Design of a Chemically Enhanced Wastewater Treatment Lagoon in Brazil

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Abstract

This paper describes the design of an upgrade for an overloaded wastewater treatment facility in the state of São Paulo, Brazil. The current facility serves 50,000 people and consists of an anaerobic lagoon followed by a facultative lagoon that only removes 42% of the chemical oxygen demand. The design proposed by Sabesp, the state environmental agency, will replace the existing lagoons with mechanically aerated basins followed by settling basins.

The authors were given permission to visit the current lagoons and to offer alternate design(s). We recommend chemically enhanced primary treatment (CEPT) as the central feature of the alternate design. CEPT is the process whereby metal salts are added to the wastewater to enhance the removal of solids, organics, and phosphorus via coagulation and flocculation. Two design alternatives are presented and compared, on the basis of performance and cost, with the proposed Sabesp design. The first involves the construction of a small CEPT tank ahead of the lagoons. The second is the addition of the chemical coagulants directly to the inlet of the first lagoon. Jar-tests conducted at the site show that both design alternatives have comparable removal efficiencies with respect to the proposed Sabesp design, while significantly reducing both capital and operations and maintenance costs.

Introduction

The treatment and disposal of wastewater is of prime importance for environmental and health reasons. Yet, costs and available space are often limiting factors in the improvement or creation of wastewater treatment systems in developing countries.

This report centers on the design of a chemically enhanced primary treatment station in Brazil, for a small city located approximately 140 km inland from the city of São Paulo, that has a population of about 120,000. The present treatment facilities are over-loaded, and hence insufficient.

The objectives of this project are to design a CEPT lagoon treatment plant, and compare this new design with the design currently proposed by the State of São Paulo Environmental Agency (Sabesp.) The proposed design consists of mechanically aerated basins followed by settling basins. It is thought that the operations and maintenance costs of the CEPT plant will be more competitive than those of the Sabesp design.

During a field visit to Brazil in January 1999, the authors assessed the conditions of the treatment lagoons, and conducted jar-tests with the local raw sewage to predict the dosage and efficiency of CEPT treatment.

Chemically Enhanced Primary Treatment: An Overview

CEPT is the process by which chemicals (metal salts) and/or organic polyelectrolytes (polymers) are added to primary sedimentation basins to enhance the removal of solids (TSS) and their associated biochemical oxygen demand (BOD)[1] from wastewater via coagulation and flocculation. The chemicals typically involved include iron salts and/or aluminum salts and the polymers utilized can be anionic, cationic, or non-ionic. It is important to note that the chemicals added in CEPT are the same ones commonly added in potable water treatment, and that there is largely no residual iron or aluminum in the supernatant from the metal salts (Harleman & Murcott, 1992).

One of the key benefits of CEPT sedimentation basins is that they can be operated at overflow rates 2 to 3 times greater than those of conventional primary settlers, while still maintaining a high removal rate of TSS[2] and BOD (due to increased settling velocities) (Murcott and Harleman, 1992).

CEPT has been around for over one hundred years, yet it is not as commonly used as would be expected upon analysis of its performance. The notion is that CEPT utilized far too great an amount of coagulants and therefore incurred high costs and also dramatically increased sludge production. The use of polymers along with relatively low doses of metal salts as in Southern California (Harleman & Morrissey, 1992) allows treatment in which the greatest portion of the increase of sludge production is due to its increased efficiency of TSS removal in primary clarifiers.

As early as the 1960's, an attempt was made to treat the wastewater in stabilization lagoons by chemical addition (Hanaeus, 1991). These chemically enhanced lagoons work in relatively the same manner as conventional lagoons. The only difference is the chemical addition and thus a higher sludge accumulation due to an increased removal efficiency. In-pond CEPT lagoons are most prevalent and have been most-extensively studied in Scandinavia, where they are called fellingsdams (Hanaeus 1991).

