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682
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Stratification and equalization cycles in shallow maturation ponds with different operational configurations and at different periods of the year

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Abstract

This study aimed at evaluating the occurrence of stratification/equalization cycles in two full-scale shallow maturation ponds in Brazil, with different operational configurations and different periods of the year, through monitoring of temperature and other constituents in the vertical profile of the ponds. The study comprised two operational phases: one phase in which both ponds had no baffles and operated in parallel (one pond had sludge accumulated on the bottom while the other did not); and another phase in which the ponds operated in series, the first pond without baffles and with accumulated sludge on the bottom while the second pond had two longitudinal baffles, a shallower depth and no accumulated sludge. Overall, there were systematic daily periodic events of thermal stratification followed by temperature equalization and vertical mixing in both ponds and operating phases. Vertical temperature gradients were predominantly in the 0–7 °C m^{-1} range. Statistical tests showed a significant positive correlation between the thermal gradient in the pond and air temperature, but not between the thermal gradient and wind speed. Data suggested that ponds remained 56% of the time under thermal stratification and 44% in vertical mixing. The data also highlighted the importance of sludge in the thermal balance of ponds.

Key words: maturation ponds, sludge, thermal gradient, thermal stratification, vertical mixing, wastewater treatment

INTRODUCTION

Hydrodynamics of wastewater stabilisation and maturation ponds are much more investigated in terms of surface geometric relationships (length and width), seeking to establish their suitability to the well-known hydraulic reactor models (complete-mix, plug flow, dispersed flow). However, the vertical component, linked to depth, is also important for pond behavior and has been much less covered in the literature. For the design of pond systems, the dimensions are usually determined based on theoretical and empirical relationships that provide, directly or indirectly, an estimation of the theoretical hydraulic retention time (HRT) required to achieve a given effluent quality. However, many factors can cause disturbances in the flow pattern, influencing the actual HRT. One of these factors is thermal stratification, a natural phenomenon that is often neglected in the design of pond units (Kellner & Pires 2002).

doi: 10.2166/wpt.2019.054

Due to differences in temperature or salinity between the liquid layers in ponds, a density gradient can be formed and the less dense layer (epilimnion zone) tends to overlap the denser layer (hypolimnion zone), creating a stratification condition (Dor *et al.* 1993). This phenomenon tends to be detrimental to the desired hydrodynamic behavior in the stabilisation pond, since it can cause short-circuiting in the surface or bottom of the pond; essentially, if the influent temperature is significantly different from the liquid in the pond and if there is no mixing occurring at the inlet of the pond (Shilton 2005). Therefore, the actual HRT is reduced and possibly the efficiency also decreases.

The opposite situation of turn-over or destratification can occur when temperatures are matched during cooling of the liquid mass, causing vertical mixing which can be beneficial for pond efficiency, both from a hydrodynamic point-of-view (decrease in short circuiting) and a pollutant removal point-of-view (e.g. better oxygenation of the liquid and redistribution of components throughout the vertical profile). On the other hand, destratrification can contribute to decreasing the effluent quality if sludge resuspension occurs during mixing. In large areas, when waving may become important, stratification may also be broken by wind blowing on the surface of the water. In this case, the surface layers of the pond are mixed by the shearing effects that the wind exerts on the liquid. Thus over time, the denser and less turbulent layers mix with the less dense layers (Chu & Soong 1997). Shilton (2005) and Abis & Mara (2006) suggested that mixing and turbulence provided by the inlet may also break up stratification. According to Uhlmann (1979), the breakdown of the thermal stratification is often accompanied by vertical mixing and homogenization of the constituents in the ponds, at least in some areas of the pond.

The idea that wind may be responsible for the cessation of stratification is commonly found in literature. Sweeney *et al.* (2005), studying larger ponds, stated that even gentle winds ($\sim$1.5 m s^{-1}) partially break up stratification and suggested the inclusion of mixing effects due to wind in models that include energy transfer and stratification. On the other hand, Abis & Mara (2006) concluded that the main reason for stratification breakdown in an experimental stabilisation pond in the UK was the drop in air temperature, stating that neither the inlet nor the wind speed had a significant impact on the thermal profile. However, the authors attributed this fact due to the small area of the ponds (33.6 m^2, 40.6 m^2 and 39.5 m^2).

According to Kellner & Pires (2002), the main cause for thermal stratification occurrence in stabilisation ponds is the warming of the surface layers due to solar radiation; and destratification is mainly attributed to the cooling of these surface layers. The authors suggested a thermal gradient of 0.6 °C m^{-1} as a threshold to identify the occurrence of stratification in tropical regions. However, this phenomenon must be evaluated in conjunction with the laws of thermodynamics, fluid dynamics and the characteristics of the external environment, such as energy transfer from different light wavelengths of the solar radiation and its penetration into the fluid column. In the ponds, the multiphase fluid presents different particles and regions with different thermal properties, influencing the whole in-pond thermal balance.

The duration of thermal stratification may only occur for a few hours a day or even months (Dor *et al.* 1993; Pedahzur *et al.* 1993; Torres *et al.* 1997; Sweeney *et al.* 2005). In deeper ponds, stratification tends to be more stable because temperature gradients tend to be greater. Abis & Mara (2006) observed long periods of stratification throughout a year in 1.5 m deep pilot-scale stabilisation ponds in the UK. Silva (1982) and Vidal (1983) reported vertical temperature profiles in ponds with depths of 1.25 and 1.50 m, respectively, indicating daily periods of stratification and destratification.

