Performance evaluation and spatial sludge distribution at facultative and maturation ponds treating wastewater from an international airport

Ricardo Gomes Passos, Marcos von Sperling and Thiago Bressani Ribeiro

ABSTRACT

This paper presents a performance evaluation of facultative and maturation ponds in series treating wastewater from a large and intensively used international airport in Brazil, based on 16 years of regular monitoring. The wastewater from the airport showed similar or slightly lower concentrations compared to typical domestic sewage for most of the quality parameters. The contribution of effluents with possible industrial features (aircraft toilets and hangar effluent) did not seem to have adversely affected the characteristics of the influent in terms of aptitude to biological treatment. Overall, the ponds operated under very underloaded conditions (mean loading rate of 44 kg biochemical oxygen demand/ha.d in the facultative pond) and presented a satisfactory quality in terms of effluent concentrations for most parameters. A bathymetric survey of the ponds was done manually by a low-cost measurer constructed specifically for this purpose. After 27 years of operation, only 25% and 18% of the volumes of the facultative and maturation ponds were occupied by sludge. Specific sludge accumulation rates were 0.0071 m^3/passenger.year for the facultative pond and 0.00017 m^3/passenger.year for the maturation pond.

Key words | airports, full-scale facultative pond, full-scale maturation pond, GIS (geographic information system), sludge accumulation rates

Ricardo Gomes Passos (corresponding author)
Marcos von Sperling
Thiago Bressani Ribeiro
Department of Sanitary and Environmental Engineering,
Federal University of Minas Gerais,
Av. Antônio Carlos 6627 – Escola de Engenharia,
Bloco 1 - sala 4622; 31270-901 – Belo Horizonte – Brazil
E-mail: *ricardogpassos@yahoo.com.br*

INTRODUCTION

Knowledge about the quality of the influent to any wastewater treatment plant (WWTP) is essential for designing and operating the system. This is especially the case when the influent is considered as non-domestic, such as in an airport. In a typical airport complex, the effluent originates from bathrooms, airplanes, washing vehicles, aircraft toilets, aircraft and vehicle traffic, airplane fuelling, load transportation, cleaning of work areas, maintenance of green spaces, rubber removing from the runway, among others (Gnecco *et al.* 2008; SDCRAA 2008; Calijuri *et al.* 2011). Possible industrial features can be observed in aircraft toilets and hangar effluents. Literature is sparse regarding characterization of effluent from airports as well as regarding performance of stabilization ponds treating such type of effluent.

The performance of stabilization ponds may be related to several factors, such as weather conditions, influent quality, sludge accumulation, geometric configuration, positioning of inlet and outlet devices and the presence or absence of baffles. Regarding sludge, there may be a relationship between effluent quality and sludge accumulation in the units, due to the possible loss of settled solids with the effluent. Other factors associated with the accumulated sludge can be the loss of useful pond volume, with decreased hydraulic retention time (HRT) and possible short circuits (Schneiter *et al.* 1984; Abis & Mara 2005). However, it is observed that there are large gaps in quantifying the generation of sludge in ponds that receive airport effluents.

Literature reports that sludge accumulation in ponds is not evenly distributed throughout the pond area and, in general, varies with the geometry of the unit, positioning of the inlet and outlet devices and flow conditions. Peña *et al.* (2000) observed the strong influence of the geometry and the relative positioning of the inlets and outlets in the sludge deposition patterns in two experimental anaerobic ponds in Colombia. Nelson *et al.* (2004) studied three

doi: 10.2166/wst.2014.215

full-scale facultative ponds in Mexico, and found that the maximum sludge accumulation occurred near the single inlet and in some of the corners (dead zones). Abis & Mara (2005) and Picot *et al*. (2005) reported a similar behaviour of sludge accumulation around the inlet area in three pilot-scale ponds in the UK and in 19 primary facultative ponds in France, respectively. Sludge accumulation patterns in ponds, therefore, are mainly influenced by the pond geometry and consequently by the hydrodynamic profile (Alvarado *et al*. 2012). In the same way, knowledge of such conditions is fundamental for evaluating a possible interference of accumulated sludge in the treatment efficiency, or as an aid in the definition of strategies to desludging operations.

