Dynamic Model of Different Configurations of Stabilization Pond Systems

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Abstract. In this work different configurations of stabilization ponds are considered. Dynamic modeling of each pond was implemented within a dynamic optimization environment and the whole system was simulated during a time horizon of four months. A detailed mechanistic model is constructed, based on first principles of mass conservation, of different types of systems of anaerobic, aerobic and facultative ponds in series in order to compare their performance.
Model takes into account dynamic mass balances of biomass of algae, the main groups of bacteria: heterotrophic bacteria, autotrophic bacteria, fermenting bacteria, acetotrophic sulphate reducing bacteria and acetotrophic methanogenic bacteria. Also, mass balances for organic load were formulated, such as slowly biodegradable particulate COD (Xs), inert particulate COD (XI), fermentation products (SA), inert soluble COD (SI), and fermentable readily biodegradable soluble COD (SF). For nutrients, ammonium and ammonia nitrogen (NH), nitrate and nitrite nitrogen (NO), sulphate sulphur (SO_4) and dissolved oxygen (DO). Finally, molecular nitrogen (N_2) and methane (CH_4) emissions were considered in the model.
For the whole time horizon, we find that the conventional configuration is better than the actual configuration of the wastewater treatment plant. Even though the differences are not as high as expected, this fact influences the total energy consumption by the aerators of the aerobic ponds.

Keywords: Wastewater - Stabilization Ponds System – DAE

1 Introduction

Wastewater generation is inevitable and its discharge into surface waters leads to environmental problems such as odor, eutrophication, depletion of dissolved oxygen, loss of biodiversity, also health risk, etc. For these reasons, with growing environmental concern, standards for wastewater discharge have been enforced and are expected to become stricter [1].

Waste stabilization pond systems offer the simplest solution for treatment of wastewater and are a suitable and widespread technology in developing countries especially in rural areas. It usually requires low investment costs and also has low operation and maintenance costs. Wastewater treatment in stabilization ponds mainly results from settling and complex symbiosis of bacteria and algae where the oxidation of organic matter is accomplished by bacteria in presence of dissolved oxygen supplied by algal photosynthesis and surface re-aeration [2].

The major aim of wastewater treatment is to convert the waste materials into stable oxidized end products which can be safely discharged to inland or coastal waters without any adverse ecological effect. The quality of the effluent and its volume determine the unit processes selected in the design of a wastewater treatment plant [3].

Waste stabilization pond systems (WSPS) normally consist of a combination of three different types of ponds: anaerobic, facultative and maturation ponds. They are generally classified by the type of biological activity. Anaerobic ponds are primarily designed to enhance settling and subsequent bulk removal of organic load via the anaerobic digestion of particulate organic solids. In this process the removal of biochemical demand of oxygen (BOD) is a combined effect of sedimentation and biological degradation via hydrolysis, acidogenesis, acetogenesis and methanogenesis. A facultative pond mainly focuses on the removal of BOD and nutrients, but can also remove pathogens. The symbiosis between photosynthetic algae and heterotrophic bacteria is the key feature of this type of ponds. In addition, the simultaneous presence of aerobic, facultative and anaerobic zones results in a high complexity. Finally, a maturation pond is a shallow basin in which an aerobic condition is maintained over the entire depth of the pond [1].

In this paper, we present the application of a detailed mechanistic model, based on first principles of mass conservation, of different types of systems of anaerobic, aerobic and facultative ponds in series in order to compare their performance. One configuration consists of two aerobic ponds in series followed by a facultative one, which represents a wastewater treatment plant from a juice industry [4]. The other is the conventional configuration, as shown in Fig. 1. Dimensional parameters are listed in appendix.

Dynamics mass balances for biomass, nutrients, dissolved oxygen and COD concentrations are formulated. It reasonably represents the process dynamics to be used in estimating the effluent quality under different operating conditions.

Obtained results provide useful information about the complex relationships between microorganism, nutrients and organic matter concentration of the pond's systems.

2 Model Stabilization Ponds System

Model takes into account dynamic mass balances of biomass of algae (ALG), the main groups of bacteria: heterotrophic bacteria (HB), autotrophic bacteria (AB), fermenting bacteria (FB), acetotrophic sulphate reducing bacteria (ASRB) and acetotrophic methanogenic bacteria (AMB). Also, mass balances for organic load were formulated, such as slowly biodegradable particulate COD (Xs), inert particulate COD (XI), fermentation products (SA), inert soluble COD (SI), and fermentable readily biodegradable soluble COD (SF). For nutrients, ammonium and ammonia nitrogen

(NH), nitrate and nitrite nitrogen (NO), sulphate sulphur (SO_4) and dissolved oxygen (DO). Finally, molecular nitrogen (N_2) and methane (CH_4) emissions were considered in the model.

