Assessment of classical surface organic loading design equations based on the actual performance of primary and secondary facultative ponds

Sílvia C. Oliveira and Marcos von Sperling

ABSTRACT

This article presents results from a performance evaluation of 73 full-scale primary facultative ponds and 37 secondary facultative ponds in Brazil. The data were used to test the applicability of some classical design equations for recommended surface BOD loading rates. The empirical equations proposed by Mara in 1976 and 1987 and the equation developed by McGarry and Pescod in 1970 were evaluated. The loading and hydraulic operating conditions were also evaluated to support the analysis of the influence of the parameters surface BOD loading (L_S) and hydraulic retention time (HRT) on the performance of the ponds. The results showed that the design equations proposed by Mara showed good applicability for primary facultative ponds, representing good indicators of the limit value of loading rates to be applied on the units. But the secondary facultative ponds showed good and poor performances for all loading rates and the best ponds, in general, were not those which followed the design equations recommendation. Finally, the influence of the actual loading conditions on the ponds performance was very small and scattered, indicating that other unquantified design and operational aspects were playing an important role.

Key words | effluent quality, performance evaluation, primary and secondary facultative ponds

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INTRODUCTION

Most waste stabilisation pond (WSP) systems are comprised by anaerobic, facultative and, in some cases, maturation ponds. Anaerobic ponds are applied in many situations, but in other cases the influent wastewater goes directly to the facultative ponds. Facultative ponds that receive raw sewage are termed primary ponds, and those that receive the effluent from an anaerobic pond are named secondary ponds.

WSP are applied worldwide, but they particularly suited to tropical and subtropical countries, since sunlight and ambient temperature are key factors in their process performance. Basically, the biological process consists of retaining the wastewater for periods long enough so that the natural organic matter stabilisation processes take place. A series of mechanisms contribute to the purification of the wastewater, as a result of the complex mutualistic relationship of bacteria and algae. The oxidation of organic matter is accomplished by bacteria in the presence of dissolved oxygen, which is mainly supplied by algal photosynthesis (Mara 2003; Peña & Mara 2004; von Sperling & Chernicharo 2005; Curtis & Mara 2006). This balance between oxygen production and consumption is likely to influence pond performance.

In order to allow this balance, facultative ponds are designed for BOD removal on the basis of a specified surface organic loading. If they are properly designed and not significantly overloaded the systems can work well, achieving up to around 80% BOD removal and 50–80 mg L^{-1} of effluent BOD concentration (von Sperling & Chernicharo 2005). Various empirical approaches have been proposed for the design of facultative ponds, and some

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of these models relate pond loading to temperature or to BOD removal (McGarry & Pescod 1970; Mara 1976; Arthur 1983; Mara 1987; Ellis & Rodrigues 1995).

The operational records gathered from 73 full-scale primary facultative ponds and 37 secondary facultative ponds in Brazil were used to check the applicability of some of these design equations and, also, to verify the existence of a relationship between design/operational parameters and the performance of the ponds.

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 WSP are located in Southeast Brazil (latitudes 20–22° South, tropical climate, average liquid temperatures between 20 and 25°C), in the states of São Paulo and Minas Gerais. The treatment plants received typical urban wastewater, comprised mainly of domestic sewage.

Three empirical equations frequently used for establishing the design surface organic loading were evaluated. The equations proposed by Mara 1987 (Equation 1) and McGarry & Pescod 1970 (Equation 2) use the *mean air temperature of the coldest month*. It should be noted that Equation (2) is not a design equation *per se*, but rather an envelope of failure, that is, it sets the limits above which failure is expected to occur.

$$L_s = 350\,(1.107 - 0.002T)^{(T-25)} \quad (1)$$

and

$$L_s = 60\,(1.099)^T \quad (2)$$

where

L_s surface BOD loading (kg BOD $ha^{-1}\,d^{-1}$)
T mean air temperature of the coldest month (°C)

Equation (3), proposed by Mara (1976), is based on the *mean air temperature*:

$$L_s = 20T - 120 \quad (3)$$

where

T mean air temperature (°C)

The loading and hydraulic operating conditions were also evaluated to support the analysis of the influence of the parameters surface BOD loading (L_s) and hydraulic retention time (HRT) on the performance of the ponds.

