Strategies for upgrading primary facultative ponds in Fortaleza, Northeast Brazil

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Abstract

During the last two decades waste stabilization ponds had a considerable advance in Brazil. In parallel, the evolution of this technology was accompanied by an increasing restrictive environmental regulation with regard to effluent standards. Thus, old plants comprised basically by single primary facultative ponds do not meet new stringent demands. The present paper deals with upgrading alternatives for six full-scale pond systems located at Fortaleza (38° 32' W; 3° 43' S), northeast Brazil. For each plant six different arrangements were considered with the inclusion of anaerobic reactors and maturation ponds. In three of them a polishing filter was considered. For those without a polishing filter the removal of unfiltered BOD and COD would reach 84 and 79%, respectively. For filtered samples the performance would increase to 95 and 91%, respectively. For the new arrangements with a polishing filter the performance would be 92 and 90% for BOD and COD, respectively. On average faecal coliform removal would rise from 1.362 logs in primary facultative ponds to 3.916 logs in the new plant schemes.
Keywords: Waste stabilization ponds. Pond plant upgrading. Effluent quality.

Resumo

Durante as últimas duas décadas o emprego de lagoas de estabilização teve avanço considerável no Brasil. Ao mesmo tempo, a evolução desta tecnologia foi acompanhada por normas ambientais mais restritivas com respeito à qualidade dos efluentes. Assim, os sistemas de lagoas mais antigos, compostos essencialmente de lagoas facultativas primárias, não atendem às demandas normativas mais estritas. O presente estudo lida com alternativas de projeto para seis sistemas de lagoa localizados em Fortaleza (38° 32' O; 3° 43' S), Nordeste do Brasil. Para cada planta seis arranjos diferentes foram considerados com a inclusão de reatores anaeróbios e lagoas de maturação. Em três deles foi incluído um filtro de polimento. Nos sistemas sem filtro de polimento a remoção de DBO e DQO não filtradas alcançaria 84 e 79%, respectivamente. Com amostras filtradas o desempenho seria de 95 e 91%, respectivamente. Para os novos arranjos com filtro de polimento o desempenho seria de 92 e 90% de BOD e DQO, respectivamente. A remoção de coliformes fecais subiria em média de 1,362 logs nas lagoas de facultativas primárias para 3,916 logs nos novos arranjos propostos.
Palavras-chave: Lagoas de estabilização. Redesenho de sistemas de lagoas. Qualidade de efluente.

1 Introduction

Waste stabilization ponds are presented as the best alternative for domestic wastewater treatment in many situations. They are especially advantageous for warm climate regions, where land is available at a low cost and effluent reuse is intended. Pearson (1996) and Mara (2007) agree that waste stabilization pond technology is continuously evolving.

Pond technology has been used in the Brazil since the 1970s. First plants were commissioned in the Southeast region of the country (Azevedo Netto, 1975). They were basically comprised by single pond units or in parallel, following engineering concepts at that time, and based on Marais and Shaw (1961) and McGarry and Pescod (1970).

The Brazilian pond research had important contribution from Silva (1982) and his co-workers (*e.g*. KÖNIG, 1987; DE OLIVEIRA, 1990; CURTIS, MARA and SILVA, 1992; ORAGUI *et al*., 1993). Findings showed that the inclusion of anaerobic cells and arrangement of ponds in series provided better performance, mainly for pathogen removal.

Despite of the improvement in the design methods many single cell plants (*i.e.* primary facultative ponds) were built in the Ceará state (37°14' W; 7°52' S), northeast Brazil during the 1980s. These plants are still operating and the majority is located at the Metropolitan Region of Fortaleza (38° 32' W; 3° 43' S). So far, the performance of these plants has been considered satisfactory as shown by da Silva *et al*. (2007).

