Performance assessment of a vertical flow constructed wetland treating unsettled combined sewer overflow
T. G. Pálfy, M. Gerodolle, R. Gourdon, D. Meyer, S. Troesch and P. Molle

ABSTRACT
The performance of a vertical flow constructed wetland for combined sewer overflow treatment (CSO CW) has been evaluated. The full-scale site has been monitored for 3 years for major pollutants and for two load events for a range of micropollutants (metals, metalloids and polycyclic aromatic hydrocarbons (PAHs)). Performance were predominantly high (97% for total suspended solids (TSS), 80% for chemical oxygen demand (COD), 72% for NH₄-N), even if several loads were extremely voluminous, pushing the filter to its limits. Two different filter materials (a 4:1 mixture of sand and zeolite and natural pozzolana) showed similar treatment performance. Furthermore, environmental factors were correlated with COD removal efficiency. The greatest influencers of COD removal efficiency were the inlet dissolved COD concentrations and the duration and potential evapotranspiration during inter-event periods. Furthermore, sludge was analysed for quality and a sludge depth map was created. The map, and calculating the changes in sludge volume, helped to understand solid accumulation dynamics.

Key words | combined sewer overflow, constructed wetland, CSO CW, micropollutant removal, sludge blanket

INTRODUCTION
Urbanization impacts waters greatly via elevating flood risks and pollution. Storm-generated urban runoffs increase in volume and cause hydraulic shocks in natural streams. Such runoffs carry pollutants as well, such as dry weather and atmospheric deposits (Chocat et al. 1994; Walsh et al. 2005). Mitigation measures have become not only an environmental but also a regulatory concern and a social need. Decision makers and stakeholders face a challenge to achieve a good ecological status of waters, as defined in the European Water Framework Directive (2000/60/CE).

Urban runoff and sewage are often collected in combined sewers and mix with parasitic waters (e.g. infiltration/ inflow). These waters cause physical, chemical and ecological degradation of the natural environment (Angerville 2009). Pollution takes effect due to the overflow mechanisms (combined sewer overflow (CSO)), which is allowed to limit flows to the capacity of sewer pipes or that of the wastewater treatment plant. Pollutant concentrations in a CSO are comparable to or greater than in sewage regarding metals and total suspended solids (TSS) (Dembélé et al. 2009). Furthermore, CSO means a shock-like pollution due to organics and nutrients, notably ammonia with acute toxicity.

To deal with these problems, municipalities are required to implement management strategies. Common solutions are tanks for settling and storage or network separation, but the economic implications of these are often major and benefits may be partial. Consequently, there is a real development need for alternatives such as constructed wetlands (Dittmer 2006).

Constructed wetlands for combined sewer overflow treatment (CSO CWs) are cost-efficient and can reduce or reverse degradation of streams by buffering hydraulic loads, filtering suspended solids, and retaining a large proportion of organics and nutrients (Uhl & Dittmer 2005; Frechen et al. 2006; Dittmer & Schmitt 2011).

CSO CWs in France were inspired by retention soil filters (vertical flow filters treating CSO tank overflows in Germany, Uhl & Dittmer 2005) and by ‘French design’ CWs treating raw municipal wastewater (Molle et al. 2005). The new technology has several innovations such as: (i) coarser media allows feeding without pre-treatment (eliminating the CSO tank and minimizing sludge management); (ii) a permanently saturated bottom zone mitigates water stress during extended dry periods; (iii) aeration...
pipes are at an elevated position above the permanently saturated layer; (iv) zeolite is added to the filter media if high ammonium removal is needed, and (v) the wetland is separated into two twin filter sides, enabling alternated operation and quicker regeneration of the secondary side (mineralization of organics) (Meyer et al. 2013).

The full-scale facility at Marcy-L’Etoile is the first to have these innovations. The main goal of this study is to assess the performance of the system according to three criteria: filter hydraulics, treatment efficiency (major pollutants and micropollutants) and pollutant accumulation and retention in the sludge. Another objective is to understand the impact of environmental factors on the removal; for example, that of the temperature and length of inter-event (unloaded) periods. The final aim is, subsequently, to provide data for the optimization of CSO CWs by testing system limitations.

**MATERIALS AND METHODS**

**The studied CSO CW**

Figure 1 shows the layout of the full-scale CSO CW at Marcy-L’Etoile. Discharged from the sewer [1], the flow reaches the filter through a 20 m\(^3\) sand and grease trap [2] and a Venturi channel [3]. The wastewater is loaded on the primary filter, which can be selected from F1 (253 m\(^2\)) and F2 (245 m\(^2\)) by a splitter [4]. The kinetic energy of the water is mitigated by gabions below the inlet points [5] to avoid the remobilization of the filter material. The filter media in the two sides differs for research purposes: F1 has a mixture of sand and zeolite and F2 has pozzolana (Figure 2). The infiltrated water is collected by a drain network. The detention time in the media is regulated by outflow orifices, which are the single effluent points at both sides [6]. Their vertical position sets permanent saturation within the drainage layer. Extreme events might cause overflows through a trapezoid weir [7] at the rim of the 2.1 m deep basin.

The design load is the event volume, which the CSO CW needs to detain and treat effectively. It was set by the water authorities to 1,160 m\(^3\), which equals a 2.3 m\(^3\)/m\(^2\)/event. The targeted annual hydraulic load was 40 m\(^3\)/m\(^2\)/year when the filter was scaled. Some events of the presented experiments were particularly big (above 2.3 m\(^3\)/m\(^2\)) to see the limitations of the system.

