Reduction of area and influence of the deposit layer in the first stage of a full-scale French system of vertical flow constructed wetlands in a tropical area

Camila Maria Trein, Jorge Alejandro García Zumalacarregui, Mirene Augusta de Andrade Moraes and Marcos von Sperling

ABSTRACT

Utilization of the French system of vertical wetlands for treating raw sewage keeps increasing, but there is still limited consolidated information on their long term use in tropical countries. Under these conditions, there are indications that surface area requirements can decrease, whilst still keeping a satisfactory performance. However, variations in the operational mode and the role of the surface organic deposit layer under warm climatic conditions have not been fully investigated. The goal of this work was to evaluate the performance of a system comprised of only the first stage of the French system, with a further reduction of 1/3 of the area (utilization of only two units in parallel, instead of three) in terms of organic matter removal and nitrogen conversion, with one unit with a deposit layer accumulated over 9 years of operation, and the other unit without sludge layer, under Brazilian tropical conditions. The system was originally designed according to Cemagref/Instea recommendations for the first-stage of the French system for the treatment of raw sewage generated by an equivalent population of 100 inhabitants. However, it was later on changed, and operated with only two units, using only 0.6 m²·pe⁻¹. Feeding and resting periods were of 7 days each. In order to evaluate the influence of the sludge layer, the top sludge from one of the units was removed, and the performance of both units was compared by the Mann-Whitney test. The database comprises the wetland performance values in terms of dissolved oxygen (DO), redox potential (Eh), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), NH₄⁺-N and NO₃⁻-N, covering a monitoring period of 15 months. The effluent DO concentrations were significantly lower in the unit with top sludge, but still sufficiently high in both units. Although there were some variations between both units, effluent concentrations of the major pollutants were not significantly different in the units with and without sludge, and removal efficiencies based on mean values were considered good, given the reduced area of the system: BOD (80% and 79%), TSS (85% and 82%), TKN (60% and 63%) for the units with and without sludge, respectively. Under Brazilian climatic conditions, with the reduced area and employing longer feeding cycles (7 days), the sludge accumulation rate (less than 1 cm·year⁻¹) was lower compared to the French mean values.

Key words | organic deposit accumulation, raw sewage, sewage treatment, treatment wetlands

INTRODUCTION

The configuration of the French system of vertical constructed wetlands (VCW-FS) eliminates the need for pre-treatment (e.g. septic tanks) and is comprised of two stages in series. In regions where the effluent discharge standards are not stringent, only the first stage may suffice, associated with the non use of the second stage. With only the first stage, consisting of three units in parallel (representing an area of 1.2 m²·pe⁻¹), the suspended solids and organic matter removal may be satisfactory, as indicated by the broad survey undertaken by Morvannou et al. (2015)
in systems operating in France, with mean efficiency values of 83% and 77% for total suspended solids (TSS) and chemical oxygen demand (COD), respectively. This can be achieved with surface loads of approximately 300 g COD·m⁻²·d⁻¹ and 150 g TSS·m⁻²·d⁻¹ in the unit in operation, as recommended by Molle et al. (2005). Nitrification is expected to be around 50% for loads ranging from 25 to 30 g TKN·m⁻²·d⁻¹ (Molle et al. 2005).

Under favorable climatic conditions, Molle et al. (2015) highlight the possibility of reducing the area of the first stage of VCW-FS, whilst still maintaining good performances of organic matter removal (91% for COD, biochemical oxygen demand (BOD) and TSS) and total Kjeldahl nitrogen (TKN) removal efficiency (90%), with only the first stage, and only two units in operation (0.9 m²·pe⁻¹). The possibility of working with only two filters was investigated by Manjate et al. (2015), and also endorsed by a French guide for tropical applications (Lombard Latune & Molle 2017).

The nitrification process in VCW-FS is strongly dependent on surface area, operating conditions and climatic season of the year (Boller et al. 1993; Molle et al. 2006; Torrens et al. 2009; Prost-Boucle & Molle 2012; Molle 2014; Millot et al. 2016; Nakamura et al. 2017). It occurs mainly after NH₄⁻N is adsorbed onto the biofilm and organic matter layers during the feed period, is then transformed into NO₃⁻N in the rest period, and is further released at low concentrations in the next cycle, as reported by Boutin et al. (1997), Molle et al. (2006), Morvannou (2012) and Paing et al. (2013).

