Outflow dynamics in a French system of vertical wetlands operating with an extended feeding cycle

Mirene Augusta de Andrade Moraes, Jorge A. García Zumalacarregui, Camila Maria Trein, Vinícius Verna M. Ferreira and Marcos von Sperling

ABSTRACT

The possibility of using the first stage of the French System (FS) of vertical wetlands composed of only two units in parallel requires hydraulic investigations to allow a better understanding of its operation under tropical climatic environments. This study evaluated the pattern of the outflow hydrograph along an extended cycle of operation (seven days of feeding) and the influence of the sludge deposit, rainfall occurrence and duration of pulse application on the outflow hydrograph in a modified full-scale FS in Brazil. The results indicated that, as the feeding cycle days increased, there was an increase in the time of filtration and the internal storage of the liquid volume, probably due to a reduction in the filter permeability. Greater hydraulic gradient favoured the infiltration velocity, decreased the amount of liquid stored within the system, and delayed the loss of permeability. The sludge layer contributed to a momentary liquid retention, and also allowed greater evapotranspiration, reducing the liquid volume to be treated. The sludge deposit seemed to hinder the liquid percolation, especially at the end of the cycle, modifying the hydraulic conductivity of the filter as a whole. Intense rainfall events demonstrated that precipitation could modify the flow dynamics within the system.

Key words | filter medium breakthrough, hydraulic behaviour, permeability, raw sewage, vertical flow infiltration, warm climate

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INTRODUCTION

The French System (FS) of vertical flow wetlands has been widely used in decentralised sewerage systems and in small communities (Molle *et al.* 2005; Dotro *et al.* 2017). The units comprising the first stage of the system are disposed in parallel (typically three units) and alternate the functions of feeding and resting. The system receives raw sewage as influent, which is introduced in pulses or batches during the feeding period. Typically, the number of pulses per day varies from 6 to 24, and the feeding period lasts between 2.5 to 7.0 days, after which the unit enters its resting period. Throughout the sequence of days that comprise each feeding cycle, a reduction in the infiltration rate is expected to occur (Molle *et al.* 2006) as a result of solids retention and biomass accumulation on the surface of the filter, reducing the filter's hydraulic conductivity (Hajra *et al.* 2000) and the oxygen supply (Molle *et al.* 2004). As a consequence, the reduction of the oxygen supply may affect the process performance (Torrens *et al.* 2009). Therefore, there must be a balance between the development of the biofilm and the mineralization of the solids (Kadlec & Wallace 2008).

Understanding the hydraulic behaviour of the filter during the feeding phase is essential. The discharge of the wastewater in the form of pulses on top of the filter and the unsaturated conditions of the porous medium, through which the liquid percolates, pose challenges for the hydraulic representation of the unit, the estimation of the actual retention time, and the resulting temporal profile of the effluent flow. Langergraber (2008) stated that a good match between simulation results and measured pollutant data could be obtained if the hydraulic behaviour of constructed wetlands systems could be well described. Therefore, it is believed that studies that seek to clarify the hydraulic

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behaviour of the French System are fundamental for the continued improvement of this technique.

Under warm-climate conditions, solids at the top deposit layer undergo faster stabilisation and dewatering compared with wetlands located in temperate climates, from which most of the existing literature and experience comes. Additionally, the possibility of using only the first stage of the French System, and having this first stage composed of only two units in parallel, is an option when applying these vertical filters under favourable climatic environments (Manjate *et al.* 2015; Molle *et al.* 2015; Lombard Latune & Molle 2017; García Zumalacarregui & von Sperling 2018). Therefore, hydraulic investigations under these specific operational conditions are required in order to allow a better understanding and dissemination of the French System in warm climates.

This study was conducted in a full-scale French System operating in a warm-climate country (Brazil). The main objective was to evaluate the pattern of the outflow hydrograph through the days that comprise the sequence of seven days of feeding. The study analysed specifically the volumes recovered in relation to the volumes applied between batches through the cycle, plus the influence of the following factors: sludge deposit height, rainfall occurrence and duration of pulse application on the outflow hydrograph pattern.

MATERIAL AND METHODS

The study was carried out at the Centre for Research and Training in Sanitation (CePTS UFMG/Copasa), located at the Arrudas Wastewater Treatment Plant in Belo Horizonte city, Brazil (coordinates 19°53′42″ S, 43°52′42″ W). Belo Horizonte has a Cfa or Cwa humid subtropical climate, according to the Köppen classification, with a mean annual rainfall of 1,450 mm.

The French System of vertical filters comprised only the first stage and was designed to treat a flow of raw sewage of 13 m^3/d (approximately 100 p.e.). The influent passed through only preliminary treatment at the Arrudas treatment plant, composed of screening (coarse screen with 10 cm, fine screen with 15 mm and sieve with 6 mm) and grit removal (square mechanically-cleaned grit chambers). After preliminary treatment, a fraction of the Arrudas treatment plant was diverted to the system under study. The wetland system consisted of a storage tank and three filter units in parallel (only two were used in this study), planted with the grass species tifton 85 (*Cynodon* spp.). Each filter had a surface area of 29.1 m^2 and dimensions of 3.1 m × 9.4 m (Supplementary material, Figure 1, top, available with the online version of this paper). The resulting surface hydraulic loading rate on the filter in operation was 0.45 $m^3.m^{-2}.d^{-1}$, higher than the French specification of 0.37 $m^3.m^{-2}\,d^{-1}$ (Molle *et al.* 2005; Morvannou *et al.* 2015). On the other hand, since the influent chemical oxygen demand (COD) concentrations were low, the resulting average surface organic loading rate was 202 $gCOD.m^{-2}.d^{-1}$ (together with 182 $gTSS.m^{-2}.d^{-1}$) (García Zumalacarregui & von Sperling 2018), lower than the maximum recommended by Dotro *et al.* (2017) of 350 $gCOD.m^{-2}.d^{-1}$. Details of the influent concentrations can be found in Trein *et al.* (2018).

