Vertical flow constructed wetlands for municipal wastewater and septage treatment in French rural area

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Abstract This paper presents the purification performance of 20 wastewater treatment plants with vertical reed bed filters (Macrophyltres®), built between 1998 and 2003 by SAS Voisin, for communities of between 150 and 1400 PE. The first stage vertical reed bed (directly fed with raw wastewater by intermittent feeding) achieved high removal of SS, BOD and COD (mean respectively 96%, 98%, 92%). The second stage permitted compliance easily with effluent standards (SS < 15 mg/l, BOD < 15 mg/l, COD < 90 mg/l and mean TKN < 10 mg/l). Performance was not significantly influenced by variations of organic and hydraulic load, nor by seasonal variations. Rigorous operation and maintenance were required to obtain optimal performances. Another application of vertical reed beds is the treatment of septage (sludge from individual septic tanks). The results obtained on two sites operating for 2 and 3 years are presented. The first site achieved complete treatment of septage (solid and liquid fraction), the second permitted a pre-treatment for co-treatment of percolate with wastewater.

Keywords Constructed wetland; vertical flow reed-bed filter; municipal wastewater; septage treatment

Introduction
The construction of subsurface constructed wetlands with vertical flow (or vertical reed bed filters) for municipal wastewater treatment has been increasing in development in France, with a design based on the recommendations of CEMAGREF (1998) and the Office International de l’Eau (2001). The unusual feature of the system is to receive raw wastewater directly on the first stage vertical reed bed, without primary sedimentation. Sludge is retained on the surface of the filter, where it is mineralised. This ecological technique, particularly adapted for small communities in rural areas (between 50 and 2000 PE), presents several advantages:

– very low production of stabilized sludge
– high treatment efficiency
– low costs and simplicity of operation and maintenance
– no chemical and energy consumption (if there is sufficient natural slope)
– no odour and good landscape integration

Since the first plant was built in 1987 at Gensac-la-Pallue (described in Liénard et al., 1993), the system has been improved from the experience gained on-site and in our experimental centre at Beaumont-la-Ronce, until we developed our own process named Macrophyltres®. Since 1997, more than 130 wastewater treatment plants have been designed and built in this way by SAS Jean Voisin.

In this paper, the performance of 20 wastewater treatment plants (WTPs) with vertical reed beds will be analysed in order to compare the results and determine factors that could affect performance, define the quality of the final effluent, and discuss possibilities to improve the system.

Another application of reed beds is the treatment of faecal sludge evacuated from on-site sanitation. In France and other European countries, the treatment of septage from individual septic tanks became a priority because: first, on-site sanitation is now...
recognized to be an alternative technique to centralised wastewater (principally in rural area with isolated habitations). And secondly, the control of all individual treatment system and of their frequent sludge collection should be done by local authorities.

Disposal and treatment of these increasing quantities of wastes still remains un-resolved. Their main destination is direct agricultural reuse or co-treatment with wastewater in large treatment plants (>10000 PE). However, the first solution is not recommended because faecal sludge contains low concentrations of total solids, high septicity and ammonia concentrations leading to odour nuisances and sanitary risks. The second solution is limited by the small number of large units in rural areas and the capacity of treatment plants to receive additional organic load. According to CEMAGREF (2004), faecal sludge should represent less than 20% of total organic load. Also to minimize the cost of transport, it is better to envisage small units of treatment with two alternatives: first, co-treatment with wastewater in small plants (<10000 PE) with pre-treatment of faecal sludge for separating the solid and liquid fraction. And secondly, specific plants for complete treatment of faecal sludge: solid and liquid fraction.

For both those solutions, vertical reed beds could be an interesting system, which had been tested for several years in our experimental site at Beaumont-la-Ronce (first results presented in CEMAGREF, 2004). This paper will presents the results obtained in two sites in operation for 2 and 3 years: Beaumont-la-Ronce for complete treatment of septime and Athée-sur-Cher for co-treatment with wastewater.

Materials and methods

Treatment of municipal wastewater

This paper will present the results obtained on 20 wastewater treatment plants built between 1998 and 2003, treating municipal wastewater, with capacities between 150 and 1400 population equivalents (1 PE represents, for 1 day: 150 L with 60 g BOD₅, 90 g SS, 120 g COD, 15 g TN and 4 g TP). Most of these plants are fed from separate sewer systems, collecting principally domestic wastewater.

