On-site single-stage constructed wetland fed by raw wastewater: performances and resilience of the system

V. Dubois and P. Molle

ABSTRACT

On-site sanitation systems in Europe are evaluated through a CE marked procedure done on a platform test under a specific schedule of loads. Nevertheless, the test procedure conditions do not represent the real conditions of treatment systems in terms of wastewater characteristics and loads.

On another angle, in France, systems implemented for capacities above 20 p.e. do not need the CE marked procedure but have to comply with performance requirements. French on-site treatment regulations lead to a paradoxical situation where constructed wetlands (CW) designed for 21 p.e. can be more compact than for 15 p.e. Here we focus on a single-stage vertical flow CW treating raw wastewater from a six-person house. Working with a (compact) community CW design, the objectives were to evaluate, in real-world conditions, the limits of the system and its ability to handle the high hydraulic and organic load variations found in on-site sanitation. Concentrations and fluxes showed high inter-day and intra-day variability, confirming the necessity for treatment systems to be robust enough for on-site sanitation. The compact CW appeared very efficient and stable for organic pollutants and nitrification (average removal rates of more than 98%, 99%, 94% and 97% for TSS, BOD$_5$, COD and TKN, respectively). Denitrification has been optimized to reach 70% of TN removal, but seems unable to go higher due to a lack of carbon.

Key words | constructed wetlands, denitrification, on-site sanitation, performance robustness

INTRODUCTION

On-site sanitation systems in Europe are evaluated through an EU-labeled procedure done on a test platform under a specific loading schedule (NF EN 12566-3 + At 2009 – ‘Small wastewater treatment systems for up to 50 PT’), but these test procedure conditions are not representative of real-world treatment-system conditions in terms of wastewater characteristics and loads. Studies on household pollutant outputs often find higher concentrations and variable characteristics (Matulova et al. 2010). In some counties, specific national guidelines were established before the EU-labeled procedure to implement constructed wetlands (CW) for on-site sanitation, like in Denmark (Brix & Arias 2009), Austria (Österreichisches Normeringsinstitut 1997) or Germany (revised DWA-A 262 German constructed wetland guideline – Nowak et al. 2018), for example. These configurations can lead to different required filter areas from 3 to 5 m$^2$/p.e. and always implement a primary treatment like a septic tank. However, in France, constructed wetland systems fed with raw wastewaters have to pass the labeled procedure for capacities up to 20 p.e. while, for capacities above 20 p.e., they only have to comply with performance requirements. For CW, this leads to a situation where a 21-p.e. design can be more compact than a 15-p.e. design due to larger labelled designs for on-site sanitation. Some companies offer systems that pass the EU-labeled procedure for a single-stage vertical-flow CW (VFCW) receiving raw wastewater with designs of 1.2–2 m$^2$ per inhabitant. These designs concern VFCW that are unsaturated or combined with horizontal-flow CW (HFCW), resulting in either possible solids release according to load variation (VFCW) or a high footprint of 5 m$^2$/p.e. (HFCW). The trade-off between system compactness and system reliability is crucial in the response to high load variations. Design efforts have recently turned to developing compact VFCW to treat raw wastewater from municipalities using recirculation (Prost-Boucle & Molle 2012) or unsaturated/saturated VFCW systems (Prigent et al. 2013; Silveira et al. 2015; Morvannou et al. 2017), but always with fairly regular feeding from...
municipalities. Nevertheless, biological communities vary (in quality and quantity) in response to feeding/resting period strategies or high load variations (weekdays, holidays, weekends), thus affecting treatment performances, as studied during start-up periods with regular loads (Weber & Legge 2011). Hydraulic load variation can also induce different retention times within the system, again affecting performances. Implementing a saturated vertical layer at the bottom can increase the retention time while promoting the denitrification process and, consequently, consumption of carbon. This type of design may appear more robust in buffering outlet quality than totally unsaturated VFCW systems.

The aim of this study was to evaluate, in real-world conditions, the behavior of a single-stage unsaturated/saturated VFCW (as designed for small communities) fed by raw wastewater (with no septic tank). The objectives were to evaluate system performances, robustness and resilience in response to high load variations from households, and to optimize the unsaturated layer depth.