Facultative ponds are the most used and investigated types. Design methods are either based on analytical or empiric models (YÁNEZ, 1993; ELLIS and RODRIGUES, 1995). According to Mara *et al*. (1992) a properly designed primary facultative pond reaches from 70 to 80% of BOD removal for unfiltered samples and about 90% for filtered samples. Removal of faecal coliforms and streptococci reach from 1.81 to 2.00 log units (ARRIDGE *et al*., 1995; CEBALLOS *et al*., 1996; DE OLIVEIRA *et al*. 1996). However, environmental regulation is becoming more restrictive and demands studies for upgrading existing plants, mainly for pathogen removal. For instance SEMACE (2002) establishes for faecal coliforms or *Escherichia coli* a limit of 5.0×10^3 cells/100 ml. Thus, the present paper approaches different strategies for upgrading six full-scale primary facultative ponds (PFPs) in Fortaleza.

2 Methodology

The Company for Water and Wastewater Services of Ceará (Companhia de Água e Esgoto do Ceará - CAGECE) and the Environmental Agency of the Ceará State (Superintendência Estadual do Meio Ambiente - SEMACE) provided documental information on the six full-scale primary facultative ponds (PFPs) located at Fortaleza. The design characteristics of the plants are shown in Table 1.

New plant schemes were designed with the inclusion of anaerobic reactors: septic tank (ST), anaerobic filter (AF) and up-flow anaerobic sludge blanket (UASB). The use of anaerobic ponds was avoided due to possible odour nuisance. A coarse rock filter was admitted for polishing final pond effluent in three alternatives.

Table 1: Design characteristics of the primary facultative ponds at Fortaleza.

Pond system	*HRT (d)*	*λs (kg BOD/ha.d)*	*Volume (m^3)*	*Width to length ratio*	*Mean depth (m)*
João Paulo III - JPII	26.9	178	22,194	1:1.52	1.70
Nova Metrópole - NM	62.0	128	168,400	1:1.52	2.00
Jereissati III -JIII	25.7	261	25,710.4	1:2.10	1.60
Lagamar - LG	25.0	230	51,000	1:2.04	1.70
Conjunto Esperança - CE	22.3	283	45,736.8	1:1.78	1.70
Planalto Caucaia - PC	18.8	287	17,910	1:1.84	1.80

The characteristics of the raw domestic wastewater considered in the study are presented in Table 2. A recent operational *status* of the pond plants is in Table 3. Except for Lagamar all other plants were under loaded.

As design assumption a safety factor of 1.25 was applied to the original influent flow rate calculated from data in Table 1. Also, the area occupied by every upgrading option should be in principle limited to the total area of the plant. Six schemes were selected for each pond plant. They are shown in Figures 1 to 6.

Table 2: Typical characteristics of domestic wastewater in Ceará, Northeast Brazil

Parameter	*Mean*	*Range*	*σ*	*Number of samples*
BOD (mg/l)	431	116 – 1,168	160	168
COD (mg/l)	725	182 – 1,818	279	268
Faecal coliforms (MPN/100 ml)	3.0E+7	2.4E+6 – 2.4E+8	-	86

Source: da Silva *et al*. (2009).

Table 3: Operational performance of primary facultative ponds in Fortaleza.

Pond system	*HRT (days)*	*λsDBO (kg/ha.d.)*	*λsDQO (kg /ha.d.)*	*Removal*				
				BOD (%)	BODf[a] (%)	COD (%)	CODf[a] (%)	FC (log units)
JPII	51.8	117	188	71	87	55	82	1.273
NM	64.0	148	225	73	89	48	83	1.097
JIII	80.7	80	145	71	90	52	86	1.301
LG	25.2	338	501	73	90	46	78	1.585
CE	41.5	130	270	63	88	51	83	1.737
PC	139.9	65	105	75	89	45	87	1.176
Mean	67.0	146	239	71	89	50	83	1.362
σ	40.0	99	141	4	1	4	3	0.248

[a] for filtered effluent.
Source: da Silva *et al*. (2007).

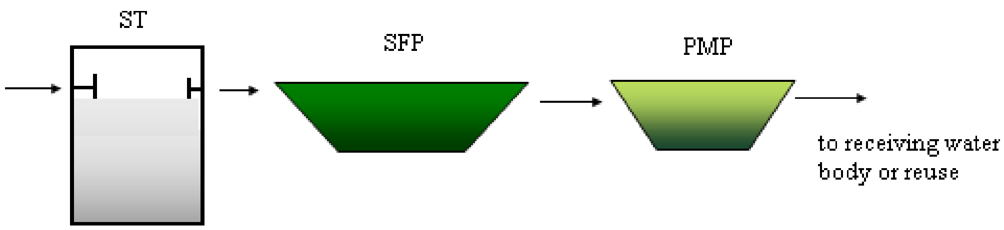

Figure 1: Scheme 1 – septic tank followed by secondary facultative pond, and primary maturation pond.

