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A MODEL FOR COST ESTIMATION OF SYSTEM FOR PIGGERY WASTES TREATMENT PONDS – A CASE STUDY

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Abstract

This article presents the results from the monitoring of a system of ponds for the treatment of piggery wastes, carried out during a 20 months period, with the objective to determine design parameters for the optimization of the treatment system. A series composed of two anaerobic ponds, one facultative pond and one water hyacinth pond, gave an efficiency of 97% in the removal of BOD_5, 93% for total phosphorus, 91% for total Kjeldahl nitrogen and a removal of 7 log units for fecal coliforms. A model of the optimization incurred in the treatment of these wastes was developed, within economic concepts.

Keywords: costs; piggery wastes; ponds; treatment.

Resumo

Este artigo apresenta resultados do monitoramento de um sistema de lagoas para tratamento de dejetos suínos, realizados durante um período de 20 meses, com o objetivo de encontrar parâmetros operacionais para otimização do sistema de tratamento. O sistema é composto por duas lagoas anaeróbias, uma facultativa e uma de aguapés, em séries, com uma eficiência de 97% na remoção da DBO_5, 93% para o fósforo total, 91% para o nitrogênio total e uma redução de 7 unidades log para os coliformes fecais. Um modelo de otimização para tratamento destes resíduos foi desenvolvido usando os conceitos econômicos.

Palavras-chave: custos; dejetos de suínos; lagoas; tratamento.

1. Introduction

In the western region of the state of Santa Catarina, the greatest concentration of pig breeding activities in Brazil is found, with an estimated number of around 4.5 million head, which corresponds to 11.7% of the national herd, constituting an important activity from the social and economic viewpoints and especially with regard to maintain the rural populations (*PorkWorld*, 2002). However, this activity is carried out in confined systems generating high concentrations of waste, which are potential causes of environmental degradation.

The storage of piggery wastes through laystalls allows their use as soil fertilizers, since these wastes are rich in nutrients such as nitrogen and phosphorus and should be utilized in agriculture (Belli Filho *et al.*, 1997). However, since the local producers don't allow a sufficient area to absorb all of the organic load, there is an excess of waste which must be treated before its final disposal.

In Santa Catarina, Brazil, the systems utilized for the treatment of these wastes, generally stabilization ponds, are constructed without scientific criteria. The ponds used manage to attain a good removal of the organic load (BOD), but show insufficiencies in the removal of nutrients (N, P) and of pathogenic microorganisms (Costa *et al.*, 2000). The purpose of this study is to develop a model for the estimation of pond systems applied to the treatment of piggery wastes, with the involvement of economic aspects and desired quality of the treated effluent.

In the stabilization pond systems, optimization means to minimize the total cost and to obtain an adequate efficiency in terms of treatment. The costs include capital costs and operational costs, which are influenced by the distribution of the organic load of each pond (Meisheng *et al.*, 1992; Kezhao, 1994; Yang & Chen, 1994). According to Li (1995), the cost of a pond system is characterized by direct and indirect costs. The direct costs include: the costs of construction, installation and the land; and the indirect costs consist of: taxes, design and costs of operation and maintenance. Therefore, it is necessary to obtain models for the costs of land, construction and pond maintenance. Besides these, this study presents a model of the cost of lining the ponds and models of treatment efficiency.

2. Materials and Methods

2.1 Site description

The piggery waste treatment system, in real scale, consists of an equalizer, followed by a rising flow decanter, two anaerobic ponds (AP1 and AP2), a facultative pond (FP) and a water hyacinth pond (WHP), disposed in series (Figure 1). This system is installed at the Brazilian Company of Agricultural Research – National Center of Research of Pig and Poultry (EMBRAPA – CNPSA) in Concórdia, Santa Catarina, Brazil. Table 1 shows the physical and operational characteristics of the ponds.

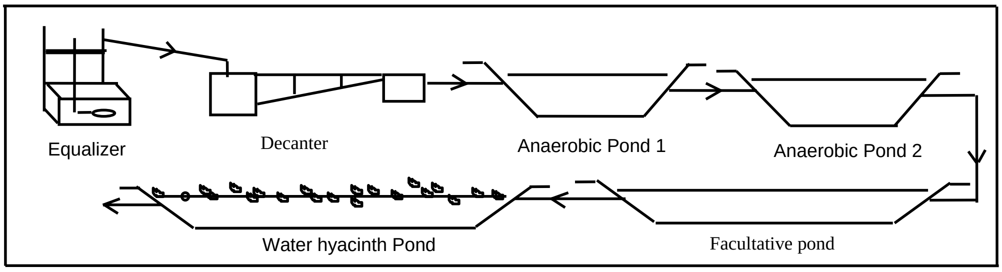

Figure 1 – Schematic diagram of real scale continuous flow plant.