**MATERIAL AND METHODS**

Monitoring was conducted on an unsaturated/saturated VFCW treating the wastewater from a six-person family in the south of France (Crest, Drôme department). The system consists of:

- A pumping station receiving all wastewaters from the house (no screening) and delivering, on average, four or five batches a day to the treatment system. Batch feeding flow is 3 m$^3$/h for an average batch volume of 80 liters (so each batch lasts around 1.5 minutes). Batches are applied on one filter surface by one feeding point.

- An unsaturated/saturated VFCW divided into two parallel filters to implement one-week feeding/one-week resting cycles. The filters (1.2 m deep) comprise a 70 cm layer of 2/6 mm crushed-washed gravel (unsaturated layer), a 10 cm transition layer (6/12 mm) with an aeration pipe inside (0.3 m/m$^2$), and a saturation layer composed of pea gravel (20/40 mm). We tested saturation layer depths between 22 and 40 cm to optimize denitrification. Each filter has a surface of 7 m$^2$ (3.5 m × 2 m). Filter borders have a 1-to-1 slope and the filters are sealed thanks to a polypropylene geomembrane.

Treated wastewaters were infiltrated into the ground in winter and reused for irrigation of bushes the rest of the year. Monitoring started after 3 years of operation and was continued for 18 months, and consisted of:

- Counting the number of people present in the house overnight and at lunch and dinner every day.
- Measuring daily flow via a pressure probe (STS) in the pumping station recording measurements at one-minute time-steps.
- Performing 24 h flow proportional samples at the inlet/outlet of the system to analyze global parameters by standard methods (APHA 2012) for chemical oxygen demand (COD), dissolved COD, total organic carbon (TOC), dissolved organic carbon (DOC), total suspended solids (TSS), biochemical oxygen demand (BOD$_5$), total Kjeldahl nitrogen (TKN), N-NH$_4^+$, N-NO$_2^-$, N-NO$_3^-$, P-PO$_4^{3-}$ and total phosphorus (TP). A total of 31 campaigns were done in different seasons. Samplings were performed over 7 to 10 consecutive days to analyze the dynamics of treatment performances. Total nitrogen (TN) was estimated by the sum of TKN and N-NOx.
- For some campaigns, N-NO$_3$/N-NH$_4$ were measured online at the outlet at one-minute time-steps (Ion Selective Electrode sensor, WTW Varion).

Sampling raw wastewater with high solids concentrations is a tricky exercise, so we were particularly careful with the inlet sampling method. Inlet wastewater sampling was done using a water detector inserted in the feeding pipe at the filter surface. During a batch, the water arriving at the detector made the sampler work for a specific volume, which made the samplings proportional to batches (and thus to flow) and perfectly representative of the wastewater arriving on the filter.

**RESULTS AND DISCUSSION**

**Characterization of per-inhabitant pollutant production**

On-site observation of wastewater characteristics found that concentrations were much higher than usually used in EU-labeled tests (see Table 1) and closer to the concentrations observed for on-site sanitation (Cauchi & Vignoles 2002), even from small communities (Butler et al. 1995; Henze 2008; Mercoiret 2010). This reveals that wastewater characteristics from households are highly concentrated and highly variable.

The hydraulic loads received varied significantly, with high loads (maximum of 4.4 m$^3$/d representing a hydraulic load of 65 cm/d on the filter in operation) for some individual events. Excepting these special events (three datapoints),
daily volume production and classical within-day variation are shown in Figure 1.

Average daily flow volume was 290 liters per day. Compared to the effective human occupancy each day, daily volume generated per capita was 54 liters on average (Figure 2).

The measurements quantify volume variations that are often doubled, or even tripled or more during special events, from one day to another. The unique special event, with more than 10 times the average hydraulic load, corresponds to an open tap that was forgotten and left running on a day when occupancy was high (the 5th of July 2016). While this event can be seen as an accident and an unusual situation, it is still important to evaluate whether this kind of event can be accepted by the system or damages its functional operation.