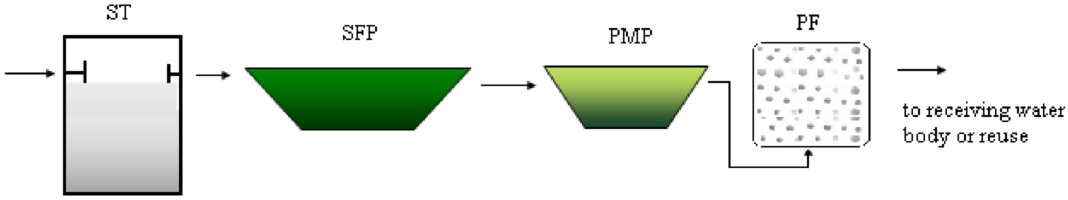

Figure 2: Scheme 2 – septic tank followed by secondary facultative pond, primary maturation pond, and polishing filter.

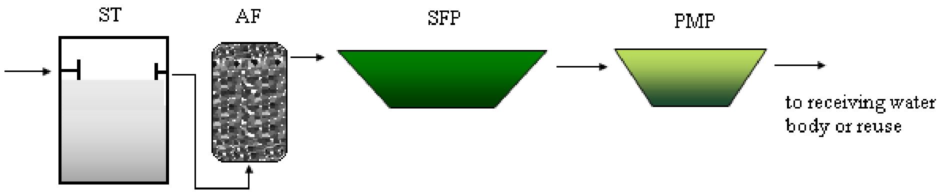

Figure 3: Scheme 3 - septic tank followed by anaerobic filter, secondary facultative pond, and primary maturation pond.

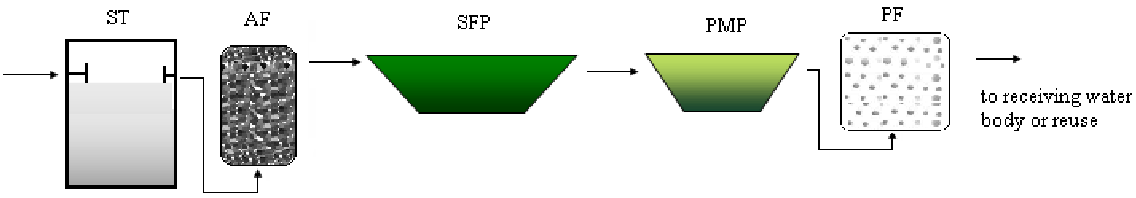

Figure 4: Scheme 4 - septic tank followed by anaerobic filter, secondary facultative pond, primary maturation pond, and polishing filter.

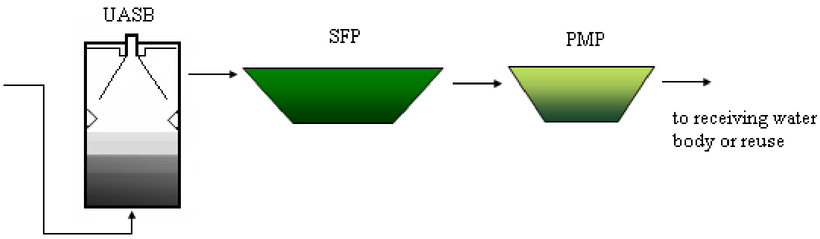

Figure 5: Scheme 5 - UASB reactor followed by secondary facultative pond, and primary maturation pond.