There are also reports about thermal stratification in full-scale shallow ponds (0.2 m in depth) in Nigeria (Agunwamba 1997; Ukpong *et al.* 2006a); in laboratory-scale ponds with 0.40 m in depth (Ukpong *et al.* 2006a); and in laboratory-scale ponds with depths of 0.36 m and 0.54 m (Bokil & Agrawal 1977). Ukpong *et al.* (2006a, 2006b) and Kellner & Pires (2002) argue that high turbidity favors stratified conditions even in ponds with very shallow depths. In the work of

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

Dias & von Sperling (2017), data of solar irradiance in terms of photosynthetically active radiation (PAR), UV-A and UV-B, together with turbidity, have been acquired from different depths for over one year in the same ponds of this study. UV-A and UV-B were still detected at 10 cm from the surface, but from 15 cm both were undetectable. PAR was still detected at 30 cm of depth. In that work, irradiation attenuation showed to be related to turbidity. On the other hand, solid material tends to be more efficient at heat conduction than water can be. Thus, temperature difference between upper and bottom layer can be driven by this phenomenon rather than light attenuation. It is important to note that turbidity in stabilisation ponds is much higher than in natural lakes because of higher algal concentrations.

Temperature, dissolved oxygen and pH profiles indicated strong thermal stratification in a pond in Israel, with temperature differences between the top and the bottom of the pond of 10 °C (Pedahzur *et al*. 1993). This caused the influent (relatively cold) to flow to the bottom of the pond, resulting in a fast, preferential path towards the outlet. Tracer studies in the same research confirmed the occurrence of short-circuiting, attributed to stratified conditions. Short-circuiting associated with thermal stratification was also reported by MacDonald & Ernst (1986). However, despite this association, no experiments in the pond were carried out to confirm this behavior.

Regarding the behavior of the flow as to the degree of dispersion, Torres *et al*. (1997) studied thermal stratification influence for mixing efficiencies in a pond in southeast Spain. During winter months, after the surface temperature layer reduced, the active zone (mixing) of the pond was extended throughout the depth. During the summer months, a stable thermocline was formed due to stratification, resulting in an active zone that extended only from the surface of the pond to a depth of the outlet. The volumes of active zones were estimated to be about 70% and 20% of the total volume of the pond during the winter and summer, respectively, affecting the HRT in the same proportion.

Accurate temperature measurements taken simultaneously along the depth of a pond are necessary for a good understanding of the stratification-mixing phenomenon, but only preliminary work has been carried out in ponds (Shilton 2005; Sweeney *et al*. 2005). Abis & Mara (2006) stated that continuous temperature readings in ponds for more than 2–3 months are rare because of the difficulty and costs of long-term monitoring. Moreover, there are very little data for shallow ponds (such as maturation ponds) in literature, compared to facultative ponds, which have greater depths.

In this context, this research aimed at contributing to the existing data in the literature, by a long-term monitoring to assessing temperatures and other parameters in shallow maturation ponds in a tropical climate (Brazil) with different operational configurations and at different periods of the year. Monitoring data in the same pond with and without baffles are presented (geometry influence), while monitoring data from different points of the same unit and the influence of accumulated pond sediment were also evaluated, covering even more scarce aspects in the literature.

MATERIALS AND 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 (latitude 19°53′S). Belo Horizonte is located in either a Cfa or Cwa humid subtropical climate, according to Köppen classification, with a mean annual temperature of 22.1 °C and mean annual rainfall of 1,540 mm year^{-1}. There are basically two seasons in the region: April to September (dry and cool, with mean temperatures of 20.9 °C and mean rainfall of 33 mm month^{-1}), and October to March (wet and warm, with mean temperatures of 23.4 °C and mean rainfall of 254 mm month^{-1}). After preliminary treatment

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

(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 setting consists 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 m^3 day^{-1} of inflow. Recent research about the performance of the system can be seen in Dias *et al.* (2018).

The experimental units were built in 2001 and began operating in 2002. During that time, the ponds have undergone different arrangements and operational conditions. This work comprises two of the recent operational phases:

- Phase 1 (May 2013 to December 2013): the two ponds operated in parallel, one with over 11 years of accumulated sediment on the bottom in approximately 40% of the useful volume, distributed as presented in the work of Possmoser-Nascimento *et al.* (2014), and the other pond without sludge (recently removed), with a depth of 0.82 m each.
- Phase 2 (January 2014 to May 2015): the ponds operated in series; the first pond with the same configuration as in the previous phase (sludge accumulated on the bottom); the second pond operated without sludge on the bottom, shallower depth (0.44 m) and was fitted with two longitudinal baffles.

More details about dimensions and characteristics of the ponds for each operating phase, and illustration of the operational arrangements are shown in Table A.1 and Figure A.1, both in Supplementary Material.

Evaluation of cycles of stratification and equalization

Vertical profiling for temperature (T), dissolved oxygen (DO), pH, electrical conductivity (EC) and redox potential (ORP) was performed over the research period. Temperature was measured continuously during the period at various points and at different times of the year in an attempt to assess whether there were thermal stratification conditions or equalization/vertical mixing in the ponds. DO, pH, EC and ORP were monitored in some tests in order to help the analysis of these conditions and to observe possible chemical gradients in the pond profile.