Nitrification is associated with the operation and physical structure of the system, and is influenced by the rapid passage of the sewage through the filter material, with limited retention time to allow contact with the bacteria responsible for the oxidation of the NH₄⁻N (Kantawanichkul et al. 2009). In order to enhance the retention of dissolved compounds, adsorption plays a very important role. A component of the French model that improves treatment efficiency in terms of ammoniacal nitrogen adsorption, percolation time and liquid distribution, is the formation of the sludge deposit on the surface of the units (Molle et al. 2005, 2006). The adsorption capacity is proportional to the organic matter content on the sludge layer (Molle 2014), and the rate of increase of this layer is around 1.5 cm·year⁻¹ to 3.0 cm·year⁻¹ (Molle et al. 2005; Molle 2014; Molle et al. 2015; Dotro et al. 2017).

In addition to the adsorption capacity, this sludge layer plays a ‘sponge effect’ (Chazarenc & Merlin 2005) that allows the release of water during the rest period (Prigent et al. 2015), maintaining the microbial community active during this period (Molle et al. 2015). However, with the passage of years of operation, the height of this layer influences the oxygen renewal (convection and diffusion), makes the infiltration more difficult due to the greater accumulation of liquid in the surface (the higher the height, the greater the volume of immobilized water) and brings a decrease in the rate of mineralization of the organic material (Molle et al. 2006; Molle 2014).

Although the French configuration has been extensively investigated in the last decades, one notes a scarcity of studies showing the influence of the height of the sludge layer on the removal of organic matter and the promotion of nitrification, especially under warm-climate conditions. Constructive and operational adaptations of the VCW-FS implemented under conditions other than the European ones are poorly reported. Therefore, the objective of this work was to obtain a better understanding of the influence of the organic matter deposit layer on the organic matter removal and nitrogen transformation in VCW-FS operating with reduced surface area (only first stage of the French system, and only two units in operation), under Brazilian climatic conditions.

**MATERIAL AND METHODS**

The wetland system evaluated is located in the city of Belo Horizonte, Brazil, at the Center for Research and Training in Sanitation of the Federal University of Minas Gerais, and is inside the facilities of the Arrudas wastewater treatment plant, operated by the Water and Sanitation Company of Minas Gerais (COPASA) (19°53′42″ S, 43°52′42″ W). Belo Horizonte is located in Cfa or Cwa humid subtropical climate according to Köppen classification, with a mean annual rainfall of 1,450 mm.

The VCW-FS, built in 2007 (started operation in 2009) was designed to treat wastewater generated by an equivalent population of 100 inhabitants (average flow of 13 m³·d⁻¹). Designed in accordance with CEMAGREF/IRSTEA recommendations and specifications, the first stage was built with three filter beds, each with a surface area of 29.4 m² (width of 3.1 m and length of 9.4 m), amounting to 88.2 m² (0.9 m²·pe⁻¹). The units were constructed in masonry with vertical walls, and filled with 15 cm of gravel #3 (19–50 mm) in the drainage zone (bottom), 15 cm of gravel #1 (4.8–25 mm) in the middle layer and 40 cm of gravel #0 (2.4–12.5 mm) in the top layer. All
units have been planted with the Tifton-85 grass (Cynodon dactylon Pers.) (Figure 1).

In addition to the intermittent feed of influent sewage on the surface of the wetland, with hourly batches, that is, 24 pulses·d⁻¹ of 0.53 m³ each, there is the alternation between the filters, which happens every 7 days. During the period of this study, only two units were in operation (representing a total area requirement of only 0.6 m⁻²·pe⁻¹), with one of the units receiving sewage for 1 week, while the other unit remained at rest during that period (total cycle of 14 days). The influent is typical urban wastewater, and undergoes only preliminary treatment (coarse and medium screening and grit removal).

Since the beginning of the operation, the units have been accumulating sludge on the surface of the system. Aiming to evaluate the influence of this layer, in February 2017 the sludge deposited in the upper layer of Unit II was removed. From then on, monitoring of sludge height was carried out with measurements at intervals of approximately 6 months (April 2017, October 2017 and May 2018). The first characterization was performed in 15 fixed points (every 2 m²). For the other campaigns, new 16 points were added close to the walls of the system, totalling 31 measuring points, covering in more detail the deposit height (every 0.9 m²). The sludge heights were interpolated to the entire filter surface using the Survey software by weighting the inverse distance between the points.

