Hydrodynamic characterization of shallow unbaffled and baffled maturation ponds using a saline tracer

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ABSTRACT

Results of tests with saline tracers (sodium chloride) in two shallow maturation ponds treating anaerobic effluent in Brazil are presented. One of the ponds had no baffles and presented accumulated sludge after 12 years of operation, while the other had two longitudinal baffles, a shallower depth and the sludge had been previously removed. From the tests, a general tendency to complete mixing with high dispersion was observed in both ponds, even the baffled one. The values of the dispersion number $d$ suggest a high dispersion in both ponds. Daily cycles of stratification and destratification could be seen from the tracer curves. The main results of this study and authors’ perceptions regarding the tests allowed practical considerations about the use of saline tracers in pond systems.

KEYWORDS

Baffles; hydrodynamic characterization; polishing ponds; saline tracer.

INTRODUCTION

From a hydraulic point of view, ponds are conceptually simple. Design criteria must result in an adequate hydraulic retention time (HRT), sufficient for the occurrence of the required biological reactions. However, the HRT value (volume/flow) is only theoretical and can hide short-circuiting phenomena, dead zones, stagnant areas, dispersion degree, thermal stratification, wind influence, among others, making the actual HRT different from the theoretical, possibly resulting in low treatment efficiencies. In polishing or maturation ponds, which are designed primarily for removing pathogens, the influence of HRT on the efficiency is even greater. Therefore, knowledge of the real hydraulic behavior is critical for proper operation of these systems.

In most researches on ponds, determining these hydraulic factors is carried out by means of the stimulus-response technique by using tracers. Levenspiel (2000) presents one of the best-known theoretical references on this subject. Among the available types of tracers, radioactive, fluorescent, dyes, saline and even biological tracers (using bacteria) can be mentioned. Advantages and disadvantages in using each type, with emphasis on natural wastewater treatment systems, can be found in several publications, as Whitmer et al. (2000), Chazarenc et al. (2003); Lin et al. (2003); Keefe et al. (2004); Xu et al. (2004); Camargo Valero and Mara (2009); Silva et al. (2009); Alvarado et al. (2011); Lange et al. (2011). Saline tracers, for example, are usually cheap and easy for acquisition and quantification (even a simple conductivity meter can be used), are not toxic and present no risk for environmental pollution.
or human health, but can present disadvantages such as adsorption (on ponds, by organic matter, biomass or sludge), high solution density and the need of using large quantities of the substance due to the high background concentration usually found in sewage.

With respect to the results obtained from tracer tests in ponds, almost all researchers mention the existence of hydraulic short circuit, thus reducing the actual HRT. Shilton (2001) suggests that this behaviour is actually an inherent feature of all ponds systems.

This paper reports the main results of a saline tracer tests in two shallow maturation ponds designed for small communities. The tracer used was common table salt (sodium chloride) dispersed in an aqueous solution. The results obtained show the main hydraulic parameters of the ponds and perceptions regarding the use of the chosen tracer were pointed out.

METHODS

Study area and experimental unit
The experiments were undertaken at the Centre for Research and Training in Sanitation UFMG-Copasa (CePTS), located in the Arrudas Wastewater Treatment Plant (WWTP), which receives municipal sewage from the city of Belo Horizonte, Minas Gerais, Brazil. After preliminary treatment (coarse and medium screening followed by grit removal) in Arrudas treatment plant, a small fraction of the wastewater is directed to the experimental treatment plants.

The experimental apparatus consisted of two shallow maturation ponds, designed for post-treatment of the effluent from a UASB (Upflow Anaerobic Sludge Blanket) reactor. The system was designed to serve an equivalent population of 250 inhabitants, receiving approximately 40 m³/day of inflow. This work comprises the operational setting in which two ponds were operating in series, with the first pond containing sludge accumulated on the bottom (12 years of operations) and the second pond operating without sludge on the bottom, with a shallower depth and with two longitudinal baffles. The main dimensions and characteristics of the ponds are presented in Table 1.

