Revisiting the influence of loading on organic material removal rates in primary facultative ponds

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Abstract The present paper investigated the organic material removal in six full-scale primary facultative ponds that have been operated for 22 years. The average BOD and COD removal were 72 e 50%, respectively. For filtered samples the removals were 89 and 83%, respectively. Hydraulic and organic loading were on average 50% below the design assumptions. First order removal rates for ideal hydraulic patterns (complete mixing and plug-flow) converged with increase of HRT and decrease of loadings. Aid design models were developed based on HRT and surface loading as a hybrid approach.

Keywords: *Primary facultative ponds, organic matter removal, design models.*

INTRODUCTION

Individually or in series, primary facultative ponds are the most used pond type as well as the most investigated one. Analytical models for the design of primary facultative ponds are based on first-order kinetics, assuming either completely mixed (equation 1) or plug-flow (equation 2) (USEPA, 1983; Preul and Wagner, 1987; Yánez, 1993; Ellis and Rodrigues, 1995).

$$L = Lo / (1 + k\ HRT) \tag{1}$$

$$L = Lo\ e^{-k\ HRT} \tag{2}$$

where: L and Lo are the effluent and influent BOD in mg/L, k is the first-order reaction rate for BOD removal (d^{-1}), and HRT is the mean hydraulic retention time in days.

The k value is temperature (T) dependent and the appropriate correction is obtained through the Arrhenius-style equation for completely mixed (equation 3) by Mara (1976) and plug-flow (equation 4) by USEPA (1983).

$$k = 0.3\ (1.05)^{T\ -\ 20} \tag{3}$$

$$k = 0.071\ (1.09)^{T-20} \tag{4}$$

Thirumurthi (1974) and Uhlmann (1979) observed that the reaction rate also varies with organic loading, decreasing as loading is lowered. Ellis and Rodrigues (1995) reported that k varied from 0.22 to 0.54 d^{-1} at 20° C. In an earlier study Ellis and Rodrigues (1993) found k values in a wider range (0.053 to 0.311 d^{-1}) at 30° C (computed from equation 1). The average value for unfiltered samples was 0.168 d^{-1}. Taking into account the filtered effluent for algae removal, the k value was

0.327 d^{-1}. They suggested that a value of 0.3 d^{-1} at 20° C, from equation 3, would be more appropriate when used for filtered BOD. For unfiltered samples a more realistic k value at 20° C would be 0.201 d^{-1}. The paper also indicated a good correlation between BOD loading (λs in kg/ha.d) and k (d^{-1}), represented by the equation below.

$$k = 2.622x10^{-3}\lambda s - 0.194 \qquad (5)$$

Actually, pond flow is neither completely mixed nor plug-flow. Thus, Thirumurthi (1969) considered the dispersed flow as more appropriate, based on the Wehner-Wilhelm kinetic equation. The main difficult in using this approach is the lack of data from field studies. The use of the dispersion-based model is still debatable because extensive investigation would be required for obtaining reliable figures.

A generalized application can be limited by a number of factors such as unsteady flow, wind, inlet and outlet structures that may significantly influence dispersion in ponds. Juanico (1991) made an analysis of this subject and found that the plug-flow model fitted better for bacterial removal in contrast with BOD removal, which was more likely to approach the completely mixed conditions. In fact investigation on hydraulic pattern has been mainly focused on coliform removal with good results (Lloyd and Vorkas, 1999, Shilton and Harrison, 2003; von Sperling, 2003; Shilton and Mara, 2005, Bracho *et al.*, 2006).

The limitations of the "rational" methods based on first-order kinetics led to empirical procedures, considering temperature as the governing parameter (Mara and Pearson, 1986; Mara *et al.* 1992). A properly designed primary facultative pond has its performance ranging from 70 to 80% for unfiltered samples and about 90% for filtered samples. As the debate is still present in design procedures, the present paper addresses this discussion based on results from full-scale pond systems.

METHODOLOGY

Six full-scale primary facultative ponds (PFPs) located in Fortaleza (38° 32' W; 3° 43' S, 15.5 m above the sea level.), in Northeast Brazil, were investigated during 28 weeks in 2007. These pond plants have been operating for 22 years on average. Their design characteristics are in Table 1.

Table 1. Design characteristics of the primary facultative ponds.

Pond system	*HRT (d)*	*λs (kg BOD/ha.d)*	*Volume (m^3)*	*Width to length ratio*	*Mean depth (m)*
PFP1	26.9	178	22,194.0	1:1.52	1.7
PFP2	62.0	128	168,400.0	1:1.52	2.0
PFP3	25.7	261	25,710.4	1:2.10	1.6
PFP4	25.0	230	51,000.0	1:2.04	1.7
PFP5	22.3	283	45,736.8	1:1.78	1.7
PFP6	18.8	287	17,910.0	1:1.84	1.8

Raw wastewater and treated effluent samples were collected at 10:00 am. Flow measurements were performed through the clockwork device at the pumping station of each plant. The following parameters were analyzed in the raw wastewater: temperature, pH, BOD and COD. In the treated effluent these parameters were complemented with dissolved oxygen, and filtered BOD and COD. The analytical procedures followed the methods described in APHA (1992).