As a case study for the evaluation of a pond system using monitoring data and a bathymetric survey, this paper presents a performance evaluation from facultative and maturation ponds in series treating wastewater from a large and intensively used international airport in Brazil, based on 27 years of operation and 16 years of regular monitoring. The WWTP treats wastewater for the entire airport complex, including administrative and operational areas, hangars and aircraft wastewater (with non-domestic components). The plant started operation in 1985 and the sludge has never been removed. The airport started operating with around 1,000,000 passengers per year, and is currently in the region of 10,000,000 passengers per year.

METHODS

WWTP under study

The WWTP serving the Tancredo Neves International Airport, in Confins, near Belo Horizonte, Brazil, consists of preliminary treatment (coarse screen, without grit removal), flow measurement (Parshall flume) and a pond system composed of a facultative pond followed by a maturation pond. The average flow during the period was 8.0 L/s, well below the system's design capacity, which led to an average theoretical HRT of 193 days in the facultative pond and 18 days in the maturation pond. The side dimensions of the facultative pond are 190, 118, 145 and 126 m (trapezoidal shaped) with internal slopes of 1.0:2.5 and liquid depth of 2.90 m. The inlet is divided into two pipes that advance into the pond. The pipes have a 90° curve directed to the bottom, through which the influent is released into the pond. The side dimensions of the maturation pond are 118, 118, 48 and 20 m (trapezoidal shaped) with internal slopes of 1.0:2.5 and liquid depth of 2.90 m. The maturation pond inlet is a single pipe, also with a 90° curve directed to the bottom.

In addition to the effluent coming from the passenger terminal, cargo terminal and administrative offices (from the toilets and kitchens), the WWTP receives occasional contributions of wastewater with predominantly non-domestic characteristics: waste from aircraft toilets and effluent from a hangar, where maintenance activities of painting and aircraft repair take place. The hangar has an industrial WWTP (consisting of an oil and water separator, coagulation units, mixing and sludge dewatering) for effluent pre-treatment before discharge into the airport sewerage system.

Monitoring data

The monitoring data of the ponds were provided by the sanitation company that operates the system (COPASA). Statistical analyses were performed for physical, chemical and microbiological parameters in the ponds, from 1994 to 2010. Three sampling points were used: raw wastewater (influent), effluent from facultative pond and effluent from maturation pond (final effluent). The monitoring programme (parameters and frequency) varied over the years but, in general, comprised weekly samples for air and liquid temperature, pH and dissolved oxygen (DO) (grab samples) and monthly or biweekly samples for the other parameters, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total solids (TS), total suspended solids (TSS), fixed suspended solids, volatile suspended solids (VSS), settleable solids, *Escherichia coli*, chloride, ammonia, total nitrogen, total phosphorus, oil and grease, detergents, alkalinity (composite sampling) and phytoplankton, resulting in a total of approximately 9,000 data values. Flow measurement was always continuous, and the records were presented as mean monthly averages. The influence of the wastewater from aircraft toilets was verified by comparing monthly volumes released in a manhole.

Bathymetric survey of the sludge

The points for sludge level measurement were homogeneously distributed within the ponds, covering parallel transects that uniformly covered the surface water in both ponds. In total, 109 measurement points were used, including 72 points for the facultative pond and 37 for the maturation pond. The sections were marked and covered with a boat for the measurements. Measurements were made using a device comprising a PVC rod connected to a disc-shaped acrylic base (with small holes equally distributed) and a metal rod of smaller gauge with metric scale. (Gonçalves *et al.* 1997). The first rod (outer rod) was used to determine the depth of the solids–liquid interface, by touching the sediments without penetrating the sludge layer owing to the existence of the circular acrylic plate at its base. After determination of the depth of the liquid layer, the second rod (smaller gauge) 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.

