

UASB-polishing ponds design parameters. Contributions from a pilot scale study in southeast Brazil.

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Abstract. This paper presents the results of five years monitoring of an experimental wastewater treatment plant in southeast Brazil, comprised of a UASB reactor followed by a submerged aerated biofilter (BF) (field scale) and shallow polishing ponds (pilot scale). Three ponds in series achieved high quality effluent standards in terms of ammonia and *E.coli*, but a fourth did not result in further efficiency. Well established models to predict ammonia and *E.coli* removal in facultative and/or maturation ponds were, in a way, validated for polishing ponds too. The paper also includes results of input design parameters, such as pH and *E.coli* die-off rate constants, and their variation along the pond series.

Keywords: ammonia, BOD, *E.coli*, pH.

INTRODUCTION

Waste stabilization ponds (WSP) have long been considered a good choice for wastewater treatment, mainly in developing and/or warm climate countries. Their many advantages include: simplicity, low cost, low maintenance, robustness, and sustainability (Mara, 2004). Shallow ponds following UASB (Upflow Anaerobic Sludge Blanket) reactors have been named polishing ponds to differentiate them from the classical concepts of facultative and maturation ponds. However, when the organic matter removal is 'completed', and the main, or the only, objective is the removal of pathogenic organisms, the most usual term is maturation ponds. In any case, polishing/maturation ponds can provide further removal of organic matter (BOD), achieve high ammonia removal and produce effluents of excellent bacterial quality, as long as they are properly designed (i.e. shallow ponds) (von Sperling, 2007).

The removal of BOD, nitrogen and coliforms within WSP in warm climates is well documented (Silva *et al.*, 1995; Soares *et al.*, 1996; Mara, 2004; von Sperling, 2007), but not so much their specific modelling in polishing ponds. The Brazilian experience has shown that polishing ponds can absorb the UASB effluent's organic load, so that they can be designed as maturation-like ponds, i.e. shallow ponds, aiming at pathogens removal (von Sperling and Mascarenhas, 2005; Cavalcanti, 2003).

Regarding coliforms removal, ponds are usually designed assuming that bacterial decay follows first order kinetics. Many researchers have found that the main mechanisms of bacterial die-off are associated with the pond depth (full penetration of the solar radiation in shallow ponds, leading to intense photosynthesis, significant production of oxygen and pH rising, thereby facilitating the photo-oxidation process that kills bacteria) (Curtis *et al.*, 1992; Pearson *et al.*, 1995; Pearson *et al.*, 2005; von Sperling, 2005). von Sperling (2007) proposed empirical equations for predicting coliforms die-off rate constants, based on field data from facultative and maturation ponds (pilot and field scale), and on a dispersed hydraulic flow regime (Equations 1 and 2). With specific

regards to polishing ponds, it is generally accepted that the die-off rates should be similar, or even higher than those usually assumed for facultative or maturation ponds (von Sperling, 2007).

$$K_b \text{ (dispersed flow)} = 0.542 H^{-1.259} \text{ (82 ponds in several countries) } (R^2 = 0.505) \quad (1)$$

$$K_b \text{ (dispersed flow)} = 0.917 (H)^{-0.877} (\text{HRT})^{-0.329} \text{ (33 ponds in Brazil) } (R^2 = 0.847) \quad (2)$$

where:

K_b = first-order rate constant for *E. coli* removal (20°C) (d^{-1})

H: pond depth (m)

HRT: hydraulic retention time (days)

Pano and Middlebrooks (1982) proposed a model (Equations 3 and 4) for ammonia removal, based on field data from facultative ponds in the USA receiving low surface organic loading ($< 40 \text{ kg BOD ha}^{-1} \cdot \text{d}^{-1}$). The model assumes that ammonia volatilization is the main mechanism of nitrogen removal. It also assumes first order removal kinetics and complete mixing flow regime, and incorporates values for hydraulic loading, pH, temperature and coefficients derived from empirical data. However, the model requires that pH values be assumed, which is difficult to do with accuracy. Soares *et al.* (1996) found that Pano and Middlebrooks model were in good agreement with data from ponds in northeast Brazil. However, there still is little information about how well this model predicts ammonia removal in polishing ponds.