All the plants have been constructed following the same design (Figure 1). First a screen to retain coarse particles (>32 mm). Secondly, a storage tank with a self-priming siphon, in order to obtain a hydraulic batch mode for feeding the reed bed filters. For land without sufficient ground slope, the self-priming siphon was replaced by a storage tank with pumps. The principal stage of treatment was constituted by 3 (or 6) reed bed filters with vertical flow, operated in parallel (named Macrophyltres®). From the top to

![Diagram of wastewater treatment plant](https://iwaponline.com/wst/article-pdf/51/9/145/434737/145.pdf)

Figure 1 Typical wastewater treatment plant with vertical reed bed filters (Macrophyltres®)
the bottom, the filter media was: a 50 cm layer of small gravel (Ø 2–8 mm), 20 cm of middle gravel (Ø 10–20 mm) and 20 cm of large gravel (Ø 20–40 mm). The feeding system was constituted by a network of PVC pipes under the surface (to facilitate maintenance) with several outlets permitting an optimum distribution of the influent over the whole surface. The drainage system was a network of perforated PVC pipes at the bottom connected to several vent pipes for aeration. The reeds were Phragmites australis.

The second stage of treatment was constituted by 2 or 3 sand filters with vertical flow, operated in parallel. From the top to the bottom, the filter media was: a 40 cm layer of sand (Ø 0–4 mm), 30 cm of gravel (Ø 3–8 mm) and 20 cm of large gravel (Ø 10–20 mm). The distribution and drainage system was similar to the first stage except a perforated pipe was added in the middle to enhance the sand layer aeration. For these sand filters, the planting of reeds was optional because the role of plants on this second stage was not proved to be significant.

The first stage was designed with a range of 1.2–1.3 m²/PE, corresponding to a hydraulic load of 0.12 m³/m² d (0.35–0.38 m³/m² d for the operating bed, one third of the surface operating weekly). The second stage was designed with a ratio of 0.7–0.8 m²/PE, corresponding to a hydraulic load of 0.2 m³/m² d (0.38–0.60 m³/m² d for the operating bed, half or one third of the surface operating weekly). The rotation of the beds was operated weekly in order to have feeding periods of one week following by resting periods of 1 or 2 weeks. The volume of each batch feed was designed to be around 30 mm over the surface of the operated bed for the first stage and around 40 mm for the second stage (between 10 and 15 batch feedings per day).

Sampling and analysis were performed by the French departmental services that control the wastewater treatment plants (chemical analysis according to standard methods: SS, COD, BOD₅, TKN, NH₃, NO₃, TP). Grab samples and flow proportional composite 24 h composite samples were taken for raw wastewater, effluent from the first stage and final effluent from the second stage. Hydraulic load was measured by flow meters or evaluated by the number of batch feedings from the self-priming siphon.

Treatment of faecal sludge (septage)

This paper presents the results obtained in the Beaumont-la-Ronce and Athée-sur-Cher sites (French department no 37) both for the treatment of septage from individual septic tanks. The design and operating conditions are described in Table 1. At Beaumont-la-Ronce, the first stage vertical reed bed was built based on the same model as the

![Table 1 Design and operating conditions of both sites for septage treatment on vertical reed beds](image)

<table>
<thead>
<tr>
<th></th>
<th>Beaumont-la-Ronce</th>
<th>Athée-sur-Cher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of commissioning</td>
<td>April 2001</td>
<td>June 2002</td>
</tr>
<tr>
<td>Volume of septage</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Mean concentration of SS (g/l)</td>
<td>28*</td>
<td>20**</td>
</tr>
<tr>
<td>Chemical pre-treatment of septage</td>
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<td>yes</td>
</tr>
<tr>
<td>Surface of 1st stage vertical reed beds (m²)</td>
<td>612</td>
<td>184</td>
</tr>
<tr>
<td>Surface loading rate (kgSS/m² year)</td>
<td>46</td>
<td>109</td>
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<tr>
<td>Number of beds</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Feeding period for each bed (days)</td>
<td>7</td>
<td>3.5</td>
</tr>
<tr>
<td>Rest period for each bed (weeks)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Hydraulic load during a feeding period (cm)</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Volume of each batch feeding (m³)</td>
<td>5,2</td>
<td>10</td>
</tr>
<tr>
<td>Number of batches during feeding period</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Percolate treatment</td>
<td>vertical sand filter + pond</td>
<td>activated sludge</td>
</tr>
<tr>
<td>Co-treatment with wastewater</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

*mean of 8 analyses performed during the 3 years operation. **estimated
Macrophyltes® used for wastewater treatment described above. At Athée-sur-Cher, the total depth of filter media was only 45 cm. In both sites, the raw faecal sludge was first passed through a screen to remove coarse objects, and then homogenised in a mixing tank before feeding the reed beds with a self-priming siphon or pumps. At Athée-sur-Cher, a preliminary treatment with ferrous chloride and other chemical was used for coagulation and flocculation before feeding the beds.