CEPT removes a high amount of phosphorus[3], which can prevent the eutrophication of receiving waters. Biological secondary treatment removes TSS and BOD at a very high efficiency, but does not effectively remove phosphorus. If this effluent does not undergo nutrient removal (an expensive process) before it is released into a body of water, eutrophication resulting in algal blooms will deprive the water body of oxygen, which would, in effect, be the same as releasing a high-BOD effluent into that body of water.

The type of metal salt and polymer, as well as the optimal dosage, are determined by performing jar-tests at the intended wastewater site. It should be noted that jar-tests slightly over-predict TSS removal (Harleman & Murcott, 1992)

The chief mixing regime for the jar-test consisted of a mixing intensity of 100 rpm for a duration of 15 seconds to mix the raw sewage. Then the primary coagulant was added and the mixing continued for 30 more seconds. The polymer was then added and the mixing continued for another 30 seconds. The sample was then mixed for 2.5 minutes at 70 rpm, then 2.5 more minutes at 30 rpm, then allowed to settle for 5 minutes, at which the samples were taken (Gotovac, 1999). In the case that no polymer was added, that 30-second-100-rpm-mixing period was omitted. The chemical coagulants utilized were ferric sulfates and ferric chlorides[4]. Tests were conducted to test the use of recycled chemical sludge as a coagulant, but did not improve effluent quality. CEPT is a very low-cost, effective, and easily implemented treatment process.

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[1] Along with a high removal of phosphorus and heavy metals.

[2] A high removal rate of TSS is always desired due the adsorption of toxins to particulates.

[3] CEPT is utilized for phosphorus removal by a number of facilities which discharge their effluent into the Great Lakes (Harleman & Murcott, 1992).

[4] Lime was not chosen as a candidate for the optimum chemical coagulant because of the increased sludge generation.

Lagoon Modeling

Modeling the processes that occur in a waste stabilization lagoon is an essential part of this study. Indeed, the model will compare the proposed design with that of a CEPT system and smaller lagoons. The model will also be useful for lagoon sizing and configuration.

The waste-stabilization lagoon model developed at MIT (Ferrara & Harleman, 1980), describes both hydraulic transport and biological and chemical transformation of material. The model was extensively tested on waste stabilization lagoons in the United States. The dynamic mathematical model for predicting the effluent quality of stabilization lagoons (Ferrara & Harleman, 1981) shows that the fully mixed hydraulic assumption is valid for most waste stabilization lagoons. The underlying hydraulic assumption in the model is therefore that the concentration of all model variables is uniform in the entire pond. The implications of assuming the ponds to be fully mixed are that the predicted efficiency will be less than a plug-flow model. However, the fully mixed assumption ignores dead-zones and short-circuiting.

The bio-geo-chemical part of the MIT model is based on five general principles:

1. Mineralization of organic compounds: assumed to be first-order with respect to organic matter concentration.
2. Organism growth: proportional to organic matter concentration.
3. Net loss of material by settling of non-biodegradable organic matter, precipitation and adsorption of inorganic phosphorous, and denitrification: assumed to be first-order.
4. Atmospheric release of CO_2: first-order reaction with respect to difference between saturation and actual concentration of CO_2.
5. Removal of fecal coliform by death and predation: assumed to be first-order.

The MIT model was developed and tested with data from lagoon treatment systems in Corinne, Utah and in Kilmichael, Mississippi.

In our case, the data available and output desired were much related. Indeed, in Brazil, the main effluent constraints pertaining to environmental legislation revolve around oxygen demand. The model was therefore restricted to two governing equations that consider mineralization of organic compounds, settling of organic matter, atmospheric losses and organism growth (Chagnon, 1999).

The governing equations were programmed using the Runge-Kutta 4^{th} order algorithm for numerical approximation. The parameters were fit to data from a coastal resort community located about 140-km northeast of São Paulo. A private company manages the water supply and sanitation, and the resort-city is fully sewered. The wastewater treatment plant is a system of lagoons. The raw influent is directed through an anaerobic pond, and it is subsequently directed to one of three facultative ponds.