$$C_e = \frac{C_o}{1 + [(A/Q) \cdot (0.0038 + 0.000134 \cdot T) \cdot e^{(1.041 + 0.044 T) \cdot (pH - 6.6)}]} \quad T < 20^\circ\text{C} \quad (3)$$

$$C_e = \frac{C_o}{1 + [5.035 \times 10^{-3} \cdot (A/Q) \cdot e^{(1.540 \times (pH - 6.6))}]} \quad T \geq 20^\circ\text{C} \quad (4)$$

where:

C_o = ammoniacal nitrogen concentration in pond affluent (mg L^{-1})

C_e = ammoniacal nitrogen concentration in pond effluent (mg L^{-1})

Q = wastewater flow rate ($\text{m}^3 \text{d}^{-1}$);

A = pond area (m^2);

T = water temperature ($^\circ\text{C}$);

pH = pond water pH

METHODS

Description of the wastewater treatment systems

The experiments were conducted in Viçosa, Minas Gerais State, Southeast Brazil (latitude: $20^\circ 45' 14''\text{S}$, longitude: $42^\circ 52' 53''\text{W}$, altitude: 650 m). The experimental wastewater treatment plant initially consisted of UASB reactor (field scale, $115 \text{ m}^3 \text{d}^{-1}$) followed by series of three polishing ponds (pilot scale); afterwards a submerged aerated biofilter (BF) (field scale) was placed between the UASB reactor and the pond series, to which a fourth pond was later on incorporated. This system was monitored for about five years (October 2001 to February 2007), along which it was operated under variable conditions (Table 1); however, only the results of those periods when all ponds were operated in series are presented in this paper.

Table 1. Ponds characteristics

Parameter	Period 1 (Oct 2001-Apr 2002) ⁽¹⁾				Period 2 (Jun-Nov 2002) ⁽¹⁾				Period 3 (Mar-May 2003) ⁽²⁾			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Q (m ³ d ⁻¹)	1.5	1.5	1.5	-	2.0	2.0	2.0	-	2.0	2.0	2.0	-
HRT (d)	9.4	9.4	9.4	-	7.0	7.0	7.0	-	7.0	5.4	2.3	-
h (m)	0.9	0.9	0.9	-	0.9	0.9	0.9	-	0.9	0.7	0.3	-
Parameter	Period 4 (Mar-Sep 2004) ⁽²⁾⁽³⁾				Period 5 (Sep 2004-Jul 2005) ⁽²⁾⁽³⁾				Period 6 (Oct 2005-Mar 2006) ⁽²⁾⁽³⁾			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Q (m ³ d ⁻¹)	4.2	4.2	2.1	2.1	3.0	3.0	1.5	1.5	1.5	1.5	0.7	0.7
HRT (d)	3.4	3.4	5.1	5.1	4.7	4.7	7.2	7.2	5.1	4.1	18.8	18.8
h (m)	0.9	0.9	0.7	0.7	0.9	0.9	0.7	0.7	0.5	0.4	0.9	0.9
Parameter	Period 7 (Apr-Aug 2006) ⁽²⁾⁽⁴⁾				Period 8 (Sep-Nov 2006) ⁽²⁾⁽⁴⁾				Period 9 (Nov 2006-Feb 2007) ⁽¹⁾⁽⁴⁾			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Q (m ³ d ⁻¹)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
HRT (d)	5.1	4.1	4.1	9.4	7.2	7.2	4.1	4.1	7.2	7.2	4.1	4.1
h (m)	0.5	0.4	0.4	0.9	0.7	0.7	0.4	0.4	0.7	0.7	0.4	0.4

Q: flow rate; HRT = hydraulic retention time; h: pond depth; (1) the pond series received the UASB effluent; (2) the pond series received the UASB+BF effluent; (3) ponds 3 and 4 in parallel; (4) all ponds in series. All ponds (P) had a length-to-breadth ratio =2.0.

Sample collection and analysis

Raw wastewater (RW), UASB, BF and ponds effluents were sampled on a weekly-biweekly basis. RW, UASB and BF effluents were sampled hourly, from 6:00 am to 6:00 pm, and analysed as composite samples. Pond effluents were sampled using a column sampler (grab samples), usually in the morning. All these samples were analyzed for *E. coli*, BOD, and nitrogen. In addition, pond profile measurements (every two hours, for 24 hours) were obtained for DO, pH and temperature at 15-cm depth intervals from the ponds surface. In general, sample collection and analyses were carried out according to the Standard Methods for the Examination of Water and Wastewater (APHA, WEF, AWWA, 1998). *E. coli* were enumerated using the chromogenic substrate method (Colilert®).