The performance of the Beaumont-la-Ronce plant was measured by grab samples (2–3 times a year) and analyses were performed by the departmental laboratory according to standard methods (SS, COD, BOD, TKN, N-NO₃ and TP). Accumulated sludge depth was measured at both sites in January 2004, dry solids content was measured on several points according to standard methods in the laboratory of SAS Jean Voisin.

**Results and discussion**

**Treatment of municipal wastewater**

The results presented in Table 2 were measured after a minimum of 4 months of operation with organic load over 20% of the design capacity (necessary to reach the optimum performances). Removal efficiencies calculated from the concentrations are shown in Table 3.

The first stage vertical reed bed achieved high SS removal (between 86 and 99%), as a result of physical filtering by the gravel bed, enhanced by the filtering action of the organic deposits layer which accumulated at the surface. As noted by Boutin et al. (1997), this clogging layer remained self-managing with the action of reed stems and roots and with alternative feed and rest periods (contrary to the conclusions of Winter and Goetz, 2003). High removal of BOD and COD (respectively between 87–99% and 80–97%) were due to the retention of particulate organic compounds but also to the action of the biomass attached to the filter media. The TKN removal was between 44 and 84%, principally due to the retention and ammonification of organic nitrogen, and by a partial nitrification.

The effluent from the first stage was significantly purified achieving the following concentrations: SS < 30 mg/l, BOD₅ < 40 mg/l, COD < 130 mg/l and TKN removal >40%. Despite this very good efficiency, the effluent quality was not sufficient to comply in all cases with French effluent standards (usually the minimum standards required are: 25 mg BOD/l and 125 mg COD/l).

The second stage vertical sand filter easily reached these standards with the following effluent concentrations: SS < 15 mg/l (except 1 grab sample), BOD₅ < 15 mg/l, COD < 90 mg/l and TKN < 10 mg/l with some peaks < 20 mg/l. Phosphorus removal was generally low with a mean of around 40%. Thus, the second stage ensured further treatment of SS and organic compounds and the reliability of the system. It also completed the nitrification started in the first stage (with a high variability). It was also noted that the nitrate concentration in the final effluent showed a high variability (N-NO₃ between 14 and 84 mg/l). Indeed, the nitrate concentration depends on the feeding cycle: during the rest period, ammonia ions absorbed onto filter media are transformed into nitrates which are washed out at the start of the next feeding period (Boutin et al., 1997).

It is interesting to note that no significant differences can be observed in the effluent quality (first and second stage) with variations in hydraulic load (between 19 and 320% of the design capacity) and organic load (between 19 and 96% of the design load). Composite 24-h sampling performed at Adrier (86) during rain showed that with an hydraulic load 3 times superior to the design capacity, effluent quality was not affected. This capacity to support variations of organic and hydraulic loads is a strong advantage of the reed beds treatment system. This is interesting for communal wastewater that often...
Table 2 Results of measurements performed on 20 wastewater treatment plants in France, concentrations expressed in mg/l

<table>
<thead>
<tr>
<th>WTP locality (French department)</th>
<th>Capacity (PE)</th>
<th>Analysis date</th>
<th>Sampling type</th>
<th>Months of operation</th>
<th>Hydraulic load</th>
<th>Organic load</th>
<th>Raw wastewater</th>
<th>Vertical reed bed (1.2–1.3 m²/PE) 1st stage effluent</th>
<th>Vertical sand filter (0.7–0.8 m²/PE) 2nd stage effluent</th>
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<td>87%</td>
<td>175</td>
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<tr>
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<td>07/2000</td>
<td>G</td>
<td>15</td>
<td>102% +</td>
<td>57%</td>
<td>221</td>
<td>303</td>
<td>622</td>
</tr>
<tr>
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<td>1000</td>
<td>03/2001</td>
<td>24 h</td>
<td>23</td>
<td>102% +</td>
<td>57%</td>
<td>221</td>
<td>303</td>
<td>622</td>
</tr>
<tr>
<td>Autainville (41)</td>
<td>450</td>
<td>06/2003</td>
<td>24 h</td>
<td>37</td>
<td>32% +</td>
<td>23%</td>
<td>140</td>
<td>260</td>
<td>760</td>
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<tr>
<td>Azerat (24)</td>
<td>300</td>
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<td>20%</td>
<td>7.4</td>
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<td>19%</td>
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<td>96%</td>
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Table 2 (continued)