The influent and effluent samples were monitored over 15 months (from February 2017 to May 2018) and analyzed for hydrogenionic potential (pH), temperature, DO, redox potential (Eh), COD, biochemical oxygen demand – 5 days (BOD₅), TSS, TKN, ammoniacal nitrogen (NH₄⁺-N), nitrite nitrogen (NO₂⁻N) and nitrate nitrogen (NO₃⁻N), following recommendations from Standard Methods (AWWA/APHA/WEF 2012). Samples were collected on the second day during the 7-day feeding cycle. To evaluate the influence of the sludge layer, the results of the physico-chemical parameters were compared using the Mann-Whitney test with a significance level (α) of 5%, using Statistica 10.0 software.

RESULTS

Treatment performance

The main characteristics (number of samples, influent and effluent concentration medians and coefficient of variation, removal efficiency) of the parameters analyzed during the monitoring period are summarized in Table 1 and Figure 2. The interpretation of the table and the figure is presented in the subsequent sections.

Organic matter and suspended solids

The removal of COD, BOD₅ and TSS in the first stage of the French system comprising only two units showed relatively good removal efficiencies, 72% and 60% for COD, 80% and 79% for BOD₅ and 85% and 82% for TSS, for units I (with sludge) and II (with sludge previously removed), respectively. However, these are lower when compared with those reported for the traditional concept of three parallel units in the first stage, as found in the surveys carried out by Molle et al. (2005) and Morvannou et al. (2015) in France, with mean values of 79% and 77% for COD and 86% and 83% for TSS, respectively. During the study period, the applied surface organic loads in the filter in operation were similar in both units: Unit I, minimum-maximum range between 77 and 400 g COD·m⁻²·d⁻¹, median of 202 g COD·m⁻²·d⁻¹; Unit II, range between 69 and 510 g COD·m⁻²·d⁻¹ and median of 172 g COD·m⁻²·d⁻¹. The median values are within the design recommendations of 300 g COD·m⁻²·d⁻¹ (Molle et al. 2005) or 350 g COD·m⁻²·d⁻¹ (Dotro et al. 2017; Lombard...
In this period, the median values of the applied surface hydraulic loading rates in the unit under feeding were $0.43 \text{ m}^3 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for both units. The results presented here are associated with some-what dilute influent concentrations, which may alter the relationship between applied organic and hydraulic loads. In the present case, in which the wastewater was generated in a large city, with medium to high values of water consumption, influent concentrations were not high. However, in small communities, either in Brazil or in other developing countries, water consumption may be lower, leading to a more concentrated raw sewage. Therefore, when designing and evaluating a treatment wetland, it is always important to consider both hydraulic and mass loading rates. However, it should be noted that Lombard Latune & Molle (2017), evaluating French systems that received variable loads under tropical climatic conditions, did not observe process limitations in terms of COD and TSS, since the performances remained stable, even when operating above the nominal load.

Removal efficiencies were similar in both units, and there were no significant differences between the effluent concentration from both units (see also Figure 2), different from what was postulated by Chazarenc & Merlin (2005),

### Table 1: Influent and effluent characterization throughout the study period (February 2017 to May 2018), covering Unit I (with top sludge) and Unit II (with sludge previously removed)

<table>
<thead>
<tr>
<th>Unit (with accumulated sludge)</th>
<th>Influent (raw sewage)</th>
<th>Effluent (effluent previously removed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>21 7.38</td>
<td>21 7.05</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>18 25.4</td>
<td>18 25.9</td>
</tr>
<tr>
<td>DO (mg·L$^{-1}$)</td>
<td>21 0.56</td>
<td>21 3.41</td>
</tr>
<tr>
<td>Eh (mV)</td>
<td>11 72</td>
<td>11 241</td>
</tr>
<tr>
<td>COD (mg·L$^{-1}$)</td>
<td>18 467</td>
<td>18 129</td>
</tr>
<tr>
<td>BOD$_5$ (mg·L$^{-1}$)</td>
<td>17 286</td>
<td>17 57</td>
</tr>
<tr>
<td>TSS (mg·L$^{-1}$)</td>
<td>15 415</td>
<td>15 64</td>
</tr>
<tr>
<td>NH$_4^+$-N (mg·L$^{-1}$)</td>
<td>21 0.04</td>
<td>21 0.14</td>
</tr>
<tr>
<td>NO$_2$-N (mg·L$^{-1}$)</td>
<td>-</td>
<td>17 15</td>
</tr>
</tbody>
</table>