A GPS (global positioning system) navigator, Garmin model 76, was used for recording the points. The bathymetric maps were prepared with the software ArcGIS 9.3® (ESRI Inc.), with the spatial interpolator Natural Neighbour tool, using Thyessen polygon interpolation method. With the ArcGIS 9.3 software, the useful volume and volume of the sludge layer in the ponds were determined, which allowed calculation of the average generation of sludge per passenger. The cumulative number of passengers was obtained from the records of the company that operates the airport (Infraero).

RESULTS AND DISCUSSION

Analysis of monitoring data

Table 1(a) summarizes concentration values in the raw wastewater, facultative pond effluent and maturation pond effluent. Table 1(b) shows the average removal efficiency for each pond and for the system as a whole. Because of the large number of data obtained, it is difficult to interpret and discuss all of them in a single paper. Only major comments will be made here.

Generally, the effluent from the airport (influent to the treatment plant) showed similar or slightly lower concentrations compared with diluted domestic sewage for most of the quality parameters. The average concentrations of BOD, COD, TSS, VSS, total phosphorus, oil and grease, detergents and chloride were below those reported in the literature for typical domestic wastewater (Metcalf & Eddy, Inc. 2003; Von Sperling & Chernicharo 2005). However, nitrogen and alkalinity exceeded typical values. Probably, the highest ammonia concentrations were due to the high proportion of urinals (urine) at the airport when compared to residences, since these toilets are probably used more to urinate than to defecate. Alkalinity can be explained by the greater water hardness in the airport area (karstic region), since the supplied water comes from an underground water source. VSS/TSS and BOD/COD ratios were within commonly seen values in domestic sewage, suggesting good biodegradability.

Liu *et al.* (2007), in a study at the airport of Qingdao, China, obtained similar findings: concentrations of physical and chemical parameters were below those found in domestic wastewater, except for pH and total nitrogen (within range) and ammonia (slightly above).

In general, the overall pond system showed typical removal efficiencies for BOD, but somewhat lower than expected efficiencies for COD. It should be noted that mean negative efficiencies have been found in the maturation pond with respect to organic matter and solids. Although BOD and COD analyses have not included their composition in terms of soluble and particulate fractions, it is strongly believed that the increase in the effluent concentration was due to the presence of algae (particulate organic matter). The large values of the standard deviations of the removal efficiencies of the major constituents in the maturation pond reflect this instability associated with episodes of large solids loss in the pond effluent. The large presence of solids in the final effluent indicates that improvements in the performance of the system in terms of organic matter should concentrate on the particulate fraction, and not on the soluble one. Removal of suspended solids from pond effluents can be undertaken by several processes, ranging from simple ones, such as coarse rock filtration (Von Sperling *et al.* 2007), to more sophisticated ones, such as dissolved air flotation (Barros *et al.* 2013).

E. coli removal efficiency was high (4.7 log units), mainly due to the high reduction that occurred in the facultative pond. Nutrients were also reasonably well removed, especially in the facultative pond (good removal of total nitrogen, ammonia nitrogen and total phosphorus). In the maturation pond there was a small removal of ammonia and no substantial removal of total nitrogen and total phosphorus.

The calculated daily average of volumetric wastewater generation per passenger (pax) was 26 L/pax.d, higher than the typical range quoted by Metcalf & Eddy, Inc. (2003), of 11–19 L/pax.d. Similarly, the daily averages of BOD and COD generation rates per passenger were, respectively, 7 and 17 g/pax.d.

