First stage of the French vertical flow constructed wetland system: experiments with the reduction of surface area and number of units

E. S. Manjate, L. C. O. Lana, D. C. Moraes, G. R. Vasconcellos, G. R. M. Maciel and M. von Sperling

ABSTRACT

Small vertical-flow constructed wetland units comprising the first stage of the French system were studied in Brazil for the treatment of raw sewage. Planted and unplanted units and different feeding strategies were tested. In the first phase, hourly batches of a daily flow of 13 m$^3$ d$^{-1}$ were applied over three alternating units, resulting in an average hydraulic loading rate (HLR) on the full system of 0.15 m$^3$ m$^{-2}$ d$^{-1}$. A second phase, aimed at reducing land requirements, kept the same daily flow and batch frequency, but used two alternating units, resulting in a HLR on the full system of 0.22 m$^3$ m$^{-2}$ d$^{-1}$. Removal efficiencies were very good when the system operated with three units, with mean values of 82% for biochemical oxygen demand (BOD), 81% for chemical oxygen demand (COD), 85% for total suspended solids (TSS) and 59% for NH$_4^+$-N. With two units, the equivalent values were 74% for BOD, 59% for COD, 67% for TSS and 51% for NH$_4^+$-N. There were significant differences in the median removal efficiencies of COD and TSS. No significant differences were found between planted and unplanted units for most constituents. In both phases, the overall good performance and the simplicity of the system make this treatment process a very attractive alternative for developing countries.

Key words | domestic sewage, feeding operation, vertical-flow constructed wetlands

INTRODUCTION

Vertical-flow constructed wetlands can adequately treat raw domestic sewage in several regions of the world, including developing countries. Vertical-flow constructed wetlands of the French/Cemagref type are known to be an efficient and economical system, since they are able to receive raw sewage and require no sludge disposal over more than 10 years of operation (Molle et al. 2005, 2006). Their configuration traditionally encompasses two stages in series (three parallel units in the first stage and two units in the second stage), but it is expected that most conversion processes can take place in the first stage in warm climate regions, thus not requiring the second stage, thus bringing considerable land and construction savings. Molle (2002) reinforces the need for seeking different configurations in order to further reduce costs. If only the first stage of the French system is adopted, additional savings could be achieved by having only two units instead of three (a third less in terms of land requirements). This adaptation of the French system is new and thus less covered in the international literature.

The aim of this study was to investigate the performance of the first stage of the French system of vertical-flow constructed wetlands treating raw municipal sewage in Brazil, operating with three or two units in parallel.

MATERIAL AND METHODS

Investigations were conducted at the Centre for Research and Training in Sanitation (CePTS) UFMG/COPASA, in

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Belo Horizonte, Brazil. The system was built in 2007 and designed for approximately 100 population equivalents according to the French system criteria, but with only the first stage, with the usual three units in parallel. Two beds were planted with Tifton 85 (Cynodon spp.) and the third was not planted, in order to act as a control unit. Each unit was 3.1 m wide and 9.4 m long, giving an area of 29.1 m². The total area occupied by the units was 87.3 m² (approximately 0.9 m²/inhabitant). The system received sanitary raw sewage, after only screening and grit removal. Figure 1 shows a view of the system and a schematic cross-section of one of the beds, including the composition of the filtering and draining layers.

The start-up of the system was carried out from July to December 2009, and in January 2010 the system started full operation. In 2010 and 2011, the operational mode (batch frequency) was different from that discussed here, and is thus not covered in the paper. From 2012, two different operational phases were investigated:

- Phase 1: nine months (January–October 2012) – system with three units in parallel (traditional first-stage of the French system). The system operated in weekly cycles, with the units alternating in the feed and rest stages. As there were three units, each one was fed during 1/3 of 7 days (2.3 days) and rested during the rest of the week (4.7 days). The daily inflow of raw sewage was 13 m³ d⁻¹, resulting in a surface hydraulic loading rate (HLR) of 13 m³ d⁻¹ over 29.1 m² equivalent to 0.45 m³ m⁻² d⁻¹ in the working bed. In order to allow comparison of land requirements with other treatment systems, the daily flow is divided by the total area, thus leading to an equivalent surface HLR. Since there were three units (always one working and two resting), the total applied surface HLR in the overall system was equivalent to 0.45 m³ m⁻² d⁻¹ per three units equivalent to 0.15 m³ m⁻² d⁻¹. This value has no direct implication in terms of the operation per se, but it is useful as an overall value that allows the calculation of the total land requirement of the system.

- Phase 2: eight months (February–October 2013) – system received the same flow, but had only two units working in parallel (only 2/3 of the total area taken by the traditional first-stage of the French system). The system operated in fortnightly cycles, with the two units alternating in the feed and rest stages. Each one was fed for 7 days and rested for 7 days. The daily inflow of raw sewage was also 13 m³ d⁻¹, resulting in the same surface HLR of 13 m³ d⁻¹ over 29.1 m² equivalent to 0.45 m³ m⁻² d⁻¹ in the working bed. However, since there were only
two units (always one working and one resting), the total applied surface HLR in the overall system was equivalent to $0.45 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$ per two units equivalent to $0.22 \text{ m}^3 \text{ m}^{-2} \text{ d}^{-1}$.