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<th>Sampling type</th>
<th>Months of operation</th>
<th>Raw wastewater</th>
<th>Vertical reed bed (1.2–1.3 m²/PE) 1st stage effluent</th>
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<td>780</td>
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</table>

G = grab samples, 24 h = flow composite samples, PE = population equivalent, hydraulic and organic loads are expressed as a percentage of design capacity: around 0.12 m³/m² d and 50 gBOD/m² d for the first stage, 0.2 m³/m² d and 5 gBOD/m² d for the second stage, *collected during rain.
carries some stormwater or infiltration water even with a separate sewer system. Nevertheless, for combined sewer systems or partially-separate systems, the hydraulic load could be controlled by a stormwater overflow or a regulation system if there is a pumping station.

No significant differences can be observed between performances measured in winter and in summer, nor between WTPs located in the north or south of France, in spite of wide variations of temperatures in the French temperate climate.

It should be noted that the performances presented in this paper were obtained with an optimal operation and maintenance, particularly the feeding mode with alternative resting periods and the well functioning of the batch feeding. The self-priming siphon should be regularly checked and washed (especially the first siphon receiving raw wastewater). Its malfunction leads to continuous feeding and poor distribution of influent over the surface, that significantly reduces removal performance. Moreover, the efficiency of the first stage was optimum when organic deposits accumulated on the surface of the filters. On the one hand, this “clogging layer” favours the distribution of the influent on the entire surface and slows down the infiltration, and on the other hand it constitutes an active zone for filtration and biological degradation with attached micro-organisms. To accelerate the start up of the reed beds, some WTPs were first fed with septage from individual septic tanks. The experiment conducted at St Honorine la Guillaume (61) and Thales (45) showed good results with a septage layer around 5 cm over the surface. This operation also accelerated the growing of reeds.

To enhance the efficiency of total nitrogen removal and reduce the high concentration of nitrate in the final effluent, it would be interesting to replace the second vertical sand filter by a horizontal filter. As underlined by Cooper (1999), and Platzer (1999), there is a growing interest in combined or hybrid systems. Indeed, reed beds with horizontal flow and continuous feeding can provide denitrification because of the low oxygen transfer capacity. Following a vertical system, horizontal filters could achieve more than 50% denitrification, despite the relatively low concentration of BOD. Moreover, this solution could be cheaper when the natural ground profile provides insufficient slope for two vertical stages fed with self-priming siphons, thus requiring an electric pumping system. Already several WTPs have been built in France under the design model: VRB + HF, but insufficient results are available as yet.

### Treatment of septage

The results obtained at Beaumont-la-Ronce, for complete treatment of faecal sludge evacuated from on-site sanitation are shown in Table 4. Raw septage characteristics showed a typical high variability with SS content between 13500 and 58000 mg/l. The high ratio COD/BOD between 3 and 5 showed the low biodegradability of faecal sludge because of the high residence times in septic tanks (sludge emptying recommended after 4 years operation), so that the easily biodegradable fraction was mostly already decomposed.

<table>
<thead>
<tr>
<th>Table 3 Mean removal efficiency (minimum–maximum) calculated from concentrations</th>
<th>Parameters</th>
<th>SS</th>
<th>BOD</th>
<th>COD</th>
<th>TKN</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st stage – vertical reed bed</td>
<td>94% (86–99)</td>
<td>88% (80–97)</td>
<td>69% (44–84)</td>
<td>31% (— 14–78)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd stage – vertical sand filter</td>
<td>59% (0–93)</td>
<td>77% (41–97)</td>
<td>52% (10–76)</td>
<td>78% (16–92)</td>
<td>5% (— 39–34)</td>
<td></td>
</tr>
<tr>
<td>1st + 2nd stage</td>
<td>96% (90–99.6%)</td>
<td>98% (97–99.7)</td>
<td>92% (82–98)</td>
<td>91% (66–98)</td>
<td>43% (9–76)</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 Results obtained at Beaumont-la-Ronce for the treatment of raw septage with vertical reed bed (VRB) + vertical sand filter (VSF)