The filters had three layers arranged in increasing grain size from top to bottom: main layer (0.40 m): gravel #0 (2.4 to 12.5 mm); intermediate layer (0.15 m): gravel #1 (4.8 to 25 mm); and drainage layer (0.15 m): gravel #3 (19 to 50 mm) (Supplementary material, Figure 1, bottom). The influent distribution in each of the two units was done by one manifold and 16 laterals with open ends, as shown in Supplementary material, Figure 1, top. This resulted in 1.8 m^2/feed point, which is well below the maximum recommended value of 50 m^2/point (Dotro *et al.* 2017). The influent was well distributed on most of the filters' surface, but full homogeneity was not observed due to there being some dead zones, especially in the corners.

The typical operation of the first stage of a French System comprising three units in parallel varies from three to four consecutive days of feeding and seven days of resting (Dotro *et al.* 2017). However, in this research, only two units were used (I and II), and the operational cycle was composed of alternation every seven days, with seven days of feeding followed by seven days of resting in each unit. The two cells in operation differed only by the height of the surface deposit layer of sludge. In May 2018, unit I had an average height of 7.2 cm, while unit II had only 0.5 cm, since its sludge had been removed prior to the experiments, for research purposes. The sludge accumulation was not uniform over the surface (see details in Trein *et al.* 2018), and the thicknesses were greater closer to the feeding points, as also described by Morvannou *et al.* (2012).

Feeding was carried out in the form of pulses and the unit in operation received 24 pulses per day of 0.55 m^3 each, using an interval of 45 min to one hour between batches. There was a level float inside the storage box that sent a signal to the data logger when the tank was empty (after each discharge). This allowed the counting of the number of pulses and their duration, which depended on the inflow to the tank. After percolating downwards through the filter media, the effluent was collected at the bottom by a perforated pipe and then transported to an exit box. Inside the exit box from Unit II there was a tipping bucket

(2.65 L) coupled to a data logger, used as a flow-measuring device (Supplementary material, Figure 1). In Unit I, the outflow was measured manually with the aid of a 2 L beaker and a stopwatch.

Four main flow monitoring campaigns were carried out in Unit II (Supplementary material, Table 1, available with the online version of this paper). Each monitoring campaign lasted seven days, following the duration of the feeding cycle. It can be noted that there was one campaign (Monitoring 1) in the rainy season (October to March, in Brazil) and three in the dry season (April to September). The investigation into the influence of rainfall was an *a posteriori* decision. After doing the four campaigns, when analysing the results, the authors noticed that rainfall could be a factor of interference, and then decided to include it in the analysis of the results.

RESULTS AND DISCUSSION

Hydraulic dynamics inside the filter are influenced by different factors, among them: (1) filter material, grain size distribution and depth; (2) placement and characteristics of the distribution and drainage systems (Moraes *et al.* 2018; Paul *et al.* 2018); (3) plant development (Molle *et al.* 2006; Arias *et al.* 2014); (4) organic and suspended solids loading (Xu *et al.* 2013); (5) inflow to the storage box, which is related to the hydraulic loading (Xu *et al.* 2013); (6) current status of the filter medium in relation to the alterations during the feeding cycle; (7) pulse duration, which is related to the instantaneous hydraulic loading rate – HLR_{inst}) (García Zumalacarregui & von Sperling 2018); (8) seasonality and climate (Arias *et al.* 2014); (9) height of the sludge deposit layer. This research targeted the last four cases (6 to 9), which are presented and discussed in the following sections. It should be emphasised that all the results shown are from the dry seasons, except in the subsection 'Influence of rainfall'.

Relation between the influent flow and the volume stored inside the system

Figure 1 shows the inflow and outflow on the left Y-axis and the accumulated volume of liquid stored inside the filter on the right Y-axis as functions of time. The data used were from one typical sequence of five consecutive pulses, representing a typical situation that is repeated in any pulse.

The inflow to the filters, or the outflow from the storage box, was controlled by a hydraulic device (dosing syphon), and so it was dependent on the liquid height above the syphon's mouth, which varied linearly with time. The syphon's discharge equation (Equation (1)) was obtained by Moraes *et al.* (2018), who worked on the same system:

$$Q_{in} = -0.0011\,t + 1.9809 \qquad R^2 = 0.529 \tag{1}$$

where Q_{in} is the inflow to the filters ($L.s^{-1}$) and t is the time of emptying the storage box (s). The outflow was obtained by the measured data stored in the data logger. The accumulated storage volume in the filter was simply the difference between the input volume and the output volume during a particular time *t* added to the storage volume at time *t* – 1. In this case, no other form of liquid output was considered.