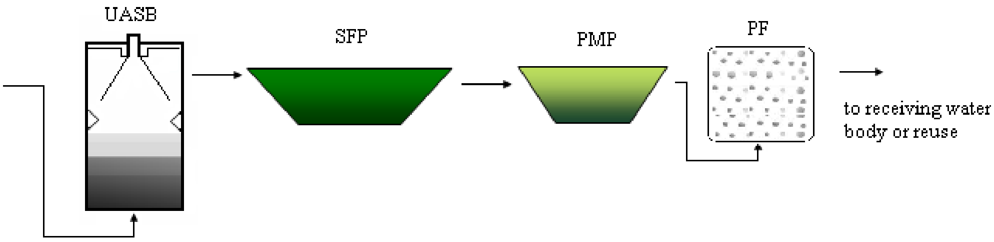

Figure 6: Scheme 6 - UASB reactor followed by secondary facultative pond, primary maturation pond and polishing filter.

The organic loading applied to the ponds was calculated according to Mara (1997) (Eq. 1). The reference temperature (T) was 23^{o} C, the lowest monthly value in the region (IPLANCE, 2002). Thus, the maximum allowable surface loading (λs) was 310.9 kg BOD/ha.d. for a facultative pond, and 233.2 kg BOD/ha.d (75% of the loading admissible for a facultative pond) for a maturation pond. The hydraulic loading of the polishing filters was 1.0 m^3/m^3.d, as suggested by Mara and Johnson (2007). Other characteristics of the reactors considered in the new design schemes are presented in Table 4.

$$\lambda s = 350\ (1.107 - 0.002T)^{T-25} \tag{1}$$

Design assumptions were conservative and considered a BOD removal of 40% in the ST, 65% in the ST followed by AF and for UASB (CHERNICHARO, 1997), 80% for any anaerobic reactor followed by a secondary facultative pond, 20% for a primary maturation pond and 50% for a polishing filter (MARA, 1997). Faecal coliforms in the treated effluent were estimated by Marais (1974) model (Eq. 2). The kb rate was estimated according to Equation 3.

$$Ne = \frac{Ni}{(1 + kb\,HRT_1)\,(1 + kb\ \ HRT_2)...(1 + kb\,HRT_n)} \tag{2}$$

$$kb = 2.6\ (1.19)^{T-20} \tag{3}$$

where: Ne is the effluent concentration (cells/100 ml); Ni is the influent concentration (cells/100 ml); kb is the first order decay rate for faecal coliforms (1/d); HRT is the mean hydraulic retention time (d) of each reactor and T is the water temperature in ^{o}C. As a simplification T was considered equal to the ambient temperature.

Table 4: Minimum hydraulic retention time (HRT) and depth of the reactors for the upgrading schemes.

Treatment unit	*Minimum HRT (days)*	*Depth (m)*
UASB	0.5	4.0
Septic tanks	0.8	2.8
Anaerobic filters	Based on 40% of the volume of the filter media	1.8
Secondary facultative pond	≥ 5.0	Same of the original pond
Maturation ponds	≥ 5.0	Same of the original pond
Polishing filters	Based on 40% of the volume of the filter media	1.5

3 Results and discussion

Table 5 presents the internal area of the reactors in each proposed scheme. The ratio between the area of each designed scheme in every plant and the original value is shown in Table 6. Most favorable alternatives are regarded to schemes where the ratio was ≤ 0.75, since the remaining area would be used for construction arrangements such as pond embankments and reactors walls. The plants Conjunto Esperança and Planalto Caucaia require a more detailed analysis.

According to the design assumptions the unfiltered BOD concentration in the effluent of schemes without a polishing filter would be 69 mg/L. In Ceará state Silva *et al*. (2009) found that in 3 pond series or equivalent, the COD to BOD ratio in the treated effluent is about 2.2. Therefore, in schemes without a polishing filter the treated effluent COD concentration would be around 152 mg/L. In filtered samples BODf can be computed according to Eq. 4, and CODf represents about 42% of the value observed in the unfiltered sample (DA SILVA, FERREIRA and FREITAS, 2000). Thus, BODf and CODf would be 23 and 64 mg/L, respectively. In the designed schemes with polishing filters the treated effluent would have BOD and COD of 35 and 76 mg/L, respectively, according to the performance previously mentioned. Table 7 shows the organic material removal rates, surface (λrs) and volumetric (λrv), in which the best results include UASB and polishing filter (Scheme 6).

$$\mathrm{BODf} = 0.2284\,\mathrm{BOD}^{1.0925} \tag{4}$$

Table 5: Internal area of each reactor and plant in the schemes (in m^2).

