Evaluation of the overall performance and relationship with operational variables at 73 full-scale primary facultative ponds

Sílvia C. Oliveira, Marcos von Sperling

Department of Sanitary and Environmental Engineering, Federal University of Minas Gerais; Av. Contorno 842 – 7th floor; 30110-060 - Belo Horizonte – Brazil.
Corresponding author: Tel.:+55 31 3409-1935; e-mail: silvia@desa.ufmg.br; marcos@desa.ufmg.br

Abstract This article reports on the overall performance of 73 full-scale primary facultative ponds located in Brazil, comparing the observed effluent concentrations and the typical values reported by the technical literature. The parameters investigated were BOD, COD, SS, TN, TP and FC. Variations in the BOD effluent from facultative ponds were investigated through a multivariate statistical method (PCA). The results showed that many ponds are facing difficulties in achieving a satisfactory performance, as compared with the expected performance stated in the literature, probably due to lack of proper operation and maintenance. PCA has allowed the identification of the effect of the parameters surface organic loading, length/breadth ratio, hydraulic retention time, surface area and depth on the effluent BOD concentration. Higher surface BOD loading, age and length/breadth ratio lead to higher effluent BOD concentration. The increase of retention time, area and depth had positive influence on ponds performance.

Keywords Effluent quality; performance evaluation; principal component analysis; facultative ponds.

INTRODUCTION

Waste stabilisation ponds (WSP) have proven to be effective alternatives for treating wastewater, and constitute the simplest form of wastewater treatment. WSP are highly recommended for warm-climate areas and developing countries, but they are also used in small rural communities in developed countries. In Europe, for example, thousands of stabilisation pond systems are widely used in communities with populations of up to 2000 inhabitants, but larger systems exist in Mediterranean France, and also in Spain and Portugal (Mendes *et al.*, 1994; Racault *et al.*, 1995; Curtis and Mara, 2006).

The many advantages of the WSP include: simplicity, easy construction, low cost, low maintenance, sludge storage within the pond, no energy consumption, robustness and sustainability. The principal disadvantage is that they require much more land than conventional electromechanical processes, because they are an entirely natural method of wastewater treatment, obtaining all their energy directly from the sunlight (Mara, 2003; Peña & Mara, 2004; von Sperling & Chernicharo, 2005; Curtis and Mara, 2006).

The actual performance of full-scale waste stabilisation ponds is not covered in the literature in the detail it deserves, especially in systems operating in tropical developing countries. In general, there are very few consolidated reports on the existing performance, based on an evaluation of operating records of the ponds.

In this study the main objective was to report on the overall performance of 73 full-scale primary facultative ponds located in Southeast Brazil (latitudes 20 to 22^{o} South, tropical climate), in the states of São Paulo and Minas Gerais. Variations in the effluent quality from facultative ponds were investigated and some internal and external factors, such as influent variables, environmental conditions, biological, operational and design parameters of all ponds were considered in the analysis. Since the systems analyzed cover a very wide spectrum of operating conditions and physical characteristics, a multivariate statistical data analysis method (Principal component analysis) was used for a simultaneous interpretation of the data. The influence of operational conditions on the performance of stabilisation ponds has already been analysed, although using a different approach, in a previous study published by von Sperling and Oliveira (2006).

METHODS

The data used have been obtained directly from the operational records of the Water and Sanitation companies responsible for the operation of the ponds. The descriptive statistics of the influent and effluent concentration data for BOD (biochemical oxygen demand), COD (chemical oxygen demand), TSS (total suspended solids), TN (total nitrogen), TP (total phosphorus) and FC (faecal or thermotolerant coliforms) were determined, and a comparison was made between the observed concentrations and the typical values reported by the technical literature on prevailingly domestic wastewater.

The relationship between some parameters and the performance of the ponds was evaluated through a multivariate statistical method. The exploratory data analysis was performed by linear display method (principal component analysis) on experimental data normalized to zero mean and unit variance. This procedure was necessary in order to avoid misclassification arising from the different orders of magnitude of both numerical value and variance of the parameters analysed.