RESULTS AND DISCUSSION

Water temperature

Base on local climate data and field measurements, an equation relating air and water temperature was derived (Equation 5)

$$T_w = 8.7 + 0.73 T_a \quad R^2 = 0.79 \quad (5)$$

where:

T_w = water temperature (°C)

T_a = air temperature (°C)

The local mean temperature of the coldest month is around 17°C. Based on Equation 5, the correspondent mean water temperature would be 20.6°C, which could be taken as a local input design parameter, for instance in Pano and Middlebrooks equations or in the dispersed flow model for coliforms removal.

BOD surface loading rates and BOD removal

Over the entire period of the study the UASB +BF presented high removal efficiency of total BOD₅ (70% - 80%, mainly in the UASB). Consequently, the surface organic loading rates on the first pond were relatively low. In the ponds series, BOD removal took place basically in the first unity, which added up to 30% of total BOD removal, producing effluents with average values around 20-80 mg BOD L⁻¹ when it received the UASB and the UASB +BF effluents, respectively. After the first pond there was no clear further BOD removal (Figure 1); similar results were found by von Sperling and Mascarenhas (2005).

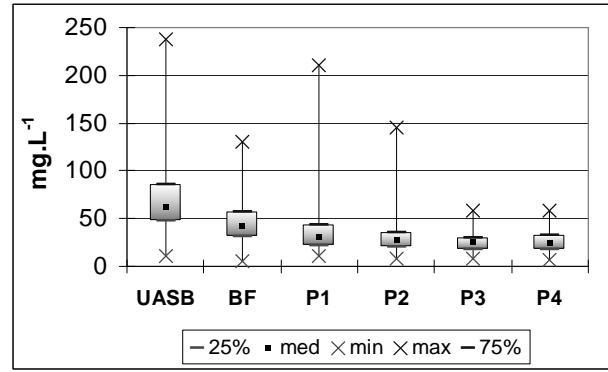
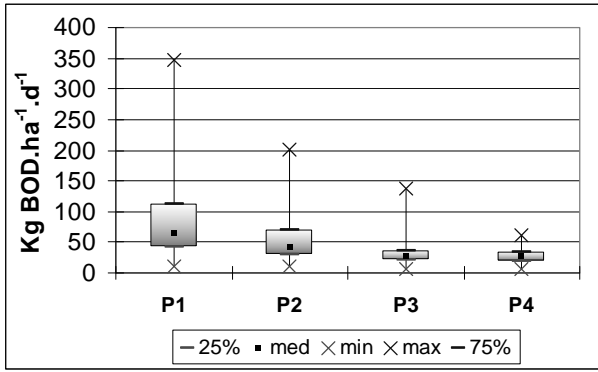


Figure 1. Surface organic loads (left) and effluent BOD concentrations (right) along the treatment system

DO and pH

The surface organic (and ammonia) loading rate variations did not impair algal photosynthesis and the predominance of aerobic conditions in the ponds. Even in the first pond, and at the deepest measuring points, DO were at the worst in the range of 2 - 3 mg L⁻¹, usually at dawn (Figure 2). As a result, pH was also kept at high values in all ponds, always above 7.5 at mid-depth and never below 7 (Figure 3).