This results in a complex system of differential and algebraic equations. However, homogeneous conditions are supposed in the aerobic and anaerobic lagoons, whereas two horizontal layers describe the facultative pond.

Sedimentation processes are neglected due to the previous primary separation stage in the rotary sieves.

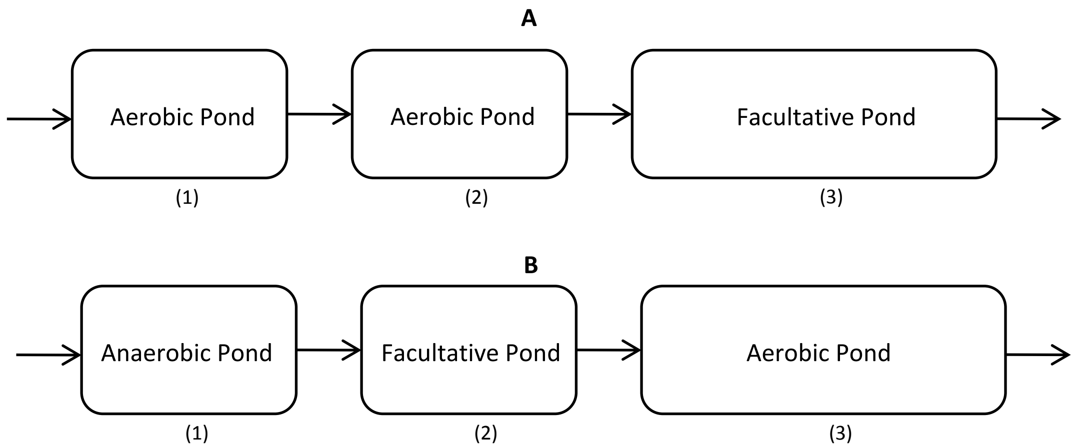

Fig. 1. (A) Actual configuration and (B) conventional configuration of the pond system.

Balances include inlet and outlet flows, generation, consumption, transfer between layers and volume variation terms.

$$\frac{dC_{Uj}}{dt} = \frac{Q_{IN}}{V_U} C_{IN_{Uj}} - \frac{Q_{OUT}}{V_U} C_{Uj} + r_{Uj} - \frac{k_d A}{\Delta h\, V_U} \quad C_{Uj} - C_{Lj} \quad - \frac{C_{Uj}}{h_U} \frac{dh_U}{dt} \tag{1}$$

$$\frac{dC_{Lj}}{dt} = r_{Lj} + \frac{k_d A}{\Delta h\, V_U} \quad C_{Uj} - C_{Lj} \tag{2}$$

j=ALG, HB, AB, FB, ASRB, AMB, S, PI, A, SI, F, NH, NO, SO_4, N_2, CH_4, DO.

Where C represents the concentration of j component in the upper (U) and lower (L) layer, Q_{in} and Q_{out} represent the inlet and outlet flow respectively, r_{Uj} and r_{Lj} correspond to net generation of j in each layer, k_d is the diffusion rate between layers, h is the water column height, A is the pond transversal area, V is the pond volume, Δh is the sum of the middle height of each layer.

An overall mass balance is also formulated, where contributions of rain (Q_{rain}) and evaporation (Q_{evap}) are considered.

$$\frac{dh_T}{dt} = \frac{1}{A} \quad Q_{in} - Q_{out} + Q_{rain} - Q_{evap} \tag{3}$$

Where h_T is the total water column height.

The external forcing functions for the model are temperature, solar radiation, precipitation, evaporation, inlet flow and concentration of nutrients. Sinusoidal functions were used to approximate them [5]. Other algebraic equations correspond to generation and consumption of modelled biomass, considering growth and decay.

Nutrients availability (N), temperature (T) and light intensity (I) impact on biomass growth and are included thought limiting functions using a multiplicative model. This type of functions decreases the maximum growth rate by taking values between 0 and 1.

$$R_{ij,growth} = k_{ij,growth}\, f\ T\ _{ij} f\ N\ _{ij} f\ I\ _{iALG} f\ COD\ _{ij\neq ALG}\, C_{ij} \tag{4}$$

$$R_{ij,decay} = k_{ij,decay}\, f(T)_{ij}\, C_{ij} \tag{5}$$

j=ALG, HB, AB, FB, ASRB, AMB. *i*= Upper layer, Lower layer.