Regarding BOD surface loading rate, Figure 1 shows the historical time series in both ponds, with moving average of

Table 1 | (a) Mean, median and standard deviation of the concentrations along the system; (b) average removal efficiency of selected constituents in each pond and in the system

	Raw wastewater			Facultative pond			Maturation pond		
(a) Concentration	**Mean**	**Median**	**Standard deviation**	**Mean**	**Median**	**Standard deviation**	**Mean**	**Median**	**Standard deviation**
BOD	235	201	148	41	32	35	45	36	35
COD	472	417	288	152	133	97	188	157	119
TSS	201	163	147	52	39	46	46	37	39
VSS	174	146	132	46	36	43	40	31	36
Total solids	713	718	252	391	382	112	444	402	170
Total N	57	51	28	17	14	12	14	12	11
Ammonia-N	49	41	28	11	9	9	9	7	7
Phosphorus	4.9	4.4	3.0	1.9	1.7	1.1	1.8	1.5	1.3
Oil/grease	48	40	40	20	14	23	27	20	34
Detergents	2.4	2.2	1.5	0.6	0.6	0.3	0.2	0.1	0.2
Acidity	51	46	34	11	7	16	2	0	4
Alkalinity	318	310	130	141	140	64	127	122	48
Chloride	40	39	16	38	40	12	58	48	27
pH	7.6	7.6	0.4	8.8	8.8	0.6	9.6	9.6	0.7
DO	–	–	–	5.3	4.9	2.3	9.1	9.4	2.7
Settleable solids	8.7	8.8	3.7	0.0	0.0	0.0	0.0	0.0	0.0
E. coli	1.94×10^{7a}	1.80×10^{7}	6.60×10^{8}	5.96×10^{3a}	1.10×10^{4}	1.19×10^{6}	3.06×10^{2a}	3.30×10^{2}	3.57×10^{4}

	Facultative pond		Maturation pond		System	
(b) Removal efficiency	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
BOD	77	17	– 22	55	77	17
COD	52	30	– 16	55	52	27
TSS	59	38	– 31	95	62	48
VSS	56	41	– 32	117	57	73
Total solids	28	42	– 4	33	35	27
Total N	59	29	1	44	67	29
Ammonia-N	63	31	16	38	73	24
Phosphorus	43	27	18	29	53	30
Oils/greases	48	50	1	69	50	55
Chloride	– 1	27	– 8	28	– 9	39
Settleable solids	100	0	100	0	100	0
E. coli	3.5	1.4	1.4	1.0	4.7	1.4

Part (a): unit is mg/L, except for pH (unitless), settleable solids (mL/L) and *E. coli* (MPN/100 mL).
[a]Geometric mean.
Part (b): efficiency in %, except for *E. coli* – log units removal.

12 terms representing annual averages. It is evident that the ponds always operated in underloaded conditions. The average BOD load in the facultative pond, 44 kgBOD/ha.d, was well below the usual range (100–350 kgBOD/ha.d) adopted in designs in tropical countries (Von Sperling & Chernicharo 2005). Mara (1997) presents an equation (Equation (1)) that uses the average air temperature in the coldest month (T, in °C) to estimate the BOD surface loading rate (L_s, in kgBOD/ha.d) to be considered in the design of facultative ponds

$$L_S = 350x(1.107 - 0.002xT)^{(T-25)} \quad (1)$$

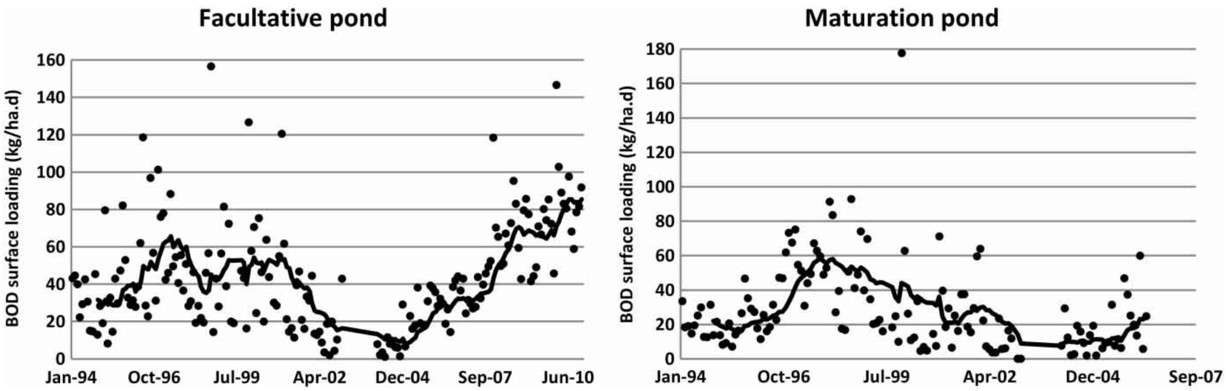

Figure 1 | Time series of BOD surface loading rate (kgBOD/ha.d) in the facultative pond and maturation pond with moving average of 12 terms.