Table 1. Dimensions and characteristics of the maturation ponds

<table>
<thead>
<tr>
<th></th>
<th>Pond 1 (P1)</th>
<th>Pond 2 (P2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (bottom)</td>
<td>25.00m x 5.25m</td>
<td>25.00m x 5.25m¹</td>
</tr>
<tr>
<td>Sludge (average height)</td>
<td>Yes (~0.34m²)</td>
<td>No</td>
</tr>
<tr>
<td>Length / Width</td>
<td>~ 4</td>
<td>~ 44</td>
</tr>
<tr>
<td>Liquid depth</td>
<td>0.80 m</td>
<td>0.44 m</td>
</tr>
<tr>
<td>Inner dyke slopes</td>
<td>1 : 1</td>
<td>1 : 1</td>
</tr>
<tr>
<td>Theoretical HRT</td>
<td>2.1 d³</td>
<td>1.6 d</td>
</tr>
</tbody>
</table>

¹ The second pond has two equally spaced longitudinal baffles, dividing it into 3 channels. ² Bathymetry performed by Possmoser-Nascimento et al. (2014). ³ Excluding the volume occupied by the sludge obtained in a bathymetric survey performed by Possmoser-Nascimento et al. (2014).

Tracer tests
The tracer used was common table salt (sodium chloride) in an aqueous solution. The tests were performed according to stimulus-response technique (Levenspiel, 2000) by means of a tracer pulse injection at the pond's inlet and measurement of electrical conductivity at the outlet. The conductivity readings were performed with Global Water WQ301A-O probes (detection range from 0 to 5.000 μS/cm), coupled to a GL500-7-2 Global Water® datalogger and YSI 600XLM V2® probes (detection range from 0 to 100 mS/cm) with internal datalogger. The sensors were attached near the outlet, at a depth of 0.10 m from the liquid.
surface. The measurement frequency varied according to the data collection schedule, storage capacity of the devices and phase of the test (beginning or end), comprising intervals of 10 or 15 minutes. The probes set automatically the conductivity to a reference temperature (25°C).

The tracer solutions were prepared in tanks of 200 and 800 L (household water reservoirs), with salt addition and continuous homogenization. Measurements of the pond's natural conductivity were done prior to application of salt, to define the background values. The necessary amounts of table salt were defined from exploratory testing, when it was found a minimum quantity per pond (according to volume) capable of overcoming the background value in 3 to 4 times peak level and not exceed the quantification limit of the probes. In order to reduce the tracer volume, to approximate the application to a pulse-type injection and to facilitate liquid mixing, the water volume used for dilution was the minimum necessary, observing the NaCl solubility limit at ambient temperature. After preparation of the tracer solution, it was slowly introduced in the ponds in order to reduce sedimentation of the saline solution (denser), but always in a period of less than 2% of the ponds HRT, such as not to mischaracterize the pulse injection, according to recommendations by Bracho et al. (2009). The flow in the ponds was also assessed before and during each test. Conductivity values (cond) were converted to tracer concentration using the calibration equation presented by Possmoser-Nascimento (2014) who researched the same system ([tracer]=0.5258.(cond)-3.4836). Table 2 summarizes the conditions of the tests in the two ponds.

