Sludge accumulation in shallow maturation ponds treating UASB reactor effluent: results after 11 years of operation

Thiago Emanuel Possmoser-Nascimento, Valéria Antônia Justino Rodrigues, Marcos von Sperling and Jean-Luc Vasel

ABSTRACT

Polishing ponds are natural systems used for the post-treatment of upflow anaerobic sludge blanket (UASB) effluents. They are designed as maturation ponds and their main goal is the removal of pathogens and nitrogen and an additional removal of residual organic matter from the UASB reactor. This study aimed to evaluate organic matter and suspended solids removal as well as sludge accumulation in two shallow polishing ponds in series treating sanitary effluent from a UASB reactor with a population equivalent of 200 inhabitants in Brazil, operating since 2002. For this evaluation, long-term monitoring of biochemical oxygen demand and total suspended solids and bathymetric surveys have been undertaken. The ponds showed an irregular distribution of total solids mass in the sludge layer of the two ponds, with mean accumulation values of 0.020 m^3 $person^{-1}$ $year^{-1}$ and 0.004 m^3 $person^{-1}$ $year^{-1}$ in Ponds 1 and 2, leading to around 40% and 8% of the liquid volume occupied by the sediments after 11 years of operation. The first pond showed better efficiency in relation to organic matter removal, although its contribution was limited, due to algal growth. No simple input–output mass balance of solids can be applied to the ponds due to algal growth in the liquid phase and sludge digestion in the sludge.

Key words | bathymetry, performance evaluation, polishing ponds, sludge layer, UASB reactors

Thiago Emanuel Possmoser-Nascimento
Valéria Antônia Justino Rodrigues
Marcos von Sperling (corresponding author)
Department of Sanitary and Environmental Engineering,
Federal University of Minas Gerais,
Av. Antônio Carlos, 6627 – School of Engineering - Block 1 – room 4622, 31270-901,
Brazil
E-mail: *marcos@desa.ufmg.br*

Jean-Luc Vasel
Department of Science and Environmental Management,
Unit Environment and Sanitation; University of Liege,
Campus Arlon,
Belgium

INTRODUCTION

The use of natural systems such as stabilization ponds and their variants for sewage treatment in small and medium-size cities in warm-climate regions is due to their simplicity, low operating costs, no mechanization and satisfactory organic matter removal. Widely used configurations are facultative ponds or anaerobic ponds followed by facultative ponds. If high levels of pathogen removal are desired, maturation ponds can be added at the end of the treatment line. However, one of the drawbacks of these configurations is the need for very large areas. One way of reducing the land requirements is by using polishing (maturation) ponds after UASB (upflow anaerobic sludge blanket) reactors. The anaerobic and facultative ponds are replaced in their role of organic matter removal by the UASB reactor, which is much more compact. This configuration still maintains low operating costs, simplicity and no mechanization, while being able to remove efficiently organic matter, nitrogen, and especially pathogens (Cavalcanti 2003; Chernicharo 2003; Oliveira & von Sperling 2011). Khan *et al.* (2011), in a literature review, indicated UASB reactors followed by an aerobic stage as an ideal concept for feasible and sustainable environment protection in a decentralized sanitation concept.

An important feature in pond systems is the sludge accumulation due to influent solids, as well as bacterial and algal biomass that grow and die within the pond and are deposited at the bottom. In traditional primary facultative ponds, sludge removal is usually required only after very long periods, such as 20 years. However, little is known about long-term sludge accumulation in polishing ponds treating effluents from UASB reactors. The sludge layer characteristics vary along the bottom of the pond. This can be attributed to the configuration, geometry and positioning of the inlet and outlet structures of the ponds

doi: 10.2166/wst.2014.224

(Von Sperling & Chernicharo 2005). In addition, processes related to organic matter conversion, algal production and sludge digestion influence the solids balance in the system and affect the effluent solids concentrations and sludge accumulation rates.

Algal sedimentation, on the other hand, is less common at the entrance of the first pond because the conditions created by turbidity and organic loading inhibit their full development. As the effluent moves towards the outlet of the pond and through the ponds in the series, the solids from the anaerobic reactor decrease in concentration, and algal sedimentation becomes more important (Catunda *et al.* 2000).