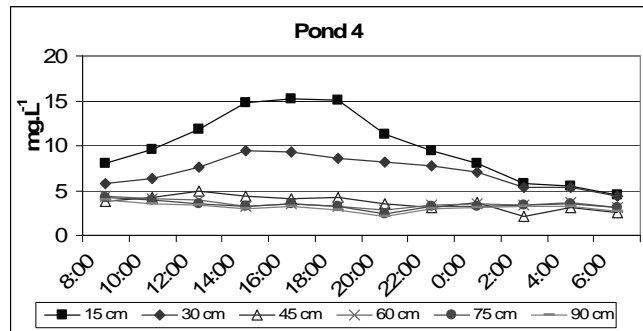
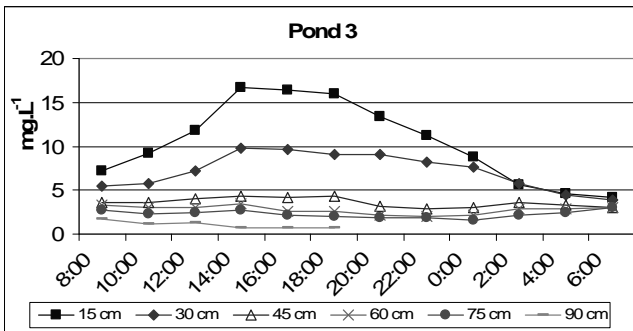
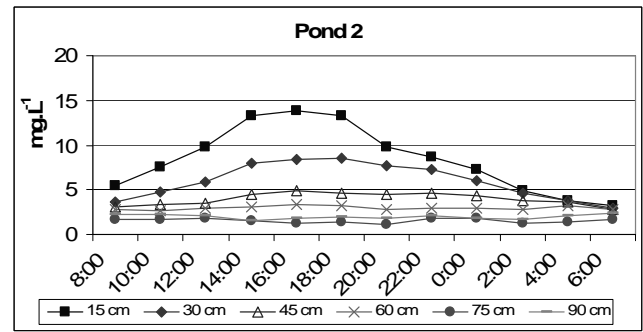
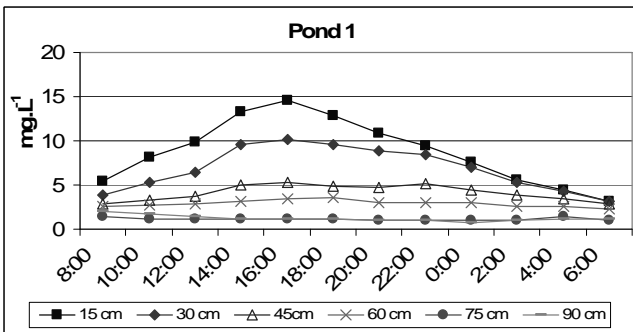


Figure 2. Daily variations of dissolved oxygen, mean values along the pond depths.

Overall, pH increased along the pond series, reflecting the prevailing conditions in each unity: more intense algal activity in the last ponds and, consequently, higher uptake of carbon dioxide, along with lesser carbon dioxide production due to lower bacterial activity. Negative correlations were found between pH values and pond depths, although neither strong nor statistically significant; Spearman correlation coefficients were: all ponds = -0.4906; pond 1 = -0.4325; pond 2 = -0.2478; pond 3 = -0.1382; pond 4 = -0.6475.

Considering the entire period of study, mean pH values at the surface level (0.15 m) and at mid depth were: 7.7 and 7.6 (pond 1), 8.1 and 7.8 (pond 2), 8.7 and 8.2 (pond 3), 8.7 and 8.4 (pond 4). Therefore, as an input design parameter, a minimum pH value of 7.5 could be assumed for the first pond and, subsequently, pH rise of around 3-5% in the second pond and 5-7% in the third pond. Apparently, no marked further increase is to be expected in a fourth pond.