Principal component analysis (PCA) was applied to the data to assess associations between variables, since this method evidences participation of individual parameters in several influencing factors. This statistical tool transforms the original variables into new, uncorrelated variables (axes), called the principal components (PCs), which are weighted linear combinations of the original variables. PC provides information on the most meaningful parameters, which describe a whole data set affording data reduction with minimum loss of original information (Helena *et al.*, 2000, Hair *et al.*, 2006). The characteristic roots (eigenvalues) of the PCs are a measure of their associated variances, and the sum of eigenvalues coincides with the total number of variables.

Table 1 displays the parameters analyzed by means of the multivariate analysis in an attempt to discriminate sources of variation of BOD effluent quality from the facultative ponds.

Table 1 Design and operational parameters, abbreviations and units

Parameters	**Abbreviations**	**Units**
Flow	FLOW	m^3d^{-1}
Effluent Biochemical Oxygen Demand	EFFL BOD	mgL^{-1}
BOD removal efficiency	EFFIC BOD	%
Surface BOD loading	Ls	kg BOD.$ha^{-1}.d^{-1}$
Hydraulic retention time	HRT	d
Geometry (length/breadth ratio)	L/B	
Temperature of the liquid	T LIQ	(^oC)
Area	A	ha
Depth	DEP	m
Population served by the ponds	POP	inhabitants
Age of the pond at the time of the results	AGE	years

RESULTS AND DISCUSSION

Most data comprise long-term averages, although the majority of ponds had no clearly identifiable monitoring frequency (undefined). A very wide spectrum of operating conditions and physical characteristics was observed in the systems analyzed. The age of the ponds at the time of the study is shown in Figure 1(a). The plants as a whole are relatively old since almost 70% of the ponds were over 10 years old when the research was made. In Brazil, waste stabilisation ponds are mainly for small-sized communities (almost 77% of the sample is under 5000 inhabitants), as can be seen in Figure 1(b). The average size remains close to 4200 inhabitants and the average age is over 15 years.

(a) (b)

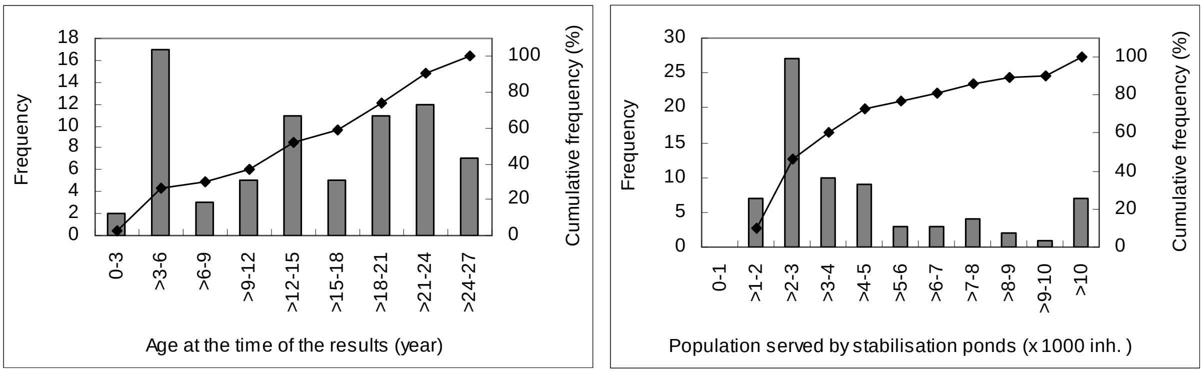

Figure 1 Age of the ponds (a) and population served by facultative ponds (b)

Table 2 presents the full descriptive statistics (including mean, standard deviation, 10% percentile, median and 90% percentile) of the BOD, COD, TSS, TN, TP, FC influent and effluent concentrations and the removal efficiencies of the ponds.