**Table 2.** Summary of the tracer test conditions in the ponds.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Period</th>
<th>Pond</th>
<th>Tracer (kg)</th>
<th>Volume (m³)</th>
<th>Injection time (h)</th>
<th>Inflow (m³/d)</th>
<th>Theor. HRT (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>02/12/13 - 06/01/14</td>
<td>1</td>
<td>320</td>
<td>1.45</td>
<td>1.750</td>
<td>19</td>
<td>6.0/3.8**</td>
</tr>
<tr>
<td>2</td>
<td>29/04/14 - 19/05/14</td>
<td>1</td>
<td>320</td>
<td>1.10</td>
<td>2.000</td>
<td>40</td>
<td>3.1/2.1**</td>
</tr>
<tr>
<td>3</td>
<td>16/07/14 - 01/08/14</td>
<td>2</td>
<td>150</td>
<td>0.50</td>
<td>1.100</td>
<td>29</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>09/08/14 - 27/08/14</td>
<td>2</td>
<td>160</td>
<td>0.60</td>
<td>0.833</td>
<td>31</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>30/08/14 - 17/09/14</td>
<td>1</td>
<td>300</td>
<td>1.00</td>
<td>0.767</td>
<td>34</td>
<td>3.5/2.3**</td>
</tr>
<tr>
<td>6</td>
<td>16/12/14 - 14/01/15</td>
<td>2</td>
<td>175</td>
<td>0.79</td>
<td>0.650</td>
<td>36</td>
<td>1.8</td>
</tr>
</tbody>
</table>

* Mean along each test; ** Excluding the volume occupied by the sludge obtained in a bathymetric survey performed by Possmoser-Nascimento et al. (2014)

From the tests results it was possible to determine the mean HRT as well as the variances. Considering that the obtained tracer curve in the field tests can be defined by a discrete distribution of time intervals \( t_i \) and tracer concentrations \( C_i \), the mean HRT \( \overline{TDH}_{\Delta t} \) can be calculated by Equation 1. The variance can be defined according to Equation 2 and its dimensionless form \( (\sigma^2) \) can be related to the dispersion number \( (d) \) using Equation 3 (Levenspiel, 2000; Metcalf & Eddy, 2003). The values obtained were compared with values estimated by empirical equations in literature, based on pond geometric characteristics.

Other hydraulic parameters were determined: short circuit index \( \varphi \) (Metcalf & Eddy, 2003); number of tanks-in-series \( N \), based on Levenspiel (2000), \( N \), based on the gamma function, and \( N_p \), based on the actual mean HRT and tracer peak time (Kadlec and Wallace, 2009); volumetric efficiency \( E_r \) (Kadlec and Wallace, 2009); fraction of dead zones \( \Psi \); and hydraulic efficiency \( \lambda \), as proposed by Persson et al. (1999). The number of tanks in series \( N_p \) was obtained based on the discrete distribution of residence times and subsequent adjustment between model and tracer data. The gamma distribution is given by Equation 10, and the gamma function, for a positive integer \( N_p \), is given by Equation 11. The tracer recovery percentage was calculated by equation 12.

\[
\overline{TDH}_{\Delta t} = \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \quad (1)
\]

\[
E_r = \frac{\overline{TDH}_{\Delta t}}{\tau} \quad (7)
\]
\[
\sigma^2_{\Delta t} = \frac{\sum C_i \Delta t}{C_i \Delta t} - (\text{TDH}_\infty)^2 \quad (2)
\]
\[
\sigma^2 = \frac{\sigma^2_{\Delta t}}{2 d - 2 d^2 [1 - e^{-2/d}]} \quad (3)
\]
\[
\phi = \frac{t_i}{\bar{c}} \quad (4)
\]
\[
N = \frac{1}{2d - 2d^2 (1 - e^{-2/d})} \quad (5)
\]
\[
N_p = \frac{\text{TDH}_\infty}{\text{TDH}_\infty - t_p} \quad (6)
\]

In equations 4 and 6, \( t_i \) is the time of the tracer first detection and \( t_p \) is the time corresponding to the peak value (highest concentration), respectively. \( Q_i \) is the inflow at time \( i \) (assumed as constant) and \( m_0 \) is the tracer mass added in the test.

**RESULTS AND DISCUSSIONS**

**Hydraulic parameters**

Figure 1 shows the tracer concentration in the effluent (mg/L) over time (days) in each test. The left column refers to tests performed in Pond 1 (blue markers) while the right column refers to tests performed in Pond 2 (red markers). The zero on the x-axis corresponds to the beginning of the tracer injection. Tests were conducted for 16 to 35 days, considerably exceeding, in all cases, the general recommendation from the literature that tracer tests should be performed during a minimum period of 3 times the theoretical HRT.