The very fast flow dynamics can be clearly seen. The time taken to empty the storage box and the distribution pipes was

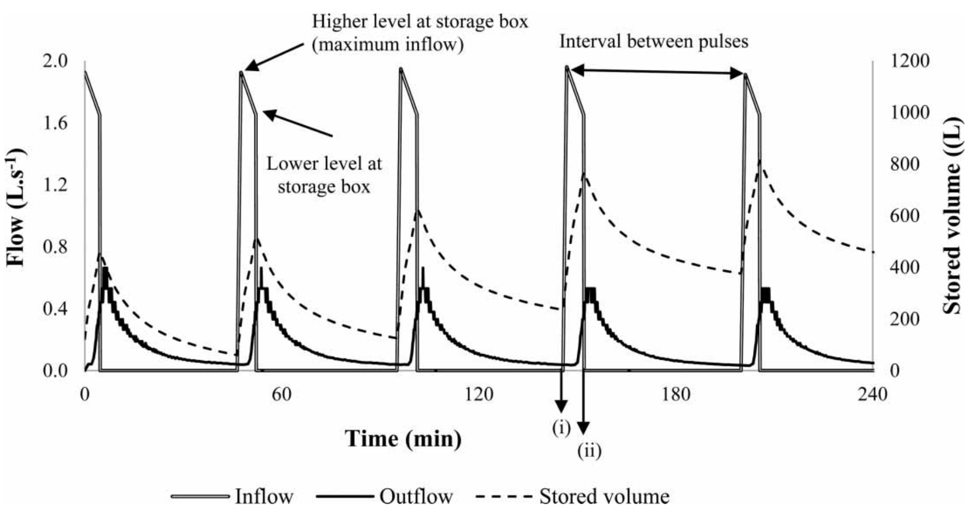

Figure 1 | Inflow, outflow and stored volume inside the filter as a function of time. Five sequential pulse events are represented.

5.5 min. The peak outflow was reached after around only 7 min from the start of the feeding process. In spite of this very short liquid passage time, the system still performed well from the pollutant removal point of view, because solids were attached on the biofilm and underwent their conversion processes, as indicated by García Zumalacarregui & von Sperling (2018) in a study of the same treatment system.

The hydraulic behaviour occurred as expected, as described in Chow *et al.* (1988) for water balances in hydrological events. There are two important times to note: (i) at the beginning of the discharge on top of the filter surface (when $Q_{in} = 1.98\ L.s^{-1}$) and (ii) at the moment of the feeding interruption (when $Q_{in} = 0$). After the first moment, the volume of liquid stored inside the system began to increase. The maximum storage during the pulse always occurred when the liquid feeding was interrupted, and the minimum storage occurred when the pulse restarted with the discharge from the storage tank (second moment). The total drainage of the liquid applied during one pulse and the following pulse was not reached (the recovered volume was less than 550 L), and, as a result, the peak in the stored volume kept increasing, since the volume variation within the filter was cumulative and positive. It is important to remember that if the volume of the filter voids were reached, the unit would be completely saturated.

Hydrograph behaviour and recovery of the applied volume

The outflow variation from the first day until the last day (seventh) of one feeding cycle at unit II (unit with sludge previously removed) was analysed and is presented in Figure 2. The graph shows the outflows on four different pulses of the cycle: pulse 1 (first day); pulse 48 (third day, after 48 h); pulse 72 (fourth day, after 72 h); pulse 168 (after 168 h, representing the last pulse in the feeding cycle). For the sake of clarity, the other pulses are not presented here, considering that these four hydrographs are sufficient for describing the system's behaviour (Supplementary material, Figure 2 includes pulse 96, fifth day, after 96 h, available with the online version of this paper). As expected, the pulse feeding caused a peak outflow with a short duration, followed by a slow decline (as described by Kadlec & Wallace 2008), tending toward zero. The first pulse, immediately following the resting period, had different characteristics, as will be further discussed below.

Table 2 (Supplementary material, available with the online version of this paper) contains the summary of three monitoring campaigns (2, 3 and 4, which were not influenced by rainfall). Values were separated by the days of the feeding cycle, showing the volume recovered after 1 h (in relation to the total volume applied) and time to recover different percentiles (10%, 50%, 75% and 90% percentiles) of the applied volume of approximately $0.55\ m^3$ per batch. In most of the pulses, no full recovery of the applied volume was obtained, which indicated inner accumulation inside the unit (even in the rest period the system still released effluent), but also possible exfiltration from the units.

On the first pulse of the feeding cycle (pulse 1), after the rest period of seven days, although it was the moment with less biofilm development and solids retention, the outflow and recovery volume (median = 72.8%) were the lowest of the seven-day cycle. This suggests that the liquid was retained in the pores of the system, and was then gradually released at subsequent pulses. It is known that organic matter accumulation occurs not only on the surface of the filter, but also on the first layer (Molle 2014). Moreover, fluid retention is related to organic matter content, so the medium's moisture decreases with depth. Thus, the finer part of the filter medium, where there are lower velocities,

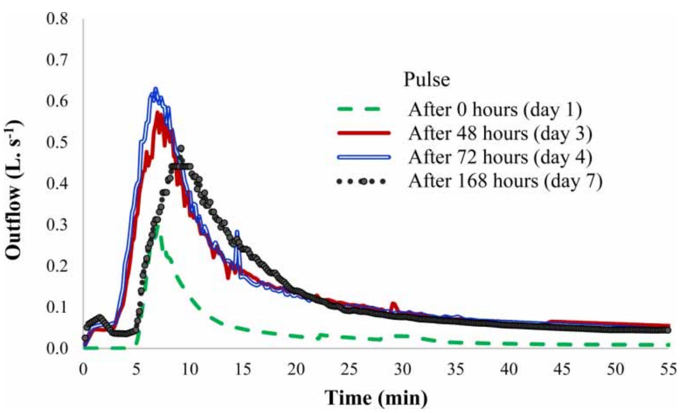

Figure 2 | Batches (pulses) on different days of one feeding cycle: outflow as a function of time.

is also where the highest moisture retention occurs during the filter operation (Maier *et al.* 2009; Morvannou *et al.* 2012).