Based on the average air temperature in July (21.7 °C), it can be estimated that the design organic surface loading rate in the facultative pond would be 285 kgBOD/ha.d, which is much higher than even the maximum value of the operating BOD surface loading rate in the pond (157 kgBOD/ha.d) found throughout the monitoring period. Despite the observed low surface loading rates, it can be observed that there is an increasing trend in recent years, due to the rise in the number of passengers using the airport. Expected increase in the number of flights in the near future will cause further elevation of the loading rate, but it can be seen that the treatment system is still able to accommodate higher loads.

Although not a direct design parameter, the HRT in the pond must be sufficient to allow for the required organic matter oxidation. According to Von Sperling & Chernicharo (2005), the HRT required in facultative ponds depends on climatic factors. A usual range cited by the authors is 15–45 days for primary facultative ponds. In the studied facultative pond, the HRT varied substantially (minimum of 75 days and average of 193 days), with values systematically much higher than the typical design ones. For maturation ponds, there is a generic recommendation to maintain a minimum of 3 days in each unit, to avoid algae wash-out (Mara 1997). The minimum HRT presented by the maturation pond was 7 days and the average HRT was 18 days, thus indicating that the unit was always underloaded from the hydraulic point of view, since it operated for 100% of the time above the recommended minimum. Because of these underloading conditions, the final effluent from the system presented high pH and DO values (Table 1), resulting from a high photosynthetic activity associated with algae.

Over the years of monitoring, the efficiency of the facultative pond in BOD removal varied, with the vast majority of data within the range 60–95%. The median and mean values (respectively 77% and 80%) are within the range reported by Von Sperling & Chernicharo (2005) for domestic sewage (75 to 85%). The mean and median COD removal efficiencies in the facultative pond, respectively 52% and 60%, are below the lower limit of the range mentioned by the same authors (65 to 80%). Analysing the performance of the overall system comprising the facultative and maturation ponds (Figure 2), it can be seen that the maturation pond did not lead to an increase in the BOD removal efficiency. In fact, COD removal even decreased, because of the presence of algae in the final effluent, resulting from the underloading conditions in the maturation pond.

No perceptible relationship between wastewater volume from the aircrafts and influent biodegradability (in terms of BOD/COD ratio) or pond efficiency (in terms of BOD or COD removal efficiency) were noted. Mean values of the COD/BOD ratio in the influent were 2.3, which is within the typical range for domestic sewage.

Bathymetric survey

The facultative pond bathymetric maps presented in Figures 3(a) and 3(b) show the space distribution of the sludge. Figure 3(a) illustrates the spatial distribution in terms of the sludge layer thickness, with values ranging from 0.15 to 1.78 m. In Figure 3(b), the values indicate the percentage of the pond depth that is occupied by the sludge layer, ranging from 7.3 to 86.6%. On average, 25% of the net volume of the facultative pond was taken up by the sludge. Most studies on the spatial distribution of sludge layers in facultative ponds indicate accumulations near the ponds' inlets and outlets (Peña *et al.* 2000; Nelson *et al.* 2004; Abis & Mara 2005; Picot *et al.* 2005; Alvarado *et al.* 2012). This is also observed here, with the

