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

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**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 existence of a relationship between design/operational parameters and the performance of the ponds was also verified. The results showed that 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 loading conditions on the ponds performance was very small and scattered, indicating the combined influence of other design and operational aspects.
**Keywords** Effluent quality; performance evaluation; primary and secondary facultative ponds.

## 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 and 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 per cent BOD removal and 50 to 80 $mgL^{-1}$ of effluent BOD concentration (von Sperling and Chernicharo, 2005). Various empirical approaches have been proposed for the design of facultative ponds, and some of these models relate pond loading to temperature or to BOD removal (McGarry and Pescod, 1970; Mara, 1976; Mara, 1987; Arthur, 1983; Ellis and 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 to 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 and 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 to 1331 m$^3$d$^{-1}$ for primary facultative ponds and 181 to 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 mgL$^{-1}$, much higher than the usual values of 300 mgL$^{-1}$ quoted in the classical literature (Arceivala, 1981; Metcalf & Eddy, 2003; Qasim, 1985; von Sperling and 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.

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 | $mgL^{-1}$ | $mgL^{-1}$ | (%) | $mgL^{-1}$ | $mgL^{-1}$ | (%) |
| **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

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 | $^oC$ | **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 | $^oC$ | **25** | 3 | 21 | **26** | 29 |
| | HRT | days | **16** | 10 | 5 | **15** | 26 |

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 $mgL^{-1}$ (percentile 10% and 90%) and 27 - 167 $mgL^{-1}$ 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.

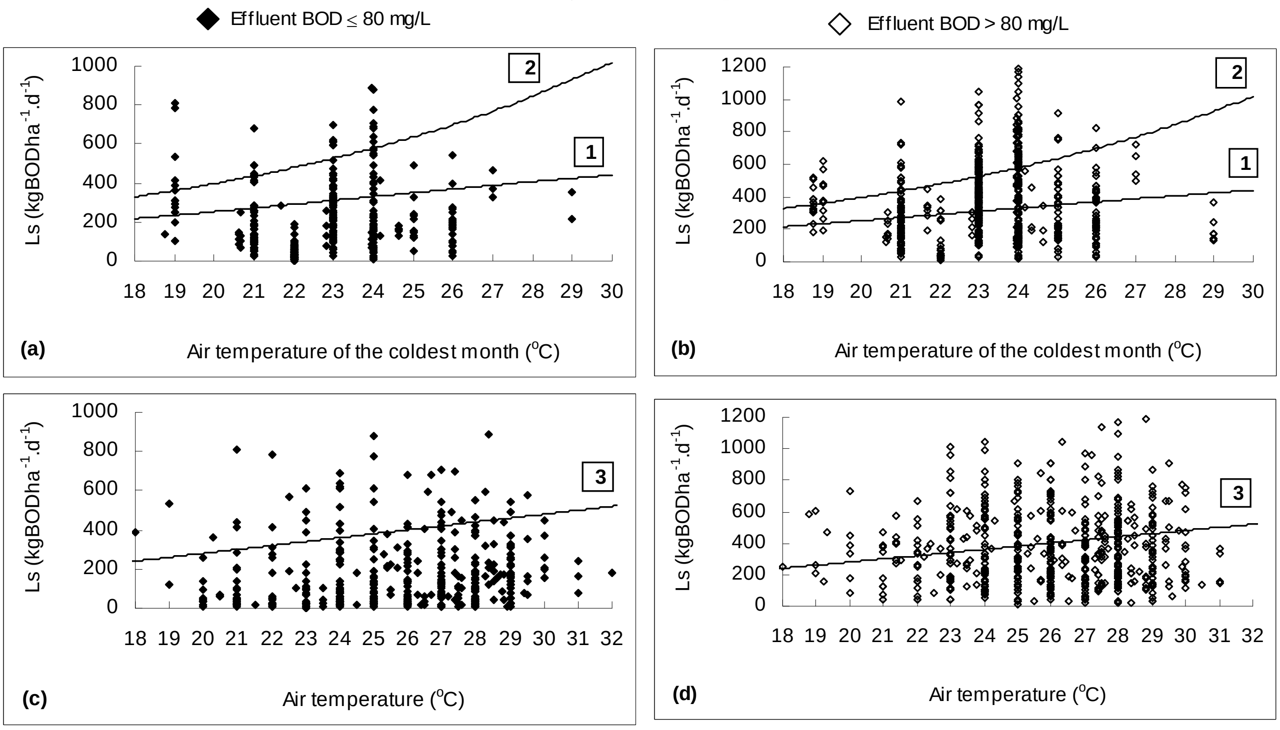
The plot of the recommended surface loading rate as a function of temperature, as indicated by equations 1, 2 and 3, is found in many textbooks on stabilisation ponds design. Figure 1 shows these plots (**a**, **b**, **c**, **d**), together with the actual surface BOD loading and temperature found in 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 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 $mgL^{-1}$ (better performance) and (b) effluent BOD > 80 $mgL^{-1}$ (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 Figures 1**a** and 1**c**, an important tendency can be observed: the primary facultative ponds that presented the best performances (mean effluent BOD concentration below 80 $mgL^{-1}$), 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.