Table 2 Descriptive statistics of the influent and effluent concentration and the removal efficiencies of the ponds

Parameter			Mean	Stand. dev.	10%ile	Median	90%ile
BOD (mgL^{-1})	Concentration	Influent (raw)	**553**	193	363	525	832
		Effluent (treated)	**137**	64	88	120	176
	Efficiency	(%)	**75**	8	65	75	84
COD (mgL^{-1})	Concentration	Influent (raw)	**1191**	348	831	1126	1637
		Effluent (treated)	**517**	151	348	524	677
	Efficiency	(%)	**55**	12	42	55	71
TSS (mgL^{-1})	Concentration	Influent (raw)	**432**	117	298	439	551
		Effluent (treated)	**215**	82	127	197	344
	Efficiency	(%)	**48**	23	70	50	83
TN (mgL^{-1})	Concentration	Influent (raw)	**72**	15	51	73	83
		Effluent (treated)	**40**	10	27	42	48
	Efficiency	(%)	**43**	14	31	43	56
TP (mgL^{-1})	Concentration	Influent (raw)	**9**	3	6	8	12
		Effluent (treated)	**5**	2	3	4	7
	Efficiency	(%)	**45**	13	32	44	59
FC (1) ($MPN100mL^{-1}$)	Concentration	Influent (raw)	**4.4E+07**	6.2E+07	1.3E+07	2.6E+07	8.6E+07
		Effluent (treated)	**1.1E+06**	9.6E+05	1.7E+05	8.4E+05	2.0E+06
	Efficiency	(%)	**96.3**	3.8	92.8	97.3	99.6
		Log units	**1.7**	0.5	1.1	1.6	2.4

(1) FC: Geometric mean used for coliform concentrations

The flow varied significantly amongst the ponds, and presented a range of 120 to 1331 m^3d^{-1} and mean value equal to 670 m^3d^{-1}.

As shown in Table 2, the raw wastewater in the ponds is very concentrated, with mean BOD concentrations close to 500 mgL^{-1}. These values are much higher than the usual values around 300 mgL^{-1} quoted in the classical literature (Metcalf & Eddy, 2003, von Sperling & Chernicharo, 2005). Possible explanations that could justify the high influent concentrations (raw wastewater) could be: unreported industrial contributions, type of sampling practiced (prevalence of grab samples, collected at peak hours), low per capita water consumption, low infiltration rates in the sewerage network, and low wastewater/water return coefficients (greywater not discharged in the network system), as discussed in more detail by Oliveira *et al.* (2006).

In general, variable effluent concentrations and removal efficiencies were obtained with all ponds, considering all the analyzed constituents. These results were compared with values considered typical by the technical literature (Mara, 2003; Metcalf & Eddy, 2003; von Sperling & Chernicharo, 2005) for facultative ponds. Table 3 presents the results related to the effluent concentrations and removal efficiencies, showing the typical values expected and the ranges effectively observed for the ponds in operation, considering the 10% and 90% percentiles.

Table 3 Comparison between mean effluent concentration and removal efficiencies with typical expected values, according to the literature

Constituent	**Ranges**	**Concentration (mgL^{-1})**	**Removal efficiencies (%)**
BOD	Literature [(1)]	50 to 80	75 to 85
	Actual [(2)]	88 to 176	65 to 84
COD	Literature	120 to 200	65 to 80
	Actual	348 to 677	42 to 71
TSS	Literature	60 to 90	70 to 80
	Actual	127 to 344	70 to 83
TN	Literature	> 20	< 60
	Actual	51 to 83	27 to 48
TP	Literature	> 4	< 35
	Actual	3 to 7	32 to 59
FC [(3)]	Literature	10^6 to 10^7	1.0 to 2.0
	Actual	$2x10^5$ to $2x10^6$	1.1 to 2.4

[(1)] Adapted from Mara (2003), Metcalf & Eddy (2003), von Sperling & Chernicharo (2005)
[(2)] Observed ranges: the 10% (minimum value) and 90% (maximum value) percentiles were used;
[(3)] Geometric mean and log- unit removed used for coliforms

In general, a great difference was noticed between the ranges reported by the literature and those effectively observed, taking into consideration all the constituents, with a prevalence of lower performance than expected, considering both mean effluent concentrations and removal efficiencies. This low performance was observed for all constituents, except for TP and FC, which presented a high percentage of ponds with performance above or within the expected range.