This research was aimed at evaluating the performance and sludge accumulation in two polishing ponds that operate in series, serving as post-treatment of a UASB reactor in Brazil, based on 11 years of operation. The performance evaluation shown here focuses on suspended solids and, because of their association with solids production, also organic matter.

It is known that the main objective of polishing ponds is the removal of pathogens and, depending on the operating conditions, also nitrogen. However, these topics have been already widely covered in the literature, including in the same pond system investigated here. Von Sperling *et al.* (2008) analysed the same system (but with three ponds and a rock filter in series) for 3 years under similar conditions, and observed an excellent performance, with a mean *Escherichia coli* removal of 5.7 logarithmic units and a mean effluent concentration of 540 MPN/100 mL. In addition, nitrogen removal has been very effective, as stated by Assunção & von Sperling (2012, 2013) and Von Sperling *et al.* (2008). Dias *et al.* (2013) presented a full description of the long-term performance evaluation of this specific treatment system. Therefore, this paper concentrates on organic matter and solids, and the resulting production of sludge.

MATERIAL AND METHODS

The study was performed in the Centre for Research and Training in Sanitation UFMG/COPASA (CePTS), in Belo Horizonte, Brazil (latitude 19°53′ S). The system, treating sanitary wastewater for an estimated population of 200 inhabitants, is composed of a UASB reactor and two polishing ponds in series.

The UASB reactor had a volume of 14.2 m³ (4.5 m in height and 2.0 m in diameter) and operated with a mean hydraulic retention time varying from 8 to 11 h. Anaerobic excess sludge was removed at approximately monthly intervals and the sludge was directed to sludge drying beds. The ponds had the following dimensions: 25.00 m in length; 5.25 m in width; depth that varied from 0.6 to 0.8 m during the operational period. During this 11-year period, the influent flow to the ponds varied between 20 and 40 $m^3 d^{-1}$. Due to flow and depth variations along the whole period, each pond operated with hydraulic retention times between 1.4 and 4.3 d.

Influent and effluent monitoring results were obtained between 2002 and 2013, based on weekly and fortnightly samplings (with some interruptions). Five-day biochemical oxygen demand (BOD_5) and suspended solids (total (TSS), fixed (FSS), and volatile (VSS)) were analysed according to the methodology described in *Standard Methods for the Examination of Water and Wastewater* (2005). Additionally, in 2013, after almost 11 years of operation, a bathymetric study was performed using a device described by Gonçalves (1999) and Passos *et al.* (2013). The device comprised PVC rods connected to metric scales on a perforated 30 cm diameter disc. The first rod (outer rod) with the disc was used to determine the depth of the solids–liquid interface, by touching the sediments without penetrating the sludge layer due to the existence of the circular plate at its base. After determination of the depth of the liquid layer, the second rod (smaller diameter) was introduced inside the first one in order to pierce the sludge layer, stopping when reaching the bottom of the pond. The difference between the measurements performed with the two graded rods provided the sludge layer thickness. Sludge level was measured in 126 points in Pond 1 and 107 points in Pond 2.

On the same day of the bathymetry, sludge samples were taken from 17 points along the ponds and analysed for total solids (TS), fixed solids (FS) and volatile solids (VS). The sampling points were evenly distributed in the ponds' surface area, in three zones: inlet, middle and outlet, each one corresponding to approximately one-third of the pond area. Sludge samples were collected using a column sampler with a bottom opening, which was closed when the sampler reached the pond bottom, thus allowing the sample to be extracted inside the column.

RESULTS AND DISCUSSION

The evaluation of influent concentrations received during the monitoring period showed that the system received lower loads than predicted in the design. Although the system has been designed for a population equivalent of 250 inhabitants, currently the influent flow has been reduced, and the total contribution can be estimated to be around 200 people, considering an average per capita sewage production of 160 L person^{-1} d^{-1}.