The recovered volume increased successively until the fourth day, after which a decline began. Except for day 3, which did not follow the behaviour, the time to reach the percentiles 10%, 50%, 75% and 90% was always increasing, indicating that with the passage of days the liquid had more difficulty in percolating, suggesting a relationship between moisture, solids and biomass. The non-parametric Kruskal-Wallis analysis of variance (ANOVA) test with a significance level $\alpha = 5\%$ was performed to test the difference among the medians of the time required to reach the 50% percentile, and the results indicated that there was no significant difference between the days.

The filter had an unsaturated porous medium and the hydraulic conductivity was expected to increase with the increase in the filter's moisture. The maximum hydraulic conductivity would be when the medium was fully saturated. However, with the typical pulse feeding characteristic of the FS, it is very unlikely that a filter would be saturated. In the filter under study, some regions with higher hydraulic loads may have become saturated, especially in the uppermost centimetres of the filter. As time progressed during the feeding cycle, the growth of the biofilm and the retention of solids started to become more influential. At the last pulses, it could be observed that the concave portion of the curve was smoother (Figure 2). The recovered volume dropped, reaching 77.1% and, as was visually observed on site, from the sixth day, there were flooded areas on the filter's surface.

Figure 3(a) contains the boxplot of the effluent volume from different pulses on each of the days of the feeding cycle, based on monitoring campaigns 2, 3 and 4. The effluent volume had a tendency to increase along the feeding cycle, followed by a drop. It can be observed that the volumes accumulated on days 1 and 7 were those that had

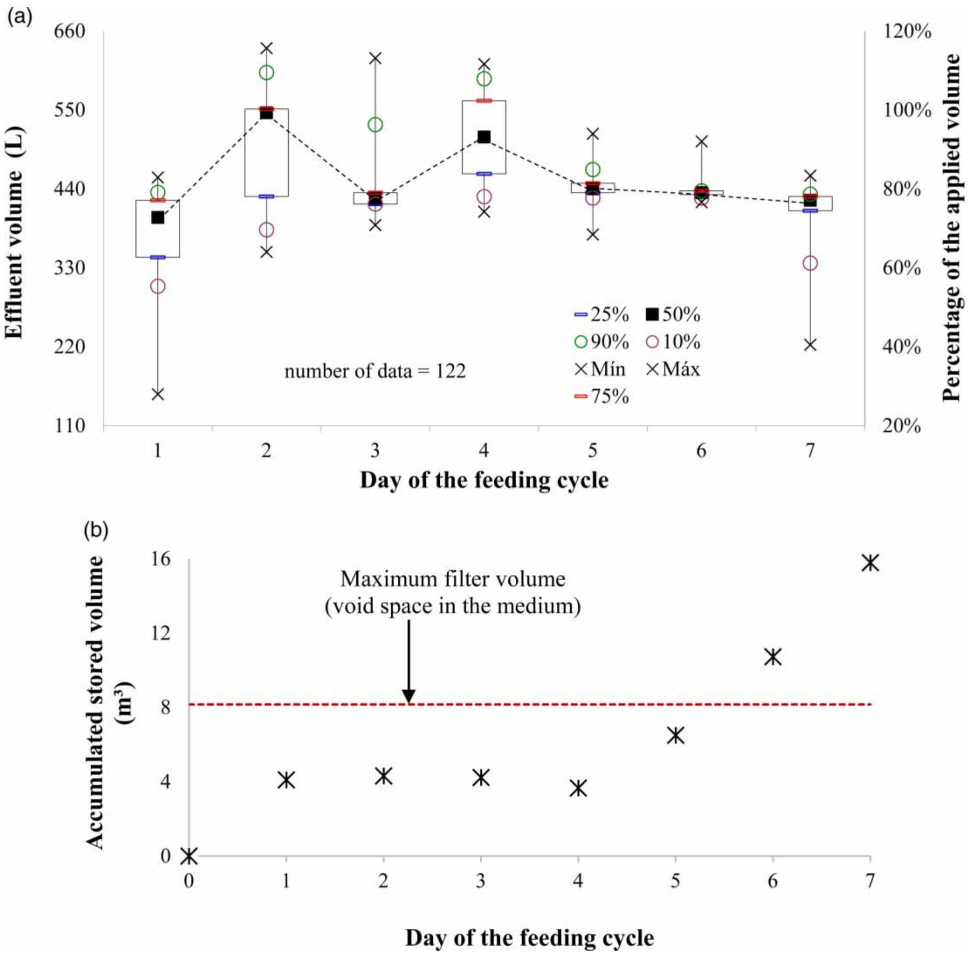

Figure 3 | (a) Effluent volume and percentage of recovery of the different pulses of each day of the cycle (top). (b) Cumulative volume stored in the filter during each day of the feeding cycle (bottom).

the greatest amplitude, since the first pulses retained much liquid inside the system and the last pulses, on the seventh day, were already affected by the system's loss of permeability. Although the median reached almost 80% of the applied volume, there were events with low recovery, on the order of only 40%. The system had already reached its maximum permeability on the second day and this remained until the end of the fourth day. From the fifth day, the recovery of the applied volume began to decrease. Figure 3(a) shows some volume recovered above 100% (more than 550 L) among days 2 and 4. It is important to note that the volume recovered referred not only to that particular pulse, but also indicated that during a given batch, there was also liquid going out from previous pulses.