At each selected monitoring point, temperature was recorded at two or three different depths (surface and bottom, or surface, middle and bottom) by means of Global Water WQ101® probes with GL500-7-2 Global Water® data logger and YSI 600XLM V2® probes with internal data loggers. The surface probe was placed in a way so that it would not emerge out of the water due to water level oscillations in the ponds. In the case of pond 1, tests were made with the bottom probe placed at the interface of the liquid with the sediment (just above the sediment) and with the probe completely immersed in the sediment. Thus, to determine the depths for placing the probes in pond 1 exactly at the interface, the bathymetric map of the pond's sediments (Possmoser-Nascimento *et al.* 2014) was consulted and preliminary field tests were done, with the same device used for Passos *et al.* (2014) and Possmoser-Nascimento *et al.* (2014) to obtain the height of the accumulated sludge. Measurement frequency varied according to the data collection program and storage capacity of the devices, comprising intervals of 1–30 minutes. Monitoring took place from October 2013 to May 2015 and resulted in more than 40,000 vertical measures. Table 1 summarizes some of the conditions under which vertical measurements were done. The notes below the table present characteristics of the tests and the asterisks highlight those with overlapping periods with saline tracer tests in the same pond (a possible interference). Figure A.2, in Supplementary Material, shows the location of the monitoring points in the two ponds, indicating which tests correspond to which monitoring point.

Meteorological data were available from test 8 onwards from a station installed on-site and programmed to record weather conditions at specified intervals (5 minutes). The station used was the Davis Vantage Pro2®, which had a set of integrated sensors including rain collector, temperature

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

Table 1 | Vertical profile monitoring points and heights in the ponds – CePTS UFMG/COPASA

Test no.	Period	Season	Operating phase	Pond	Monitoring point[a]	Heights above the pond bottom ($\times 10^{-2}$ m)
1[b]	18/10/13 to 04/11/13	wet/hot	Phase 1	2	Central point	5 and 60
2[b]	02/12/13 to 30/12/13	wet/hot	Phase 1	2	Central point	5 and 60
3[b]	28/04/14 to 05/05/14	dry/cold	Phase 2	1	Central point	35 and 68
4	23/06/14 to 25/06/14	dry/cold	Phase 2	1	Central point	35 and 70
5	25/06/14 to 01/07/14	dry/cold	Phase 2	1	0.2 m upstream outlet	25 and 75
6	01/07/14 to 07/07/14	dry/cold	Phase 2	1	0.7 m upstream outlet	10 and 67
7	07/07/14 to 12/07/14	dry/cold	Phase 2	1	3.5 m upstream outlet and 1.5 m away from right side	10 and 67
8	12/07/14 to 15/07/14	dry/cold	Phase 2	2	Beginning of the 1st channel – 2.7 m downstream inlet	7 and 41
9[b]	15/07/14 to 21/07/14	dry/cold	Phase 2	2	Middle of the 1st channel – 10.3 m downstream inlet	7 and 41
10	21/07/14 to 24/07/14	dry/cold	Phase 2	2	End of the 1st channel – 22.0 m downstream inlet	7 and 41
11	28/07/14 to 01/08/14	dry/cold	Phase 2	2	End of the 1st channel – 24.0 m downstream inlet	10, 22 and 40
12	01/08/14 to 05/08/14	dry/cold	Phase 2	2	Central point of the 2nd channel	10, 22 and 40
13	05/08/14 to 09/08/14	dry/cold	Phase 2	2	Beginning of the 3nd channel – 1.5 m from slope	10, 22 and 43
14[b]	09/08/14 to 13/08/14	dry/cold	Phase 2	2	End of the 3nd channel – 1.3 m upstream outlet	10, 22 and 43
15	03/10/14 to 09/10/14	dry/cold	Phase 2	1	Central point of the 2nd channel	10 and 80
16	21/02/15 to 28/02/15	wet/hot	Phase 2	2	Beginning of the 1st channel – 0.5 m downstream inlet	7 and 33
17	28/02/15 to 09/03/15	wet/hot	Phase 2	2	Beginning of the 1st channel – 0.5 m downstream inlet	6 and 38
18	06/03/15 to 27/0315	wet/hot	Phase 2	1	Central point	30 and 80
19	09/03/15 to 23/03/15	wet/hot	Phase 2	2	Beginning of the 1st channel – 4.3 m downstream inlet	6 and 38
20	23/03/15 to 30/03/15	dry/cold	Phase 2	2	Middle of the 1st channel – 12.3 m downstream inlet	6 and 38
21	30/03/15 to 04/04/15	dry/cold	Phase 2	2	End of the 1st channel – 1.0 m from slope	6 and 38
22	04/04/15 to 11/04/15	dry/cold	Phase 2	2	Beginning of the 2nd channel – 2.0 m from slope	6 and 38
23	10/04/15 to 17/04/15	dry/cold	Phase 2	1	Middle of the pond – 14.0 m downstream inlet	30 and 80
24	11/04/15 to 27/04/15	dry/cold	Phase 2	2	Central point of the 2nd channel	6 and 38
25	27/04/15 to 07/05/15	dry/cold	Phase 2	2	End of the 2nd channel	6 and 38

Note 1: The Global Water WQ101® probes were used in tests 1, 2, 5, 6, 7, 8, 9, 10, 17, 19, 20, 21, 22, 24 and 25. The other periods used the YSI 600XLM V2® probes.
Note 2: Measuring range of 1 minute after 10 days from the start of the test 1; 5 minutes for tests no. 17, 19, 20, 21, 22, 24 and 25; 30 minutes for tests 3 and 4; 15 minutes for the test no. 15 and 10 minutes to the other tests.
Note 3: Weather data available from test 8 onwards.
[a]Points illustrated in Figure A.2, at Supplementary Material.
[b]Overlapping periods with saline tracer tests in the same pond.

and humidity sensor, anemometer (direction and speed, measured at 2.3 m from the ground, at a distance of 8.0 m from the side of pond 2), barometric sensor and solar panel. Data for air temperature and wind direction and speed were used. There were no obstacles around the pond.