Kayombo *et al*. (2005) also relate that many ponds operating in other tropical climate countries (e.g., Tanzania, Kenya, Malawi, Uganda, Zambia, Botswana, Zimbabwe) have been performing below the required standards, due to lack of proper operation and maintenance. Although these factors were not measured directly in this study, the wide variation, from pond to pond, of the monitoring practice, the range of operating conditions and physical characteristics can also be related to the level of process control and the attention to operational and maintenance requirements.

In view of the large performance heterogeneity observed in the ponds investigated, a multivariate statistical analysis was used for a simultaneous interpretation of the factors that could affect the effluent variability.

Over 15800 operational data from the 73 facultative ponds were used in this study, comprising 12 design and operational parameters (Table 1). Although there were more than 30 quality parameters available from some ponds, only some parameters were selected due to their importance and continuity in measurement at all systems.

Principal components (PCA) was carried out by a diagonalization of the correlation matrix, so the problems arising from different measurement scales and numerical ranges of the original variables were avoided, since all variables were auto scaled to mean zero and variance unit.

Table 4 summarizes the PCA results including the loadings (participation of the original variables in the new ones) and the eigenvalue of each principal component (PC). The amount of variance (i.e. information) spanned by each PC (also shown in Table 4) depends on the relative value of its eigenvalue with respect to the total sum of eigenvalues. The absolute value of the loadings is an indicator of the participation of the variable in the PCs, and the maximum contribution is highlighted in Table 4. The scores and loadings of the first two principal components (PCs) presented in Figure 2 reflect the main groupings in the data set. The vicinity of most variables to the correlation circle confirms that only two principal components are sufficient to describe the main behaviour of the systems of variables. When two variables are far from the centre of the diagram and if they are close to each other, they are significantly positively correlated (r close to 1). If they are orthogonal, they are not correlated (r close to 0) and, finally, if they are on the opposite side of the centre, then they are significantly negatively correlated (r close to -1). When the variables are close to the centre, it means that some information is carried on other axes, and that any interpretation might be hazardous (Hair *et al.*, 2006).

Table 4 Loadings of 11 variables on four significant principal components

Variable	**PC1**	**PC2**	**PC3**	**PC4**
EFFL BOD	**0.552**	-0.274	**-0.589**	-0.076
EFFIC BOD	-0.111	0.034	**0.912**	-0.179
FLOW	-0.499	**-0.827**	-0.009	0.076
HRT	**-0.582**	**0.590**	-0.064	0.131
Ls	**0.412**	**-0.680**	0.193	-0.256
A	**-0.883**	-0.270	-0.086	0.266
DEP	**-0.808**	0.166	-0.106	0.100
L/B	**0.540**	-0.183	0.159	**0.593**
T LIQ	-0.123	0.240	0.050	**0.299**
POP	-0.464	**-0.842**	0.024	0.131
AGE	**0.506**	-0.001	0.148	**0.662**
Eigenvalue	3.3	2.5	1.3	1.1
% Total variance	29.9	22.5	11.7	10.0
Cumulative %	29.9	52.3	64.1	74.1