![Figure 1. Curves of tracer concentration versus time from tests.](image_url)
Tests 2, 3, 5 and 6 suffered inflow interruption due to lack of power supply for a few hours, which were not accurately registered. At that time, Arrudas WWTP, in whose area is situated the experimental site, was undergoing construction works that required electrical interventions, which unfortunately also impacted the experimental area. In the other tests there were no reports of power interruptions, although they probably happened (given the high frequency at which interruptions were occurring).

In general, the shapes of the curves indicate a complete mixing tendency, even in the pond with baffles, in which near plug-flow conditions were expected. It is remarkable to see that fluctuations observed in all curves occurred at daily cycles and can be attributed to the thermal stratification events, causing movement of part of the tracer solution to the bottom, and then destratification, with vertical mixing. Therefore, during these events, the surface sensors continuously recorded more concentrated fluid layers and less concentrated at each occurrence of thermal events. These hypotheses are supported by the data of the thermal profile in the same ponds, proving daily events of thermal stratification and destratification (Passos et al., 2015). There were no records in literature about tracer tests with these explicit oscillations, possibly due to the measurement frequency in other ponds or their thermal profile (without occurrence of vertical mixing in daily cycles, deeper ponds etc.). In this research, high frequency monitoring (measurements every 5-30 minutes) showed these oscillations.

The hydraulic parameters obtained in the tests are shown in Table 3.

<table>
<thead>
<tr>
<th>Test no. (pond)</th>
<th>1(d)</th>
<th>2(d)</th>
<th>%R</th>
<th>d</th>
<th>N</th>
<th>Np</th>
<th>Nt</th>
<th>φ</th>
<th>t (min)</th>
<th>t (min)</th>
<th>E</th>
<th>Ψ</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (Pond 1)</td>
<td>6.0/3.8'</td>
<td>6.5</td>
<td>48</td>
<td>0.72</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.01</td>
<td>98</td>
<td>4617</td>
<td>1.09</td>
<td>-0.58</td>
<td>0.53</td>
</tr>
<tr>
<td>4 (Pond 1)</td>
<td>3.1/2.1''</td>
<td>7.1</td>
<td>93</td>
<td>0.37</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.00</td>
<td>0</td>
<td>5600</td>
<td>2.27</td>
<td>-1.27</td>
<td>1.25</td>
</tr>
<tr>
<td>5 (Pond 2)</td>
<td>2.2</td>
<td>4.1</td>
<td>100</td>
<td>0.31</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0.06</td>
<td>430</td>
<td>3885</td>
<td>1.85</td>
<td>-0.85</td>
<td>1.22</td>
</tr>
<tr>
<td>6 (Pond 2)</td>
<td>2.1</td>
<td>6.2</td>
<td>89</td>
<td>0.73</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.11</td>
<td>320</td>
<td>575</td>
<td>2.98</td>
<td>-1.98</td>
<td>0.19</td>
</tr>
<tr>
<td>7 (Pond 1)</td>
<td>3.5/2.3''</td>
<td>9.0</td>
<td>21</td>
<td>0.19</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>0.00</td>
<td>10</td>
<td>9720</td>
<td>2.59</td>
<td>-1.53</td>
<td>1.95</td>
</tr>
<tr>
<td>8 (Pond 2)</td>
<td>1.8</td>
<td>5.2</td>
<td>100</td>
<td>0.30</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0.02</td>
<td>1130</td>
<td>1730</td>
<td>2.95</td>
<td>-1.95</td>
<td>0.68</td>
</tr>
</tbody>
</table>

- Pond 1: un baffled; with bottom sludge; Pond 2: baffled; without bottom sludge
- t(d) = theoretical HRT; TDH = mean HRT; %R = tracer recovery percentage; d = dispersion number; φ = short circuit index; N,Np,Nt = number of tanks-in-series; E = volumetric efficiency; Ψ = fraction of dead zones; λ = hydraulic efficiency.