Data analysis and interpretation was based on descriptive statistics and hypotheses tests. Raw data were analyzed using descriptive statistics and was statistically tested for normality

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

(Kolmogorov-Smirnov and Lilliefors tests), before defining the hypothesis tests to be used. Hypothesis tests were used to compare sample groups from different periods (dry/cold vs wet/hot seasons). The t-Student test for independent samples was used for data with normal distribution to assess whether there were significant differences between the mean values in both periods analyzed (two independent groups). Likewise, the Mann-Whitney U test was used for comparison between the medians in the pairs of data with skewed distribution. Spearman correlation test (for nonparametric data) and the Pearson correlation and linear regression analysis (for parametric data) were also carried out. Software's Statistica 8.0® and Microsoft Excel 2010® were used to perform the statistical analysis.

Kellner & Pires (2002) suggested a thermal gradient of 0.6 °C m^{-1} along the depth of a pond as a threshold value for thermal stratification identification. The same value was used by Sweeney *et al.* (2005). In this research, thermal stratification and vertical mixing (destratification) events were identified in each test also based on this suggestion. It is important to note that these values refer to ponds of larger dimensions than the ponds under study. However, references like these for full-scale shallow ponds were not found.

RESULTS AND DISCUSSION

Stratification and equalization events

In general, data suggested daily periodic events of temperature differences during the day between surface and bottom followed by temperature equalization at night, for both ponds and operating phases, regardless of their geometrical configuration or monitoring location. A typical example is presented in Figure 1(a), which shows the temperature values (surface and bottom) in pond 1, in test no. 4. The x-axis represents the time of day and the vertical lines indicate the separation between days. During this test, temperature differences were observed from 07:00 h, with total equalization occurring around 22:00 h. This suggests that the pond can stay in thermal stratification during the day and remained in vertical mixing for about 9 hours (equalization), as observed in tests 1 and 2 in Pond 2, phase 1. The mean maximum temperature amplitude observed in the test was 5.1 °C between the surface and the bottom (occurring close to 15:00 h every day), translating into a maximum thermal gradient of about 15 °C m^{-1}. The position of the bottom probe in pond 1 was chosen in this test in order to stay very close to the sludge interface, but not immersed in it, representing the bottom of the pond in relation with the liquid and not with the pond itself (including bottom sludge).

Vertical mixing was inferred by DO, pH and ORP monitoring on the surface and bottom of the pond (Figure 1(b)–1(d), respectively). The triangle markers and dashed lines represent the surface and the dotted markers and solid lines represent the bottom of the pond, with the x-axis representing the time of day and vertical lines the separation between days. DO values on the surface were very high, meaning that supersaturation took place during most of the day (due to hours of sunshine and the result of high algal photosynthetic activity). Naturally, pH values were also higher on the surface. In turn, the bottom was absent of DO, and pH values were lower than those at the surface. Data reveal a sharp rise in DO concentration and pH at the bottom of the pond just after temperature equalization, validated by positive ORP values during the same time. Thus, DO and pH levels were equalled throughout the vertical profile by advection and diffusion, with vertical mixing occurring about 1 hour after the temperatures were equalled. This same behavior was observed in the other tests, highlighting the multiphase features of in-pond fluid.

In Supplementary Material is presented, in Figure A.3, results and discussion from other tests, as example (tests 11, 12, 13 and 14 in Pond 2, which occurred during phase 2). The results of the tests in the same pond during the previous phase (Tests 1 and 2, not presented), in which the pond