Figure 1 shows the surface loading rates in the ponds in terms of BOD and TSS. The organic surface loading of BOD had median values of 117 kg ha^{-1} d^{-1} for Pond 1 and 84 kg ha^{-1} d^{-1} for Pond 2, which are typical low values for maturation and polishing ponds. Pond 2 received a lower organic loading, due to the previous additional removal of organic matter in Pond 1. However, in terms of TSS, both ponds received similar loadings, because in Pond 1 effluent TSS from the UASB reactor was removed but, at the same time, algae was produced.

Figures 2 and 3 present the effluent characteristics for TSS and BOD, as well as their removal efficiencies along the treatment system. The global system showed median removal efficiencies of 66% for TSS and 76% for BOD, and median effluent concentrations of 60 mg L^{-1} for TSS and 40 mg L^{-1} for BOD, which are within typical ranges for well functioning ponds (Oliveira & von Sperling 2011).

From the figures, it can be seen that Pond 1 performed some additional BOD removal, but Pond 2 contributed very little to the removal of organic matter and solids. The poor performance for removing organic matter and solids can be explained by the intense algal production in the ponds, thus generating solids and particulate BOD. As a matter of fact, analysing removal efficiencies of suspended solids and total BOD in ponds may lead to contradictory interpretations, since these constituents are simultaneously removed and produced in the ponds. However, removal efficiencies have been included here in order to highlight the role played by algae, and also to allow comparisons with other pond systems.

In order to estimate a simple input–output solids balance for the units, Figure 4 presents the TSS mass (kg) entering each of the treatment units (UASB reactor and Ponds 1 and 2) over the entire period of 11 years. The mass was calculated based on the sum of the influent TSS loads, using average values of influent flow and TSS over the entire period. It can be seen that the largest TSS mass was related to the untreated wastewater (influent to the UASB reactor). The UASB reactor is effective

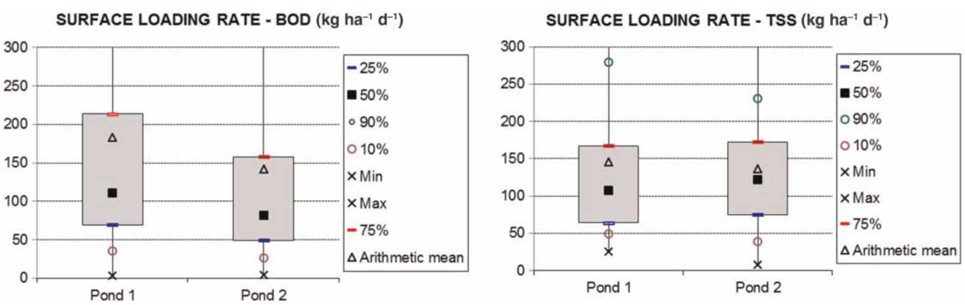

Figure 1 | Surface loading rates in Ponds 1 and 2 in terms of BOD and TSS.

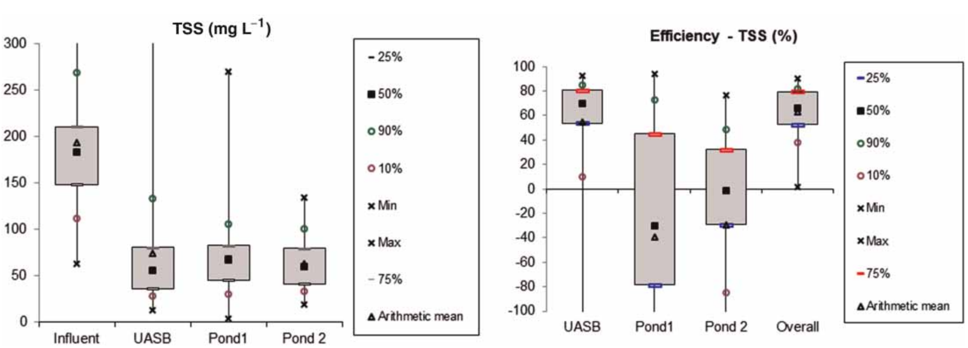

Figure 2 | Suspended solids concentrations and removal efficiencies along the system.