The d values indicate high dispersion in both ponds (d ≥ 0.25), according to Metcalf and Eddy (2003). Short-circuit indexes near zero and low equivalent numbers of tanks-in-series (the mean value was 2 to both ponds) also indicate a high degree of mixing in both ponds, close to the theoretical perfect mixing model (N=1). Tracer peak value anticipation was more pronounced in Pond 2, resulting in substantially lower λ values, which was also not expected. The fact that the hydraulic behaviour in the baffled pond was not as expected is important and highlights the relevance of tracer tests. The results obtained may be indicative of short-circuiting between the baffles, via fluid flow under the deflectors or near the attachment points of the tarps on the dykes' wall and also short-circuiting induced by thermal stratification or even a combination of these two factors. The anticipation of the peak value is also related to significant dispersion in the units. Almost all researchers that used tracer on pond's hydrodynamic studies have reported hydraulic short-circuits.

Another important observation is that the mean HRTs were higher than the theoretical ones (in most cases more than double), which may be due to interruptions of the inflow that occurred during the test, as well as stagnant and slow-change zones in the ponds, causing, in both cases,
longer tracer permanency in the system. These results also led to $E_v$ values higher than unity and hence negative values for the fraction of dead zones.

The results of the comparison of the calculated value of the dispersion number $d$ and empirical equations from the literature are presented in Table 4. The corresponding equations are inserted as table note.

**Table 4.** Dispersion numbers ($d$) based on empirical equations from literature and compared with those obtained from the tracer tests.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (Pond 1)</td>
<td>0.027</td>
<td>0.187</td>
<td>0.221</td>
<td>0.321</td>
<td>0.234</td>
<td>0.72</td>
</tr>
<tr>
<td>4 (Pond 1)</td>
<td>0.020</td>
<td>0.212</td>
<td>0.221</td>
<td>0.323</td>
<td>0.234</td>
<td>0.37</td>
</tr>
<tr>
<td>5 (Pond 2)</td>
<td>0.001</td>
<td>0.033</td>
<td>0.024</td>
<td>0.045</td>
<td>0.025</td>
<td>0.31</td>
</tr>
<tr>
<td>6 (Pond 2)</td>
<td>0.001</td>
<td>0.034</td>
<td>0.024</td>
<td>0.045</td>
<td>0.025</td>
<td>0.73</td>
</tr>
<tr>
<td>7 (Pond 1)</td>
<td>0.022</td>
<td>0.203</td>
<td>0.221</td>
<td>0.323</td>
<td>0.234</td>
<td>0.19</td>
</tr>
<tr>
<td>8 (Pond 2)</td>
<td>0.001</td>
<td>0.036</td>
<td>0.024</td>
<td>0.045</td>
<td>0.025</td>
<td>0.30</td>
</tr>
</tbody>
</table>

- Pond 1: unbaflled, with bottom sludge; Pond 2: baffled, without bottom sludge
- Polprasert e Bhattarai (1985): $d = 0.184L/L(H+2H)^{0.440}B^{-0.311}/(L/H)^{0.440}$; Von Sperling (1999): $d = 1/(L/B)$
- Polprasert e Bhattarai (1992): $d = 0.102(3(B+2H)L/L/d/4LBH)^{0.410}(H/L)-(H/B)^{(0.961+0.385)/(L/B)}$; Nameche e Vasel (1998): $d = 1/(L/B)+0.05(L/H)$

Table 4 suggests that Yanez (1993), Nameche and Vasel (1998) and von Sperling (1999) predictions are closer to the results obtained in the field tests. Results of Polprasert and Bhattarai (1985) models were the most discrepant in relation to the others and field data. This characteristic is especially observed in this model at higher ranges of $d$, as in this case. For these equations, it is important to note that they are empirical and generally used to predict the dispersion number in pond designs (von Sperling, 2005). Moreover, their formulations do not include other influential factors in hydrodynamic behaviour, such as inlet-outlet conditions, thermal stratification, wind and turbulence. Excluding the comparisons with Polprasert and Bhattarai (1985) model, Table 4 showed that the predicted $d$ obtained through the tracer curves in pond 1 were slightly higher or lower than those obtained from equations in literature, in spite of the value obtained in test 2, which was much higher. However, these values were significantly different in pond 2, where the high dispersion was not expected.