Monod type kinetics is used to model most of the nutrients concentration and all types of COD as limiting for biomass growth.

Physical, chemical and biochemical reactions are highly influenced by temperature. In general, organic matter degradation rate increases with temperature. Biomass growth and decay are assumed to increase exponentially with temperature, following an Arrhenius' type behaviour.

On the other hand, light intensity plays a fundamental role in the photosynthetic activity. Steele's equation with Beer's law is used to model its effect though the water column depth [5].

Main processes that take place within the lagoons are listed in Table 1, whose kinetic expressions were taken from Sah et al. [6]. They are classified by the condition of the pond where they are most likely to occur. Within the aerated pond and the upper layer of the facultative pond aerobic processes are favoured, where the availability of dissolved oxygen is higher. However, anaerobic and anoxic processes are favoured in the anaerobic pond and in the lower layer of the facultative pond.

3 Numerical Results

The model was formulated in the gPROMS platform and solved by DASOLV [9].

The main objective of the work is to compare the performance of the different configuration pond system, by the amount of organic matter in the effluent of the treatment plant.

Globally, it can be observed in Fig. 2 that the total COD concentration in the effluent is lower in the conventional configuration (B) than the actual configuration of the plant (A).

Different types of sources of COD were analyzed. Inert particulate COD (XI) and inert soluble COD (SI) contribution was almost the same for both configuration due to its inertness. In addition to, the fermentable readily biodegradable soluble COD's (SF) contribution was low, being lower for the conventional configuration because of the fermenting bacteria action.

Table 1. Main processes of the different ponds.

<table>
<tr><th>Aerated Pond</th><th>Upper Layer
Facultative Pond</th><th>Lower Layer
Facultative Pond</th><th>Anaerobic Pond</th></tr>
<tr><td colspan="2">Algal growth on ammonium and ammonia</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Algal growth on nitrate and nitrite</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Aerobic growth of Heterotrophic Bacteria on fermentation products</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Aerobic growth of Heterotrophic Bacteria on fermentable readily biodegradable soluble COD</td><td>-</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td colspan="2">Anoxic growth of Heterotrophic Bacteria on fermentation products</td></tr>
<tr><td>-</td><td>-</td><td colspan="2">Anoxic growth of Heterotrophic Bacteria on fermentable readily biodegradable soluble COD</td></tr>
<tr><td colspan="2">Growth of Autotrophic Bacteria</td><td></td><td></td></tr>
<tr><td>-</td><td>-</td><td colspan="2">Growth of Fermenting Bacteria</td></tr>
<tr><td>-</td><td>-</td><td colspan="2">Growth of Acetotrophic Sulphate Reducing Bacteria</td></tr>
<tr><td>-</td><td>-</td><td colspan="2">Growth of Acetotrophic Methanogenic Bacteria</td></tr>
<tr><td colspan="3">Decay of Algae</td><td>-</td></tr>
<tr><td colspan="4">Decay of Heterothopic Bacteria</td></tr>
<tr><td colspan="2">Decay of Autotrophic Bacteria</td><td>-</td><td>-</td></tr>
<tr><td colspan="4">Decay of Fermenting Bacteria</td></tr>
<tr><td colspan="4">Decay of Acetotrophic Sulphate Reducing Bacteria</td></tr>
<tr><td colspan="4">Decay of Acetotrophic Methanogenic Bacteria</td></tr>
<tr><td>-</td><td>-</td><td colspan="2">Hydrolysis</td></tr>
<tr><td colspan="2">Natural Reaeration</td><td>-</td><td>-</td></tr>
<tr><td>Mechanical Reaeration</td><td>-</td><td>-</td><td>-</td></tr>
</table>

On the other hand, the main contribution to the total COD concentration was the slowly biodegradable particulate COD (Xs) concentration followed by the fermentation products (SA) concentration. The former was higher in the actual configuration because of the higher concentration of death biomass within this pond system. However, the latter was higher in the conventional configuration due to the fermenting bacteria production.