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

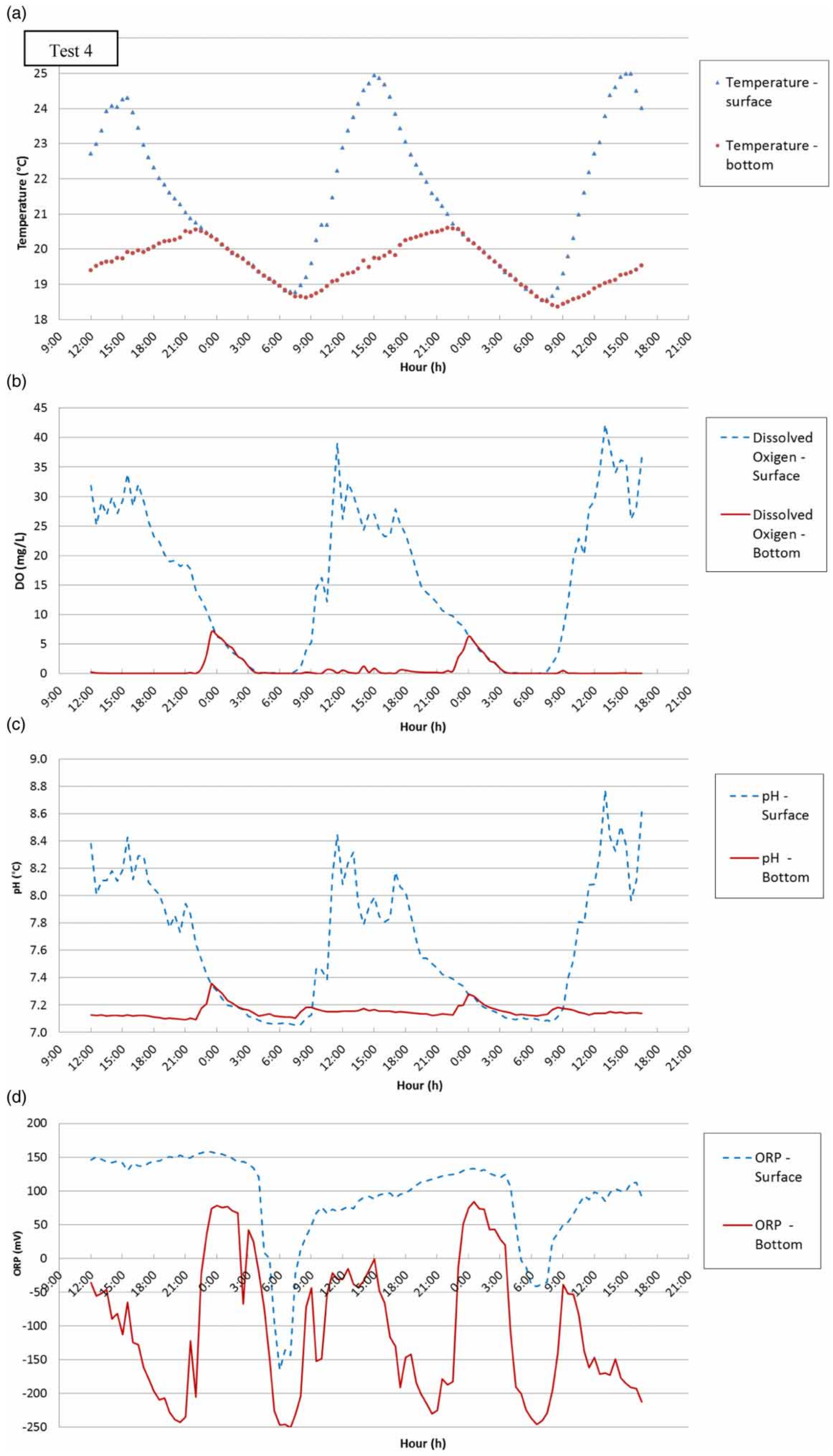

Figure 1 | (a) Temperature, (b) dissolved oxygen, (c) pH and (d) ORP vertical profiles in pond 1 (surface and bottom) for test no. 4 - Phase 2 - H = 0.80 m.

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

operated with nearly double the depth and without baffles, show that it remained for longer periods of time stratified in phase 1 than in phase 2, but still with daily cycles of temperature fluctuations. Results also suggest no significant difference of thermal behavior regarding the position in the horizontal plane of the pond and no indication that momentum and turbulence provided by the inlet structure (confirmed by experimental tests with drogues and dyes, and simulation using computational fluid dynamics – CFD, detailed in Passos *et al*. (2019)) can be able to avoid stratification.

To illustrate the typical behavior of the ponds over a day in relation to its vertical profile, monitoring data from pond 1 from 07 h of 06/23/2014 (to match the beginning of the cycle with the start of thermal stratification) until 07 h of 06/24/2014, were used for T, DO, ORP and pH variables (Figure 2). Although the figure is complex to interpret because it contains eight curves, its goal is to serve as a didactic synthesis of the typical behavior of the vertical profile in a shallow maturation pond. Figure 2 shows the main features already mentioned above, the beginning of thermal stratification followed almost immediately by chemical stratification (DO and pH gradients), in which DO and pH levels start increasing in surface due to algal activity. The maximum gradients occurring around 15 h and vertical mixing occurring shortly after thermal equalization, with sudden increase in DO and pH at the bottom.

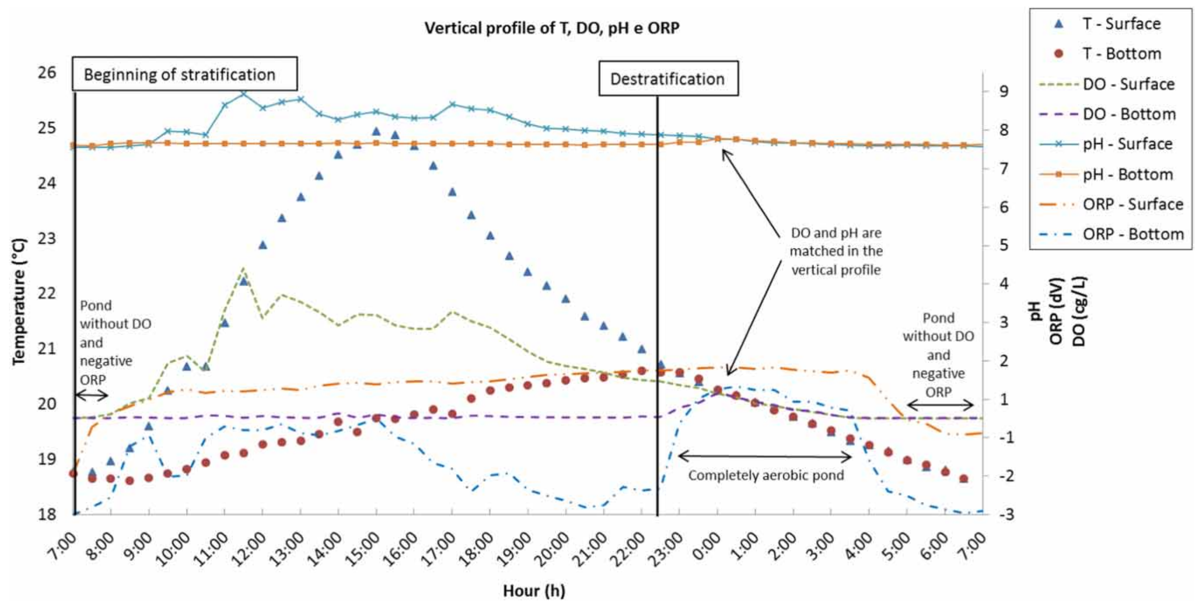

Figure 2 | Typical T, DO, pH and ORP profile for one day: monitoring in pond 1 from 07:00 h of 06/23/14 to 07:00 h of 06/24/14.