In both phases, the working beds were fed in batch mode. Each batch was discharged as a pulse, every hour (24 batches per day, each batch with a volume of $0.540 \text{ m}^3$ of raw wastewater; total daily flow $= 24 \times 0.540 \text{ m}^3 = 13 \text{ m}^3$).

Influent and effluent samples were collected weekly, and analyses carried out according to the Standard Methods (APHA/AWWA/WEF 2005). During Phase 1, since the two planted units operated in a similar fashion, only one of them was monitored. Monitoring data were collected from the same two beds (planted and unplanted) that were used in both phases. Statistical analyses were performed using the Mann–Whitney $U$-test at 5% significance level for comparing median effluent concentrations and removal efficiencies from Phases 1 and 2, and also a comparison between the planted and unplanted units.

During Phase 1, samples of Tifton 85 were collected for evaluation of productivity and nutritional analysis. The samples were collected in a triplicate experimental randomized block design covering an area of $1 \text{ m}^2$ of the bed surface.

**RESULTS AND DISCUSSION**

Table 1 presents the mean influent and effluent concentrations, together with the mean removal efficiencies, for the planted and unplanted units, during Phases 1 and 2. Table 2 presents the $p$-values of the Mann–Whitney $U$-test comparing median effluent concentrations and removal efficiencies in both phases, and also a comparison between the planted and unplanted units. Figures 2–5 present box-and-whisker plots of the concentrations of the parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration (mg L$^{-1}$)</th>
<th>Influent</th>
<th>Effluent</th>
<th>Removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>279</td>
<td>36</td>
<td>38</td>
<td>82</td>
</tr>
<tr>
<td>COD</td>
<td>465</td>
<td>71</td>
<td>70</td>
<td>81</td>
</tr>
<tr>
<td>TSS</td>
<td>293</td>
<td>34</td>
<td>39</td>
<td>85</td>
</tr>
<tr>
<td>Total N</td>
<td>31</td>
<td>27</td>
<td>23</td>
<td>56</td>
</tr>
<tr>
<td>TKN</td>
<td>31</td>
<td>14</td>
<td>15</td>
<td>59</td>
</tr>
<tr>
<td>NH$_4^+$-N</td>
<td>26</td>
<td>10</td>
<td>11</td>
<td>65</td>
</tr>
<tr>
<td>NO$_3$-N</td>
<td>0.1</td>
<td>13</td>
<td>8</td>
<td>67</td>
</tr>
<tr>
<td>NO$_2$-N</td>
<td>0.01</td>
<td>0.2</td>
<td>0.1</td>
<td>71</td>
</tr>
<tr>
<td>Total P</td>
<td>3.9</td>
<td>2.1</td>
<td>2.0</td>
<td>60</td>
</tr>
</tbody>
</table>

**Table 1 | Average influent and effluent concentrations and removal efficiencies in the vertical flow wetland in Phases 1 and 2**
analysed in both phases, allowing visualization of central tendency and dispersion.

In Phase 1, when the system operated with three beds, the mean removal efficiencies of chemical oxygen demand (COD), total suspended solids (TSS) and total Kjeldahl nitrogen (TKN) in the planted unit were 81%, 85% and 56%, respectively. These results are very similar to those found by Molle et al. (2005), based on a comprehensive survey of the first stage (also with three beds) of the French system treating raw domestic sewage in France: mean values of 79%, 86% and 58% respectively.

Table 2 | \( p \)-values of the Mann-Whitney \( U \)-test comparing effluent concentrations in both phases and planted and unplanted units

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Phase 1 - Phase 2</th>
<th>Removal efficiencies</th>
<th>Planted - unplanted (effluent concentrations)</th>
<th>Planted - unplanted (removal efficiencies)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effluent concentrations</td>
<td>Removal efficiencies</td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>BOD</td>
<td>0.3013</td>
<td>0.1615</td>
<td>0.3298</td>
<td>0.7875</td>
</tr>
<tr>
<td>COD</td>
<td>0.0000*</td>
<td>0.0000*</td>
<td>0.8878</td>
<td>0.1682</td>
</tr>
<tr>
<td>TSS</td>
<td>0.0005*</td>
<td>0.2720</td>
<td>0.1341</td>
<td>0.4010</td>
</tr>
<tr>
<td>TKN</td>
<td>0.0005*</td>
<td>0.2720</td>
<td>0.0317*</td>
<td>0.1944</td>
</tr>
<tr>
<td>NH(_4)^+</td>
<td>0.0007*</td>
<td>0.1700</td>
<td>0.2953</td>
<td>0.3628</td>
</tr>
</tbody>
</table>

\(*p \leq 0.05\): sample medians are significantly different. TKN, total Kjeldahl nitrogen.

Figure 2 | Box-plot of BOD concentration during Phases 1 and 2 in the planted and unplanted units.

Figure 3 | Box-plot of COD concentration during Phases 1 and 2 in the planted and unplanted units.

Figure 4 | Box-plot of TSS concentration during Phases 1 and 2 in the planted and unplanted units.