RESULTS

Table 1 presents the full descriptive statistics (including mean, standard deviation, 10% percentile, median and 90% percentile) of the BOD influent and effluent concentrations and removal efficiencies of all pond systems. Table 2 presents the descriptive statistics of the surface BOD loading (L_s) applied to primary and secondary facultative ponds, the mean hydraulic retention time (HRT) and the liquid temperature observed.

The systems treated different population sizes, and thus the flow varied significantly amongst the ponds, within a range of 120–1331 $m^3\,d^{-1}$ for primary facultative ponds and 181–6518 $m^3\,d^{-1}$ for the secondary facultative ponds.

As shown in Table 1, the raw wastewater in the primary facultative ponds is very concentrated, with mean BOD concentrations close to 500 mg L^{-1}, much higher than the usual values of 300 mg L^{-1} quoted in the classical literature (Arceivala 1981; Qasim 1985; Metcalf & Eddy 2003; von Sperling & Chernicharo 2005). The removal efficiencies reported for the secondary ponds are the removal achieved in these units only, and not the overall efficiency obtained in the system anaerobic-facultative ponds.

In general, a prevalence of lower than expected performance was noticed, considering both BOD effluent concentrations and BOD removal efficiencies. The observed range of BOD effluent concentration generated by primary facultative ponds was 29–230 mg L^{-1} (percentiles 10 and 90%) and 27–167 mg L^{-1} by secondary facultative ponds, values higher than the expected range reported in the literature. One of the possible causes could be the high influent BOD concentrations. The same was observed for BOD removal efficiencies, with a great difference between the values reported by the literature and those effectively observed.

The plot of the recommended surface loading rate as a function of temperature, as indicated by Equations (1)–(3), is found in many textbooks on stabilisation ponds design.

Table 1 | Descriptive statistics of the BOD influent and effluent concentration and BOD removal efficiencies of the pond systems

System	Primary facultative ponds (FAC.1ary)			Secondary facultative ponds (FAC.2ary)		
Parameters	Influent (raw)	Effluent	Removal efficiencies	Influent (raw)	Effluent	Removal efficiencies
Unit	$mg\,L^{-1}$	$mg\,L^{-1}$	%	$mg\,L^{-1}$	$mg\,L^{-1}$	%
Mean	516	120	73	183	84	48
Stand. dev.	348	97	28	145	77	34
10%ile	150	29	51	63	27	12
Median	466	95	78	150	64	55
90%ile	905	230	91	317	167	79

Number of ponds: primary facultative ponds: 73; secondary facultative ponds: 37.

Figure 1 shows these plots (a, b, c, d), together with the actual surface BOD loading and temperature found in the investigated primary facultative ponds. For each parameter, 1006 operational data were analysed in this study. Regarding temperature, the long-term mean air temperature (required for the equations) was adopted as equal to the mean liquid temperature (measured). For the mean air temperature of the coldest month, the value of the 1/12 percentile of all recorded liquid temperatures (measured) for each pond was adopted (approaching the condition of the critical month within the 12 months of the year).

In Figure 1, the primary facultative ponds were also separated into two groups, based on their performance. The criterion adopted for the separation of the groups was: (a) effluent BOD $\leq 80\,mg\,L^{-1}$ (better performance) and (b) effluent BOD $> 80\,mg\,L^{-1}$ (poorer performance). These values are based on the pond systems investigated and their actual performance, and in other studies different cut-off values may be adopted.

As observed in Figure 1a and c, an important tendency can be observed: the primary facultative ponds that presented the best performances (mean effluent BOD concentration below $80\,mg\,L^{-1}$), in general, operated at loadings below those given by Equations (1) and (3), and naturally lower than those obtained from Equation (2), which represents an envelope of failure. It was found that 80 and 88% of the data from these ponds presented L_s values according to what is recommended by Equations (1) and (3), respectively. Considering Equation (2) (envelope of failure), 93% of the surface loading rates applied were below the maximum recommended.