Monitoring campaign 4 was also used to make a water balance in the system (Figure 3(b)). It is important to emphasize that the data logger had the capacity to store only eight hours of data, and so the remaining 16 hours were assumed to have the same behaviour as the measured eight hours (total daily volume was estimated by multiplying the measured volume by $24 \div 8 = 3$). The accumulated stored volume is the difference between the total input volume and the total output volume that occurred on the day plus the volume stored from the previous day.

On the first day, the volume stored inside the filter increased rapidly, due to the time required for wetting the system. At the end of this day, the system had already accumulated around 4 m^3. From the second to the fourth day, the volume variation was very small. As can be seen in Figure 3(a), during these days it was even possible to recover more than 100% of the applied volume. The moisture of the medium increased progressively during the cycle, but the permeability did not. This was probably because of the biofilm growth and the increase in retained solids, which became substantial. From day 5, the system's hydraulic conductivity and the volume recovered began to decrease; consequently, there was a rapid increase in the volume stored in the system, reaching its maximum at the end of the seventh day.

It is important to note that the volume of the liquid stored during the cycle exceeded the maximum capacity of the filter (8.2 m^3, considering a porosity of 40%, a surface area of 29.1 m^2 and a filter depth of 0.7 m). It is also known that the water level on the system was very small. Thus, the stored volume represented in Figure 3(b) was maximised and it seems that there were other output routes not accounted for. Part of the outflow that was not measured could have left the system by exfiltration or evapotranspiration. As the system stores liquid for a long time, especially in the first layer where the most developed biofilm is able to retain more moisture, evapotranspiration may have taken place and should probably not be disregarded.

Influence of the instantaneous hydraulic loading rate (HLR_{inst})

As expected, the peak outflow always occurred after the inflow on top of the filter was interrupted (or when the stored volume was maximum – Figure 1). This lag time depended on the characteristics of the filter media and its current status. The higher the instantaneous hydraulic loading rate $\left(\frac{\text{batch volume}}{\text{unit area} \times \text{tank discharge time}}\right)$, or feeding load, or still the shorter the tank discharge time, the sooner the peak occurred and the greater its intensity (Figure 4).

Figure 4 shows the outflow hydrograph and the recovered volume from the first pulse from two distinct feeding

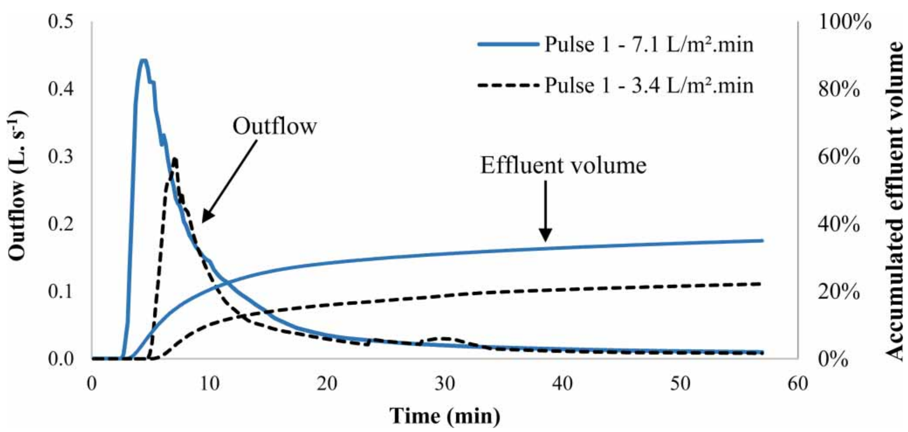

Figure 4 | Difference between instantaneous hydraulic loading rates: outflow and accumulated effluent volume as a function of time (in relation to the applied volume of 0.55 m^3 in the pulse).

strategies: one with an instantaneous hydraulic loading rate of 7.1 $L.m^{-2}.min^{-1}$ and the second with a lower value of 3.4 $m^{-2}.min^{-1}$. It should be noted that, in both cases, the HLR_{inst} was lower than the minimum recommended by Dotro *et al.* (2017), which is 0.5 $m^3.m^{-2}.h^{-1}$ (8 $L.m^{-2}.min^{-1}$). In the first case, the full batch volume (550 L) was released in 2.67 min (the peak flow of 0.44 $L.s^{-1}$ occurred 4.25 min after the discharge), while in the second case the release of the batch volume (550 L) was slower, taking 5.5 min (the peak flow of 0.30 $L.s^{-1}$ occurred 7.14 minutes after the discharge).

The higher HLR_{inst} led to a higher hydraulic gradient, increasing the percolation rates, decreasing the peak time and allowing a larger volume recovery. Therefore, the stored volume was expected to be smaller as the HLR_{inst} increased. Molle *et al.* (2006) investigated the influence of operating conditions and compared three different heads (x, 2x and 4x), discharged at intervals t, 2t and 4t. They noticed that the larger the head, the greater the hydraulic gradient and the higher the volume recovery, but, on the other hand, the shorter the hydraulic residence time within the system.

Influence of rainfall

Monitoring campaign 1 was conducted in the rainy season. The hiethogram of this week (main vertical axis) as well as the rainfall volume that entered cell II (secondary vertical axis) are shown in Supplementary material, Figure 3 (available with the online version of this paper). Unfortunately, the rainfall measured this week was given by a pluviometer, as the pluviograph was under maintenance. Because of this, only the total rainfall accumulated over 24 h could be obtained, and not the instantaneous one. On day 5, it rained 54.5 mm, which is equivalent to 1,588 L of rain incorporated into the unit. Figure 5(a) shows the effluent volume accumulated in the pulses that were measured during that week. In order to compute the cumulative volume percentage, the rainfall volume was not included. This was why, on day 5, there were two pulses that had a recovery of 130%, larger than the pulse flow of sewage (100% = 550 L).