To analyze whether volume variations correlated to occupancy variations in the house, we defined the daily average occupancy by cumulating the number of meals (lunch and dinner) plus the number of people who slept overnight in the home, divided by 3. Figure 3 (left) shows a slight correlation between occupancy and emitted volume of domestic wastewater ($R^2 = 0.26$). Volume increased on aggregate with increasing occupancy, but also showed one to six-fold variation for the same occupancy rate. Every day has its specific pattern in terms of wastewater emissions. Figure 3 (right) shows the amplitude and average between open days, weekends and weekdays (the three special events have been removed).

The results obtained for the concentrations and pollutant loads (in carbon, nitrogen and phosphorus) were similar to the emitted volumes (results not shown). Note that even after excluding outliers induced by special events, the treatment system still has to handle huge variations (hydraulic and organic), which underlines how it is vital for real-world treatment systems to be robust enough to maintain treatment performances.

### Treatment performances

Based on 60 g of BOD$_5$/p.e./d and 150 g of COD/p.e./d, the system received a corresponding average organic load of about 4 p.e. (one inhabitant is not equal to a population equivalent) with a maximum measured load of 10.5 p.e.

---

**Table 1: Wastewater characteristics**

<table>
<thead>
<tr>
<th>Volume (L)</th>
<th>COD</th>
<th>dCOD</th>
<th>TSS</th>
<th>BOD$_5$ (mg/L)</th>
<th>TKN</th>
<th>N-NH$_4$</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>521 (54 L/cap/day)</td>
<td>1,853</td>
<td>467</td>
<td>1,032</td>
<td>767</td>
<td>209</td>
<td>152</td>
</tr>
<tr>
<td>Median</td>
<td>347</td>
<td>1,780</td>
<td>470</td>
<td>1,065</td>
<td>784</td>
<td>207</td>
<td>148</td>
</tr>
<tr>
<td>Min</td>
<td>67</td>
<td>358</td>
<td>53</td>
<td>213</td>
<td>530</td>
<td>29</td>
<td>16.8</td>
</tr>
<tr>
<td>Max</td>
<td>4,397</td>
<td>2,750</td>
<td>708</td>
<td>1,590</td>
<td>1,100</td>
<td>330</td>
<td>252</td>
</tr>
<tr>
<td>Butler et al. (1995) (average values)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>492</td>
<td>22</td>
</tr>
<tr>
<td>Cauchi &amp; Vignoles 2012 (average values)</td>
<td>84 L/pe/day</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>633</td>
<td></td>
</tr>
<tr>
<td>Mercoiret 2010 (average values)</td>
<td>645</td>
<td>288</td>
<td>265</td>
<td>67</td>
<td>55</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Henze (2008) (maximum values)</td>
<td>80 L/cap/day</td>
<td>2,750</td>
<td>1,125</td>
<td>185</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU-labeled tests (range)</td>
<td>150 L/pe/day</td>
<td>300–1,000</td>
<td>200–700</td>
<td>150–500</td>
<td>25–100</td>
<td>22–80</td>
<td>5–20</td>
</tr>
</tbody>
</table>

---

**Figure 1:** Daily hydraulic load (left) and average hydraulic load distribution during a day (right).
Even organic load showed strong and sudden variations (Figure 4).

Inlet-outlet concentrations for all measured parameters are presented in Table 2. Whatever the inlet concentration variations, outlet concentrations always remained low for carbon pollutant parameters, solids, and ammonia. This demonstrates that the system is stable to inlet hydraulic and organic load variations. For nitrogen removal, inlet/outlet concentrations do not show more variations. There are no obvious differences to observe, according to saturation level, on nitrate outlet concentrations, as inlet TKN concentrations were not similar in the two experimental phases. We will see later that it is clearer on removal performances. Figure 4 charts the organic and hydraulic load variations over consecutive days for two seasons. While hydraulic load remains globally low (excepting the on-off event) compared to what this system is able to accept (Molle et al. 2006), the organic load varies a lot, which could compromise biological stability and efficiency.

Despite these high load variations, removal performances remained extremely stable, as shown in Figure 5, with average removal rates of more than 98%, 99%, 94% and 97% for TSS, BOD₅, COD and KN, respectively whatever the saturation level. Even though hydraulic load is usually low, organic load can reach values similar to nominal design of French VFCWs (Molle et al. 2005).

