in the High Rate Algal Pond train(1)

	Area (m^2)	Depth (m)	Volume (m^3)	Flow rate (m^3/day)		Retention time (day)	
				WR	R	W R	R
Anaerobic, An_2	887	3.0	1,826	345	432	5.2	4.2
HRAP (1)	3,023	0.4	1,209	345	432	3.5	2.8
Maturation M31	400	1.0	400	345	432	1.15	0.9
Maturation M32	400	1.0	400	345	432	1.15	0.9
Total maturation	800	–	800	–	–	2.30	1.8
Total	4,710	–	3,835	–	–	11.0	8.8

(1) The HRAP content was continuously mixed using a paddle wheel allowing a surface water circulation speed of 0.2 m/s; R: episodic recycling (hot season); WR: without recycling (cold season)

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Table 3 Surface loading rate (SLR)(1) of the HRAP and the series of 3 FP of WSP train no 2 during the two-year follow-up period

	COD mg/l	Flow rate $m^3/d^{(2)}$	Pond area ha	SLR kg COD $ha^{-1}.d^{-1}$	SLR kg BOD $ha^{-1}.d^{-1}$
HRAP	208	376	0.3023	260	190
Facultative F_{21}	210	188	0.066	600	430
Facultative F_{22}	175	188	0.0436	750	540
Facultative F_{23}	165	188	0.1530	200	150
Total SLR $F_{21}+F_{22}+F_{23}$(3)	210	188	0.2627	150	110

(1) Cold season covers five months out of twelve; (2) Annual average flow including recycling is calculated as follows: [(173 m^3d^{-1} *30* 7 months) + 216 m^3d^{-1} *30* 5 months]/365 for the FP and [(345 m^3d^{-1} *30* 7 months) + 432 m^3d^{-1} *30* 5 months]/365 for the HRAP; (3) Considering the total area covered by the 3 FP together and the COD concentration entering F_{11}

$$C_i/C_e = 4a\exp(1/2d)/[(1+a)^2\exp(a/2d) - (1-a)^2\exp(-a/2d)] \quad (1)$$

with $a = (1+4ktd)^{1/2}$

where, d is the dispersion number, k the first order reaction rate constant and, t the retention time. k may then be calculated if C_i and C_e and the dispersion number, d, are known. Here C_i and C_e were obtained through the biweekly sampling and analysis during the two-year follow-up period. The tracer study gave values for d and t for the HRAP, respectively 0.014 and 70 hours, and for one of the 3 FP, respectively 6.66 and 52 hours. Standard, $k_{20°C}$ was then calculated using Eq. (2)

$$k_{T°C} = k_{20°C}\,\theta^{(T°C-20)} \quad (2)$$

where $k_{T°C}$ and $k_{20°C}$ are the value of k at temperature T°C and at 20°C respectively and θ is an Arrhenius constant taken as 1.047. For COD removal an annual average $k_{20°C}$ of 0.123 d^{-1} was established for the HRAP. Those calculated for the 3 FP in series were 0.097, 0.025 and 0.003 d^{-1} respectively for FP1, 2 and 3.

Linear regression between k and the SLR

Simple linear regression analysis between the SLR and $k_{20°C}$ for the HRAP produced a straight line as described by Eq. (3) with $R^2 = 0.548$ (Figure 2). No such relationship was found for any of the facultative ponds.

$$SLR_{HRAP} = 0.1429\mathrm{Ln}(k) - 0.6521 \quad (3)$$

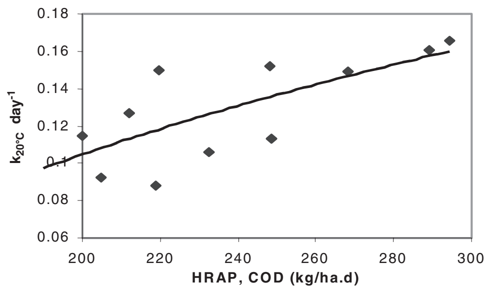

Figure 2 Linear regression analysis between the COD loading rate and COD removal, $k_{20°C}$ in the HRAP (Ouarzazate, Morocco)

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Optimal chlorophyll-a concentration

Figure 3 shows the relationship between chlorophyll-a concentration and $k_{20°C}$ for COD removal in the HRAP and in the FP (F_{12} taken as example). For the HRAP, the optimal chlorophyll-a concentration was 3 mg/l while it did not exceed 1.1 mg/l for the FP.