RESULTS AND DISCUSSION

The raw wastewaters entering the pond had temperature ranging from 22.0 to 26.2° C (mean of 24.9° C), while in the treated effluents the variation was from 24.9 to 29.1° C (mean of 27.2° C). The pH was around the neutral (7.11, ±0.19), while BOD and COD showed typical values of domestic wastewater: 430 mg/l (±150) and 707 mg/l (±278), respectively.

The HRTs were on average 51% below the design assumptions. Actual surface BOD loadings were on average 56% below the design considerations. Table 2 shows the operational conditions of the ponds plants investigated.

Table 2. Operational performance of primary facultative ponds in Fortaleza.

Pond system	*HRT (days)*	*λs_{DBO} (kg/ha.d)*	*λs_{DQO} (kg /ha.d)*	*Removal %*			
				BOD	*BODf*	*COD*	*CODf*
PFP1	51.8	117	188	71	87	55	82
PFP2	64.0	148	225	73	89	48	83
PFP3	80.7	80	145	71	90	52	86
PFP4	25.2	338	501	73	90	46	78
PFP5	41.5	130	270	63	88	51	83
PFP6	139.9	65	105	75	89	45	87

Removal of unfiltered BOD was in the lower limit suggested by literature (around 70%). As a consequence COD removal was also in the lower limit. Average concentrations of BOD and COD in the treated effluent of the pond systems were 121 mg/l (± 36) and 343 mg/l (± 115), respectively. For filtered samples results were satisfactory and represented 39% (±15) and 36% (±18), of the respective unfiltered BOD and COD. The removal rates of BOD and COD as a function of the surface loading are shown in Figures 1 and 2.

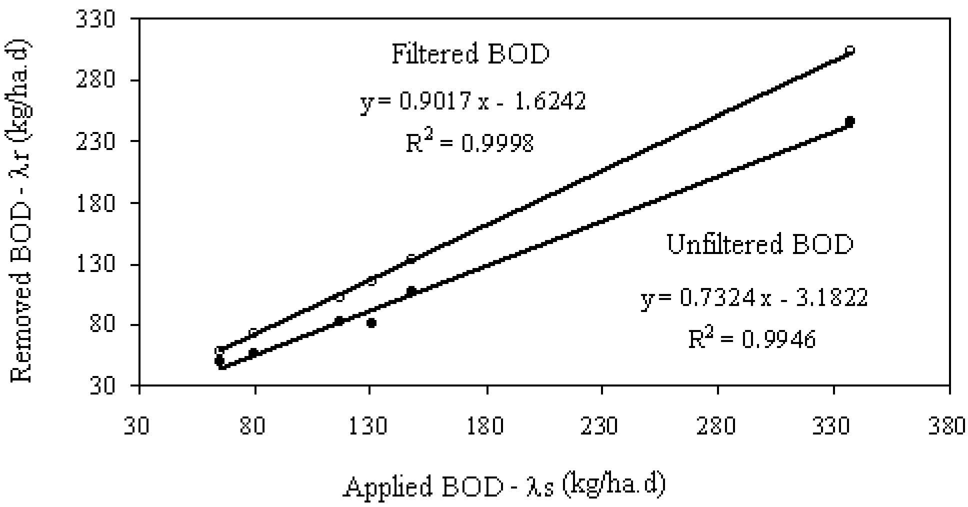

Figure 1. Unfiltered and filtered BOD removal rates as a function of surface loading.

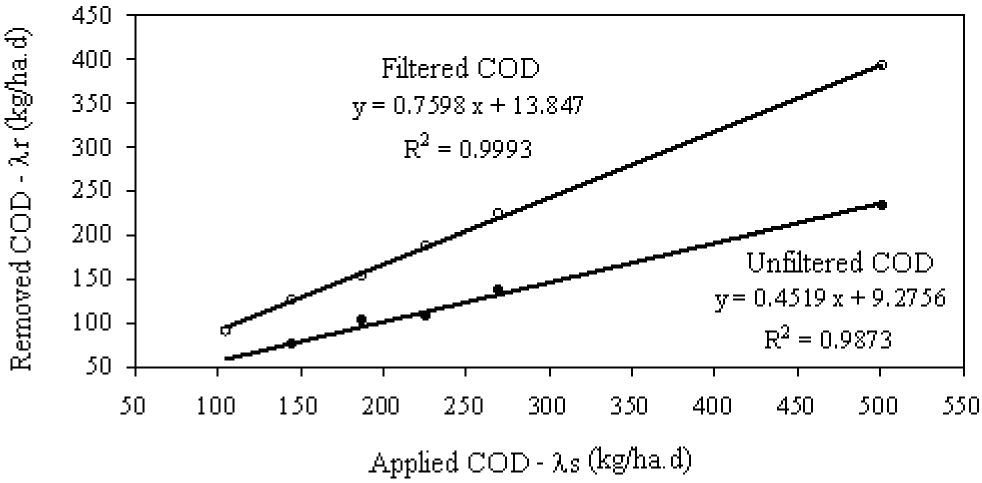

Figure 2. Unfiltered and filtered COD removal rates as a function of surface loading.