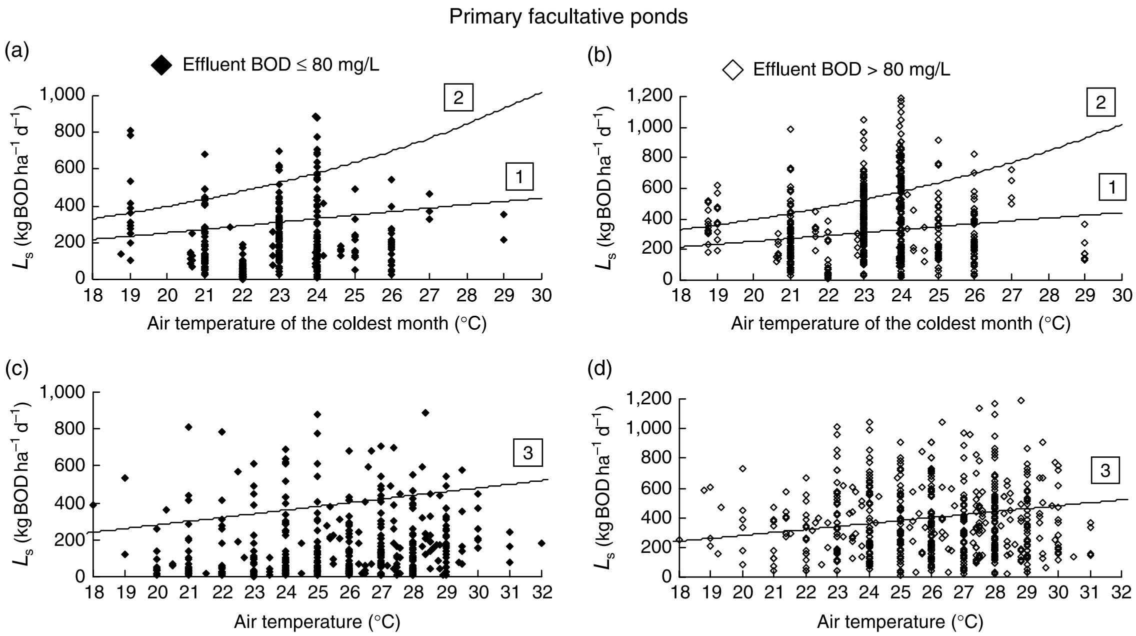
Figure 1b and d show that the primary facultative ponds which generated effluent BOD concentrations above $80\,mg\,L^{-1}$ presented lower percentage of L_s values under the curves generated by Equations (1) and (3) (48 and 62%, respectively). The maximum loading rates given by Equation (2) are very high, due to its concept of limit for failure, but the majority of the ponds that presented poor performance operated with L_s under curve 2 (75% of the data).

Figure 2 shows the variation of L_s with temperature on the investigated secondary facultative ponds, and comparison with classical design equations. In this case, 388 operational data of each parameter were analysed.

The values of the observed surface loading rate from secondary facultative ponds that presented the best