Figures 1**b** and 1**d** show that the primary facultative ponds which generated effluent BOD concentrations above 80 $mgL^{-1}$ 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).

Primary facultative ponds




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

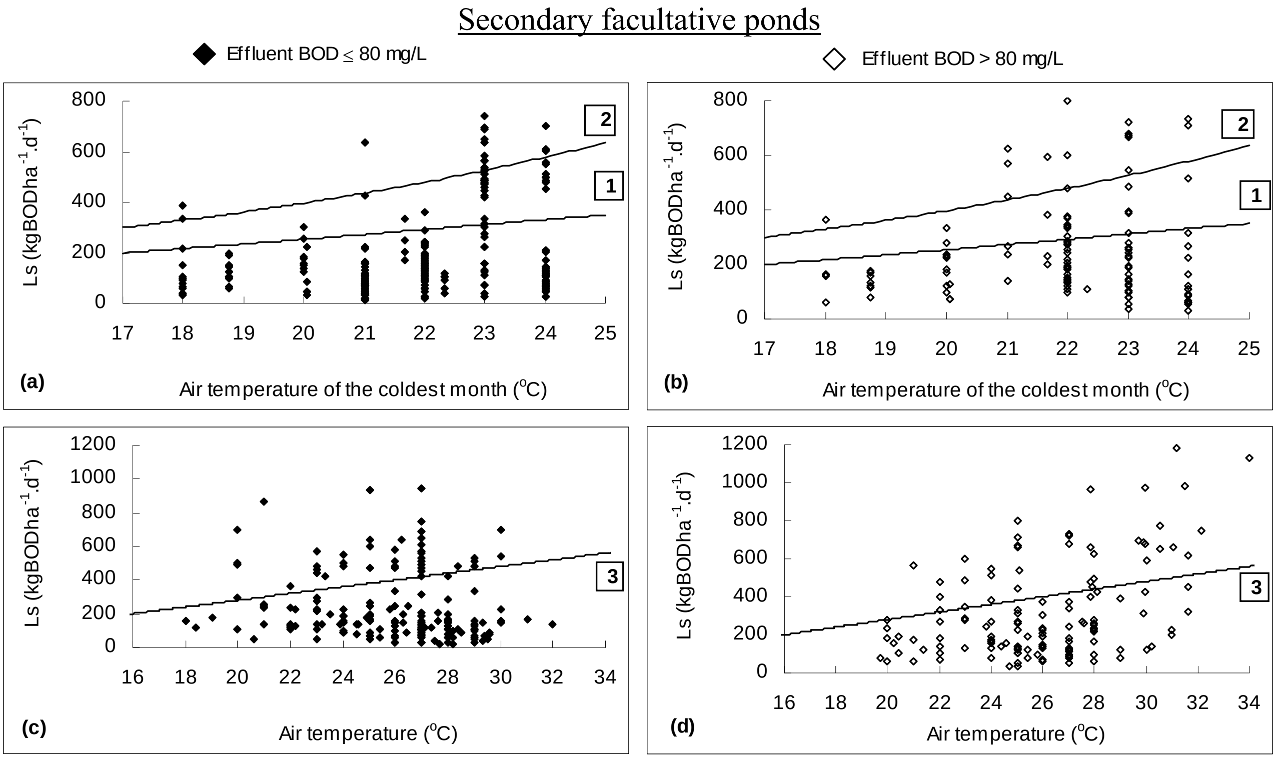
Figure 1 Variation of $L_s$ with temperature on **primary** facultative ponds, and comparison with classical design equations

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 performances (effluent BOD concentration ≤ 80 $mgL^{-1}$) (Fig. 2**a** and 2**c**) were, in most cases, lower than the values obtained by the equations 1, 2 and 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 $mgL^{-1}$. The percentage of $L_s$ values under the curves generated by equations 1, 2 and 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 to 350 kg $BOD.ha^{-1}.d^{-1}$) (Mara, 2003; von Sperling and 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 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 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.