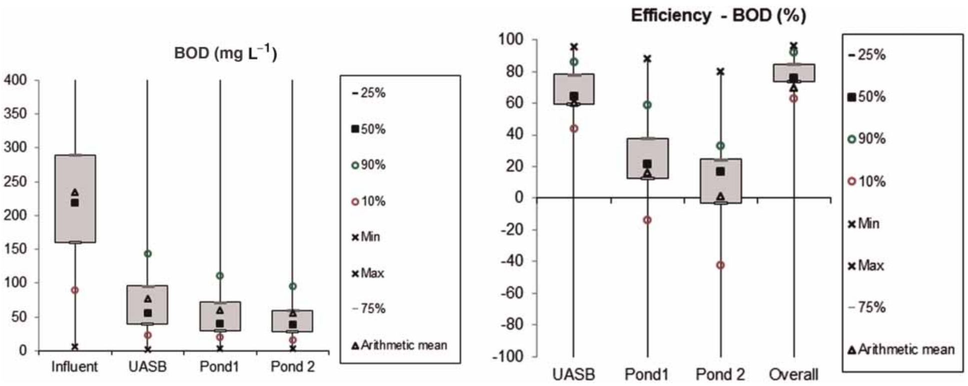

Figure 3 | BOD concentrations and removal efficiencies along the system.

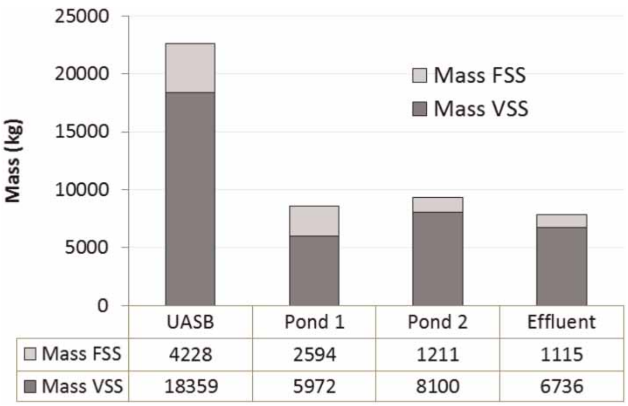

Figure 4 | Masses of TSS, FSS and VSS in the influent to the main treatment units and in the final effluent. Masses were accumulated over the entire operational period of 11 years.

in reducing the TSS mass, and the masses entering and leaving Ponds 1 and 2 are of the same order of magnitude. Figure 4 also presents data on the average VSS and FSS. The VSS/TSS ratio in the treatment plant influent was 81%, a typical value for sanitary wastewater. The effluent from the UASB reactor (influent to Pond 1) had an average VSS/TSS of 70%, indicating that these solids were mainly biological solids that underwent anaerobic digestion inside the UASB reactor, thus reducing their organic matter content. The effluents from Ponds 1 and 2 had VSS/TSS ratios of 87% and 86%, respectively, showing that the solids had increased their organic content, most likely due to the production of biological solids in the form of algae.

Figure 5 also presents the actual mass of solids accumulated in the pond's sediments, based on the bathymetric survey and the measurements of TS in the sludge. These values are expressed as TS (and also VS and FS) in the figure. The figure also presents a simple mass balance around each unit, expressed as the difference between the influent and effluent TSS (and also VSS and FSS) masses in each pond during the 11 years of operation. Positive values of this difference indicate that the effluent mass was higher than the influent mass in that particular pond. For instance, it can be seen that in Pond 1 the mass balance was negative for TSS and VSS, due to the intense algal production. Pond 2