Pond plant	*Scheme 1*					*Scheme 4*					
	ST	SFP	PMP	-	Total	ST	AF	SFP	PMP	PF	Total
JPII	295	8,579	3,813	-	12,686	295	733	5,004	38,13	296	10,141
NM	970	28,239	12,551	-	41,760	970	2,414	16,473	12,551	976	33,384
JIII	357	10,397	4,621	-	15,375	357	889	6,065	4,621	359	12,291
LG	729	21,210	9,427	-	31,365	729	1,813	12,372	9,427	733	25,074
CE	733	21,324	9,477	-	31,534	733	1,823	12,439	9,477	737	25,209
PC	340	9,905	4,402	-	14,647	340	847	5,778	4,402	342	11,709
Pond plant	*Scheme 2*					*Scheme 5*					
	ST	SFP	PMP	PF	Total	UASB	SFP	PMP	-	-	Total
JPII	295	8,579	3,813	296	12,982	129	5,004	3,813	-	-	8,946
NM	970	28,239	12,551	976	42,736	424	16,473	12,551	-	-	29,448
JIII	357	10,397	4,621	359	15,734	156	6,065	4,621	-	-	10,842
LG	729	21,210	9,427	733	32,098	319	12,372	9,427	-	-	22,118
CE	733	21,324	9,477	737	32,271	320	12,439	9,477	-	-	22,237
PC	340	9,905	4,402	342	14,989	149	5,778	4,402	-	-	10,329
Pond plant	*Scheme 3*					*Scheme 6*					
	ST	AF	SFP	PMP	Total	UASB	SFP	PMP	PF	-	Total
JPII	295	733	5,004	3,813	9,845	129	5,004	3,813	296	-	9,242
NM	970	2,414	16,473	12,551	32,408	424	16,473	12,551	976	-	30,424
JIII	357	889	6,065	4,621	11,932	156	6,065	4,621	359	-	11,201
LG	729	1,813	12,372	9,427	24,341	319	12,372	9,427	733	-	22,850
CE	733	1,823	12,439	9,477	24,472	320	12,439	9,477	737	-	22,974
PC	340	847	5,778	4,402	11,367	149	5,778	4,402	342	-	10,671

Table 6: Ratio between the area of each new scheme and the original value in the plants.

Pond plant	*Scheme 1*	*Scheme 2*	*Scheme 3*	*Scheme 4*	*Scheme 5*	*Scheme 6*
JPII	0.97	0.99	0.75	0.78	0.69	0.71
NM	0.50	0.51	0.38	0.40	0.35	0.36
JIII	0.96	0.98	0.74	0.76	0.67	0.70
LG	1.05	1.07	0.81	0.84	0.74	0.76
CE	1.17	1.20	0.91	0.94	0.83	0.85
PC	1.47	1.51	1.14	1.18	1.04	1.07

Table 7: Surface (λrs) and volumetric (λrv) removal rates in the new plant schemes.

Pond plant	*Surface removal rate(λrs)*		*Volumetric removal rate(λrv)*	
	kg BOD/ha.d	*kg COD/ha.d*	*g BOD/m^3.d*	*g COD/m^3.d*
Scheme 1	294 (332)[a]	466 (537)	17[c] (19)[c]	26 (30)
Scheme 2	315	516	18	30
Scheme 3	379 (427)	600 (692)	22 (25)	35 (41)
Scheme 4	403	660	24	40
Scheme 5	417 (470)	661 (762)	24 (27)	37 (43)
Scheme 6	442	724	25	42

[a] filtered samples in brackets; [b] average value; [c] average value for filtered samples in brackets.

Expected concentrations of faecal coliforms in the treated effluent are shown in Table 8. The lowest value would be for the Scheme 2, corresponding to a higher HRT (22 days). Table 9 shows faecal coliforms removal rates, with highest values in Scheme 4.

Table 8: Expected FC numbers in the treated effluent of the proposed designed schemes.