Table 1 – Physical and operational characteristics of the ponds.

Parameters		AP1	AP2	FP	WHP
Surface Area	(m^2)	83.62	83.62	105.60	100.00
Bottom Area	(m^2)	44.50	44.50	67.60	46.00
Depth	(m)	1.70	2.20	0.85	0.80
Volume	(m^3)	106.40	137.70	73.00	58.00
Flow rate	(m^3/d)	3.00	3.00	3.00	3.00
Retention time	(d)	35.00	46.00	24.00	19.30

2.2 Methodology

The wastes produced on a small farm of 350 animals were transported daily to the equalizer, by tractor tank, with a capacity of 4 m^3, passing afterwards to the decanter, with a flow rate of approximately 20 L/min, until reaching a volume of 3 m^3, passing after this, by gravity, to the ponds.

The monitoring of the treatment system was carried out for a period of 20 months. The samples for analysis of the parameters were collected weekly, except for the analysis of COD, collected twice a week. The following analyses were carried out: Temperature and pH (HI 9145, Hanna Instruments, Germany); Total Biochemical Oxygen Demand (BOD – respirometric method Hach, mod. 2173B); Total Chemical Oxygen Demand (COD – closed reflux, colorimetric method Hach, mod. DR2000); Total Nitrogen (TN – micro-Kjeldahl method), Total Phosphorus (TP – vanadomolybdophosphoric acid colorimetric method); Fecal coliform (FC – Colilert Fecal Coliform test); Total Solids (TS), Fixed Solids (FS), and Volatile Solids (VS) were conducted using the evaporation of the samples and its subsequent drying in an oven at a defined temperature. All parameters following the methods established by the *Standard Methods* (1995).

3. Results and Discussion

The average results and the efficiencies obtained in the monitoring of the piggery wastes treatment system are given in Table 2.

Table 2 – Results of the monitoring to the influent and effluent of each pond (total retention time = 125 days).

Parameter	Influent	AP1	AP2	FP	WHP	Total Removal
pH	7.0	7.4	7.7	7.8	7.7	–
$TBOD_5$ (mg/l)	8,304	1,833 (78%)	778 (64%)	435 (48%)	213 (53%)	97%
TCOD (mg/l)	15,153	3,308 (78%)	1,438 (56%)	807 (46%)	355 (58%)	98%
TS (mg/l)	9,950	4,773 (52%)	3,266 (39%)	2,254 (34%)	1,320 (47%)	87%
FS (mg/l)	4,056	2,543 (37%)	1,962 (22%)	1,360 (32%)	779 (48%)	81%
VS (mg/l)	5,894	2,230 (62%)	1,305 (39%)	894 (35%)	541 (46%)	91%
TN (mg/l)	1,825	1,409 (23%)	970 (32%)	413 (59%)	173 (59%)	91%
TP (mg/l)	391	140 (64%)	67 (52%)	48 (30%)	26 (54%)	93%
FC (mpn/100ml)	2.1E10	4.9E7 (3 log units)	4.5E5 (2 log units)	1.5E4 (1 log unit)	3.7E3 (1 log unit)	(7 log units)

It can be seen in this table that the BOD_5 was reduced principally in the first anaerobic pond (AP1), showing around 78% removal of this parameter. For the other ponds there were removals of: 64% in the anaerobic pond 2 (AP2), 48% in the facultative pond (FP) and 53% in the water hyacinth pond (WHP), resulting in 97% removal for the pond series. The behavior of the ponds in the removal of COD was identical to that obtained for BOD_5. The removal of total phosphorus was achieved principally in the anaerobic ponds (64% in AP1 and 52% in AP2), along with the solids, settling on the bottom of these ponds. Note however, that the water hyacinth pond was responsible for 54% of the residual phosphorous removal after treatment in ponds AP1, AP2 and FP. The removal of nitrogen occurred principally in the facultative pond (59%) and in the water hyacinth pond (59%). These two ponds removed around 83% of the total nitrogen remaining after treatment in the two anaerobic ponds. In relation to the fecal coliform the pond system was shown to be efficient, with a reduction of 7 log units, the final effluent was found to be within the limits established by the environmental legislation of the state of Santa Catarina-Brazil (FATMA, 1981).