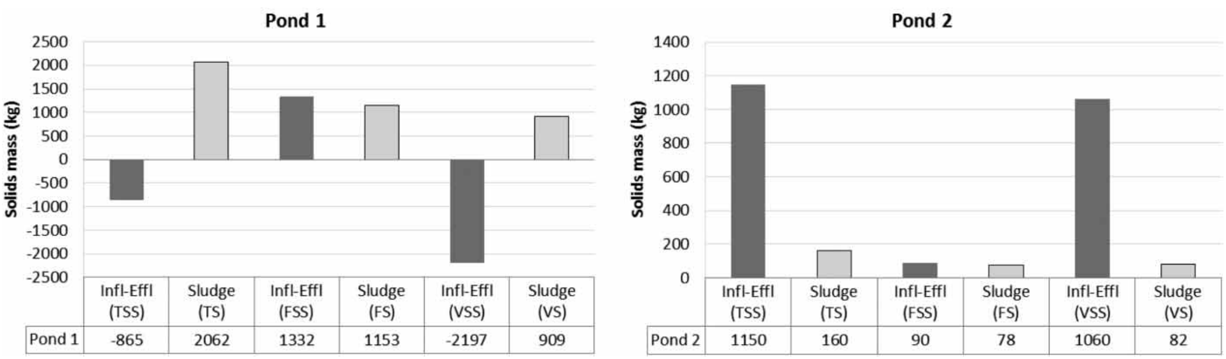

Figure 5 | Comparison between the difference between influent and effluent suspended solids masses in the liquid phase (TSS, FSS and VSS) and the accumulated mass in the sludge layer (TS, FS and VS) in ponds 1 and 2.

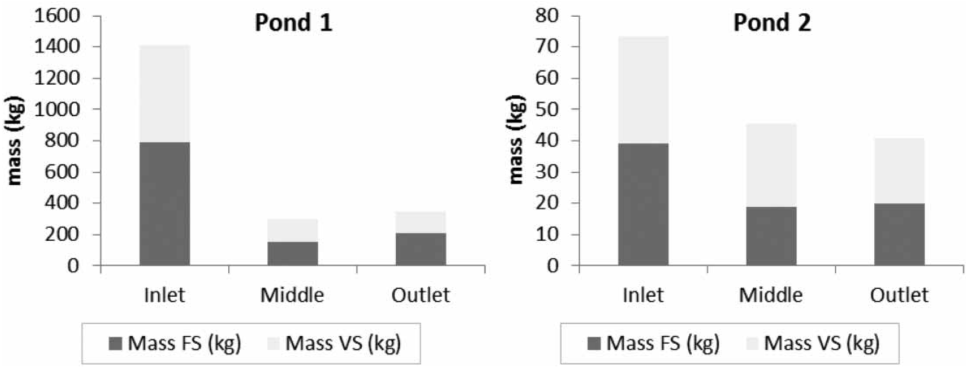

Figure 6 | Solids mass in the sludge in three different zones of Ponds 1 and 2, after 11 years of operation.

received an influent with a high algal content (high TSS and VSS), and the difference between influent and effluent was smaller, but positive. When comparing the influent and effluent solids masses (expressed as TSS, VSS and FSS) with the masses accumulated in the sediments in the ponds (expressed as TS, VS and FS), of course it was not expected that this simple input–output mass balance would represent the actual mass of bottom sludge, because of anaerobic digestion that takes place (reducing the sludge mass) and algal production and sedimentation (increasing the sludge mass). From this simple mass balance, it seems that only the fixed solids (FSS and FS) masses are similar.

Figure 6 shows a more detailed view of the solids composition in the sludge in both ponds, separated in three zones with the same dimensions (inlet, middle and outlet zones), after the 11 years of operation. In Pond 1 most of the sludge solids are of an inorganic nature, but in Pond 2, which has much lower solids masses, the organic and inorganic fractions are similar. Figure 6 also shows that most of the TS mass in the sediments was retained in the inlet zone (68% or 1,412 kg in Pond 1 and 46% or 73 kg in Pond 2), which is in agreement with the findings from other authors (Gonçalves 1999; Nelson *et al.* 2004). The remainder of the TS mass accumulated in the middle and outlet in similar proportions. This accumulation pattern is associated with the ponds' geometric configurations (predominantly rectangular, with a length-to-width ratio of 5) and with the characteristics of the UASB effluent. From the TS mass accumulated in both ponds, most of it is present in Pond 1 (2,062 kg or 92%) and only a small fraction in Pond 2 (160 kg or 8%). This is probably due to the incoming solids mass originating from the UASB reactor, which is likely to settle in the first pond, because of its higher settleability, as compared with algae.