The lagoons are monitored regularly in terms of water quality and organic-load removal efficiency. Data from the plant (Tsukamoto, 1999) was used for model-fitting purposes. The MIT model had previously only been applied to waste stabilization ponds in the United-States. It was therefore necessary to calibrate the model to Brazilian data, before using it in a predictive mode at other locations in Brazil.

The calibrated MIT model applied to the anaerobic lagoon data is presented in Figure 1. Visual inspection of the model reveals that the fit is rather good. The calibrated parameters are extremely close to the parameters for the Kilmicheal and Corinne ponds. This tends to show that the modeling framework used is robust.

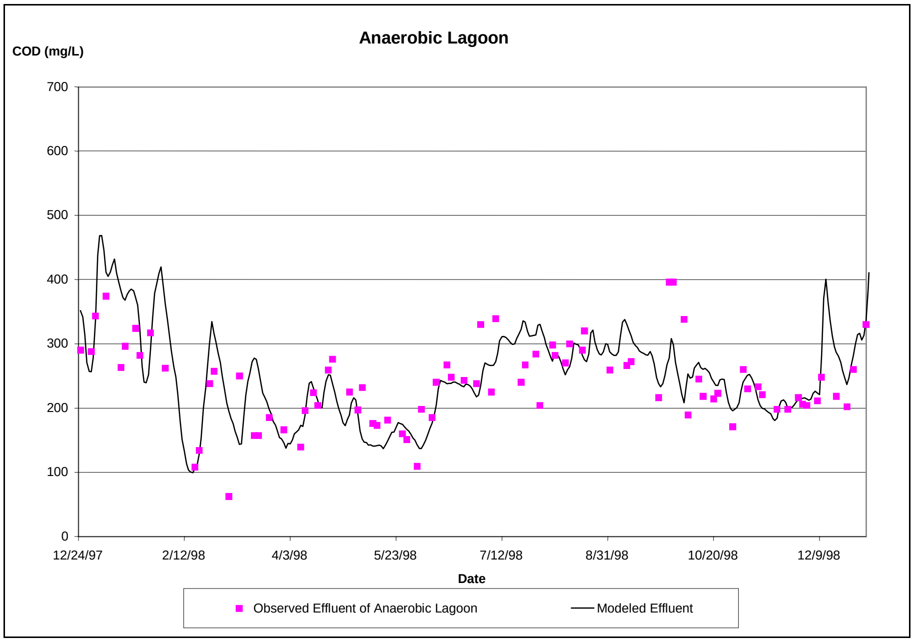

Figure 1: MIT-Model calibrated to Resort-Community Anaerobic Lagoon

Sabesp Design

The Sabesp design for the inland wastewater treatment plant (WWTP) is composed of mechanically-aerated basins followed by a settling basins. The aeration basins have a 4-day retention time, and are equipped with a total of 20 aerators rated at 15hp each. The area occupied by the aeration basins is 1.2 ha and each basin operates with five aerators. This 300hp aeration system is designed to prevent solids from settling and promote aerobic biodegradation. The particles from the aerated basins' effluent are removed by sedimentation in the following 1-day retention time settling basins. These settling basins are designed to accumulate sludge for one or two years. The expected total efficiency of the system is expected to be 92% for BOD removal, which would produce an effluent with 24 mg/L of BOD5, well under the State limit of 60 mg/L of BOD. However, supporting data from operating aerated basins was not available. The sludge would be removed from the settling tank after degrading, and de-watered in sludge drying beds. Figure 2 shows the scheme of Sabesp´s treatment system.