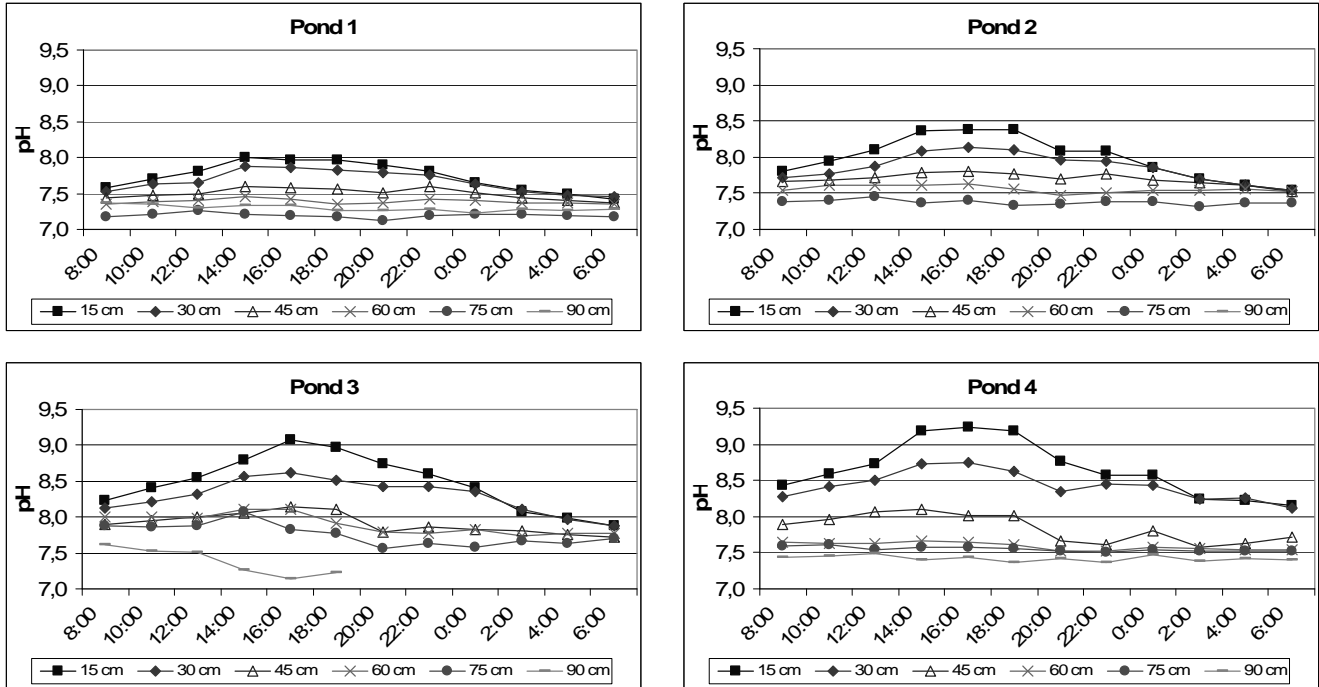


Figure 3. Daily variations of pH, mean values along the pond depths.

Nitrogen removal

Ammonia concentration in the UASB effluent was approximately 60% higher than in raw wastewater. Nevertheless, the pond series provided substantial TKN ($\text{NH}_3 + \text{Norg}$) ($\approx 70\%$) and ammonia ($\approx 90\%$) removal, producing effluents in compliance with strict surface water discharge standards and suitable for fish culture ($3\text{--}5 \text{ mg NH}_3 \text{ L}^{-1}$). Pano and Middlebrooks model (Equation 4) found good agreement with the experimental data (Figure 4): Willmott coefficient (d) = 0.88. In the Willmott test, the ‘coefficient of agreement’ (d) ranges from zero (complete dispersion) to 1 (perfect agreement between two models) (Willmott *et al.*, 1985).

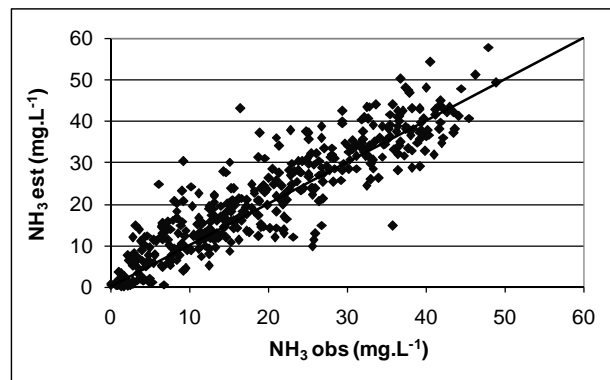


Figure 4. Ammoniacal nitrogen concentration in pond effluents: estimated values according to Pano and Middlebrooks model ($\text{NH}_3 \text{ est}$) and measured values ($\text{NH}_3 \text{ obs}$).

***E. coli* removal**

The treatment system reached high *E. coli* removal efficiency: ≈ 0.7 log unit reduction in the UASB+BF followed by ≈ 4 log units reduction up to the third pond. The fourth pond did not add further removal. Pond 3 consistently produced effluent qualities complying with the WHO guidelines for use in unrestricted irrigation (assumed herein as 10^3 *E. coli* per 100 mL); pond 3 (systematically) and pond 2 (most of the time) achieved the WHO guidelines for restricted irrigation and aquaculture (assumed as 10^4 *E. coli* per 100 mL) (WHO 2006a, 2006b) (Figure 5).