The seven days before the beginning of the cycle (day 1) had been rainy, with a total of 187.7 mm, which is equivalent to 5,470 L of rain incorporated into cell II during its resting period of seven days. As a result, it can be seen that a large portion of the pulses during the whole week achieved a recovery of almost 550 L (or 100%), especially on day 1. Contrary to what was observed in the dry season monitoring campaigns, all the measurements showed a recovery volume greater than 80% (except the first pulse, which was approximately 60%). This high recovery ratio is attributed to the rain that fell on the system in the preceding days. Thus, at the beginning of monitoring, the system was not dry (as is expected, at the end of the resting period) and thus the time required for wetting until maximum hydraulic conductivity had already been reached at the beginning of the cycle.

Figure 5(b) presents a sequence of three pulses that occurred on day 5, which achieved the highest volumes of effluent recovered. During the time interval between 300 and 350 min a peak was observed, soon followed by a smaller and flattened peak. This second peak was a consequence of heavy rainfall. It is thus possible to observe that an intense rain; that is, a high water accumulation in a short time, could completely change the hydraulic regime of the system at that moment. At the 350–450 min pulse, the peak was elevated (almost 1 $L.s^{-1}$). After the precipitation stopped and the rainwater drained, the system tended to return to its normal operating pattern. In the case of hydraulic overload, the design must try to reduce the surface ponding (Arias *et al.* 2014).

Influence of the presence of the sludge deposit on the top surface of the filter

The filter units began operation in 2009, and since then they have been accumulating sludge on their surfaces. Aiming to evaluate the influence of this deposit layer, in February 2017, the sludge from the upper layer of Unit II was removed. Because of this, during the current experiments, the height of this sludge layer was only 0.5 cm. This unit is the one studied in the previous items. On the other hand, Unit I worked during these nine years without any sludge removal, and at the time of these experiments the top sludge layer had a height of 7.2 cm. Further details of these deposit layers and their influence on system performance can be found in Trein *et al.* (2018).

The outflow variation from the first day of operation until the last day (seventh) of one feeding cycle at unit I (unit with sludge) was analysed and is presented in Figure 6(a) for some days and pulses during the dry season. Note that this unit behaved similarly to unit II (with sludge previously removed; presented in Figure 2 and reproduced in Figure 6(b), for comparison): low flow rates in the first pulses, due to initial liquid retention in the system caused by the previous resting period, followed by increased flow and decay at the end of the seven-day feeding cycle. The major difference was at the end of the

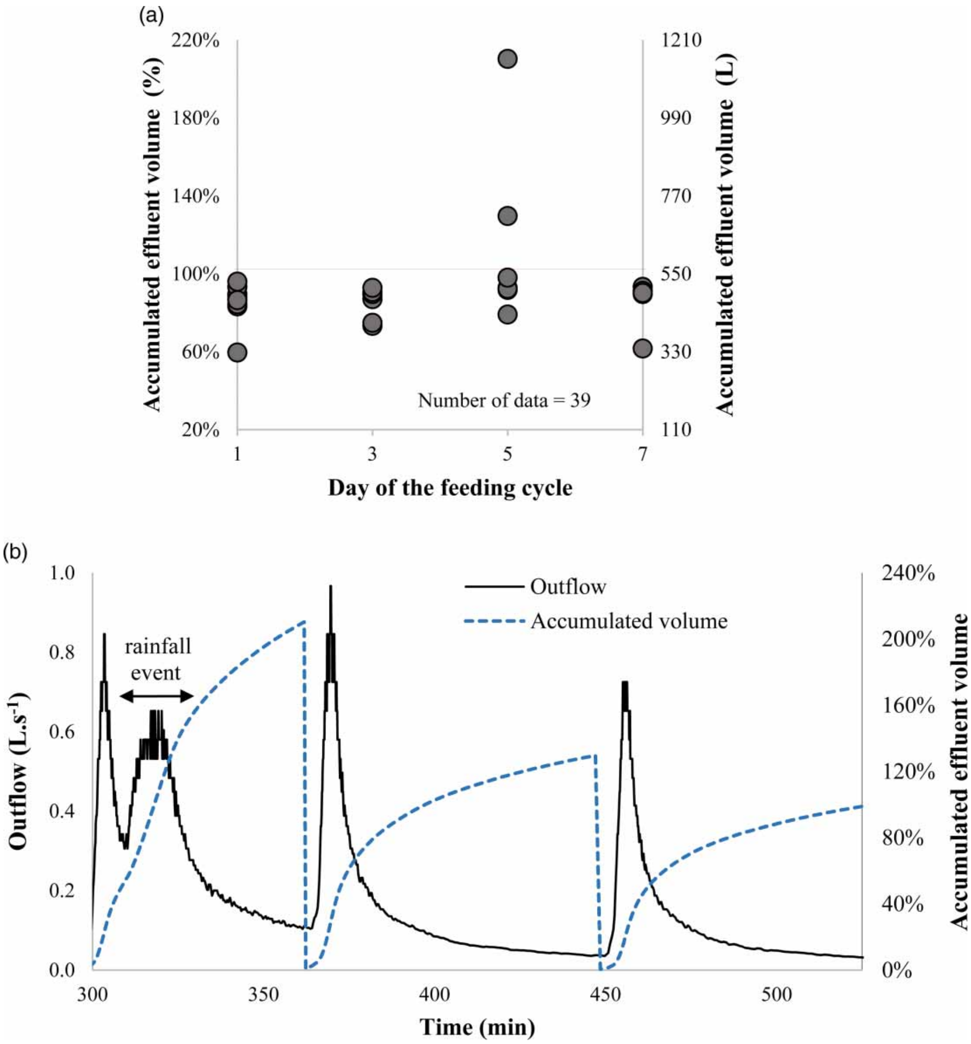

Figure 5 | (a) Effluent volume on the days of the feeding cycle during the rainy period (top). (b) Sequence of pulses during a heavy rain (rainfall event at minutes 300 to 350) (bottom).