The shape of the sludge layer volume in both ponds after 11 years of operation, obtained through bathymetry, is shown in Figure 7. The figure also shows that most of the sludge volume is accumulated closer to the inlet zones. Nelson *et al.* (2004), studying three facultative ponds, also noted that the distribution was very irregular and that the maximum sludge height occurred near the inlet and also close to the side edges. D'Castro Filho *et al.* (2005) attributed the highest sedimentation in the inlet zone to the characteristics of the input and output devices, and also to a large concentration of the settleable solids present in the influent. Passos *et al.* (2013), investigating the distribution of sludge in a primary facultative pond, noted the great influence of the distribution between the two inlet pipes, with most of the sludge accumulating close to the pipe which received a greater influent fraction. On the other hand, Bouza-Deaño & Salas-Rodríguez (2013) found that the sludge distribution

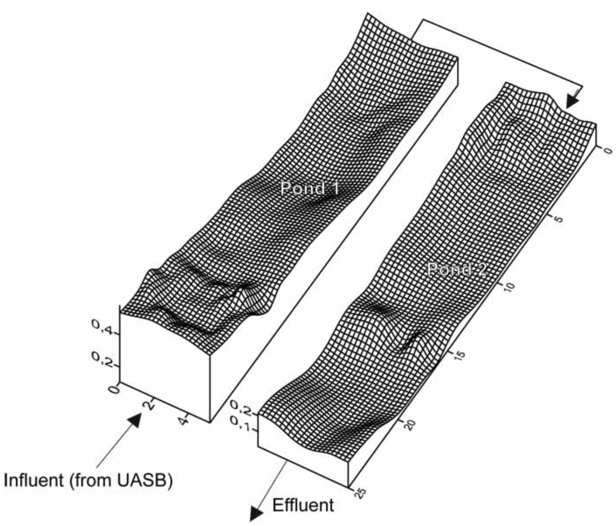

Figure 7 | Distribution of the sludge volume accumulated in the ponds.

Table 1 | Data on the accumulation of sludge in the two polishing ponds

Parameter	Pond 1	Pond 2
Average sludge height (m)	0.34	0.08
Operating time (years)	10.8	10.8
Sludge volume accumulated at the bottom (m^3)	42.6	8.9
Fraction of the total pond volume occupied by sludge[a] (%)	39.8	8.3
Mean concentration of TS in sludge ($g\ L^{-1}$)	48	18
Mean sludge accumulation rate ($cm\ year^{-1}$)	2.58	0.54
Volumetric per capita accumulation[b] ($L\ person^{-1}\ d^{-1}$)	0.058	0.012
Volumetric per capita accumulation[b] ($m^3\ person^{-1}\ year^{-1}$)	0.020	0.004

[a]Calculated for an average depth of 0.70 metres.
[b]Assuming a population equivalent of 200 inhabitants.

was uniform on the facultative and maturation ponds they investigated.

From the bathymetric data it was possible to estimate the per capita contribution of the settled sludge, the average sludge height and the average volume occupied by the sludge in the polishing ponds (Table 1).

From the table, it can be seen that approximately 40% and 8% of the liquid volume of Ponds 1 and 2, respectively, have been occupied by sludge, after this operational period of 11 years. The fraction of sludge in Pond 1 is high, and this value could be an indication of the need for removal (Von Sperling & Chernicharo 2005). These results are in agreement with those of Catunda *et al.* (2000), which indicated that the removal of the sludge in the polishing ponds after UASB reactors investigated in their work should occur after 12 years of operation.

Table 2 | Literature values of TS concentration and accumulation rates of sludges in ponds