**Practical aspects of the use of the table salt as a tracer for ponds**

A minimum quantity of 300 kg of salt was used for the tracer test in pond 1 and 150 kg in pond 2. The salt was diluted in 1.0 and 0.5 m³ of water, respectively, resulting in tracer solution concentrations of less than 300 kg/m³, sufficiently below NaCl solubility in water at 20°C (360 kg/m³), in order to allow mixing. Even for a small treatment system such as in this research, the minimum amounts used of table salt are very high and can make transportation difficult for a common vehicle (requiring load carrying vehicles), especially when one considers that WWTPs are commonly located far from city centers and commercial zones.

Homogenization of the solution also required great effort. The preparation for each test demanded about six hours to be completely finished by two people. Unless mechanically mixed, great difficulty can be found to mix the solution manually. In practical terms, the most efficient solution (less difficulty when mixing manually) is by filling half the tank with water and adding most of the salt while mixing until saturation, and then sequential addition of salt and water each time in which the saturation of the solution was observed. In terms of costs, it is estimated that US$100/test were spent, a cheap and competitive value when compared with
other tracers, those with higher costs associated with equipment), especially in cases that repetitions are planned.

The salt concentration in the effluent may be easily measured by an electrical conductivity sensor, which is able to provide semi-continuous measurements along the test period. There is no need for collecting samples and analyzing them at the laboratory, as is required in the case of other tracers.

Finally, the influence of density must be considered, since the saline tracer (denser) tends to subside to the bottom of the pond and travel towards the outlet without mixing with the upper fluid layers. In the ponds of this study there were daily destratification events, which favored vertical mixing and were responsible for smaller tracer peak values every day. However, in deeper ponds, saline tracer tests in more durable thermal stratification events can be considerably influenced by the solutions density effect, possibly revealing short-circuiting which does not occur in reality. Therefore, it is recommended to adjust the solution density via control of concentration and temperature of the solution or to conduct the tests preferably in periods in which vertical mixing in the pond is observed, in the case of long lasting mixing periods. It is also recommended avoid adding instantaneously the whole content of the salt solution in the pond.

CONCLUSIONS
A tendency of complete mixing was observed in both ponds, even in the baffled one, in which near plug-flow conditions were expected. Besides the high values of the dispersion number $d$, short-circuit indexes were close to zero and the low number of equivalent tanks-in-series $N$ also indicated a high degree of mixing in both ponds. The tracer peak anticipation was more pronounced in pond 2, which also was not expected. These results may be indicative of short-circuits resulting from imperfections in the baffles installation, induced by thermal stratification or even a combination of these two factors. The mean HRTs were higher than the theoretical ones, which may be due to interruptions of inflow that occurred during the test, as well as due to stagnant and slow-change zones in the ponds, causing, in both cases, longer tracer permanency in the system.

The main results of this study and from the authors’ perceptions regarding the tests allowed for practical considerations about the use of saline tracers in pond systems. These substances are more accessible and simple to quantify in conductivity readings, but they require large quantities which may make transportation difficult. Solution preparation and control of homogeneity demand a lot of effort and time for each test. In large ponds, the application becomes almost impossible when considering the amounts of table salt needed. The density of the solution may also result in unrealistic responses in ponds, since it is difficult to avoid tracer concentration gradients along the vertical profile, more particularly in ponds with longer thermal stratification periods (deeper ones). Thus, observing the advantages, disadvantages and the authors perceptions about the salt tracer, this method can be used more successfully in systems with lower hydraulic retention times and with porous media (constructed wetlands, for example), since the density factor influence is reduced and also the required amount of the solute (typically, half of that required in a pond with the same dimensions).

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