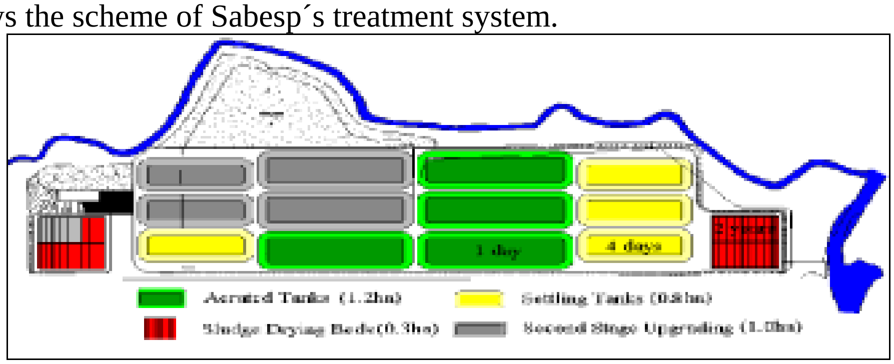

Figure 2: Proposed SABESP Design

Design Alternatives

The two design alternatives proposed by the authors use CEPT to remove organic load and solids before the biological treatment lagoons. The pre-pond CEPT alternative is composed of a CEPT tank where the precipitation and settling occurs. The CEPT tank is followed by stabilization lagoons (one anaerobic and one facultative in series.) The CEPT tank is designed to have a retention time of at least an hour. Based on jar-tests at the site, the CEPT tank is designed to remove about 75% of the solids (TSS) and 55% of the organic loud (BOD).

The MIT lagoon model was used to size the waste stabilization ponds that will follow the CEPT stage. Using the MIT model with the design values as inputs, it is found that a 1.8 ha pond of 4.5 meters depth will achieve an average yearly COD removal of 46% (Chagnon, 1999). The design of this anaerobic pond would permit the use of the existing second pond (facultative pond) as final polishing for the effluent. The average BOD removal for the existing facultative pond is 20%. Only part of the existing lagoons would be used in this scheme. The anaerobic lagoon would be partially dredged, and the exceeding area (0,6 ha) filled and used as a composting area. The existing facultative pond would not require any adaptation. With the CEPT tank associated to the lagoons, the numerical lagoon model shows an expected total efficiency of about 78%, and the final effluent would have a BOD concentration of 59 mg/L.

The final effluent concentration could be readily reduced by optimizing the CEPT tank dosage based on seasonal changes in the overall treatment. The sludge produced in the CEPT Tank would be stabilized, dewatered, and mixed with other municipal solid residues for composting. Figure 3 shows the scheme of the first CEPT treatment alternative.