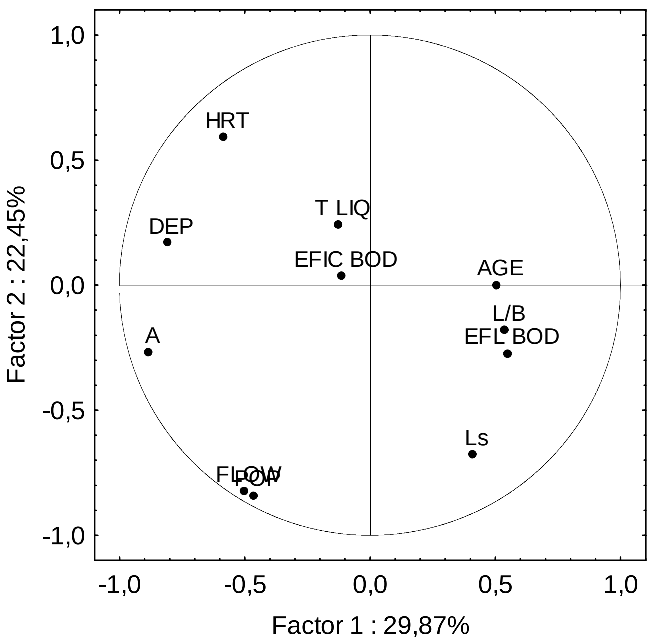

Figure 2 Score and loading of ponds data on the bidimensional plane defined by the first two principal components (PC1 and PC2) accounting for 53.4% of the total variance

The Scree plot (Figure 3) was used to identify the numbers of PCs to be retained in order to understand the underlying data structure. The Scree plot shows a pronounced change of slope after the third eigenvalue, but four PCs were retained, as suggested by Hair *et al.* (2006). Their criteria recommend using all PCs up to and including the first one after the break. Based on that four PCs were retained, which have eigenvalues greater than unity and explain 74.1% of the variance or information contained in the original data set.

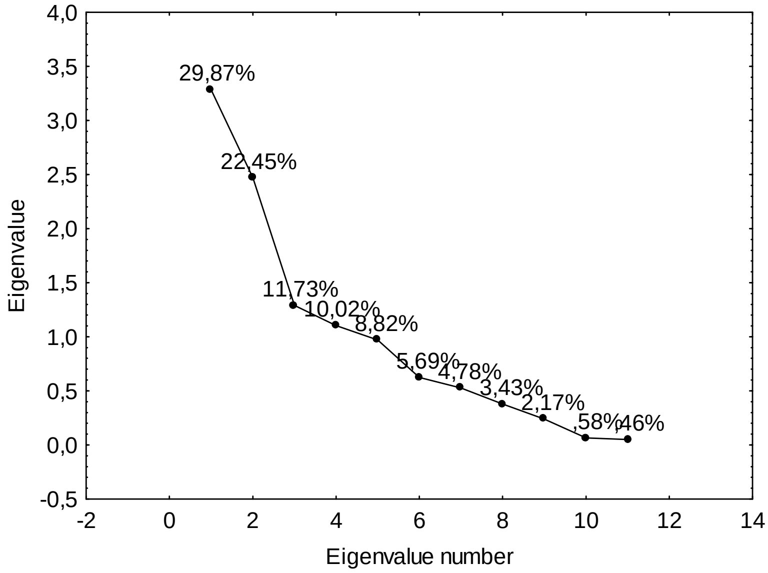

Figure 3 Scree plot of the eigenvalue of PCA

PC1 explains 29.9% of the variance and is positively contributed by the following variables: effluent BOD (EFFLBOD), surface BOD loading (Ls), length/breadth ratio (L/B) and age of the ponds (AGE). As expected, higher organic loadings (Ls) lead to higher effluent BOD concentrations. The L/B ratio affects the hydraulic regime in the ponds and primary facultative ponds are not usually designed to approach plug-flow reactors (high length/breadth ratio), due to the possibility of organic overload close to the pond inlet (von Sperling and Chernicharo, 2005). In general, old ponds present lower net depth due to sludge accumulation, reducing their volume and, consequently, their retention time. Hydraulic retention time (HRT), area (A) and depth (DEP) have a negative participation in PC1 and also presented negative correlation to effluent BOD concentration. The hydraulic retention time (HRT) is related to the time for the activity of the microorganisms. Then, higher retention times give more time for the microorganisms to stabilise the organic matter in the pond. Ponds with higher depths are associated with larger volumes and, therefore, with possibly higher retention times, as well as having more room for sludge storage.

PC2 explains 22.5% of the variance and includes the negative loadings of the flow, Ls and population served by the ponds (POP) and positive loading of the HRT. PC3 (11.7% of the variance) is positively contributed by BOD efficiency (EFFIC BOD) and negatively by EFFLBOD. Finally, PC4 explains 10.0% of the total variability of the original data and is highly participated by L/B, temperature of the liquid and age of the pond at the time of the results (AGE).