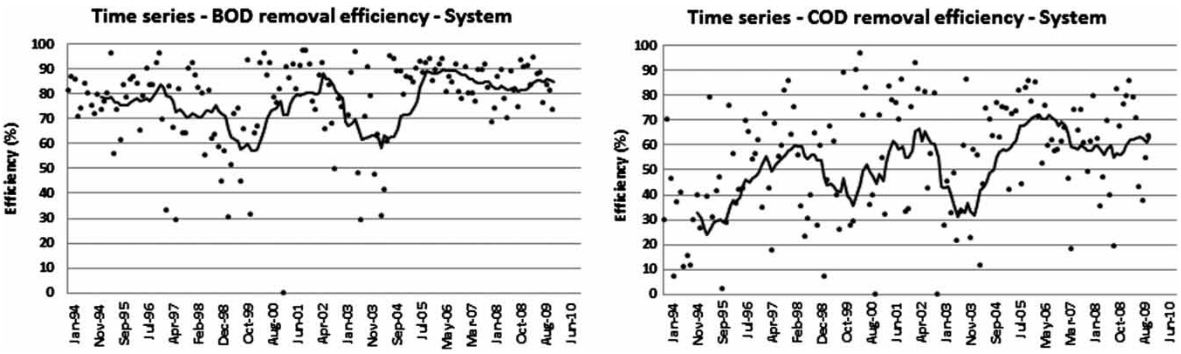

Figure 2 | Time series of the system removal efficiency of BOD and COD, with moving average of 12 terms.