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

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 kg $BOD.ha^{-1}.d^{-1}$ for design purposes (Mara, 2003; von Sperling and 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.

Primary facultative ponds | Secondary facultative ponds

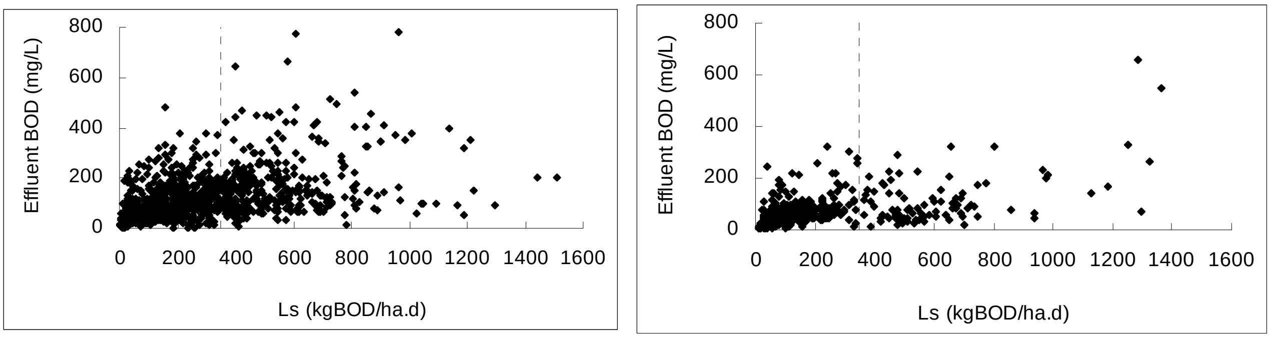
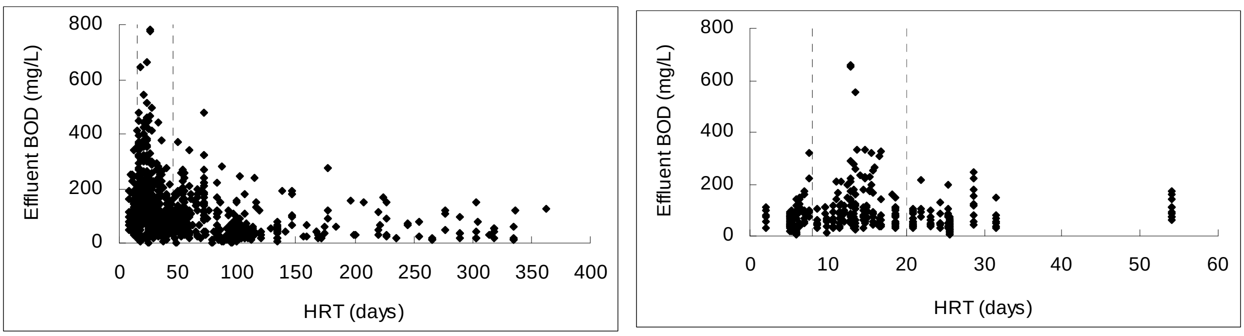



Figure 3 Relationship between applied loading rates ($L_s$) and **effluent BOD concentration**

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 to 45 days for primary facultative ponds and 8 to 20 days for secondary facultative ponds treating domestic sewage (von Sperling and Chernicharo, 2005). These values are not design parameters *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.

Primary facultative ponds | Secondary facultative ponds




Note: The dotted ranges refer to the typical intervals of HRT mentioned by the literature for domestic sewage.

Figure 4 Relationship between hydraulic retention time (HRT) and **effluent BOD concentration**

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 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 and 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.

## 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 and 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, are not those which follow the design equations recommendation.
- 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 and the attention to operational and maintenance requirements.

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