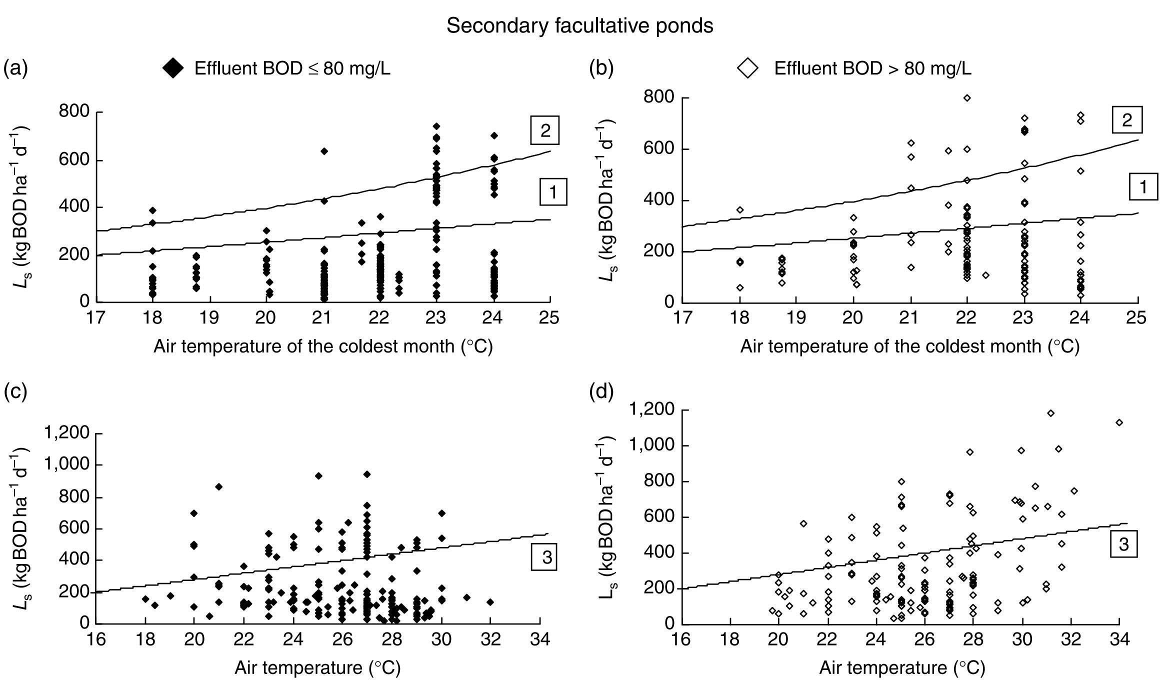
Table 2 | Descriptive statistics of loading rates, temperature and hydraulic retention time

System	Parameter	Unit	Mean	Stand. dev.	10%ile	Median	90%ile
Primary facultative ponds	L_s	$kg\,BOD\,ha^{-1}\,d^{-1}$	294	259	33	224	619
	Temperature	°C	26	3	22	26	29
	HRT	Days	54	59	15	31	108
Secondary facultative ponds	L_s	$kg\,BOD\,ha^{-1}\,d^{-1}$	264	278	47	157	622
	Temperature	°C	25	3	21	26	29
	HRT	Days	16	10	5	15	26



Equations (1): $L_s = 350\,(1.107 - 0.002T)^{(T-25)}$; (2): $L_s = 60\,(1.099)^T$; (3): $L_s = 20T - 120$

Figure 1 | Variation of L_s with temperature on primary facultative ponds, and comparison with classical design equations.



Equations (1): $L_s = 350\,(1.107 - 0.002T)^{(T-25)}$; (2): $L_s = 60\,(1.099)^T$; (3): $L_s = 20T - 120$

Figure 2 | Variation of L_s with temperature on secondary facultative ponds, and comparison with classical design equations.

performances (effluent BOD concentration $\leq 80\,\mathrm{mg\,L^{-1}}$; Figure 2a and c) were, in most cases, lower than the values obtained by Equations (1)–(3) (79, 91 and 75 of the data, respectively). However, it was not observed expressive differences between the loadings applied by secondary facultative ponds that generated effluent BOD > 80 $\mathrm{mg\,L^{-1}}$. The percentage of L_s values under the curves generated by Equations (1)–(3) was 61, 82, and 67%, respectively. The same comments made above regarding Equation (2) representing an envelope of failure can be made here.

These findings suggest that the literature design equations are more applicable for primary facultative ponds, and represent good indicators of the limit value of loading rates to be applied on ponds, above which a good performance cannot be guaranteed. The secondary facultative ponds showed good and poor performances for all loading rates and the best ponds, in general, are not those which follow the design recommendation.