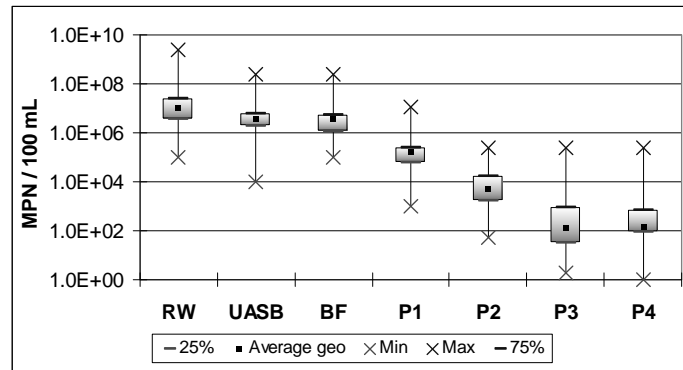


Figure 5 – *E. coli* concentrations in raw wastewater (RW), and in the effluents of the UASB, the biofilter (BF), and the pond series.

Considering the whole period of study, *E. coli* die-off rate constants (K_b) (dispersed flow, 20°C) were calculated for each pond. The dispersion number was estimated assuming $d=1/(L/B)$ (L = length, B = breadth) (von Sperling, 1999). The average K_b values were: 0.98 (pond 1), 1.11 (pond 2), 1.35 (pond 3), and 0.99 (pond 4). In other words, an increase of approximately 13% of K_b values was recorded from pond 1 to pond 2, and 22% from pond 2 to pond 3. No further removal was recorded in the fourth pond.

K_b estimated values using von Sperling equations (equations 1 and 2) were not in fine agreement with the calculated K_b values, in general underestimating them ($d = 0.64$ for equation 1; $d = 0.67$ for equation 2). Similar results were found when comparing the observed and estimated (using equations 1 and 2) values of effluent *E. coli* concentrations: $d = 0.45$ for equation 1; $d = 0.55$ for equation 2 (Figure 6).

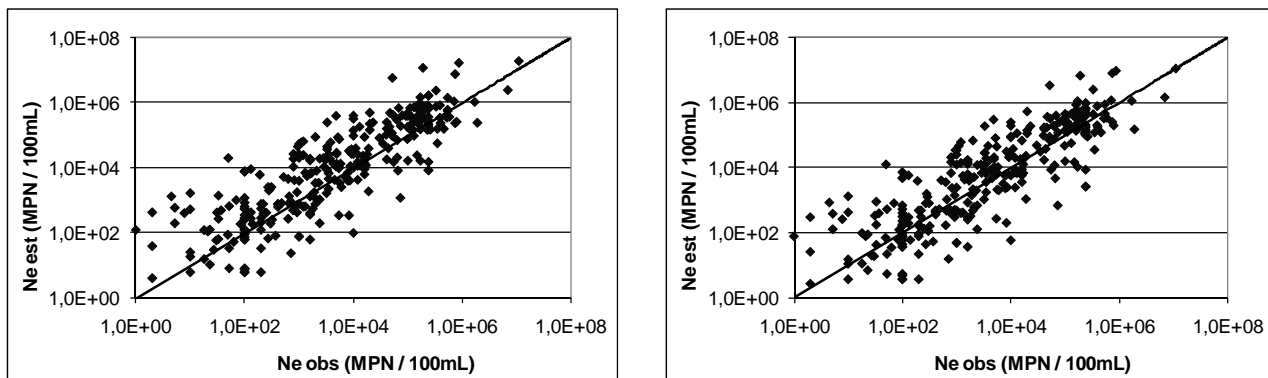


Figure 8. Observed and estimated values of effluent *E. coli* concentrations using von Sperling models, equation 1 (left) and equation 2 (right).

It is worth noticing that von Sperling models were obtained from databases which included much wider values of pond depths and hydraulic retention times than those tested in this work. von

Sperling *et al.* (2005) and von Sperling (2007) had already noticed that K_b values obtained from polishing ponds in Brazil (including the ones of this study) were higher than those predicted by Equation 1, and that shallow ponds ($h < 1.0$ m) tend to present very high K_b values.

CONCLUSIONS

In general, these results confirm a well established understanding that shallow polishing ponds designed for the removal of ammonia and coliforms provide additional BOD removal and face no problems of organic overloading.