Specific removal rates

Apparent removal rates calculated as $(C_i–C_e)/C_i \times 100$ are widely used for treatment performance comparison. Table 4 shows raw wastewater and effluent average characteristics of the HRAP and the 3 FP in series. Removal rates analysis does not give a precise idea about the way the area of land occupied was valorised by a treatment component. For this, a better approach was to take into account the mass of pollutant, Y as g (or unit forming colony: UFC) removed by the pond per day following Eq. (5):

$$Y\,(\text{g/day}) = Q_iC_i - Q_eC_e \qquad (5)$$

where C_i and C_e are respectively the concentration of pollutant at the inlet and outlet of the considered pond expressed as g m^{-3}, (or in UFC m^{-3} of fecal coliforms) and Q_i and Q_e the admitted and the treated flow, in m^3 d^{-1}, respectively. Q_i and Q_e were taken here as equal, neglecting the evaporation rate which did not exceed 10%. Also, the rate of oxidation, in biological wastewater treatment systems, is known to follow a first order rate and is therefore proportional to the concentration of the pollutant entering it as in Eq. (6):

$$dC/dt = -k\,C \qquad (6)$$

where C represents the amount of pollutant entering the pond, t is the time and k the first order reaction rate constant for the removal of the pollutant under consideration. Eqs (5) and (6) show that the comparison between the HRAP and the 3 FP is only possible if the two units were receiving the same C_i. The design of the Ouarzazate wastewater treatment plant did take this into account. The series of 3 FP and the HRAP were placed behind similar anaerobic ponds, that were producing effluents of similar characteristics (Student's test, $p<0.01$). Finally, the area, A of land occupied by the 3 FP or by the HRAP was introduced in the formula in order to calculate the Specific Removal Rates (SRR) following Eq. (7):

$$\text{SRR} = (Q_iC_i - Q_eC_e)/A \quad (\text{in g or UFC removed m}^{-2} \times \text{day}^{-1}) \qquad (7)$$

When Eq. (7) was applied to effluent of the HRAP, the following SRR were found: 6.96 for COD, 1.53 for ammonia, and 0.82 g m^{-2} day^{-1} for orthophosphates versus 3.03, 0.53, and 0.30 for the effluent of the 3 facultative ponds. The HRAP significantly improved the SRR

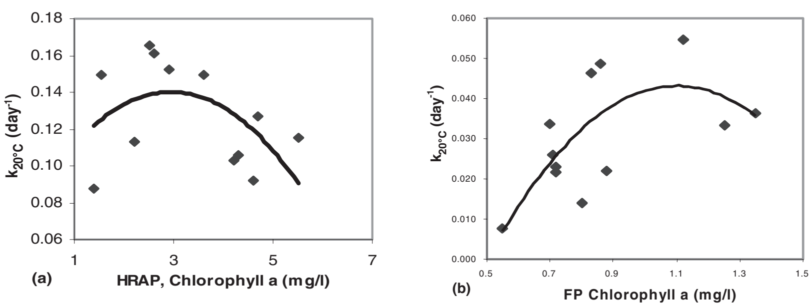

Figure 3 Optimal chlorophyll a concentration in the HRAP (3a) and the FP F_{12} (3b)

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Table 4 Removal rates of the main pollution parameters for crude wastewater, the effluent of the 3 FP and the effluent of the HRAP

Parameters	Raw	Anaerobic An_1 or An_2 (1)		3 FP in series		HRAP	
		Value ± SD	RR	Value ± SD	RR	Value ± SD	RR
Temperature (°C)	23.1	21.6 ± 7.3	–	20.3 ± 8.1	–	20.3 ± 8.6	–
pH	7.5	7.7 ± 0.2	–	8.5 ± 0.5	–	9.28 ± 0.6	–
DO (mg/l)	0	0	–	5.1 ± 7.3	–	20.3 ± 10.2	–
BOD_5 (mg/l)	340	152 ± 21	55	122 ± 21	64	118 ± 33	65
COD (mg/l)	500	210 ± 52	58	164 ± 57	68	147 ± 66	65
$N\text{-}NH_4^+$ (mg/l)	37.4	32.8 ± 5.5	12	24.8 ± 5.3	34	19.4 ± 5	48
$P\text{-}PO_4^{3-}$ (mg/l)	20.2	16.4 ± 4.2	19	11.8 ± 2.1	42	9.2 ± 3	54
Chl a (mg/l)	0	0	–	0.85 ± 0.5	–	4.9 ± 2.4	–
Helminth (egg/l)	13.0	1.2 ± 0.7	91	0	100	0	100
FC (UFC/100 ml)	4.1×10^6	5.85×10^5	0.85(2)	5.8×10^3	2.85(2)	1.5×10^4	2.44(2)