Location	Type of pond	Time of operation (year)	Mean TS in sludge ($g\ L^{-1}$)	Accumulation rate ($m^3\ hab^{-1}\ year^{-1}$)	Reference
Mexico	Anaerobic	5	171	0.022	Nelson *et al.* (2004)
Mexico	Facultative	6	–	0.036	Nelson *et al.* (2004)
Mexico	Facultative	10	112	–	Nelson *et al.* (2004)
Mexico	Facultative	15	166	0.021	Nelson *et al.* (2004)
Colombia	Anaerobic	2.6 5	– –	0.055 0.040	Nelson *et al.* (2004)
France	–	10	187	–	Nelson *et al.* (2004)
France	Facultative	3–10	54–136	0.12	Nelson *et al.* (2004)
USA	Facultative	7 13	59 77	–	Nelson *et al.* (2004)
Mediterranean	Anaerobic	15	167	0.011	Bouza-Deaño & Salas-Rodríguez (2013)
Mediterranean	Facultative	20	133	0.027	Bouza-Deaño & Salas-Rodríguez (2013)
Mediterranean	Maturation 1	20	213	0.015	Bouza-Deaño & Salas-Rodríguez (2013)
Mediterranean	Maturation 2	20	173	0.009	Bouza-Deaño & Salas-Rodríguez (2013)
Southeast Brazil	Anaerobic	–	172 –	0.023 0.026	Nelson *et al.* (2004)
Northeast Brazil	Facultative	2.5	39	–	Nelson *et al.* (2004)
Brazil	Facultative	21	–	0.007	Passos *et al.* (2013)
Brazil	Various	–	–	0.03–0.08	Gonçalves (1999)
Brazil	Polishing	7	–	0.018	D'Castro Filho *et al.* (2005)
Brazil	Polishing	2	–	0.040	Brito *et al.* (1999)
Brazil[a]	Polishing 1	11	48	0.020	–
Brazil[a]	Polishing 2	11	18	0.004	–

[a]This study.

The value found for the per capita contribution in the first polishing pond was 0.058 L $person^{-1}$ d^{-1} or 0.020 m^3 $person^{-1}$ $year^{-1}$. This value is below the range reported in the literature for anaerobic and facultative ponds, but within the range for maturation and polishing ponds, as shown in Table 2.

CONCLUSIONS

The results from the wastewater treatment configuration based on UASB reactors followed by polishing ponds in series indicated that most of the organic matter and suspended solids removal took place in the UASB reactor. The first pond in the series (Pond 1) gave an additional contribution to BOD removal, while the second pond (Pond 2) was of little importance on this regard. In terms of suspended solids, both ponds showed negative removal efficiencies, due to the intense algal production.

Pond 1 had a higher solids mass and volume in the sludge layer, compared with Pond 2. The TS mass accumulated in the sediment after 11 years of operation was different from the balance between the influent and effluent solids masses in the ponds. This imbalance was already expected, because of the production of algae in the liquid phase and the reactions that take place in the sludge, such as digestion and accumulation by settled biomass. The mass of TS in the sludge was present mainly in Pond 1 (92% or 2,062 kg), with a smaller fraction in Pond 2 (8% or 160 kg). In the sediments, most of the solids were inorganic.

The bathymetric survey showed that the sludge presented irregular distribution near the inlets and outlets of the ponds. The rates of accumulated solids (0.020 m^3 $person^{-1}$ $year^{-1}$ and 0.004 m^3 $person^{-1}$ $year^{-1}$ for Pond 1 and Pond 2, respectively) were similar to values reported in literature for polishing and maturation ponds, and, as expected, lower than those for anaerobic and facultative ponds. Approximately 40% and 8% of the liquid volume of Ponds 1 and 2, respectively, have been occupied by sludge, after this operational period of 11 years.

ACKNOWLEDGEMENTS

The authors would like to thank CAPES, CNPq and FAPEMIG for their support to the research. Thanks also to Daniel Filipe Cristelo Dias and Lívia Cristina de Oliveira Lana for their contribution to this paper.

REFERENCES

Assunção, F. A. L. & von Sperling, M. 2012 Importance of the ammonia volatilization rates in shallow maturation ponds treating UASB reactor effluent. *Water Science and Technology* **66** (6), 1239–1246.

Assunção, F. A. L. & von Sperling, M. 2013 Influence of temperature and pH on nitrogen removal in a series of maturation ponds treating anaerobic effluent. *Water Science and Technology* **67** (10), 2241–2248.

Brito, M. C. de S. O., von Sperling, M. & Chernicharo, C. A. de L. 1999 Características do lodo acumulado em uma lagoa chicaneada tratando efluentes de um reator UASB (Characteristics of the sludge accumulated in a baffled pond treating effluent from UASB reactor). In: *20th Brazilian Congress on Sanitary and Environmental Engineering, Rio de Janeiro, May 1999* (in Portuguese).