<table>
<thead>
<tr>
<th>Effluent concentrations (mg/l)</th>
<th>Percentage removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw septage</td>
<td>1st stage VRB</td>
</tr>
<tr>
<td>SS</td>
<td>27 887 (13500-58000)</td>
</tr>
<tr>
<td>BOD₅</td>
<td>7 955 (5120-13300)</td>
</tr>
<tr>
<td>COD</td>
<td>32 954 (18780-58200)</td>
</tr>
<tr>
<td>NTK</td>
<td>1 142 (466-1960)</td>
</tr>
<tr>
<td>N-NO₃</td>
<td>13 (0-34)</td>
</tr>
<tr>
<td>PT</td>
<td>360 (55-1270)</td>
</tr>
</tbody>
</table>

Mean data (minimum–maximum) with n = 6–8, sampling between February 2001 and April 2004.
The first stage vertical reed bed permitted high removal performances with means of 99% for SS, 98.5% for BOD, 98.5% for COD, 94% for TKN and 94% for TP. These very good performances can be explained by biological degradation, but especially by filtering mechanisms enhanced by the accumulation of solids that allows sustained filtering without clogging while the stems and root system secures the continuous permeability of the filter. The quality of the first stage percolate was better than that obtained by Kooštatep et al. (2002), with constructed wetlands planted with Typha and operated at higher loading rate (250 kgTS/m² year) in a tropical climate.

Phragmites australis showed a high growth rate as soon as the first year operation, and was not sensitive towards anaerobic digested sludge with low redox potential and high ammonia content. This was certainly due to the drainage with vent pipes and intermittent feeding that allowed aeration of the bottom for aerobic conditions prevailing in the roots and rhizomes zone (proved by the presence of nitrification).

The second stage vertical reed bed sand filter improved removal of SS, BOD, COD and TKN. The effluent was then discharged into a large pond (4165 m²) to complete the treatment to comply effluent standards. Note that the relatively high concentrations of COD in the effluent corresponded to a hard undegradable fraction, estimated to be around 30% of septage percolate by CEMAGREF (2004), with a little foreseeable impact on the environment.

The accumulated sludge measured in both sites are shown in Table 5. The accumulation rate was much higher in Athée-sur-Cher and the dry solids content was lower, explained by the high surface loading rate of 109 kgSS/m² year, much higher than 50 kgTS/m² year recommended for sludge treatment on temperate climate (Nielsen, 2003). Moreover, the number of 3 basins is insufficient for an optimum rotation mode with long resting periods (cf. Table 1). The usefulness of chemical pre-treatment was not demonstrated. The good results obtained in Beaumont-la-Ronce without pre-treatment proved the efficiency of reed beds for complete septage treatment (solid and liquid fraction), with a surface loading rate of 46 kgSS/m² year. After 3 years operation, the dry solids content of stabilized sludge reached a dry solid content of 38%.

Conclusions
The results performed on 20 WTPs for domestic wastewater in France, after 4 to 57 months of operation, showed that:

1. The first stage vertical reed bed permits a high removal of SS, BOD and COD (mean respectively 96%, 98% and 92%).
2. The second stage vertical sand filter easily reaches the French effluent standards of SS < 15 mg/l, BOD < 15 mg/l, COD < 90 mg/l and TKN < 10 mg/l but with some peaks < 20 mg/l.
3. The performances were not influenced by variations of organic and hydraulic load (between 20% and 330% of design capacity), nor by seasonal variations.

Table 5 Measurements of accumulated sludge layer and dry solids content in both sites for septage treatment, performed in January 2004

<table>
<thead>
<tr>
<th></th>
<th>Beaumont-la-Ronce</th>
<th>Athée-sur-Cher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Months of operation</td>
<td>34</td>
<td>20</td>
</tr>
<tr>
<td>Mean depth of accumulated sludge (cm)</td>
<td>18</td>
<td>60</td>
</tr>
<tr>
<td>Mean dry solid content</td>
<td>38%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Rigorous operation and maintenance is required to obtain optimal performances. To lower the concentration of nitrate in the final effluent, the second vertical stage could be replaced by an horizontal filter that could achieve some denitrification.

The results obtained in two sites for faecal sludge treatment operated for 2 and 3 years demonstrated the reliability of vertical reed-beds filter (fed with raw septage without chemical pre-treatment) that could achieve complete treatment of septage (solid and liquid fraction). A surface loading of 50 kgSS/m²/year with a number of 6 basins appeared to be a good design.

References