Two hours after mixing began, DO levels were matched in the vertical profile, with pH following this trend. After thermal equalization, the ORP at the bottom of the pond (which is predominantly negative) turned positive for a period, presenting complete aerobic conditions throughout the pond. Soon after this period the entire DO was consumed and, after a certain time (around 05:00 h), the pond began operating with no DO and a negative ORP.

For tests 11, 12, 13 and 14 in pond 2, phase 2 (monitoring three points along the depth), a thermal profile picture was drawn with the arithmetic mean temperature data from each depth from the two periods: when the unit was stratified and when it was in vertical mixing (Figure A.4(a), in Supplementary Material). Clearly, the distinction of the thermal profile between these two periods can be observed. Figure A.4(b) shows the DO profile for these same periods, confirming again the occurrence of mixing between the liquid layers after destratification.

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

Descriptive statistics of thermal gradient data

Usually, the beginning of the fluid heating occurred in the early morning in all trials, between 07 h and 09 h, and equalization at night, between 19 h and 22 h. Considering all the gradients obtained in the tests (for 43.951 records), the vast majority was below 14 °C m^{-1} (percentile 90) during periods of stratification, but thermal gradients were as high as 49 °C m^{-1}. The vertical temperature gradient (arithmetic mean) was 4.2 °C m^{-1} (median 1.5 °C m^{-1}). High turbidity in ponds may be responsible for high gradients, as Ukpong *et al.* (2006a, 2006b) and Kellner & Pires (2002) pointed out, even in ponds with shallow depths as those in the present research. To large ponds, Sweeney *et al.* (2005) reported an arithmetic mean temperature gradient of 0.4 °C m^{-1} (maximum of 11.7 °C m^{-1} and minimum of −0.5 °C m^{-1} in the summer and autumn, respectively) in a 112 ha pond in Australia. For the same pond, stratification events lasted on average 2.8 h (maximum duration of 35.5 h and minimum of 0.2 h). Abis & Mara (2006) found a maximum gradient just above 20 °C m^{-1} in ponds in the United Kingdom (temperate climate). Unfortunately, equations available in limnology to evaluate the thermal stratification in lakes do not apply to shallow ponds such as in this study.

Descriptive statistics of all the records of thermal gradients are illustrated by means of blox-plot in Supplementary Material, Figure A.5. Considering all the data analysed ($n = 43951$ records), and the referenced gradient threshold for the occurrence of stratification (0.6 °C m^{-1}), the ponds remained 56% of the time under thermal stratification and 44% in vertical mixing. Separating the same data by hot/humid periods and cold/dry, there were no significant difference between the gradient data with a confidence level of 99% (p value = 0.48). Also, there were no significant temperature differences between the seasonal periods at the research site (tropical climate), as is generally observed in temperate climates. These results are therefore for ponds in tropical climates.

Occurrences of negative thermal gradients

Negative gradients seen in Figure 3(a) were obtained especially in tests no. 2, 3, 5, and 15 performed in pond 1, with the bottom probe immersed in the sludge. During these tests, bottom temperatures were higher than the surface at night after destratification, suggesting that sludge plays a fundamental role in the thermal balance of the ponds, probably accumulating heat during the day and starting to supply heat to the liquid overnight. Figure 3(a) illustrates this behavior when the bottom probe was immersed in the sludge (results of the test No. 15). The zero on the x-axis corresponds to 00:00 h of 10/03/2014.

No records were found in literature about the influence of sludge on thermal behavior in ponds. However, Shilton (2005) mentioned that two separate studies performed in New Zealand (unpublished) suggested that the sludge layer often has a higher temperature than the liquid layer above it, such as the events of the negative gradients in this study. According to the author, it is possible that in such cases the sludge layer (warmer and less dense due to the presence of gases) will rise in the pond causing vertical mixing. To verify this hypothesis, tests were performed with two probes completely immersed at different depths in the accumulated sludge in pond 1. Figure 3(b) shows the results of a test conducted from 07/31/2015 to 08/03/2015 with a probe located 0.03 m from the bottom (red markers) and another located 0.15 m from the bottom (blue markers). No behavior was observed that would indicate vertical movement of the sludge layers, with temperatures matching. Sludge beds are intense biochemical reaction compartments where heat is produced but also received from the surroundings. Figure 3(b) shows that the deepest layers of sludge had a higher temperature than the more superficial layers, but remained stable with negative thermal gradients. In this case, this probably occurred due to the solid's concentration, which tended to increase along the sludge depth, increasing density and thus maintaining higher temperatures at the bottom.

Negative thermal gradients also occurred when monitoring coincided with periods of saline tracer tests (sodium chloride) in the same pond. The tests were performed according to the