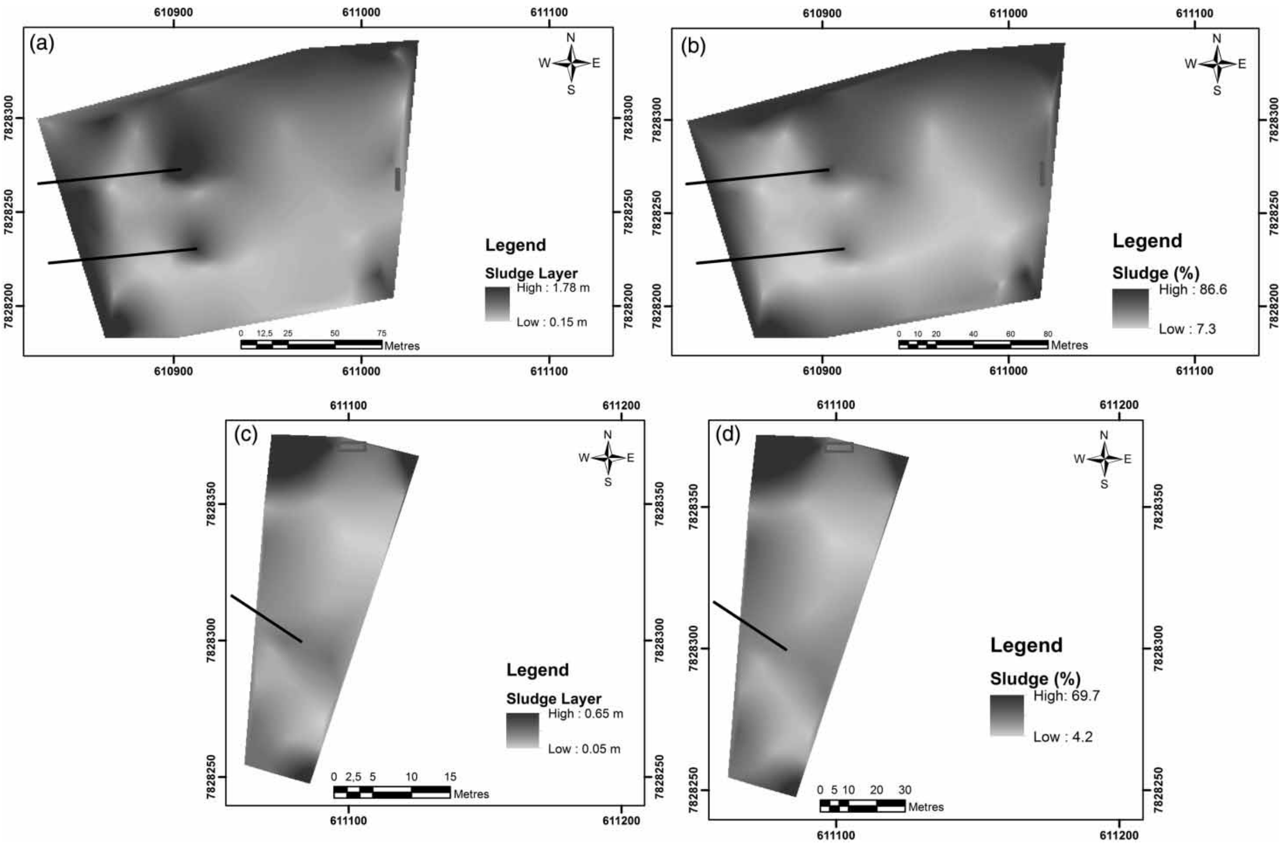

Figure 3 | Spatial distribution of the sludge accumulated in the facultative and maturation ponds. (a) and (c) Sludge height (m) in the facultative and maturation pond, respectively; (b) and (d) percentage of total depth occupied by the sludge in the facultative and maturation pond, respectively.

additional fact of higher accumulations in the left side, a situation caused by unequal flow distribution between the two pipes entering the pond (instead of having half of the flow from each of the two inlet pipes, it was observed that the north one received 80% of the flow). There was also a large zone of accumulation throughout the inlet face, constituted mainly by sand (there are no grit chambers in the system). Bathymetric maps of the maturation pond are shown in Figures 3(c) and 3(d). Figure 3(c) illustrates the spatial distribution in terms of the sludge layer thickness, with values ranging between 0.05 and 0.65 m. In Figure 3(d), the percentage of the pond depth occupied by the sludge ranged between 4.2 and 69.7%. On average, 18% of the net volume of the maturation pond was taken up by the sludge. Most of the sludge is accumulated at the edges near the outlet device.

The average rate of sludge accumulation in the facultative pond, calculated as a function of the annual average of passengers in the years 1989 to 2010, was 0.0071 m^3/pax.year, and, in terms of annual depth, 2.2 cm/year. Regarding the maturation pond, the sludge accumulation rate was in the order of 0.00017 m^3/pax.year or 3.2 cm/year.

The values obtained for the sludge accumulation rate per passenger were lower than those reported in the literature for ponds treating domestic sewage, expressed by inhabitant, generally, varying between 0.021 and 0.12 m^3/pax.year (Arceivala 1981; Gonçalves *et al.* 1997; Nelson *et al.* 2004; Picot *et al.* 2005; Alvarado *et al.* 2012). This can be explained by the underloading conditions of the studied ponds and the dynamics of passengers, which is very different from the population dynamics of a city. Similar data for comparison with ponds treating effluents from other airports, expressed in m^3/pax.year, were not found in the literature.

CONCLUSIONS

The wastewater from the airport showed similar or slightly lower concentrations compared to typical domestic sewage for most of the quality parameters. The contribution of effluents with possible industrial features (aircraft toilets and hangar effluent) did not seem to have adversely affected the characteristics of the influent in terms of suitability for biological treatment.

Overall, the ponds operated in underloaded conditions and presented a satisfactory quality in terms of effluent concentrations for most parameters. However, the presence of algae in the effluent from the ponds deteriorated the effluent quality in terms of organic matter and suspended solids.

The bathymetric survey of the ponds was done manually by means of a low-cost device, which proved to be satisfactory in measuring the thickness of the sludge layer. After 27 years of operation, only 25% of the facultative pond and 18% of the maturation pond volumes were occupied by sludge. Specific sludge accumulation rates were 0.0071 m^3/pax.year for the facultative pond and 0.00017 m^3/pax.year for the maturation pond. Both values are lower than typical per capita values based on domestic sewage.

The map of spatial distribution of the sludge, showing uneven distribution, highlights the need for a careful hydraulic design of the system. Poor flow splitting caused most of the influent wastewater to be distributed in one side of the facultative pond, therefore causing a higher sludge accumulation in this side.