However, the validity of the design Equations (1) and (3) can be better assessed when the pond is receiving its design load. In practice, ponds are normally underloaded or overloaded and only rarely operate at design load. In the present work, the design load data of the ponds were not available, but based on typical design and operational parameters recommended by the technical literature for the region (150–350 $\mathrm{kg\,BOD\,ha^{-1}\,d^{-1}}$) (Mara 2003; von Sperling & Chernicharo 2005), it was observed that 35% of the L_s data from primary facultative ponds could be classified as underloaded (actual BOD loads less than the lower end of the recommended range = 150 $\mathrm{kg\,BOD\,ha^{-1}\,d^{-1}}$), 32% with BOD loads within the range and 34% overloaded (BOD load higher than the upper end of the range = 350 $\mathrm{kg\,BOD\,ha^{-1}\,d^{-1}}$). About 72% of the data from secondary facultative ponds presented loading rates above the upper limit or below the lower limit of the recommended range.

Even though the equations lead to very high values of L_s with high temperatures (above 25°C), it is recommended that the surface loading rate be limited to a maximum value of 350 $\mathrm{kg\,BOD\,ha^{-1}\,d^{-1}}$ for design purposes (Mara 2003; von Sperling & Chernicharo 2005). There are some evidences to suggest that the L_s in secondary facultative ponds could be higher than those adopted for primary ponds. However, Mara *et al.* (1992) suggest that, for design purposes, it is better to consider both as being equal for safety reasons.

Figure 3 presents the effluent BOD concentrations in the primary and secondary facultative ponds as a function of the applied loading rates. The dotted line represents the maximum value recommended for the surface loading rate.

Only 34% of the observed L_s applied on the primary facultative ponds were above this reference value, showing that the applied surface organic rate did not substantially influence the performance of the facultative ponds.

Figure 4 presents the effluent BOD concentrations in the primary and secondary facultative ponds as a function of the hydraulic retention time. The typical intervals of HRT used as reference for the determination of the hydraulic operating conditions of the ponds were 15–45 days for primary facultative ponds and 8–20 days for secondary facultative ponds treating domestic sewage under the mentioned climatic conditions (von Sperling & Chernicharo 2005). These values are not design parameters

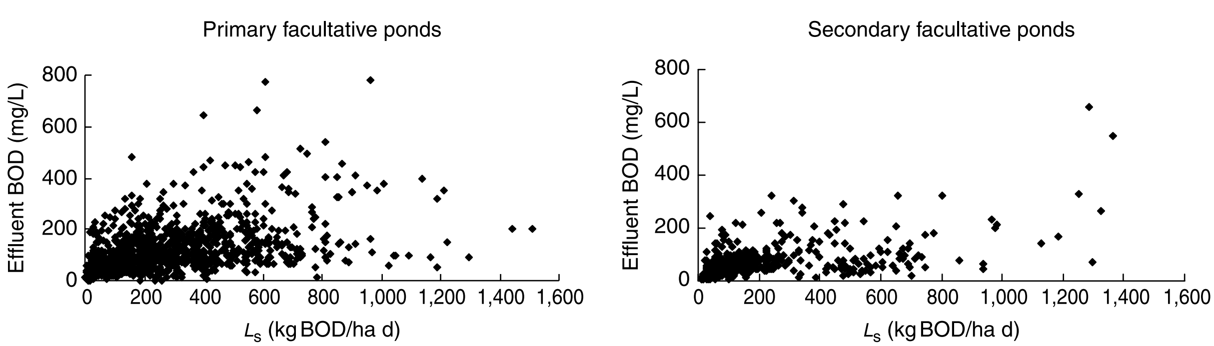


Figure 3 | Relationship between applied loading rates (L_s) and effluent BOD concentration.