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

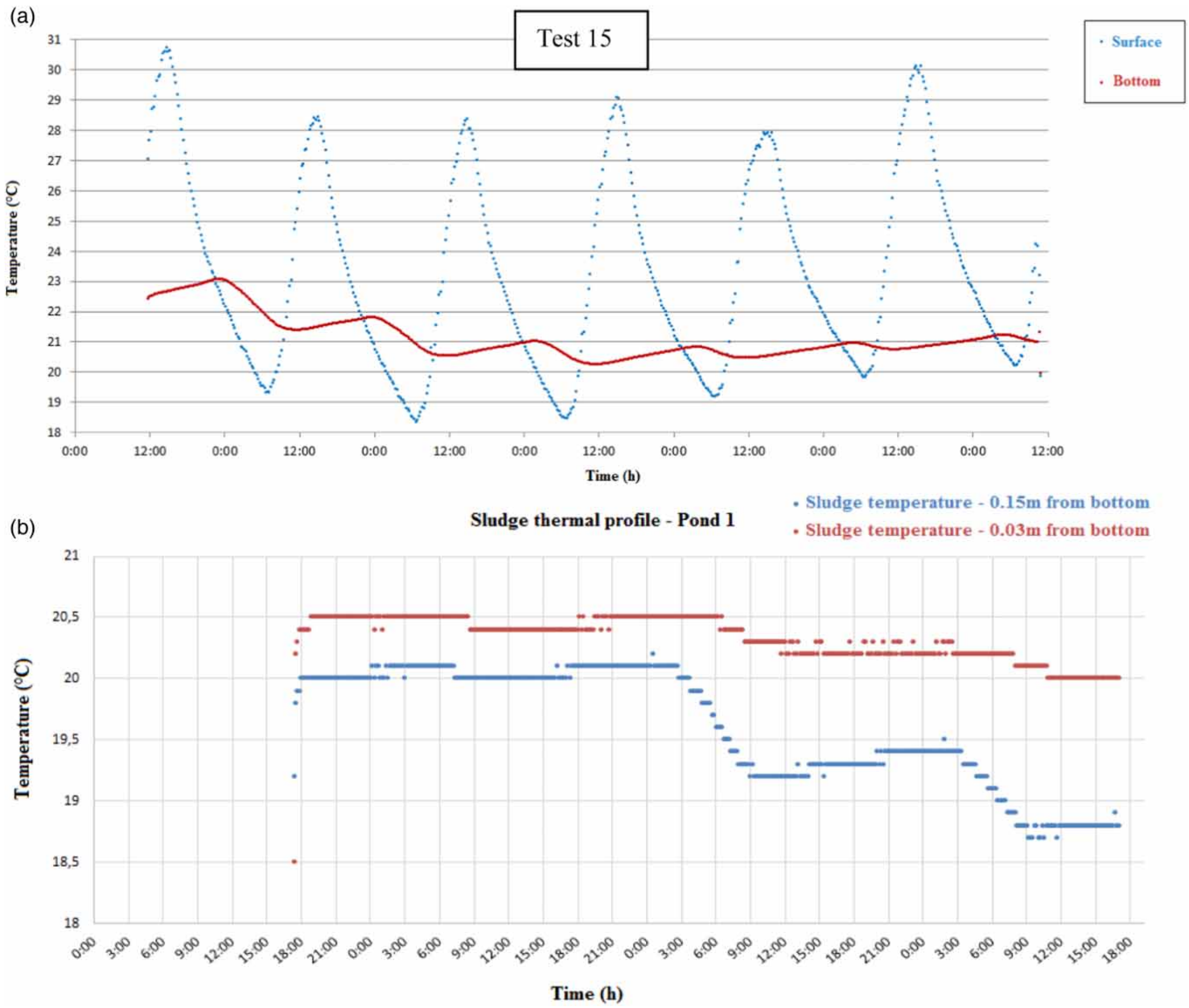

Figure 3 | (a) Temperature profile (surface and bottom) in pond 1 during test No.15 (phase 2), with the bottom probe immersed in the sludge layer, H = 0.80 m (b) Temperature of sludge in pond 1, with probes at different depths.

stimulus-response technique (Levenspiel 2000) by means of a tracer pulse injection at the pond's inlet and measurement of EC at the outlet. Tracer solution was prepared in a household water reservoir (1.1 m^3), using 320 kg of salt and continuous homogenization. After preparation of the tracer solution, it was slowly introduced in the ponds, but always in a period of less than 2% of the theoretical HRT, such as not to mischaracterize the pulse injection, according to recommendations by Bracho *et al.* (2009). Conductivity readings were performed with YSI 600XLM V2® probes (detection range from 0 to 100 mS^{-1}) with internal datalogger. Details of the saline tracer test, including discussion about density effects, can be found in Passos *et al.* (2018). In such cases, the tracer solution was responsible for increasing the density of the bottom layer, preventing mixing with the upper layers, even at higher temperatures. Figure 4 illustrates this effect with data from test 3. A stratification period and vertical mixing occurred before applying the saline tracer (expected behavior) and then the occurrence of negative thermal gradients was observed after that, with complete change of the thermal profile. In that test, the conductivity in the pond peaked of about 20,000 μS^{-1}. Note also that these negative gradients, in proportion to the temperature amplitude, gradually reduced in magnitude as the tracer concentration decreased (indicated by EC in black dots).

The influence of a saline tracer for the thermal profile in the pond is shown in Figure A.3(a), in Supplementary Material, in which a disruption caused by the application of the tracer at the beginning of test 14 can be seen (momentary inversion of the thermal profile). This fact points out the need for