Figure 5 | Box-plot of NH\(_4\)^+ concentration during Phases 1 and 2 in the planted and unplanted units.
In Phase 2, with a decrease of the total available surface area, the effluent concentrations increased and removal efficiencies decreased. However, if one considers that only a single stage was being used to treat raw sewage with only two-thirds of the area of the typical first-stage vertical wetland, the mean biochemical oxygen demand (BOD) removal of 74% in the planted unit and 76% in the unplanted unit can be considered satisfactory. In the planted unit, which represents a real wetland, 88% of the BOD samples met the regional discharge standard (Minas Gerais state, Brazil).

In Phase 2, not only the influent concentrations of some constituents were higher, but also their variability (as shown in the box-and-whisker plots). However, the system showed itself to be able to absorb well the variations, a fact that is also endorsed by Molle et al. (2005). The poorer performance for some constituents (COD and TSS) during Phase 2 is probably associated, not only with the characteristics of the influent, but also with the higher loading applied on the system, which is expected to influence organic matter removal and nitrification capacity (Brix & Arias 2005).

However, in terms of nitrification, there was a satisfactory ammonia removal in both phases (mean values of ammonia in the planted unit of 59 and 51% in Phases 1 and 2, respectively), highlighting one of the advantages of the French system, compared with many wastewater treatment systems which are not capable of removing ammonia. In spite of the higher organic loading, ammonia removal was still present in Phase 2. Total N removal could not be investigated in both phases due to the lack of laboratory results of nitrate in Phase 2. Phosphorus removal was not substantial.

In terms of statistical differences between Phases 1 and 2, it can be seen from Table 2 that effluent concentration values from most constituents were significantly different. However, as shown in the box-and-whisker plots, the influent concentration in Phase 2 was also higher. This led to the fact that the removal efficiencies in both phases were not significantly different, with the exception of COD and TSS.

Comparing the planted and unplanted units in terms of effluent concentrations and removal efficiencies, in general there were no significant differences between them (as shown in Table 2, with the single exception of TKN in Phase 1). These findings are similar to those obtained by Ciria et al. (2005) and Torrens et al. (2009).

The plant Tifton 85 showed very good adaptability to all the different hydraulic loads and feeding regimens tested. The plant grew satisfactorily and covered the whole bed surface, all year round. Similar results were observed by Matos et al. (2008), who observed good adaptability and biomass productivity with Tifton 85 in a constructed wetland treating dairy effluents. There was a concern here that plant growth could be impaired in the second phase due to the long rest period of 7 days without sewage or water supply, but this was not the case, even during the dry months without rainfall. In Phase 1, the average value of Tifton 85 biomass production observed was 2.9 kg of dry matter m⁻² year⁻¹ (29.4 t dry matter ha⁻¹ year⁻¹). Tifton 85 was responsible for removing 3.1% of the total N mass applied to the planted unit, indicating that plant uptake accounted for only a small fraction of the total N removal.

During Phase 2, clogging on parts of the surface of the unplanted unit started to be observed. However, during the four years of operation of the wetland units there are so far no signs of the need to remove sludge.

CONCLUSIONS

Two operating regimens of the first stage of the French vertical flow wetland system were tested. Phase 1 represented the typical French system, with three alternating units, whereas Phase 2 had only two units, therefore operated with only two-thirds of the total surface area. In Phase 1, feeding was over 2.3 days and resting over 4.7 days, comprising a total cycle of seven days. In Phase 2, in each unit feeding and resting lasted both seven days, with a total cycle of 14 days. Considering the total surface area of all the units involved, the mean surface HLRs in the total system were 0.15 m³ m⁻² d⁻¹ in Phase 1 and 0.22 m³ m⁻² d⁻¹ in Phase 2. In both phases, feeding was in a batch mode with hourly intervals.

The system was able to satisfactorily remove organic matter and suspended solids, when it operated according to the French recommendations for the first stage (three alternating beds in parallel – Phase 1), leading to mean
removal efficiencies around 80% for organic matter, 85% for suspended solids and 60% for ammonia in the planted unit. With only two beds and the system occupying only two-thirds of the area, there was a certain decrease in the performance in terms of organic matter and suspended solids, but the ammonia removal capacity remained similar. However, in statistical terms, the median removal efficiency in both phases was not significantly different for most constituents (with the exception of COD and TSS). When comparing the planted and unplanted units in terms of effluent concentrations and removal efficiencies, there were no significant differences for most of the constituents. However, a longer-term study is required in order to ascertain more confidently possible differences in performance and the full adequacy of the French system having only two units in the first (and possibly only) stage.

From the overall results, it can be concluded that the utilization of only the first stage of the French/Cemagref vertical-flow wetland system shows a strong potential whenever simple systems are required for the treatment of raw domestic sewage in developing and warm-climate regions. The good performance and the associated simplicity, with no pre-treatment (apart from screens and grit removal), no post-treatment, no mechanization, no energy consumption and no sludge treatment make this system a very attractive alternative for developing countries when very stringent discharge standards are not applied. If better quality effluents are required, a post-treatment step may be necessary.

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