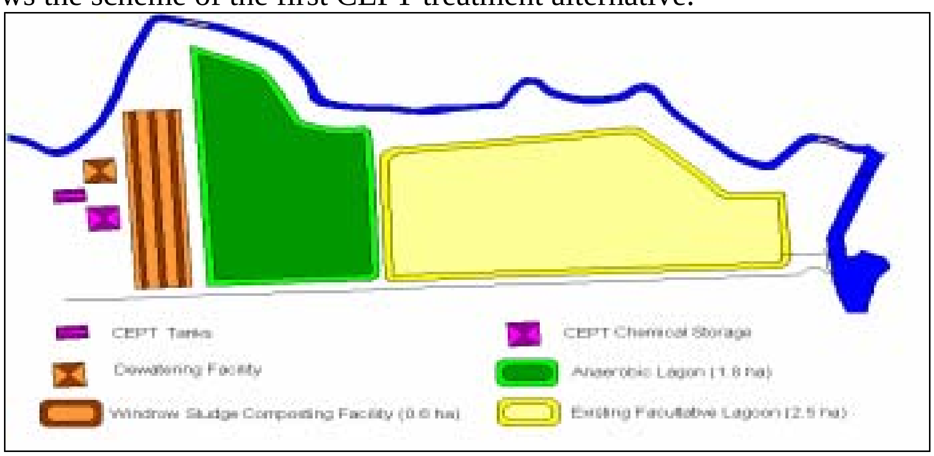

Figure 3: Pre-pond CEPT Alternative

In the In-pond CEPT alternative, chemicals are added to the inlet of the first pond. Part of the existing anaerobic lagoon (0,6 ha) is used to settle and accumulate the solids. The In-pond CEPT is a treatment system used in Sweden and Finland (Hanaeus, 1991). This CEPT lagoon would accumulate the sludge for one or two years allowing it to biodegrade. The effluent of the lagoon would undergo further treatment in the following facultative lagoons. The existing anaerobic lagoon would be dredged and a dike would be placed to separate the CEPT lagoon (0,6 ha) from the anaerobic lagoon (1,8 ha). The following facultative pond would be used for further treatment with no adaptation required. The expected efficiency of this CEPT treatment system is around 83% (47 mg/L). The sludge dredged every other year in the CEPT lagoon would be landfilled. Figure 4 shows the scheme of the In-pond CEPT treatment alternative.

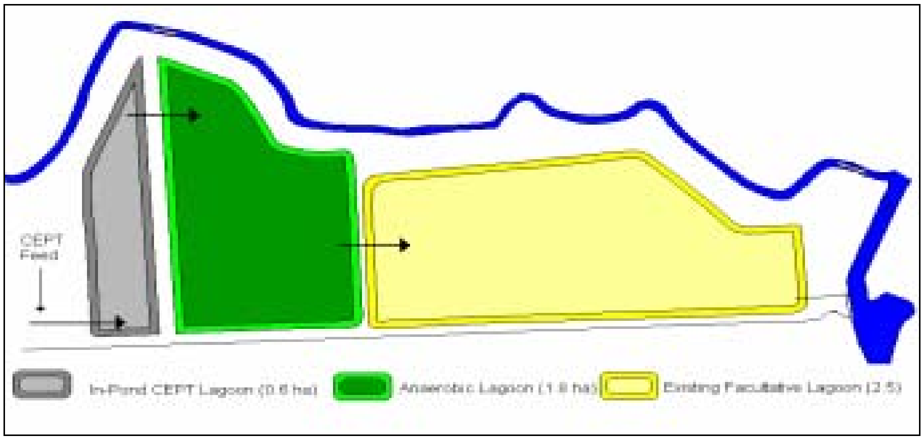

Figure 4: In-Pond CEPT Alternative

Table 1 presents the average predicted effluent BOD5 concentration from the designed first pond for Alternatives 1 and 2. The yearly averaged final effluent predictions satisfy the required effluent quality limit of 60 mg/L of BOD for both alternatives 1 & 2.

Table 1: Predicted Effluent Qualities from Lagoons

Treatment Alternative	Average Influent BOD5 [mg/L]	CEPT Effluent BOD5 [mg/L]	First Pond Effluent BOD5 [mg/L]	Final Effluent BOD5 [mg/L]
(1) Pre-pond CEPT	276	138	74	59
(2) In-pond CEPT	276	110	59	47

The predicted average COD removal of the CEPT stage is 50% for the pre-pond CEPT option (Alternative 1) and 60% for the in-pond CEPT option (Alternative 2). The design conditions for the treatment facility, outlined in a report by Sabesp in 1992, are for an average influent BOD5 concentration of 276 mg/L.

Financial Evaluation of the Alternatives

The financial evaluation of all the three designs focuses on a cost analysis. At this stage of the study, the estimated budget to build the aerated basins was presented by Sabesp, while the CEPT alternatives' costs were estimated by the authors. The capital costs are mainly attributed to soil movement, foundations and equipment. Due to the high cost of the aerators, both CEPT alternatives were around 25% cheaper to build (Cabral, 1999).

The operational cost of the Sabesp plant would be around US$ 315,000/year, largely due to the energy consumption of the 300 hp aeration system. For the CEPT alternatives, the price of chemicals is around US$0,01/m3 of treated wastewater ($65,000 / year). The sludge treatment cost in the CEPT Tank design was estimated considering no viable market for the resulting biosolids. Nevertheless, the operational cost of the two CEPT alternatives were US$ 225,000/year for the CEPT Tank plant and US$ 100,000/year for the In-Pond CEPT plant. Table 2 presents the cost analyses for the three alternatives.