SUMMARY AND CONCLUSIONS

Facultative ponds are known to be effective alternatives for sewage treatment in temperate and tropical climates, and represent one of the most cost-effective, reliable and easily-operated methods for treating domestic and industrial wastewater. However, many ponds are facing difficulties in achieving a satisfactory performance, as compared with the expected performance stated in the literature. Even though there are no technological limitations for biological treatment in Brazil, especially given the very favourable climatic conditions, other non-technical factors could be influencing the ability of these processes to meet expected levels of performance. It is believed that these relate to the level of process control and the attention to operational and maintenance requirements.

Principal component analysis allowed the reduction of the 11 variables to four significant PCs that explain 74.1% of the variance (information) of the original data set. The effect of the parameters organic loading (Ls), L/B ratio, hydraulic retention time (HRT), area (A) and depth (D) on the effluent BOD concentration could be verified. Higher surface BOD loading (Ls), age and length/breadth ratio lead to higher effluent BOD concentration. The increase of HRT, area and depth had positive influence on ponds performance.

ACKNOWLEDGEMENTS

The authors would like to thank FINEP, FAPEMIG, CNPq, SABESP, COPASA, FEAM, USP and municipalities for their support and cooperation during the course of the research.

REFERENCES

Curtis, T.; Mara, D. (2006). Waste stabilisation ponds. In: Ujang, Z. and Henze, M. (ed). *Municipal wastewater management in developing countries: principles and engineering*. London, UK: IWA Publishing. ISBN 1843390302. pp. 169-191.

Hair, J.F., Jr., Anderson, R. E.; Tatham, R.; Black, W.C. (2006) *Multivariate Data Analysis*, (6th ed.). Upper Saddle River, NJ: Prentice Hall, USA.

Helena, B.; Pardo, R.; Vega, M.; Barrado, E.; Fernandez, J.M.; Fernandez, L. (2000). Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga river, Spain) by principal component analysis. *Water Research,* **34** (3), pp. 807±816.

Kayombo, S.; Mbwette, T.S.A.; Katima; J.H.Y.; Ladegaard, N.; Jorgensen, S.E. (2005). Waste Stabilization Ponds and Constructed Wetlands Design Manual, UNEP-IETC.

Mara D. D. (2003). *Domestic wastewater treatment in developing countries*. London, UK and Sterling, USA: Earthscan, 292 pp.

Mendes, B.S.; Nascimento, M. J.; Pereira, M. I.; Bailey, G.; Lapa, N.; Morais, J.; Oliveira, J.S. (1994). Ecoclimatic influence on waste stabilisation ponds (WSP) efficiencies. Case study of the Sesimbra system. *Water Science and Technology*, **30** (8), pp 269–279.

Metcalf & Eddy. (2003) *Wastewater engineering: treatment, and reuse*. New York: Metcalf & Eddy, Inc., 4 th. Ed., 1819p.

Oliveira, S. M. A. C.; Souki, M. I. O.; von Sperling, M. (2006). Wastewater characteristics in a developing country, based on a large survey (166 treatment plants). In: 5rd IWA WORLD WATER CONGRESS, 2006, Beijing, China. *Proceedings*… Beijing, [s.n.].

Peña, V. M. R. and Mara, D. D. (2004). *Waste Stabilisation Ponds - Thematic Overview Paper.* IRC International Water and Sanitation Centre, Delft.

Racault, Y.; Boutin, C; Seguin, A. (1995) Waste stabilisation ponds in France: a report on fifteen years experience. *Water Science and Technology*, **31** (12), pp 91–101.

Von Sperling M. V. and Chernicharo, C.A.L. (2005). *Biological Wastewater Treatment in Warm Climate Regions*. London, UK: IWA Publishing, v. 1, 1496 p.

Von Sperling, M.; Oliveira, S. M. A. C. (2006). Influence of operational conditions on the performance of 151 stabilisation ponds in Brazil. In: 7th INTERNATIONAL CONFERENCE ON WASTE STABILIZATION PONDS, 2006, Thailand. *Proceedings*… Thailand: [s.n.].