(1) Effluent characteristics of An_2 are not significantly different from those of An_1 producing a COD value of 208 mg/l instead of 210 reported here; SD: standard deviation; (2) In logarithm units; RR removal rates

for all the pollutants considered. These improvements (results not shown) did not depend on the season (Student's test, $p<0.01$). For FC removal, SRR obtained on the HRAP reached 6.5×10^8 UFC m^{-2} day^{-1} versus 3.8×10^8. Here also, the improvement of the SRR by the HRAP did not depend on the season (Student's test $p<0.01$).

Land area requirement

Eq. (8) gives the rate of reduction of the net LAR for any considered pollutant for which the ratio f is defined as SRR_{FP}/SRR_{HRAP}.

$$LAR = (1-f) \times 100 \quad \text{with } f = SSR_{FP}/SRR_{HRAP} \tag{8}$$

Application of Eq. (8) led to the conclusion that the adoption of a HRAP in place of a series of 3 FP corresponded to a reduction of the net LAR by a rate of 56, 65, 63 and 41% respectively when COD, ammonia, orthophosphate and FC were considered.

Discussion

When $k_{20°C}$ for COD removal was calculated for the HRAP using the complete mixing or the plug flow pattern, the differences with the actual value were 16% and 2% respectively. When $k_{20°C}$ was calculated for the FP using these two extreme flow patterns, the differences with the actual, dispersed flow value were 6% and 14%. This shows that the use of accurate hydrodynamic parameters in combination with the dispersed flow pattern allows a more accurate design approach confirming Thirumurthi's (1974) early findings.

Better pond hydrodynamics is the major factor that explains the performance superiority of the HRAP over the series of 3 facultative ponds. The tracer study has shown that the actual mean hydraulic retention time for the HRAP was 3 instead of 3.5 days which is the design value. For the pond F_{12}, these values were 2.16 and 6.2 days respectively indicating that the FP were suffering from severe short-circuiting.

The value of $k_{20°C}$ decreased as the flow passed from the first to the third FP in the sequence of 0.097, 0.025 and 0.003 d^{-1}. A similar sequential reduction in k values with decreasing organic loading was reported for five ponds in series by Mara *et al*. (1979) in Brazil and by Ellis and Rodrigues (1993) in the Grand Cayman confirming early findings of Uhlman (1979) and Thirumurthri (1974) that *k* varies with temperature and with the organic loading rate as well.

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The fact that we did not find any simple linear regression between *k* and the organic loading for any of the 3 FP while such a relationship was found for the HRAP must be discussed in the light of the organic loading applied to the FP. Our pond configuration led to an apparent high loading rate for the first two FP with figures in the range of 400 and 500 kg BOD ha^{-1} d^{-1} respectively. However, if we add up the areas of the 3 FP or, in other words, if we have constructed one unique FP with 2,027 m^2 instead of 3 ponds in series the loading rate would have been 110 kg BOD ha^{-1} d^{-1} (Table 3). These arguments minimise any negative effect of the organic loading on the performance of the 3 FP and suggest that these ponds did rather suffer from short-circuiting and from a low efficiency in the capture and the conversion of solar energy. On the contrary, the HRAP did show a linear regression even with an organic load of 190 kg BOD ha^{-1} d^{-1}, which represents twice that applied to the 3 FP (Table 3).

The higher capacity for light capture and conversion by the HRAP is confirmed by its optimal chlorophyll-a concentration, which was 3 times higher than that of the 3 FP (Figure 3). Chlorophyll-a concentration controls the oxygenation capacity in the ponds and depends directly on the light penetration through the water column. Light penetration does not actually exceed the first 20 to 30 cm (Abeliovich, 1986), making it difficult for algae in the FP to be exposed to sunlight. On the contrary, the low depth and the continuous and gentle mixing action of the paddlewheel of the HRAP constantly brings the algae to the water surface for light capture.