Table 2: Cost Analysis of the Three Designs

	Sabesp Design	Pre-pond CEPT	In-pond CEPT
Operation and Maintenance (/year)	US$ 315,000	US$ 225,000	US$ 100,000
Capital Cost	US$ 2,400,000	US$ 1,800,000	US$ 1,800,000

Note: Values are approximate. Currency exchange rate in 1997: 1 US$ = 1,2 R$ (Brazilian Reais)

Both CEPT alternatives have approximately the same capital cost. This is due to the fact that the higher soil movement costs for the In-pond CEPT alternative (deep first pond) are offset by the higher structural (concrete) costs for the Pre-pond CEPT alternative.

The higher O&M costs for the Pre-Pond CEPT alternative arise from the need for frequent de-sludging of the CEPT settling tank. The task of removing the settled solids from the CEPT tank will have to be carried out at regular intervals during the day. Subsequently, this sludge will have to be de-watered and composted. On the other hand, the solids that settle in the first lagoon of the In-Pond CEPT alternative, will reside in the lagoon for a period of approximately 1 to 2 year, during which time the sludge will be stabilized. Sludge handling and treatment accounts for the O&M cost difference between Pre-Pond and In-Pond CEPT alternatives.

In order to evaluate each design alternative as an investment, a 10-year horizon for this project was assumed. In a concession agreement, the income from the sewage treatment would have to pay the initial investment plus the operational cost over the built operate and transfer (BOT) stages of the contract. To select the best investment, four financial parameters were selected: Internal Rate of Return (IRR), Payback Period (PP), Benefit-Cost ratio (BC) and, the most popular one, Present Value (PV). Table 3 presents the result of the financial analyses of the three investments.

Table 3: Financial Analysis of Three Alternatives

	Sabesp Design	CEPT Tank	CEPT Lagoon
IRR	3%	15%	23%
PP	N/A	8 years	3 years
BC	1.2	1.7	2.2
PV	US$ 4,200,000	US$ 3,100,000	US$ 2,400,000

Note: Values are approximate. The price charged for the sewage treatment is US$0.10 per cubic meter. The population growth was assumed to be 1,5% per year.

From a financial point of view, the In-Pond CEPT project is the most attractive alternative. In an investment for sanitation, a minimum IRR suggested would be around 15%. Hence, both CEPT alternatives' IRR are acceptable. Regarding the payback period, both CEPT alternatives are profitable, and can be amortized during the 10-year project. The main discrepancy comparing the three hypothetical investments is related to their present value. This parameter is related to the initial investment and the operational expenses over the project horizon. Since there is a considerable energy expense to run the aeration system of Sabesp´s alternative, both CEPT alternatives are more economic.

Conclusions

Two alternatives to the design proposed by Sabesp are presented and compared. The first CEPT design alternative consists of pre-pond CEPT: the chemicals are dosed and added to a settling tank that is located before the lagoons, where most of the organic load would be removed from the sewage. The second design alternative is In-Pond CEPT, where the removed organic matter would accumulate in the first lagoon, and biodegrade for one to two years.

The In-Pond CEPT treatment system was selected as the most appropriate treatment system from an economic point of view, with the same level of effluent quality as the other designs. Both CEPT designs would have accepted levels of organic load in the effluent with operational costs from 30% to 60% of the expected energy cost of the aerators. In the case of the CEPT Tank plant, the higher monthly costs of the system are mostly due to sludge composting costs. Unfortunately, there is no market for biosolids in Brazil. When compared as investments, the two

CEPT designs are more attractive due to their shorter payback period, and greater internal rate of return. Considering a 10 year Build-Operate-Transfer (BOT) agreement for the three designs, the present value of the investment in the aeration alternative is 26% more expensive than the CEPT Tank alternative and 43% more expensive than the In-Pond CEPT alternative.

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