The width to length ratio or depth of the ponds did not show correlation with the removal rates. Treated effluents showed mean dissolved oxygen concentration of 4.3 mg/l (±3.6), been higher in PFP8 (7.4 mg/l, ± 3.5) and lower in PFP 2 (2.1 mg/l, ± 1.3). There was no influence of loading on dissolved oxygen concentrations.

The computation of the first order removal rates based on ideal hydraulic flow in ponds is shown in Table 3. Values found here were lower than those expected by the Arrhenius-style equations (3 and 4) regardless ideal hydraulic conditions. First order reaction rates were HTR dependent as shown in Table 4. The plug-flow model was a little more representative since its correlation (at 0.05 level of significance) was higher.

Table 3. First order removal rates (d^{-1}) in primary facultative ponds of Fortaleza.

Statistic parameter	*Completely mixed*				*Plug-flow*			
	BOD	BODf	COD	CODf	BOD	BODf	COD	CODf
Mean	0.048	0.159	0.019	0.091	0.024	0.043	0.013	0.034
Min	0.022	0.059	0.006	0.046	0.010	0.016	0.004	0.014
Max	0.106	0.351	0.034	0.144	0.052	0.091	0.025	0.061
CV (%)	62	64	52	37	60	60	53	48

Table 4. Variation of first order removal rates in primary facultative ponds of Fortaleza as a function of HRT.

Removal parameter	*Completely mixed*	*Plug-flow*
BOD	$k = 1.3401\ HRT^{-0.851}$ $R^2 = 0.8824$	$k = 0.8719\ HRT^{-0.9141}$ $R^2 = 0.9610$
BODf	$k = 7.6572\ HRT^{-0.9889}$ $R^2 = 0.9750$	$k = 2.1546\ HRT^{-0.9952}$ $R^2 = 0.9958$
COD	$k = 1.1918\ HRT^{-1.0476}$ $R^2 = 0.9360$	$k = 0.7883\ HRT^{-1.0353}$ $R^2 = 0.9649$
CODf	$k = 1.2396\ HRT^{-0.6573}$ $R^2 = 0.9667$	$k = 0.9307\ HRT^{-0.8397}$ $R^2 = 0.9954$

These findings are contradicted when correlations with pond loadings are taken into account. For this case the complete mixing model is a little more representative, according to Table 5.

Table 5. Variation of first order removal rates in primary facultative ponds of Fortaleza as a function of surface loading.

Removal parameter	*Completely mixed*	*Plug-flow*
BOD	$k = 0.0003\ \lambda s_{BOD} + 0.0043$ $R^2 = 0.9723$	$k = 0.0001\ \lambda s_{BOD} + 0.0031$ $R^2 = 0.9594$
BODf	$k = 0.001\ \lambda s_{BOD} + 0.0132$ $R^2 = 0.9464$	$k = 0.0003\ \lambda s_{BOD} + 0.0066$ $R^2 = 0.9142$
COD	$k = 0.0172\ Ln(\lambda s_{COD}) – 0.0727$ $R^2 = 0.8305$	$k = 0.0125\ Ln(\lambda s_{COD}) – 0.0536$ $R^2 = 0.8798$
CODf	$k = 0.0601\ Ln(\lambda s_{COD}) – 0.2305$ $R^2 = 0.9092$	$k = 0.029\ Ln(\lambda s_{COD}) – 0.1213$ $R^2 = 0.9387$

The correlation discrepancies are not significant unless they are seen under statistical representation. It seems that the discussion should not be addressed to which ideal hydraulic regimen is more representative but to the fact that higher HRT values and consequently lower loading rates cause decrease in the removal rates. Also, there is a limit for primary facultative pond performances on organic material removal. Under economical and environmental perspectives the ponds are under utilized and an up-grading should be considered.

CONCLUSIONS

The study on six primary facultative ponds in Fortaleza showed that hydraulic and organic loading were at least 50% below of the values considered in the design assumptions. Higher HRT and consequent lower loading results in smaller removal rates regardless ideal hydraulic regimen, either completely mixed or plug-flow.

Organic material removal was satisfactory considering the fact that these ponds have been operating for at least two decades. The pond systems have been under utilized and an up-grading design should be considered in order to improve effluent quality.

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