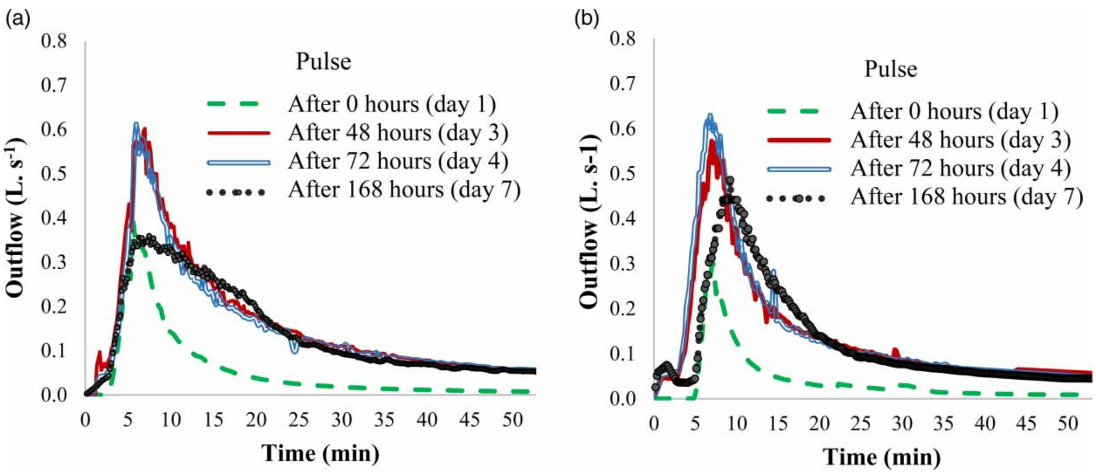

Figure 6 | Outflow hydrographs from different pulses through the seven-day feeding cycle. (a) Unit with sludge layer (left). (b) Unit with sludge layer previously removed (unit displayed in the other graphs) (right).

seven-day feeding cycle (represented here by pulse 168): the temporal profile of the outflow was smoother in the unit with the sludge layer (Unit I), indicating greater difficulty of infiltration, compared with the unit with virtually no sludge layer (Unit II).

Based on measurements of the recovered volumes in both units (122 data from unit II and 13 from unit I), there was an indication that unit I (with the sludge deposit layer) had lower volumes of recovered effluent, which suggests a greater volume stored inside the system. Thus, it is possible that the larger layer of sludge on the surface of unit I retarded the percolation of the liquid. This assumption is in agreement with Molle *et al.* (2006), who commented that the sludge deposit affected the infiltration capacity in vertical-flow units. However, it should be kept in mind that the higher layer of sludge in Unit I retained more moisture than in Unit II, so Unit I was probably subject to greater evapotranspiration. Therefore, this could reduce the possible volume recovered.

CONCLUSIONS

This work aimed to evaluate the influence of different factors on the effluent hydrograph of the first stage of a French System operated with only two units in parallel and an extended feeding time (seven days in each unit). It is important to note that the results obtained were for this non-typical French System, operating with an average surface hydraulic loading rate of 0.45 $m^3.m^{-2}.d^{-1}$ and an organic loading of 202 $gCOD.m^{-2}.d^{-1}$ on the filter in operation. The organic loading rate may influence the hydraulic behaviour of the filter, but was not evaluated in this study.

It was observed that, at the beginning of the seven-day feeding cycle, the system needed time for wetting and moisture retention. From the middle toward the end of the feeding cycle, the system increased the interior storage of liquid volume, probably due to a reduction in the filter's permeability. The liquid percolation time increased with the passing of the days in the feeding cycle, but the system was still able to maintain the liquid drainage capacity during these days.

Regarding the instantaneous hydraulic rate, which is associated with the time of the emptying of the storage box, it was seen that, in fact, it was desirable to empty the tank as quickly as possible, creating a greater hydraulic gradient, favouring the infiltration rate and decreasing the amount of liquid stored inside the system. However, with the use of the syphon applied in this research and with a frequency of 24 batches per day, the minimum instantaneous hydraulic rate recommended by the literature could not be obtained. Lower hydraulic loading rates and higher instantaneous hydraulic loading rates may delay the loss of the permeability of the system.

During intense rain events, it was noticed that precipitation could modify the flow dynamics. The rainfall during the rest period of the unit also contributed to the previous storage of liquid inside the system.

The sludge deposit seemed to hinder the passage of the liquid, especially at the end of the cycle, indicating that the sludge layer modified the hydraulic conductivity of the filter as a whole. Nevertheless, it should be noted that the sludge contributed to a momentary liquid retention, since the deposit layer allowed greater evapotranspiration, reducing the volume of liquid that percolated through the filter medium and the volume stored inside the system.

Lastly, the authors recommend more studies to be carried out under similar warm-climate conditions. This would allow for a better understanding of the filter hydraulics operating with fewer units in parallel and different feeding and resting cycles. Additionally, it would be of interest to link hydraulic behaviour with effluent quality.