| pH                                           | 18 7.36               | 18 7.01                               |
| Temperature (°C)                              | 18 25.3               | 18 25.9                               |
| DO (mg·L$^{-1}$)                              | 18 0.43               | 18 4.40                               |
| Eh (mV)                                       | 12 56                 | 12 62                                 |
| COD (mg·L$^{-1}$)                             | 25 397                | 25 157                                |
| BOD$_5$ (mg·L$^{-1}$)                         | 12 275                | 12 57                                 |
| TSS (mg·L$^{-1}$)                             | 12 352                | 12 62                                 |
| NH$_4^+$-N (mg·L$^{-1}$)                      | 18 33                 | 18 15                                 |
| NO$_2$-N (mg·L$^{-1}$)                        | 15 0.03               | 15 0.16                               |
| NO$_3$-N (mg·L$^{-1}$)                        | -                    | 16 14                                 |

*p*-value (comparing Unit I with sludge × Unit II without sludge)

<table>
<thead>
<tr>
<th>Parameter</th>
<th><em>p</em>-value for influent concentrations</th>
<th><em>p</em>-value for effluent concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO (mg·L$^{-1}$)</td>
<td>0.64</td>
<td>0.006 (*)</td>
</tr>
<tr>
<td>Eh (mV)</td>
<td>0.87</td>
<td>0.25</td>
</tr>
<tr>
<td>COD (mg·L$^{-1}$)</td>
<td>0.47</td>
<td>0.17</td>
</tr>
<tr>
<td>BOD$_5$ (mg·L$^{-1}$)</td>
<td>0.85</td>
<td>0.81</td>
</tr>
<tr>
<td>TSS (mg·L$^{-1}$)</td>
<td>0.90</td>
<td>0.98</td>
</tr>
<tr>
<td>TKN (mg·L$^{-1}$)</td>
<td>0.27</td>
<td>0.74</td>
</tr>
<tr>
<td>NH$_4^+$-N (mg·L$^{-1}$)</td>
<td>0.15</td>
<td>0.80</td>
</tr>
<tr>
<td>NO$_3$-N (mg·L$^{-1}$)</td>
<td>-</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Eh, Standard Hydrogen Electrode (SHE); n, number of samples.
**Coefficient of variation (C.V.)** = standard deviation/mean.
Removal efficiency (%) = 100 ${(\text{influent median} - \text{effluent median})/\text{influent median}}$.
(*) Significantly different ($p < 0.05$) at the Mann-Whitney test.
who highlighted the positive effect on the treatment performance in terms of organic matter removal when the sludge deposit was formed on the surface of the units, that was considered by Molle (2014) as a key element to improve treatment efficiency.

With similar concentrations, the unit with sludge previously removed retained fewer solids, probably justified by the less favorable interception condition in the filtration process, or by the higher infiltration rates of the liquid through the system. In addition to confirming higher rates of infiltration in units with less accumulation of sludge, Molle et al. (2006) reported that the treatment performance was negatively affected by a short hydraulic retention time. With an average height of 1 cm of accumulated sludge, Molle et al. (2006) reported an infiltration rate of $3.6 \times 10^{-4} \text{m} \cdot \text{s}^{-1}$, and with a height of 7 cm of sludge, a lower value ($0.5 \times 10^{-4} \text{m} \cdot \text{s}^{-1}$).

A higher infiltration is also identified in the first days of feeding (Morvannou 2012; Arias Lopez 2013). Due to the rest period, the sludge accumulated during the feeding period is subjected to natural drying, causing cracks in this layer, through which the sewage is easily drained, and decreases the flow velocity as the feed period advances, promoting a higher retention capacity of water and solids in the filter pores (Arias Lopez 2013). In the present study, the samples were collected on the second day of operation, still in the early stages of the 7-day feeding cycle.

**Dissolved oxygen**

As expected and shown in Figure 3, the dissolved oxygen concentrations in the effluent were lower in unit I (with higher accumulation of sludge) compared to Unit II (with sludge previously removed). In this study, this was
the only parameter that presented a significant difference between the units, and these results were justified by the greater layer of sludge that makes it difficult for air to pass into the filter bed. In addition to a thicker barrier, the larger amount of sludge had a greater capacity of liquid retention, thus obstructing the free spaces that allow the air flow. However, in spite of the differences, both units led to a very well oxygenated effluent, indicating the prevailing aerobic conditions inside the medium.

The vertical wetlands configuration is characterized by the aerobic conditions in the removal of pollutants, promoted by the intermittent feeding (transport via convection) and by the rest period that guarantees free surface for the diffusion of oxygen (Platzer 1999). In order to enhance air transfer, the units have passive aeration pipes installed inside the bed to allow oxygen to enter (Molvannou 2012).