Finally, it is important to mention the consequence of this finding on the cost of investment and on the land area occupation when dealing with ponds systems. The SRR study done, in this paper, clearly shows that one may expect a reduction of the net land area requirement (LAR) by at least 40% if the HRAP is to be adopted in a pond train in place of a FP unit. Reducing the LAR by such an extent will certainly minimise one of the major obstacles facing ponds technology development in many areas in the world.

Conclusion

The HRAP exhibits interesting hydrodynamic features that help in activating and speeding up the two main biological processes governing wastewater treatment in pond systems, namely, the algae growth and photosynthesis on one hand, and the bacterial degradation of wastes on the other hand. The performance superiority of the HRAP over a FP unit is demonstrated here with the consequence of a substantial reduction in the net LAR needed by ponds systems.

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References

Abeliovich, A. (1986). Algae in wastewater oxidation ponds. In *CRC Handbook of microalgae mass culture*. Richmond eds Inc., Boca Raton, Florida, 331–338.

Arther, R.G., Fitzgerald, R.R. and Fox, J.C. (1981). Parasite ova in an aerobically digested sludge. *J. Wat. Pollut. Cont. Fed.*, **53**, 1333–1338.

Arthur, J.P. (1983). "Notes on the design and operation of waste stabilization ponds in warm climates of developing countries". In: *World Bank technical papers* (7).

El Hamouri, B., Khallayoune, K., Bouzoubaa, K., Rhallabi, N. and Chalabi, M. (1994). "High-rate algal pond performances in fecal coliforms and helminth egg removals". *Wat. Res.*, **28**(1), 171–174.

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El Hamouri, B., Jellal, J., Outabiht, H., Nebri, B., Khallyoune, K., Benkerroum, A., Hajli, A. and Firadi, R. (1995). The performances of a high-rate algal pond in the Moroccan climate. *Wat. Sci. Tech.*, **31**(12), 67–74.

Ellis, K.V. and Rodrigues, P.C.C. (1993). Verification of two design approaches for stabilization ponds. *Wat. Res.*, **27**(9), 1447–1454.

Herrera, L. and Castillo, G. (2000). Dynamics of a waste stabilisation pond in Chile. *Wat Sci. Tech.*, **42**(10), 83–90.

Llorens, M., Saez, J. and Soler, A. (1992). Influence of the thermal stratification on the behavior of deep wastewater stabilization ponds. *Wat. Res.*, **26**(5), 569–577.

Mara, D.D., Silva, S.A. and de Ceballos, B.S. (1979). Design verification for tropical oxidation ponds. *J. Envir. Engng Div. Am. Soc. Civ. Engrs*, **1**, 105–151.

Nameche, T. and Vasel, J.L. (1998). Hydrodynamic studies and modelization for aerated and waste stabilization ponds. *Wat. Res.*, **32**(10), 3039–3045.

Oswald, W.J. and Gotaas, H.B. (1957). Photosynthesis in sewage treatment. *Transaction of the American Society of Civil Engineering*, **122**, 73–105.

Pearson, H.W., Mara, D.D. and Mills, S.W. (1987). Physicochemical parameters influencing fecal bacterial survival in waste stabilization ponds. *Wat. Sci. Technol.*, **19**(12), 145–152.

Pinheiro, H.M., Reis, M.T. and Novais, J.M. (1987). A study of the performance of a high-rate photosynthetic pond system. *Wat. Sci. Tech.*, **19**(12), 237–241.

Shilton, A., Wilks, T., Smyth, J. and Bickers, P. (2000). Tracer studies of a New Zealand waste stabilization pond, analysis of treatment efficiency. *Wat. Sci. Tech.*, **42**(10), 343–348.

Thirumurthi, D. (1974). Design criteria for waste stabilization ponds. *J. WPCF*, **46**(9), 2095–2106.

Uhlman, D. (1974). Design criteria for waste stabilisation ponds. *J. WPCF*, **46**, 2094–2106.

Wright, R.C. (1984). A new selective and differential agar medium for *E. Coli* and coliform organisms. *Journal of Applied Bacteriology*, **56**, 381–388.

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