4. System Optimisation

4.1 Treatment efficiency models

The results obtained in the treatment system show that the principal parameters for the optimization of the dimensions of ponds which treat piggery wastes, leaving them within the limits established by environmental legislation (FATMA, 1981), are the BOD_5 and TN.

The degradation constants for BOD and total nitrogen were determined, taking into consideration the degradation rate, through *first order kinetics* and the *complete mixing* model. This consideration is possible, once the average results, obtained at points distributed along the flow of each pond (Medri, 1997), were shown to be almost identical, being individually characterized as a system close to "complete mixing", despite the geometric relation length/width existing for each unit leading to the "piston flux" model.

The value for the degradation of BOD constant varies for each type of pond. With reference to nitrogen, due to the pH which remains almost neutral in the ponds, its removal does not occur through volatilization to the atmosphere. In this way, considering the values of the average influent and effluent concentrations (BOD_5 and TN) for each pond, the mathematical models of efficiency are presented in Equations (1) and (2).

– For the anaerobic ponds, the removal efficiency model for BOD_5 is given by equation (1):

$$Ea_i = \frac{ka_i \, . \, t_i}{1 + ka_i \, . \, t_i} Fa_i \tag{1}$$

where: Ea_i is the removal efficiency of pond i, in relation to BOD_5;
t_i is the retention time of pond i, in days;
ka_i is the degradation constant of BOD_5, in d^{-1};
Fa_i is the calibration factor of the model.

– For the facultative ponds and the water hyacinth pond, the removal efficiency models for the parameters BOD and nitrogen are characterized by the following expressions:

$$E_i = \frac{k_i \, . \, t_i}{1 + k_i \, . \, t_i} \qquad E_i = \frac{k_i' \, . \, t_i}{1 + k_i' \, . \, t_i} \tag{2}$$

where: E_i is the removal efficiency of pond i;
t_i is the retention time of pond i, in days;
k_i and k_i' are the degradation constants for BOD_5 and for TN respectively, in d^{-1}.

Although the kinetics of the removal of BOD_5 (first order kinetics) are same for the anaerobic ponds (AP1 and AP2), the removal rate for BOD_5 increases in accordance with increases in the initial concentration of this parameter. The adjusted efficiency curves for BOD_5 for the ponds AP1 and AP2 are given in Figures 2 and 3. Figures 4 and 5 show the adjusted efficiency curves for BOD_5 and TN for the facultative (FP) and the water hyacinth (WHP) ponds.

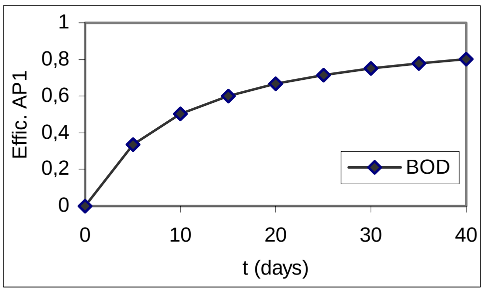

Figure 2 – Relation between BOD removal efficiency and retention in AP1

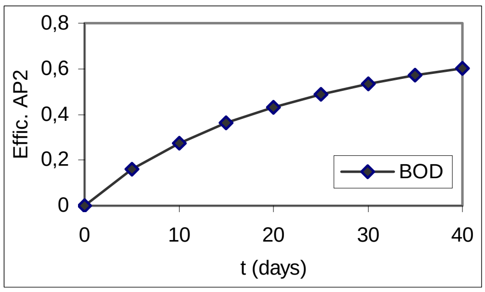

Figure 3 – Relation between BOD removal efficiency and retention time in AP2

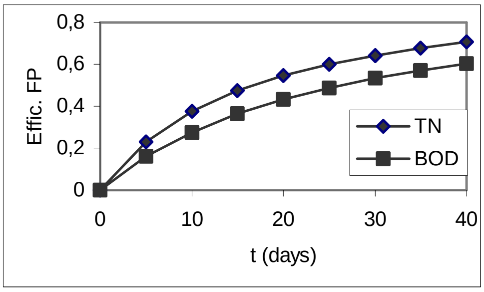

Figure 4 – Relation between BOD and TN removal efficiency and retention time in FP