Within the experimental conditions of this study (a series of four pilot scale ponds, pond depths = 0.4-0.9 m, L/B = 2, HRT = 4.1-9.4 d), the following points related to design criteria of polishing ponds are highlighted: (i) Pano and Middlebrooks model can be confidently used to predict ammonia removal; (ii) von Sperling equations tend to underestimate *E.coli* K_b values, hence *E.coli* removal; therefore, designing polishing ponds based on them incorporates a factor of safety. Additionally, a series of three ponds showed to achieve high quality ammonia and *E.coli* effluent standards; adding a fourth pond seems to be worthless.

These results also provided the following sound information about input design parameters: (i) a pH value of 7.0 can be confidently assumed in the first pond and, subsequently, a pH rise of 3-5% in the second pond and 5-7% in the third pond; (ii) an *E.coli* K_b value of 1.0 could be assumed in the first pond and, subsequently, an increase of 10% in the second pond and 20% in the third pond.

Finally, it is recognized that since these results derive from pilot scale ponds, adopting safety factors (like using von Sperling equations) may be a realistic design approach.

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REFERENCES

- American Public Health Association, American Water Works Association, Water Environment Federation (1998). *Standard Methods for the Examination of Water and Wastewater*, 20th edn, APHA, AWWA, WEF, Washington DC, USA.
- Cavalcanti, P.F.F. (2003). *Integrated application of the UASB reactor and ponds for domestic sewage treatment in tropical regions*. PhD Thesis, Wageningen University, 141 p.
- Curtis, T.P., Mara, D.D. and Silva, S.A. (1992). The effect of Sunlight on faecal coliforms in ponds: implications for research and design. *Water Science and Technology*, **26** (7/8) 1729-1738.
- Mara, D. D. (2004). *Domestic Wastewater Treatment in Developing Countries*. Earthscan Publication, London.
- Pano, A. and Middlebrooks, E. J. (1982). Ammonia nitrogen removal in facultative ponds *Journal of the Water Pollution Control Federation*, **4** (54), 344-351.
- Pearson, H.W., Mara, D.D., Arridge, H.M. (1995). The influence of pond geometry and configuration on facultative and maturation waste stabilisation pond performance and efficiency. *Water Science and Technology*, **31** (12), 129-139.
- Pearson, H.W., Silva Athayde, S.T., Athayde, G.B., Silva, S.A. (2005). Implications for physical design: the effect of depth on the performance of waste stabilization ponds. *Water Science and Technology*, **51** (12), 69-74.
- Silva, S. A.; Oliveira, R.; Soares, J.; Mara, D. D. and Pearson, H. W. (1995). Nitrogen removal in pond systems with different configurations and geometries. *Water Science and Technology*, **31** (12), 321-330.

- Soares, J., Silva, S.A., Oliveira, R., Araujo, A.L.C., Mara, D.D. and Pearson, H.W. (1996). Ammonia removal in a pilot scale waste stabilization ponds complex in northeast Brazil. *Water Science and Technology*, **33** (7), 165-171.
- von Sperling, M. (1999). Performance evaluation and mathematical modelling of coliform die-off in tropical and subtropical waste stabilization ponds. *Water Research*, **33** (6), 1435-1448.
- von Sperling, M. (2005). Modelling of coliform removal in 186 facultative and maturation ponds around the world *Water Research*, **39**, 5261-5273.
- von Sperling, M. and L. Mascarenhas, C. A. M. (2005). Performance of very shallow ponds treating effluents from UASB reactors. *Water Science and Technology*, **51** (12), 83-90.
- von Sperling, M., Bastos, R.K.X., Kato, M.T. (2005). Removal of *E. coli* and helminth eggs in UASB – polishing pond systems. *Water Science and Technology*, **51** (12). pp. 91-97.
- von Sperling, M. (2007). *Waste Stabilisation Ponds*. Biological Wastewater Treatment Series, vol 2. IWA Publishing, London.
- World Health Organization (2006a). *Guidelines for the safe use of wastewater, excreta and greywater. Volume 2: Wastewater and excreta use in agriculture*. WHO, Geneva.
- World Health Organization (2006b). *Guidelines for the safe use of wastewater, excreta and greywater. Volume 3: Wastewater and excreta use in aquaculture*. WHO, Geneva.
- Willmott, C. J.; Ckleson, S. G.; Davis, R. E. (1985). Statistics for the evaluation and comparison of models. *Journal of Geophysical Research*, Ottawa, **90**, (C5), 8995 – 9005.