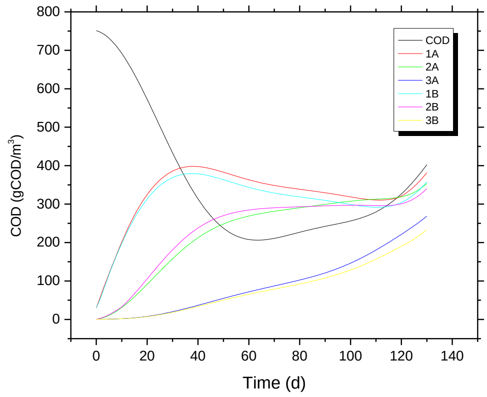

Fig. 2. Total COD concentration. — COD inlet concentration, —1A, —2A, —3A, —1B, —2B, —3B.

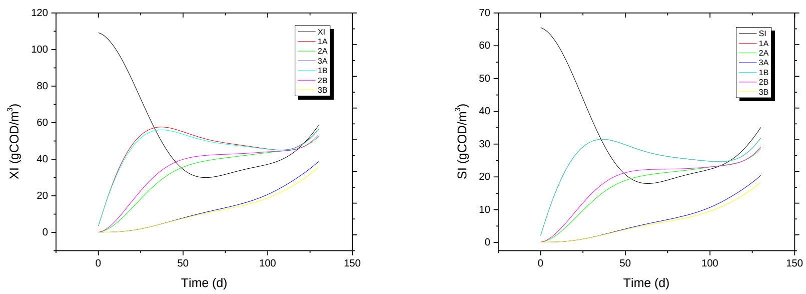

Fig. 3. Inert Particulate COD (XI) and Inert Soluble COD (SI) Concentration. — XI inlet concentration, — SI inlet concentration, —1A, —2A, —3A, —1B, —2B, —3B.

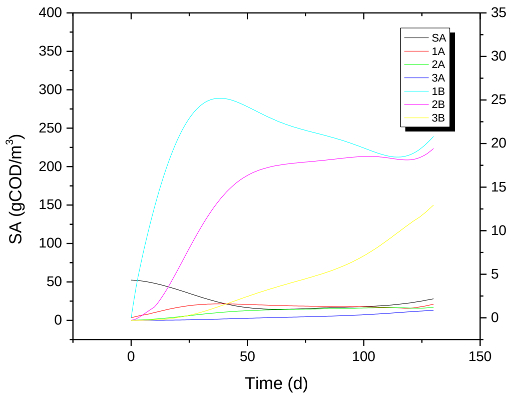

Fig. 4. Fermentation Products (SA) Concentration. — SA inlet concentration, —1A, —2A, —3A, —1B, —2B, —3B.

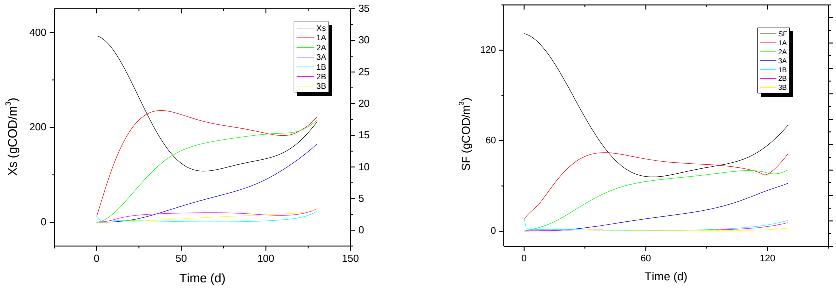

Fig. 5. Slowly Biodegradable Particulate COD (Xs) and Fermentable Readily Biodegradable Soluble COD (SF) Concentration. — Xs inlet concentration, — SF inlet concentration, —1A, —2A, —3A, —1B, —2B, —3B.

4 Conclusions

In this work, we present and adapt a detailed mathematical mechanistic model for different configurations of stabilization ponds systems in order to compare the performance of oxidizing organic matter.

It results that the conventional configuration is better, for the whole horizon of time, than the actual configuration of the wastewater treatment plant. Even though the differences are not as high as expected, this fact influences the total energy consumption by the aerators of the aerobic ponds.

The results provide useful information on the complex relationship among microorganisms, nutrients and organic matter concentration, as well as information about the impact of modification in the pond system that can be used to improve the control of the composition of the effluent.

5 Appendix

Table 1A. Dimensional parameters of the ponds.

	Pond 1	Pond 2	Pond 3
Volume (m^3)	15000	15000	55000
Area (m^2)	6250	6250	18750
Residence time (d)	3	3	11

6 Acknowledgements

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