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

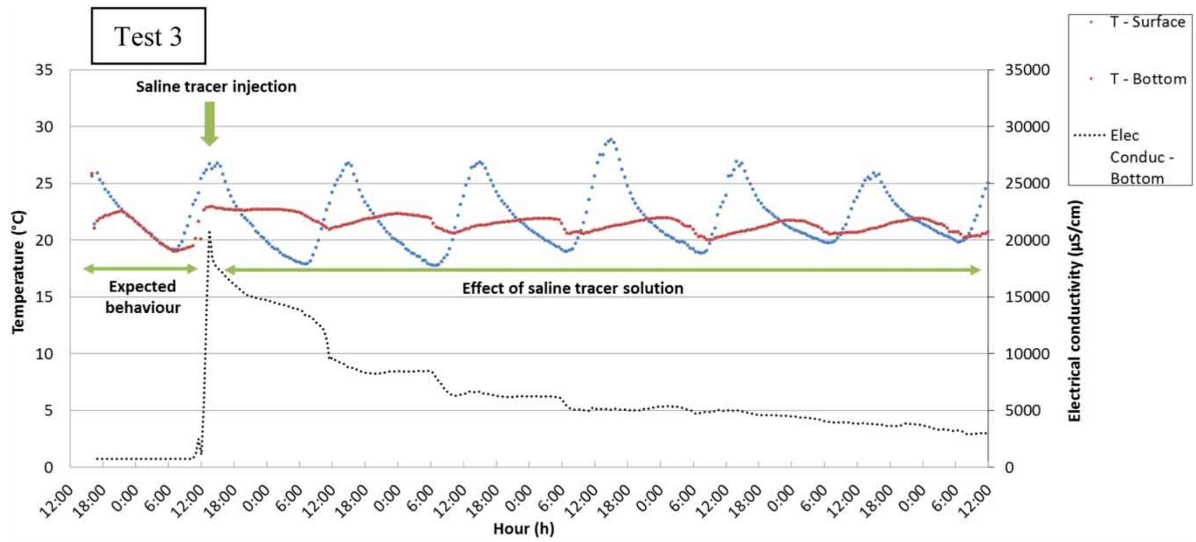

Figure 4 | Simultaneous monitoring of the temperature profile (surface and bottom) and electrical conductivity (bottom) in pond 1 during test 3 (phase 2), with saline tracer test. H = 0.80 m.

caution in interpretation of the thermal profile data when occurring simultaneously with a saline tracer test, since results may show a profile that does not occur naturally. The opposite must also be considered, as tracer measurements on the surface revealed oscillations in the concentration of the daily cycles, following thermal variations. Thus, saline tracer data must be analysed considering thermal stratification and equalization, since the thermal profile influences the concentration of the saline tracer recorded.

Effects of environmental conditions in the ponds' thermal profile

Statistical tests – Spearman and Pearson correlation at a 99% confidence level – showed a significant correlation between the liquid temperature gradient and local air temperature, but not between the thermal gradient and wind speed. The fitting equation between air temperatures and liquid thermal gradients, considering all the events in which data from the weather station (air temperature) and temperature data from the probes in the ponds were recorded at exactly the same time ($n = 9016$), was $GRAD = 1.31 \times 10^{-5}.\ T^{4.17}$ ($R^2 = 0{,}64$) (gradient in °C m^{-1} and T in °C), valid for T ranging from 9.8 to 33 °C. Considering all isolated data (not grouped by seasons), an association between higher gradients and hotter days, as well as vertical mixing with air cooling was determined. Correlation between variables was significantly positive, with p-value <0.01. The Spearman correlation coefficient (r_s) was 0.7557. Wind data recorded from the weather station and not immediately above the water surface. Figure A.6 (Supplementary Material) shows the dispersion graph between air temperatures and thermal gradients observed in the ponds, with the predictive equation adjustment.

Although the thermal gradient and wind speed variables are not related to each other at a significant level in statistical testing, stratification breakdown seemed to occur early in the day when stronger winds prevailed. Comparing the time when mixing occurred (assigned as the fraction of the day, from 0 to 1, in which the thermal gradient became less than 0.6 °C m^{-1}) with the arithmetic mean wind speeds in the previous hour (average value of all recorded data), despite the great dispersion of data, a significant negative correlation between the two variables at a confidence level of 99%, in both Pearson correlation test (p-value = 0, 0001; $r = -0.4647$) and Spearman correlation test (p-value = 0.0097, $r_s = -0.3211$) was observed. This suggested that, although not considered a determining factor, wind influenced mixing. In summary, the thermal equalization events observed

Water Practice & Technology Vol 14 No 3
doi: 10.2166/wpt.2019.054

during nightfall were more related to temperature cooling (in gentle winds conditions), whereas some thermal equalization events which were observed earlier during the day occurred because of stronger winds.

CONCLUSIONS

The following conclusions should be analyzed in the context of shallow maturation ponds operating under tropical conditions. The results suggest that there were daily periodic events of stratified conditions followed by temperature equalization and mixing in the ponds with and without sludge, baffled and unbaffled, regardless of the monitoring location in the horizontal plane. Vertical mixing was endorsed by DO, pH and ORP monitoring on the surface and bottom of the pond. Data suggest that the pond with the higher depth (around 0.80 m) resulted in longer stratified periods, but equalization/mixing still occurred. Positive temperature gradients up to 30 °C m^{-1} were found during stratification periods, suggesting that this is a common occurrence even in shallow ponds, with very high temperature gradients.

During some tests, bottom temperatures were higher than the surface temperatures in the pond (at night, after destratification), resulting in negative thermal gradients. These negative temperature gradients suggest that the sludge layer is a crucial factor for the thermal balance of ponds and should be considered in mathematical and computational hydrodynamic models. In addition, the sludge vertical profile showed that the deepest layers of sludge had a higher temperature than the more superficial layers, apparently without causing vertical movement with the rise of the settled sediment.

Negative gradients obtained in tests in the pond without sludge showed great interference of saline conditions associated with tracer tests on the thermal profile, suggesting special attention when interpreting data from simultaneous saline tracer and temperature profiling tests.

Regarding thermal equalization (or vertical mixing), data suggest that this event is much more related to air temperature cooling than to wind. However, although not decisive, strong winds appear to contribute to the anticipation of mixing, causing it to occur earlier during the day. The turbulence caused in the liquid at the inlet region of the pond (verified in Passos *et al*. 2019), was also unable to promote mixing and avoid stratification.

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