Pond plant	*Scheme 1*	*Scheme 2*	*Scheme 3*	*Scheme 4*	*Scheme 5*	*Scheme 6*
JPII	3.7E+03	2.7E+03	4.2E+03	3.7E+03	3.7E+03	3.3E+03
NM	2.1E+03	1.5E+03	2.4E+03	2.1E+03	2.1E+03	1.9E+03
JIII	1.9E+03	1.4E+03	2.2E+03	1.9E+03	1.9E+03	1.7E+03
LG	1.1E+03	8.0E+02	1.2E+03	1.1E+03	1.1E+03	9.9E+02
CE	8.9E+03	6.5E+03	1.0E+04	8.9E+03	8.9E+03	7.9E+03
PC	5.0E+03	3.7E+03	5.7E+03	5.1E+03	5.1E+03	4.5E+03

Surface and volumetric removal rates seem to be confuse for a conclusive inference. Apparently the kb rate for the entire plant could be more representative. In fact, for microbial counting, a small change in a reactor volume and especially in ponds may cause relevant variation in FC concentrations in the final effluent. However, from a practical view point FC numbers are essentially at the same log scale.

Table 9: Average faecal coliforms removal rates in the new design schemes.

Scheme	*Faecal coliforms removal rates*		
	Surface (cells/m^2.d)	*Volumetric (cells/m^3.d)*	*kb (1/d)*
1	2.4E+08	1.4E+08	573
2	2.4E+08	1.4E+08	683
3	3.1E+08	1.9E+08	1,007
4	3.1E+08	1.8E+08	1,749
5	3.5E+08	1.9E+08	231
6	3.3E+08	1.9E+08	402

A more realistic figure on the effluent quality of the proposed alternatives for pond plants upgrade can be provided with Monte Carlo simulation. This is a power full toll recommended by a number of studies (*e.g.* EPA, 1997; TUNG, YEN and MELCHING, 2006) to represent the behavior of different hydrosystems.

The organic content in the treated effluent of the existing plants can be compared to that in the designed alternatives, shown in Figures 7 to 9. For the PFPs plants it was assumed the average removal presented in Table 3. Essentially illustrative, the computation was relative to a limited number of iterations (100 runs). Other simplified approach was to assume uniform distribution with the amplitude corresponding to a coefficient of variation of 50%. For faecal coliforms numbers it was admitted a variation of one log (*i.e.* 90%) and the average in the final effluent concentration from all schemes proposed for the plants.

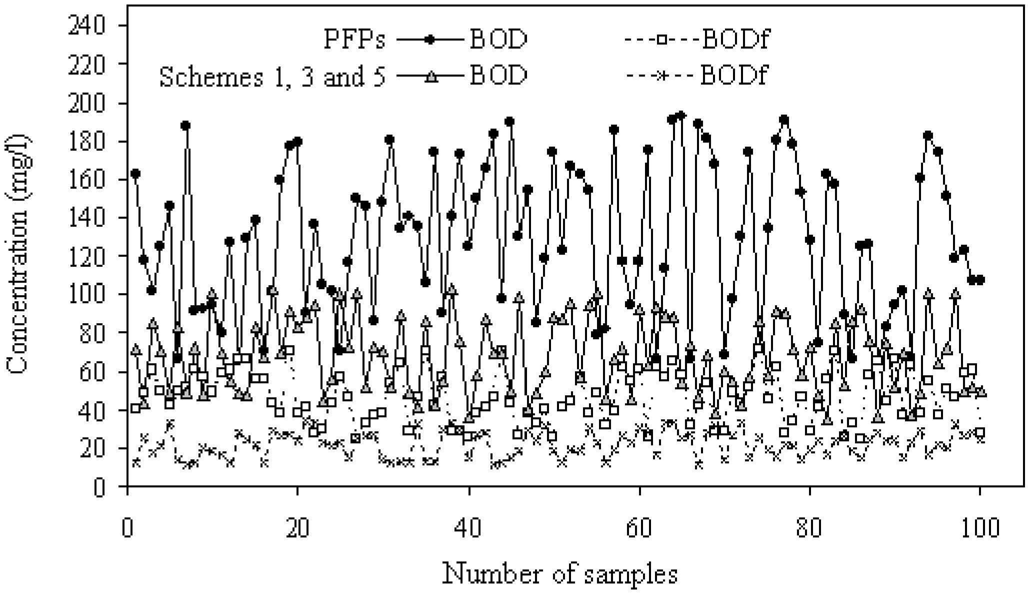

Figure 7: Effluent BOD and BODf concentrations in the existing and upgraded plants (Schemes 1, 3 and 5) by using Monte Carlo simulation in a uniform distribution and coefficient of variation of 50%.