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REFERENCES

Arias, L., Bertrand-Krajewski, J. L. & Molle, P. 2014 Simplified hydraulic model of French vertical-flow constructed wetlands. *Water Science and Technology* **70** (5), 909–916.

Chow, V. T., Maidment, D. & Mays, L. 1988 *Applied Hydrology*. McGraw-Hill, New York.

Dotro, G., Langergraber, G., Molle, P., Nivala, J., Puigagut, J., Stein, O. & Von Sperling, M. 2017 *Treatment Wetlands*, Vol. 7. Biological Wastewater Treatment Series. IWA Publishing, London, UK, p. 154.

García Zumalacarregui, J. A. & von Sperling, M. 2018 Performance of the first stage of the French System of

Vertical Flow Constructed Wetlands with only two units in parallel: influence of pulse time and instantaneous hydraulic loading rate. *Water Science and Technology* **78** (4), 848–859.

Hajra, M. G., Reddi, L. N., Marchin, G. L. & Mutyala, J. 2000 Biological clogging in porous media. *Environmental Geotechnics*. Denver, 5–8 August 2000. Edited by T.F. Zimmie. ASCE, Reston, VA. Geotechnical Special Publication No. 105, pp. 151–165.

Kadlec, H. R. & Wallace, S. 2008 *Treatment Wetlands*, 2nd edn. CRC Press, Boca Raton, Florida, p. 1016.

Langergraber, G. 2008 Modelling of processes in subsurface flow constructed wetlands – a review. *Vadose Zone Journal* **7** (2), 830–842.

Lombard Latune, R. & Molle, P. 2017 Les filtres plantés de végétaux pour le traitement des eaux usées domestiques en milieu tropical. Guide de dimensionnement de la filière tropicalisée. Agence Française pour la biodiversité, collection *Guides et Protocoles*, 72 pp.

Maier, U., DeBiase, C., Baeder-Bederski, O. & Bayer, P. 2009 Calibration of hydraulic parameters for large-scale vertical flow constructed wetlands. *Journal of Hydrology* **369** (3–4), 260–273.

Manjate, E. S., Lana, L. C. O., Moraes, D. C., Vasconcellos, G. R., Maciel, M. & von Sperling, M. 2015 First stage of the French vertical flow constructed wetland system: experiments with the reduction of surface area and number of units. *Journal of Water, Sanitation and Hygiene for Development* **5** (1), 50–55.

Molle, P. 2014 French vertical flow constructed wetlands: a need of a better understanding of the role of the deposit layer. *Water Science and Technology* **69** (1), 106–112.

Molle, P., Liénard, A., Grasmick, A. G. & Iwema, A. 2004 French vertical flow constructed wetlands: reed bed behaviour and limits due to hydraulic overloading on first stage filters. In: *9ème Conférence sur les Marais Artificiels et 6ème Conférence Sur Le Lagunage Naturel*, September 2004, Avignon, France, 5 pp.

Molle, P., Liénard, A., Boutin, C., Merlin, G. & Iwema, A. 2005 How to treat raw sewage with constructed wetlands: an overview of the French systems. *Water Science and Technology* **51** (9), 11–21.

Molle, P., Liénard, A., Grasmick, A. & Iwema, A. 2006 Effect of reeds and feeding operations on hydraulic behaviour of vertical flow constructed wetlands under hydraulic overloads. *Water Research* **40** (3), 606–612.

Molle, P., Lombard Latune, R., Riegel, C., Lacombe, G., Esser, D. & Mangeot, L. 2015 French vertical-flow constructed wetland design: adaptations for tropical climates. *Water Science and Technology* **71** (10), 1516–1523.

Moraes, M. A. A., García Zumalacarregui, J. A., Trein, C. M., Palmier, L. R. & von Sperling, M. 2018 Hydraulic analysis of the influent distribution system in a pulse-feeding vertical flow constructed wetland (first stage of French system). In: *4a Conferencia Panamericana de Sistemas de Humedales. Rede Pan-Americana de Sistemas de Humedales de Tratamiento*, 15–18 May 2018, Lima, Peru.

Morvannou, A., Forquet, N., Vanclooster, M. & Molle, P. 2012 Which hydraulic model to use in vertical flow constructed wetlands? In: *13th International Conference on Wetland Systems for Water Pollution Control*, November 2012, Perth, Australia.

Morvannou, A., Forquet, N., Michel, S., Troesch, S. & Molle, P. 2015 Treatment performances of French constructed wetlands: results from a database collected over the last 30 years. *Water Science and Technology* **71** (9), 1333–1339.

Paul, U., Karpf, C. & Schalk, T. 2018 Hydraulic simulation of perforated pipe systems feeding vertical flow constructed wetlands. *Water Science and Technology* **77**, 1431–1440.

Torrens, A., Molle, P., Boutin, C. & Salgot, M. 2009 Impact of design and operation variables on the performance of vertical-flow constructed wetlands and intermittent filters treating pond effluent. *Water Research* **43** (7), 1851–1858.

Trein, C. M., Moraes, M. A. A., García Zumalacarregui, J. A. & Von Sperling, M. 2018 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. In: *16th International Conference on Wetland Systems for Water Pollution Control*, 30 September–4 October 2018, Valencia, Spain. IWA.

Xu, Q., Cui, L., Zhang, L., Li, Z. & Yu, G. 2013 Effect of two factor combination of three kinds of loading on the soil clogging in vertical flow constructed wetland. *Frontier of Environmental Science* **2** (4), 56–63.

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