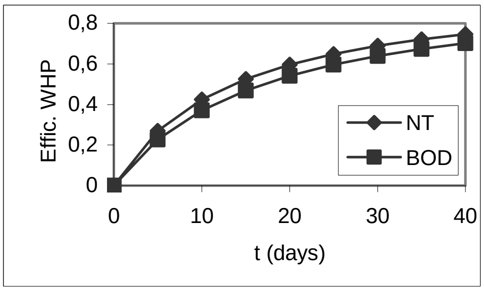

Figure 5 – Relation between BOD and TN removal efficiency and retention time in WHP

4.2 Retention time

For the effective treatment of piggery wastes, whose characteristics in terms of biochemical oxygen demand (BOD_5) and total nitrogen (TN) are 12,000 mg/l and 2,500 mg/l, respectively, the ponds must have a long hydraulic retention time (HRT). In the case of the system utilized, the 4 ponds together amount to 125 days. The retention time of each pond is given by equation (3).

$$t_i = \frac{V_i}{Q} \qquad (3)$$

where: V_i is the volume of pond i, in m^3, and Q is the flow rate of the system, in m^3/day.

4.3 Land cost

The land cost consists of the area occupied by the ponds, increased by 100% for adjacent areas for the circulation of people and/or vehicles. Since the decision variables are the pond efficiencies, which are a function of volume, the mathematical model which best characterizes this cost is given by equation (4).

$$Ct_i = 2.\gamma_i.Pt.V_i \qquad (4)$$

where: Ct_i is the cost of the land occupied by pond i, and areas adjacent to it, in US $;
γ_i is the relation between the surface area and the volume of pond i, in m^2/m^3;
Pt is the price of the land, in US $/$m^2$.

4.4 Construction cost

The cost of construction is a non linear equation, which encompasses clearing the land, mechanical excavation, transport of excess earth and correction of the slope angle of the pond walls. The mathematical model adjusted after calculation of the constants which best express the construction cost of the ponds is represented by equation (5):

$$Cc_i = 5.514\ V_i^{0.678} \qquad (5)$$

where: Cc_i is the construction cost of pond i, in US $.

4.5 Cost of lining the ponds

The ponds were recovered with a lining of flexible PVC obtaining a non linear equation. Therefore, the most adequate model, after the determination of the constants which best express the lining cost of the ponds, is expressed by equation (6):

$$Cr_i = 18.592\ V_i^{0.732} \tag{6}$$

where: Cr_i is the lining cost of pond i, in US $.

4.6 Maintenance costs

The maintenance costs of the system of ponds is estimated on the basis of the minimum number of people necessary for the cleaning of areas adjacent to them. Assuming that the maintenance area of the ponds is equal to the area occupied by them. Therefore, the maintenance of the system is characterized by the summing of the pond areas by equation (7):

$$A_t = A_1 + A_2 + \ldots + A_n \ \Rightarrow\ A_t = \sum_{i=1}^{n} A_i \tag{7}$$

in which $A_i = \gamma_i V_i$ (8)

This emphasized that the pig farmers have monthly expenses, throughout the estimated lifetime of the pond. Researchers in the area, such as Yang *et al.* (1997), through studies on pond systems for the treatment of piggery wastes, indicate a period of 10 years. Given this, the total cost will be calculated on the investment date through equation (9):

$$Ctm = \phi .\, 0.164 \left(\sum_{i=1}^{n} \gamma_i . V_i\right)^{0.830} \tag{9}$$

where $\phi = \dfrac{(1 + r)^n - 1}{r\,(1 + r)^n}$ (10)

Ctm is the total cost of maintenance of the pond system, in US $;
ϕ is the present value factor;
r is the annual interest rate;
n is the useful lifetime of the ponds, in years.

From equations (4) to (10), we have the cost of the ponds:

$$CL_i = 2\gamma_i P_e V_i + 5.514\ V_i^{0.678} + 18.592 V_i^{0.732} + Cm_i \tag{11}$$

From equations (1) and (3), we have the pond volumes:

- for the anaerobic ponds;

$$Va_i = Q.Ea_i\,[ka_i\ (Fa_i - Ea_i)]^{-1} \tag{12}$$

- for the facultative and water hyacinth ponds;

$$V_i = \frac{Q}{2}\{E_i\,[K_i(1-E_i)]^{-1} + E_i\,[k_i'(1-E_i)]^{-1}\} \tag{13}$$

Substituting equation (12) in equation (11), we have the cost of the anaerobic ponds:

$$\begin{aligned} Ca_i = {} & 2.\gamma_i.Pe.Q.Ea_i\,[Ka_i\,(Fa_i - Ea_i)]^{-1} + \\ & 5.514\{Q.Ea_i\,[Ka_i\,(Fa_i - Ea_i)]^{-1}\}^{0.678} + \\ & 18.592\{Q.Ea_i\,[Ka_i\,(Fa_i - Ea_i)]^{-1}\}^{0.732} + Cm_i \end{aligned} \tag{14}$$

where: Ca_i is the cost of the anaerobic pond i, in US \$.