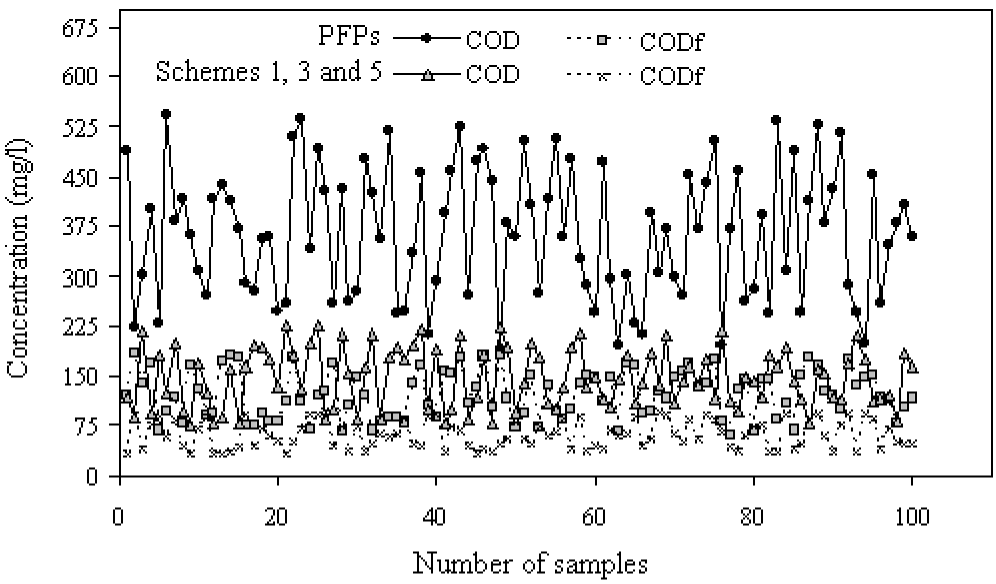

Figure 8: Effluent COD and CODf concentrations in the existing and the upgraded plants (Schemes 1, 3 and 5) by using Monte Carlo simulation in a uniform distribution and coefficient of variation of 50%.

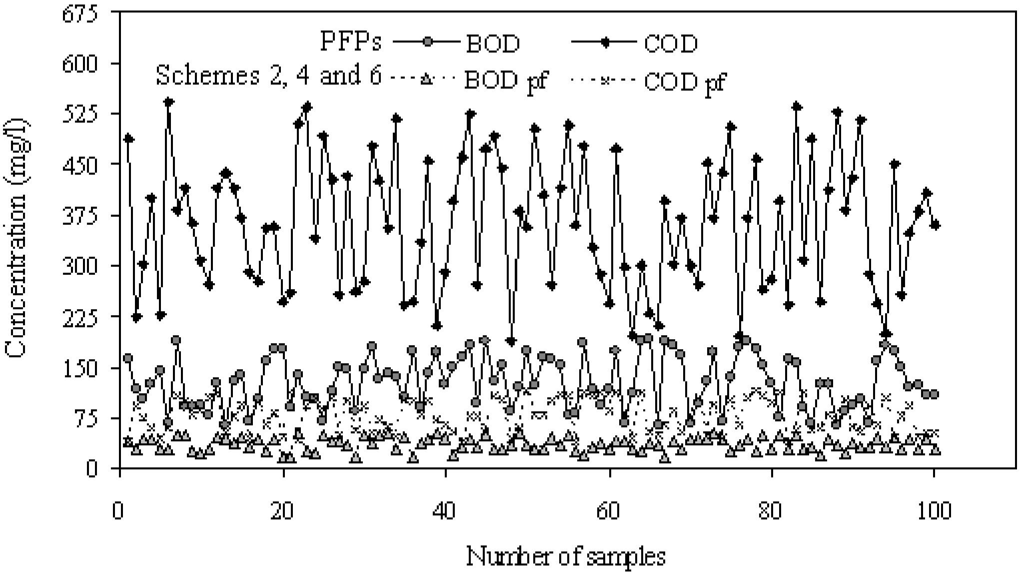

Figure 9: Effluent BOD and COD concentrations in the existing and the upgraded plants (Schemes 2, 4 and 6) by using Monte Carlo simulation in a uniform distribution and coefficient of variation of 50%.