Under unsaturated conditions, the measured redox potential in the effluent varied between 150 and 350 mV (Figure 3), indicating that aerobic conditions prevailed within the filter according to the range of oxidative potential, promoting aerobic processes such as degradation of organic matter and nitrification (+100 to +500 mV) (von Sperling 2014). Redox potential values were slightly lower in Unit I, although there was no significant difference between the units.

Nitrogen

TKN removal and nitrate formation by nitrification were accomplished in both units, without significant difference between them. Although the sludge layer may have had an influence on the removal mechanisms, it did not show a direct influence. The rest period is supposed to allow NH₄⁺-N that was adsorbed during the feeding period, to be nitrified, being released in the next cycle, as reported by Boutin et al. (1997), Molle et al. (2006) and Paing et al. (2015). However, the lower adsorption capacity in unit with sludge removed may have been compensated by the more aerobic conditions maintained in the system, sufficient for the oxidation of organic matter and nitrification.

Comparing the influence of sludge accumulation on a VCW-SF, Silveira (2015) observed that this layer influenced the spatial structure of the nitrifying microbial community, inducing a greater growth of nitrifying bacteria in the 15 cm deep layer in an unit without sludge and in the deep 30 cm layer in an unit with sludge. These results were due to the selective conditions provided by the oxygen concentration along the vertical profile of the systems, which was blocked with the layer of sludge on the surface and intensified with passive aeration tubes in the drainage zone.

Based on the TKN concentrations, removal efficiency in unit I was 60% and in Unit II 63%. These efficiencies can be considered good, given the condition of reduced area in this system, brought about by the operation of only two units in parallel. It is noteworthy that the two units have been in operation for 9 years, a condition that probably ensured the maintenance of the microbial community within the volume of the filter medium, in spite of the fact that in Unit II there was no biomass in the sludge layer, since it had been previously removed. According to Prigent et al. (2013) the development of the microbial community seems to be established after 20 months of operation of the system, with strong influence of seasonality and formation of roots.

The absence of the sludge layer did not significantly influence the good removal performance in terms of TKN and nitrate production expected for the first stage, which, according to Molle et al. (2006), can be influenced mainly
by the operating conditions (pulse frequency, instantaneous loading rates, intervals between feeding and rest).

The duration of the feeding and resting periods influences the hydraulic performance and the removal efficiency (Torrens et al. 2009). Stefanakis & Tsihrintzis (2012), when comparing resting times of 4, 6 and 8 days, suggested that, for the decomposition of organic matter, a period of 4 days of bed resting is sufficient. However, when the objective is to improve the nitrification step, better removal efficiencies of N-NH₄ are obtained with a longer resting period.

Besides the alternation of units, another important operational criterion is the interval between pulses. According to Boller et al. (1993) and Molle et al. (2006), to obtain better results in terms of nitrate formation, a suitable strategy is the application of higher volumes at lower frequencies. This procedure promotes a better oxygenation of the filter, leading to a higher nitrification potential in the unit. However, it should be considered that when raw sewage is stored for longer periods, the chances of release of malodors from anaerobic degradation in the storage box are greater.

It should be mentioned that the instantaneous hydraulic loading rate used in this system was only 0.20 m³·m⁻²·h⁻¹, well below the French minimum recommendations of 0.6 m³·m⁻²·h⁻¹ (Molle et al. 2006). These lower values were due to a long pulse duration (5.5 min with the applied dosing syphon) and to a high batch frequency (24 batches per day, with lower volumes in each batch, compared with French systems, in which there are fewer batches per day and higher volumes per batch). Although the instantaneous loading rate can affect the hydrodynamics of the liquid and the transfer of oxygen, as well as the contact of the microorganisms responsible for the transformation of the nitrogen, a good performance was still noticed.

**Accumulation of top sludge (deposit layer)**

The three measurement campaigns carried out in Units I and II resulted in the following average heights of the sludge layer: (i) 20/04/2017 – Unit I: 6.6 cm and Unit II: 0 cm; (ii) 24/10/2017 – Unit I: 7.0 cm and Unit II: 0.3 cm; (iii) 02/05/2018 – Unit I: 7.2 cm and Unit II: 0.5 cm. In Unit II, the sludge was removed in February 2017. Based on the individual values measured in each point, it was possible to make a contour map showing the spatial distribution of the deposited sludge in the upper layer of the units (Figure 4).