Substituting equation (13) in equation (11), we have the cost of the facultative and water hyacinth ponds:

$$\begin{aligned} C_i = {} & Q.Pt.\{\gamma_i[E_i(k_i(1-E_i))^{-1} + E_i(k_i'(1-E_i))^{-1}]\} + \\ & 5.514\{\frac{Q}{2}[E_i(k_i(1-E_i))^{-1} + E_i(k_i'(1-E_i))^{-1}]\}^{0.678} + \\ & 18.592\{\frac{Q}{2}[E_i(k_i(1-E_i))^{-1} + E_i(k_i'(1-E_i))^{-1}]\}^{0.732} + Cm_i \end{aligned} \tag{15}$$

5. Objective Function

The objective function in the cost estimation of the system of ponds is given by expression (16):

$$\begin{aligned} & Min\ \ C_T = \sum_{i=1}^{n} Ca_i + \sum_{i=1}^{n} C_i \\ & s.t.: \quad E_O \geq E_d \\ & \qquad 0 \leq Ea_i \leq 1 \quad and \quad 0 \leq E_i \leq 1 \end{aligned} \tag{16}$$

where: C_T is the total cost of the system, in US \$;
E_o is the efficiency obtained by the system;
E_d is the desired efficiency of the system.

6. Practical Application

Studies carried out on the water hyacinth pond with a superficial area of 100 m^3 in the experimental system for the treatment of piggery wastes at EMBRAPA-CNPSA, in Concórdia/SC, indicate that the maintenance cost of the water hyacinth pond is approximately double that of other ponds with the same area (Medri *et al.*, 1996). This emphasizes, therefore, the necessity for carrying out more detailed studies concerning the maintenance costs of water hyacinth ponds.

Assuming a 10 year lifetime and an interest rate of 15% per year, the present value factor ϕ given by equation (10) will be equal to 64.3. This considers the average concentrations at the entrance and exit of each pond and their detention times. Table 3 shows the values for the degradation constants for BOD (k_{BOD}) and for nitrogen (k_{TN}) for the ponds, the hydraulic retention time (HRT), average temperatures and the superficial area/volume relations for each pond (γ_i).

Table 3 – Results for the practical application.

Pond	k_{BOD} (d^{-1})	k_{NT} (d^{-1})	HRT (d)	Average Temperature (°C)	γ_i (m^2/m^3)
AP1	0.101	–	35	21.6	0.8
AP2	0.038	–	46	20.6	0.65
FP	0.038	0.060	24	19.8	1.1
WHP	0.059	0.074	20	22.1	1.1

Therefore, considering the four ponds studied AP1, AP2, FP and WHP at CNPSA, equation (16) can be rewritten as:

$$
\begin{aligned}
Min\ \ C_T = {} & 2x0.80.Pt.Q.Xa_1[0.101(Fa_1 - Xa_1)]^{-1} + 5.514\{Q.Xa_1[0.101(Fa_1 - Xa_1)]^{-1}\}^{0.678} + \\
& 18.592\{Q.Xa_1[0.101(Fa_1 - Xa_1)]^{-1}\}^{0.732} \quad + \\
& 2x0.65.Pt.Q.Xa_2[0.038(Fa_2 - Xa_2)]^{-1} + 5.514\{Q.Xa_2[0.038(Fa_2 - Xa_2)]^{-1}\}^{0.678} + \\
& 18.592\{Q.Xa_2[0.038(Fa_2 - Xa_2)]^{-1}\}^{0.732} \quad + \\
& 1.10.Pt.Q\{X_1[0.038(1 - X_1)]^{-1} \quad + \quad X_1[0.060(1 - X_1)]^{-1}\} \quad + \\
& 5.514\{\frac{Q}{2}[X_1(0.038(1 - X_1))^{-1} \quad + \quad X_1(0.060(1 - X_1))^{-1}]\}^{0.678} \quad + \\
& 18.592\{\frac{Q}{2}[X_1(0.038(1 - X_1))^{-1} \quad + \quad X_1(0.060(1 - X_1))^{-1}]\}^{0.732} \quad + \\
& 1.10.Pt.Q\{X_2[0.059(1 - X_2)]^{-1} \quad + \quad X_2[0.074(1 - X_2)]^{-1}\} \quad + \\
& 5.514\{\frac{Q}{2}[X_2(0.059(1 - X_2))^{-1} \quad + \quad X_2(0.074(1 - X_2))^{-1}]\}^{0.678} \quad + \\
& 18.592\{\frac{Q}{2}[X_2(0.059(1 - X_2))^{-1} \quad + \quad X_2(0.074(1 - X_2))^{-1}]\}^{0.732} \quad + \\
& 64.3x0.164\{Q[0.80.Xa_1(0.101(Fa_1 - Xa_1))^{-1} + 0.65.Xa_2(0.038(Fa_2 - Xa_2))^{-1}] \quad + \\
& \frac{Q}{2}[1.10(X_1(0.038(1 - X_1))^{-1} \quad + \quad X_1(0.060(1 - X_1))^{-1}) \quad + \\
& 2^{(1/0.830)}.\ X_2(0.059(1 - X_2))^{-1} \quad + \quad X_2(0.074(1 - X_2))^{-1}]\}^{0.830}
\end{aligned}
$$