TN removal was still not complete and there was no clear pattern of seasonal correlation. Increasing the depth of the bottom saturation layer from 22 cm to 40 cm appeared to improve TN removal (bottom right, Figure 5). With 22 cm of saturation, TN removal was about 45% and not stable, while with 40 cm of saturation, TN removal
reached around 70%. Around 68 mg N-NO₃/L were still present at the outlet. The question of whether the retention time in the saturation zone (around 1.3 days on average when saturation is fixed to 40 cm) or the source of carbon were limiting to reach higher denitrification levels can be discussed. On one hand, such a retention time appears sufficient to reach high denitrification levels when the carbon source is high enough (Morvannou et al. 2016). On the other hand, average and median outlet COD concentrations were 68 and 69 mg COD/L, respectively, when implementing a 22 cm depth of saturation and 46 and 45 mg COD/L, respectively, when implementing a 40 cm depth of saturation. Outlet median BOD₅ concentrations were 3.2 mg/l with a saturation layer of 40 cm. Those outlet COD concentrations are close to inert COD as defined by different studies (see Choi et al. 2017 for instance) and anyway not enough to denitrify 60 mg/L of nitrate. It is likely that the carbon source was the limiting factor.

Analysis of intra-day nitrogen outlet quality variation (Figure 6) showed that the system was observably robust. Even with the applied load varying from 2.5 to 19 g·m⁻²·d⁻¹, the outlet concentration for N-NH₄ and N-NO₃ remained quite stable.

Phosphorus is not correctly treated in the filter as no specific materials are implemented. Only 40% on average is removed, mainly the particulate form of P that is filtered by the system.

Feeding the system with raw wastewater should lead to an accumulation of an organic deposit on the filter surface (Molle et al. 2005). Due to the low load applied, and despite the fact that reeds were pruned but not removed from the filter, there was no measurable deposit layer depth after 5 years in operation. The bulk of the deposit is mineralized, which facilitates sludge management and confirms the value of feeding the system with raw wastewater.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Inlet-outlet concentrations during 24-h flow-proportional composite sampling campaigns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TSS</td>
</tr>
<tr>
<td>In</td>
<td>out</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1,032</td>
</tr>
<tr>
<td>Median</td>
<td>1,065</td>
</tr>
<tr>
<td>Min</td>
<td>213</td>
</tr>
<tr>
<td>Max</td>
<td>1,590</td>
</tr>
<tr>
<td>Nb of values</td>
<td>23</td>
</tr>
</tbody>
</table>

Figure 4 | Organic and hydraulic load variations over consecutive monitoring days for two seasons.
CONCLUSIONS

In real-scale monitoring over 18 months on an on-site constructed wetland system some general conclusions emerged.

In terms of wastewater production and variation for this single-household:
- Wastewater concentration characteristics are much higher than usually used in EU-labeled tests.
• There is not a proportional relationship between the number of people in the house and the amount of emitted wastewater. The emitted volume per person is on average three times lower than the reference value used in the EU-labeled tests, but can vary from 4 up to 304 liters per day.

• Organic load variation can vary from day to day by up to 10,000%, which means treatment systems are required to be robust and resilient to unexpected events. The studied system showed a decrease in the nitrification rate in Figure 6 with the special event (open tap for one day) due to the lower hydraulic retention time.

In terms of performances of the unsaturated/saturated VFCW tested, we noted that the system remained exceptionally stable whatever the variations observed during monitoring. Removal performances were very high, and outlet concentrations were low and stable despite the big inlet variations. While performances were high for solids, carbon removal and nitrification, performance in TN removal was impacted by the depth of the saturation level. The design implemented here seems unable to achieve better than 70% TN removal as it still lacks a carbon source for denitrification at the outlet. To reach higher levels, the design will have to balance TN removal against nitrification performance.

REFERENCES


NF EN 12566-3 + A1 2009 Small Wastewater Treatment Systems for up to 50 PTE. AFNOR publication.


Österreichisches Normungsinstitut 1997 Bepflanzte Bodenfilter (Pflanzenkläranlagen) Anwendung, Benennung, Bau und Betrieb. ÖNORM B 2505.


First received 5 March 2018; accepted in revised form 3 July 2018. Available online 17 July 2018