ACKNOWLEDGEMENTS

The authors would like to thank the support given by Empresa Brasileira de Infraestrutura Aeroportuária (Infraero) and Companhia de Saneamento de Minas Gerais (COPASA).

REFERENCES

Abis, K. L. & Mara, D. D. 2005 Research on waste stabilization ponds in the United Kingdom: sludge accumulation in pilot-scale primary facultative ponds. *Environmental Technology* **26**, 449–457.

Alvarado, A., Sanchez, E., Durazno, G., Vesvikar, M. & Nopens, I. 2012 CFD analysis of sludge accumulation and hydraulic performance of a waste stabilization pond. *Water Science and Technology* **66**, 2370–2377.

Arceivala, S. J. 1981 *Wastewater Treatment and Disposal*. Marcel Dekker, New York.

Barros, I. P. A. F., Queiroga, L. L., Von Sperling, M. & Pereira, C. E. B. 2013 Assessment of the implementation of final polishing by flotation at a large pond system in Brazil. In: *10th IWA Specialist Group Conference on Waste Stabilisation Ponds*. IWA – International Water Association, August 19–22, 2013, Cartagena de las Indias, Colombia.

Calijuri, M. L., Santiago, A. F., Moreira Neto, R. F. & Carvalho, I. C. 2011 Evaluation of the ability of a natural wetland to remove heavy metals generated by runways and other paved areas from an airport complex in Brazil. *Water, Air, and Soil Pollution* **219**, 319–327.

Gnecco, I., Sansalone, J. J. & Lanza, L. G. 2008 Speciation of zinc and copper in stormwater pavement runoff from airside and landside aviation land uses. *Water, Air, and Soil Pollution* **192**, 321–336.

Gonçalves, R. F., Nascimento, C. G., Ferrari, G. F. & Muller, P. S. G. 1997 *Lodos de lagoas de estabilização em operação no Espírito Santo: formação e características (Sludge in stabilization ponds in operation in Espírito Santo: formation and characteristics)*. In: Congresso Brasileiro de Engenharia Sanitária e Ambiental, ABES, 19, Foz do Iguaçu, Brazil.

Liu, Z., Qun, M., An, W. & Sun, Z. 2007 An application of membrane bio-reactor process for the wastewater treatment of Qingdao International Airport. *Desalination* **202**, 144–149.

Mara, D. D. 1997 *Design Manual for Waste Stabilisation Ponds in India*. Lagoon Technology International Ltd, Leeds, UK.

Metcalf & Eddy, Inc. 2003 *Wastewater Engineering: Treatment and Reuse*. 4th edn, McGraw-Hill, New York.

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.
Peña, M. R., Mara, D. D. & Sanchez, A. 2000 Dispersion studies in anaerobic ponds: implications for design and operation. *Water Science and Technology* **42**, 273–282.
Picot, B., Sambuco, J. P., Brouillet, J. L. & Riviere, Y. 2005 Wastewater stabilisation ponds: sludge accumulation, technical and financial study on desludging and sludge disposal case studies in France. *Water Science and Technology* **51**, 227–234.
Schneiter, R. W., Middlebrooks, E. J. & Sleter, R. S. 1984 Wastewater lagoon sludge characteristics. *Water Research* **18**, 861–864.
SDCRAA – San Diego County Regional Airport Authority 2008 *San Diego Storm Water Management Plan*. http://www.san.org/sdcraa/airport_initiatives/environmental/protection/stormwater.aspx (accessed 22 October 2013).
Von Sperling, M. & Chernicharo, C. A. L. 2005 *Biological Wastewater Treatment in Warm Climate Regions*. Two volumes. IWA Publishing, London.
Von Sperling, M., Andrada, J. G. B. & Melo Júnior, W. R. 2007 Coarse filters for pond effluent polishing: comparison of loading rates and grain sizes. *Water Science and Technology* **55** (11), 121–126.

First received 17 December 2013; accepted in revised form 17 April 2014. Available online 7 May 2014