$$
s.t.: \qquad 1 \quad - \quad [(1 - Xa_1).(1 - Xa_2).(1 - X_1).(1 - X_2) \quad \geq \quad E_d
$$

$$
0 \leq Xa_1 \leq 1, \quad 0 \leq Xa_2 \leq 1, \quad 0 \leq X_1 \leq 1, \quad 0 \leq X_2 \leq 1
$$

The results obtained in the monitoring of the treatment system indicate reductions of total nitrogen in the anaerobic ponds. These reductions are due to the sedimentation of suspended organic nitrogen and the hydraulic retention time of the ponds. Given this, a calibration factor (Fa_i) was used for these ponds, varying between 0.6 and 0.8.

Table 4 shows the physical characteristics of the ponds and the costs for land, mechanical excavation, lining of the ponds and maintenance of the system, assuming that the emptying rate is of 30 m^3/d, that the land price is US $ 3,000.00/ha and that the efficiency of the system is 98%, and considering $Fa_1 = 0.7$ and $Fa_2 = 0.8$. Table 5 presents the results for the model calibration.

Table 4 – Results of practical application to physical characteristics of the ponds and the costs.

Pond efficiency	Retention time (days)	Pond volume (m^3)	Pond area (m^2)
$E_1 = 0.508$ $E_2 = 0.390$ $E_3 = 0.761$ $E_4 = 0.721$	$t_1 = 26$ $t_2 = 25$ $t_3 = 68$ $t_4 = 40$	$V_1 = 786$ $V_2 = 750$ $V_3 = 2{,}052$ $V_4 = 1{,}183$	$A_1 = 629$ $A_2 = 488$ $A_3 = 2{,}257$ $A_4 = 1{,}301$
Earth cost (US $)	Construction cost (US $)	Lining cost (US $)	Maintenance costs (US $)
$C_{e1} = 377.50$ $C_{e2} = 292.55$ $C_{e3} = 1{,}354.50$ $C_{e4} = 780.45$	$C_{c1} = 506.68$ $C_{c2} = 490.70$ $C_{c3} = 970.87$ $C_{c4} = 668.10$	$C_{r1} = 2{,}448.83$ $C_{r2} = 2{,}365.51$ $C_{r3} = 4{,}941.77$ $C_{r4} = 3{,}300.79$	$C_{m1} = 1{,}673.14$ $C_{m2} = 1{,}296.63$ $C_{m3} = 6{,}003.38$ $C_{m4} = 6{,}918.20$
Total: 2,805.00	2,636.35	13,056.90	15,891.35

Total cost of the system: US $ 34,389.60

Table 5 – Results for the model calibration.

	P O N D S				
Efficiency	AP1	AP2	FP	WHP	TOTAL
BOD TN	0.726 0.200	0.487 0.200	0.722 0.804	0.699 0.745	0.988 0.968

In the calculation, the nitrogen reduction in the anaerobic ponds will be considered 20% for each of them, if the detention times exceed 20 days, otherwise will be 10%.

7. Conclusions

The model is dynamic and flexible, permitting the introduction of various types of ponds, selected according to their performance and economic aspects, and allowing the control of concentrations of BOD_5 and total nitrogen of the treated effluent, for discharge into the receiving bodies.

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