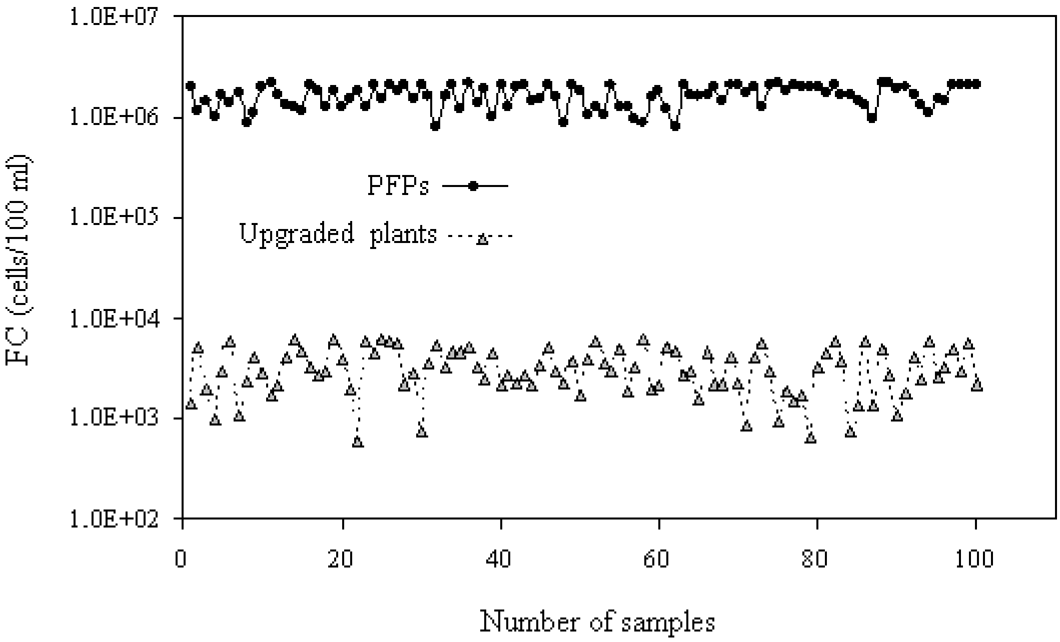

Figure 10: Effluent faecal coliforms concentrations in the existing and the upgraded plants by using Monte Carlo simulation in a uniform distribution and coefficient of variation of 90%.

4 Conclusion

It is feasible to redesign the six full-scale primary facultative pond plants in Fortaleza, northeast Brazil, in other to improve effluent quality. For each plant six potential schemes were provided, with the inclusion of anaerobic units and maturation ponds. Also, three of them had the inclusion of a polishing filter.

Results showed that the removal of unfiltered BOD and COD would reach 84 and 79%, respectively. For filtered samples the performance would increase to 95 and 91%, respectively. These numbers are for the three schemes without a polishing filter. For those that included it, the performance would be 92 and 90% for unfiltered samples of BOD and COD, respectively. Faecal coliforms removal would rise on average from 1.362 logs to 3.916 logs.

It is necessary a more detailed investigation on land availability in every plant. This is more relevant for those which may employ UABS reactors, once it is necessary de design sludge dry beds. However, in at least four of them (JPII, NM, JIII and LG) the proposed upgrade designs would not demand any additional area. The next step is to compute the expected removal of other pollutants (*e.g.* helminthes and nitrogen), a basic budget, establish priorities, and apply decision making aids.

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Recebido em: 14.11.2008
Aceito em: 10.12.2008
Revisado em: 15.04.2009