Bouza-Deaño, R. & Salas-Rodríguez, J. J. 2013 Distribution and spatial variability of sludges in a wastewater stabilization pond system without desludging for a long period of time. *Ecological Engineering* **50**, 5–12.

Catunda, P. F. C., Mayer, M. G. R., Moreira, E. A. M. & Van Haandel, A. 2000 Acumulação de lodo em lagoas de polimento tratando esgoto digerido (Accumulation of sludge in polishing ponds treating sewage digested). *Post-Treatment of Effluents from Anaerobic Reactors: a Collection of Technical Papers*. Chernicharo C. A. de L. (coord.), PROSAB, Rio de Janeiro, pp. 67–74 (in Portuguese).

Cavalcanti, P. F. F. 2003 *Integrated Application of the UASB Reactor and Ponds for Domestic Sewage Treatment in Tropical Regions*. PhD Thesis, Wageningen University, Wageningen, The Netherlands.

Chernicharo, C. A. L. 2003 *Anaerobic Reactors*. IWA Publishing, London.

D'Castro Filho, F. J., Florêncio, L., Gavazza, S. & Kato, M. T. 2005 Característica do lodo acumulado em uma lagoa de polimento (Characteristics of the sludge accumulated in a polishing pond). *23° Congresso Brasileiro de Engenharia Sanitária e Ambiental, Campo Grande, Brazil, 18–23 September 2005* (in Portuguese).

Dias, D. F., Possmoser-Nascimento, T. E., Rodriguez, V. A. J. & Von Sperling, M. 2013 Overall performance evaluation of shallow maturation ponds in series treating UASB reactor effluent: ten years of intensive monitoring of a system in Brazil. In: *3rd IWA Development Congress & Exhibition, 14–17 October 2013, Nairobi, Kenya*.

Gonçalves, R. F. 1999 Formação de lodo em lagoas de estabilização (Sludge formation in wastewater stabilization ponds). In: *Gerenciamento do Lodo de Lagoas de Estabilização Não Mecanizadas (Management of Sludge from Unmechanized Wastewater Stabilization Ponds)* (R. F. Gonçalves, ed.). PROSAB, Rio de Janeiro (in Portuguese).

Khan, A. A., Gaur, R. Z., Tyagi, V. K., Lew, B., Mehrotra, I. & Kazmi, A. A. 2011 Sustainable options of post treatment of UASB effluent treating sewage: a review. *Resources, Conservation and Recycling* **55** (12), 1232–1251.

Nelson, K. L., Cisneros, B. J., Tchobanoglous, G. & Darby, J. L. 2004 Sludge accumulation, characteristics, and pathogen inactivation in four primary waste stabilization ponds in central Mexico. *Water Research* **38**, 111–127.

Oliveira, S. M. A. C. & von Sperling, M. 2011 Performance evaluation of different wastewater treatment technologies operating in a developing country. *Journal of Water, Sanitation and Hygiene for Development* **1**, 37–56.

Passos, R. G., von Sperling, M. & Ribeiro, T. B. 2013 Performance evaluation and spatial sludge distribution at facultative and maturation ponds treating wastewater from an international airport. In: *10th IWA Specialist Group Conference on Waste Stabilisation Ponds, 19–22 August 2013. Cartagena, Colombia*.

Standard Methods for the Examination of Water and Wastewater 2005 21st edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Von Sperling, M. & Chernicharo, C. A. de L. 2005 *Biological Wastewater Treatment in Warm Climate Regions*. Two volumes. IWA Publishing, London.

Von Sperling, M., Oliveira, C. M., Andrada, J. G. B., Godinho, V. M., Assunção, F. A. & Melo Junior, W. R. 2008 Performance evaluation of a simple wastewater treatment system comprised by UASB reactor, shallow polishing ponds and coarse rock filter. *Water Science and Technology* **58** (6), 1313–1319.

First received 27 November 2013; accepted in revised form 6 May 2014. Available online 19 May 2014