Spatially, the units accumulated more sludge next to the storage box and the inlet end of the distribution pipes, which is in the upper part of the figures. This fact is due to the head loss along the distribution pipes and delays in the activation of the U-shaped siphon resulting from influent flow variations. There was also greater accumulation of sludge near the 16 distribution points, promoting a heterogeneity in the distribution of the liquid disposed on the surface of the units, not covering the entire area of the system, mainly during the first days of the feeding cycle. The lowest height (0.5 cm) recorded in Unit I was in the middle of the first branch of pipes and the highest height (11.3 cm) was in the second branch. Morvannou et al. (2017) pointed out this interference as a consequence of the rapid passage of the liquid through the filter in the first pulses, revealing the presence of preferential flow in the unit. However, the density of feeding points here is considered very good (16 points per 29.4 m², or one point per each 1.8 m²), safely complying with the French recommendations of one point per 50 m² (Lombard Latune & Molle 2017).

The units under study received an influent with prior grit removal, which was undertaken for all the treatment systems located in the experimental site. Considering the removal of 23 g of sand per m² of sewage treated (mean values from 2017), this would amount to an estimated accumulation of only 0.12 cm·year⁻¹ in each unit, in case sand had not been removed, as is usual in the French practice.

The median sludge accumulation rates in the studied units were 0.80 cm·year⁻¹ in Unit I and 0.30 cm·year⁻¹ in Unit II. If sand accumulation were to be taken into account, the total values would be 0.92 cm·year⁻¹ and 0.42 cm·year⁻¹ in Units I and II, respectively. These values are lower, compared with the range reported in the international literature, that varies from 1.5 cm·year⁻¹ to 3.0 cm·year⁻¹ (Molle et al. 2005; Dotro et al. 2017). This may be due to the tropical climatic conditions that favored faster dewatering and mineralization processes, and also due to the characteristics of the influent sewage, that had lower organic matter concentrations, when compared to those generated by the population of the small communities of the European countries investigated. According to Prigent et al. (2015), Molle (2014), Molle et al. (2015) and Dotro et al. (2017), this difference may also be related to occasional overloads during the operating periods, leading to higher accumulation rates, besides utilization of different operational conditions (interval between the pulses, feeding and resting times).

The rate of sludge accumulation was higher in Unit I (0.92 cm·year⁻¹), with 9 years of operation compared to
Unit II (0.42 cm·year$^{-1}$), that had only 1 year and 3 months of accumulation, after the removal in February 2017. Thus, it can be inferred that the beginning of sludge formation may be slowed down by the faster dewatering and mineralization rate achieved by a thinner sludge layer. Also, as time progresses and the sludge layer builds up, the filtering capacity increases, leading to a higher retention of solids in the top layer. In view of the results obtained, it is noted that the reduced area and the longer feeding cycles adopted under the Brazilian climatic conditions were able to obtain favorable conditions for sludge dewatering and mineralization.
CONCLUSIONS

The French system of vertical flow constructed wetlands has already shown its wide applicability in several countries. However, the present study endorses this applicability under the favourable conditions found in a warm climate, even with the utilization of only the first stage, which was comprised by only two units in parallel (total of 0.6 m²·pe⁻¹).

There were no significant differences between the effluent concentrations from the unit with a sludge layer accumulated over 9 years of operation and the unit in which the top sludge had been previously removed. The only significant difference was in terms of the dissolved oxygen concentration, but even so, in both units the effluent concentrations were high and indicated prevalence of aerobic conditions. The sludge layer influenced the transport of oxygen to the interior of the filter unit, but did not affect the efficiency of the treatment in terms of organic matter, suspended solids and ammonia removal.

Considering the lower land requirements of the system investigated, comprised of only two units, compared with the typical French system, with three units in parallel, the COD, BOD and TSS removal efficiencies can be considered good and capable of producing an effluent that may comply with less stringent discharge standards. TKN and ammonia removal were also good, benefiting from the aerobic conditions that prevailed in both units.

The annual sludge accumulation rates were observed to be lower than the typical values reported in the literature, which are based mainly on temperate climates.

ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian agencies CAPES, CNPq, FAPEMIG and FUNASA, the Water and Sanitation Company COPASA, and Bill & Melinda Gates Foundation (SaniUP project, under the coordination of IHE Delft, The Netherlands).

REFERENCES

APHA/AWWA/WEF 2012 Standard Methods for the Examination of Water and Wastewater, 21st edn. American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF), Washington, DC, USA.


First received 23 January 2019; accepted in revised form 7 August 2019. Available online 19 August 2019