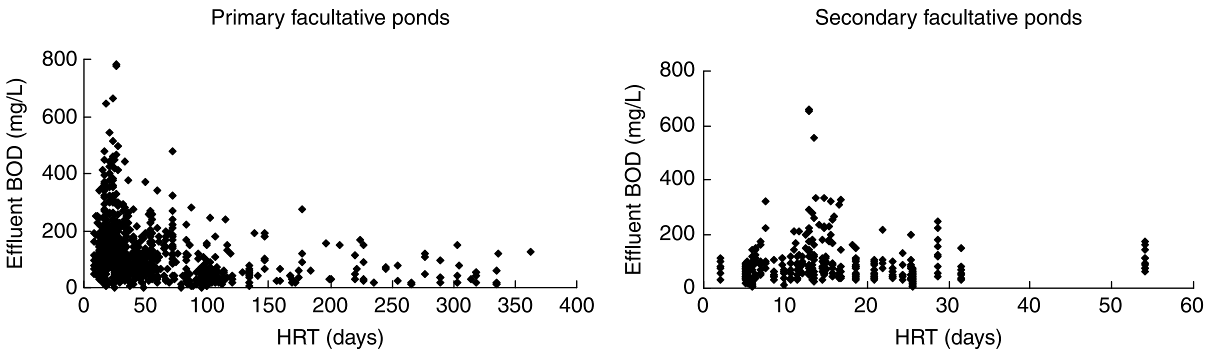


Figure 4 | Relationship between hydraulic retention time (HRT) and effluent BOD concentration. Note: The dotted ranges refer to the typical intervals of HRT mentioned by the literature for domestic sewage.

per se, but are a consequence of the calculation of the pond area based on surface organic loading and the adoption of a suitable depth, what leads to the pond volume and, consequently, to its HRT.

About 45% of the HRT values of the primary facultative ponds did not follow the usual interval (Figure 4). In general, when the ponds operated under overloading conditions, high L_s ($>350\,\mathrm{kg\,BOD\,ha^{-1}\,d^{-1}}$) or low HRT ($<15$ days), there was a tendency to an increased effluent BOD concentration. However, in some cases, very high loading rate values did not seem to have caused a significant deterioration in the effluent quality.

Concerning secondary facultative ponds, the results show that the applied surface organic rate and resulting HRT did not substantially influence the performance of the ponds. Only 25% of the L_s values were above the limit recommended by L_s and 56% of the HRT values adopted by ponds were within the usual intervals, but without a good corresponding effluent quality.

von Sperling & Oliveira (2006) discussed, in detail, a possible relationship between design/operational parameters and the ponds performance, considering the parameters BOD, COD, SS, TN, TP and FC and substantiated by a statistical multiple comparison analysis.

Generally, it was concluded that the influence of the loading conditions was very small and scattered in all stabilisation ponds. The contribution and influence of each variable seemed to differ from one system to another, and, as expected, this is likely to be a combination of design and operational aspects, related to the level of process control and the attention to operational and maintenance requirements. Although operational practices were not measured directly in this work, conditions such as failure to remove sludge may be a significant problem when the ponds are in operation for a long time. That is possibly the case of the ponds analysed in this work, mainly the primary facultative ponds, which received the raw sewage solids. The ponds analysed here are relatively old and about 75% of the primary and 41% of the secondary facultative ponds were over 10 years old when the research was made. Old ponds may present lower net depth due to sludge accumulation, reducing their volume and, consequently, their retention time, leading to a poorer performance than expected. Other factors like hydraulic short circuiting or the existence of dead zones may be also influential, but their detection or quantification was not possible in this work.

SUMMARY AND CONCLUSIONS

- Classical design equations for recommended loading rates proposed by Mara (1987 and 1976) showed good applicability for primary facultative ponds, representing good indicators of the limit value of loading rates to be applied on systems.
- The maximum loading rates recommended by the equation proposed by McGarry & Pescod (1970) are very high because they represent limits for failure, but even the ponds that presented poor performance operated with L_s under the maximum values permitted.
- The secondary facultative ponds showed good and poor performances for all loading rates and the best ponds,

in general, were not those which follow the literature design equations recommendation for loading rates.

- In general, the influence of the loading conditions on the ponds performance was very small and scattered in all the ponds. The contribution and influence of each variable seemed to differ from one system to another, and this seems to be a combination of design and operational aspects, such as the level of process control, attention to operational and maintenance requirements, sludge accumulation, hydraulic factors and others.

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