**Monitoring campaign**

**Campaign overview**

The site at Marcy-L’Etoile started operation in 2012. The presented results are based on a campaign that lasted from spring 2013 to spring 2016. Thirty-one events were monitored to gain information on performance. Most feedings were manually induced, taking advantage of the frequent and high-rate industrial releases into the sewer. The two filters were alternated seldom, to track potential clogging effects (Figure 3). The median rest period lasted for 14.6 days. Filter temperatures ranged roughly between five and 25 Celsius.

**Hydraulic monitoring**

A piezometric probe measured water level in both filter side and in the outlet structure. Furthermore, flow rates were measured by:

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**Figure 1** | The layout of the CSO CW at Marcy-L’Etoile.

**Figure 2** | Cross-section of the CSO CW at Marcy-L’Etoile. Note the different filter materials in F1 and F2 (sand and zeolite and pozzolana, respectively).
ultrasonic probe (Aqualyse AquaVenturi, 9.5/1,000 m³/h) in a Venturi channel (inlet);

- inductive flow meter (Krohne Waterflux 3070), and later by a calibrated pressure head – orifice flow correlation by filter side (outlet).

Major pollutants monitoring

Three automatic samplers were installed (two Lange Bühler 2000/1027 and an ISCO 3700R). Samples were flow composite at the inlet. At the outlet, filter sides were sampled time composite from a nearly constant flow rate. Each sampler held 24 sampling bottles with a volume of 1 L. The filling of each bottle took four to ten samples (depending on the campaign, up to 4 hours). Historical in- and outflow rates could be viewed on-site, which helped to mix bottles that belonged to similar flow patterns (e.g. water from the highest flow rate at the inlet, first samples from the outflow). The samples were kept refrigerated in the samplers at 4 °C and then fetched for laboratory analysis in portable ice chests. Furthermore, two online probes (WTW Varion) were placed in the outlet structure to monitor NH₄-N and NO₃-N concentrations. Some events were sampled only for mixed water from the two filter sides. Major pollutants have been studied in 30 campaigns. Samples were analysed for TSS, total chemical oxygen demand (COD_tot), dissolved COD (COD_S), particulate COD (COD_X), NH₄-N, NO₃-N and PO₄-P, following Standard Methods (APHA 2005). Performance was analysed according to filter side priority and filter material. The particulate and dissolved COD fractions were separated by filtration (0.7 µm glass fiber filter).

Several factors impact removal performance, e.g. the load of the previous event or temperature. In the case of NH₄-N and PO₄-P, mechanisms are well understood. These are (i) adsorption and nitrification and (ii) adsorption and progressive saturation of adsorption sites, for the two pollutants, respectively. However, COD removal has not been analysed before in CSO CWs receiving unsettled flows. Therefore a principal component analysis (PCA) has been carried out, followed by the setup of a multivariable linear model to reach quantitative predictions that can deal with factor interactions.

The selected parameters for the PCA were: (i) total COD load of the previous event, (ii) the duration of the preceding inter-event, (iii) potential evapotranspiration (PET) during the inter-event, (iv) the soil and air temperature of the inter-event, (v) the inflow for the considered event, (vi) COD concentrations.

Micropollutants monitoring

Outflows were sampled by filter side. The methods of Choubert et al. (2011) were followed. Each automatic sampler was equipped with a single 16 L glass container. Sampling tubes were changed to stiff Teflon (polytetrafluoroethylene) tubes. Samples were collected and transported in PE bottles (analysis for metals and metalloids) and in glass containers (analysis for polycyclic aromatic hydrocarbons, PAHs).

Materials were cleaned following the procedure as described below (where applicable):

- washing with tap water and scrubbing to remove potential deposits, then washing with acetone
- washing in a machine with hot water and basic then acidic solutions and finally washing with demineralized water
- washing with ultra-pure acetone and acetone evaporation under an extractor hood
- rinsing on-site with inflow/effluent.

The three sampling campaigns were 2 days long each. Two sampled the start of two events whilst the third sampled the end of the second one. Both events represented extreme loads. Samples were analysed for 25 metals and metalloids (ICP-MS) and 18 PAHs (HPLC). Removal rate was defined if the inlet concentration exceeded at least five times the quantification limit (QL). At the outlet, if concentrations did not reach the QL, removal efficiency was calculated using the half-concentration of the QL.

Monitoring of sludge depth and micropollutants

The sampling followed the protocol described in Alaphilippe et al. (2011). Along three diagonals, sampling points were set after every two metres, yielding around 30 points by side (Figure 4).
One campaign targeted sludge quality. Samples were taken using a glass jar, removing all sludge down to the compost at each point. Then, the samples were mixed with a stainless spoon in a glass bowl.

Sludge depths were recorded after two consecutive events that brought extreme solids loads, 6 days after the feeding was over. Loads were separated by a 1-month inter-event. Depths were interpolated for the whole surface (Figure 4) using the software Q-Gis® for inverse distance weighting (IDW, power parameter $P = 6$).

RESULTS

Hydraulic loads

The two filter sides were alternated irregularly and received slightly different hydraulic loads, as shown on Table 1.

In the first year of monitoring, the filter received 62% of the targeted annual hydraulic load of 40 m$^3$/m$^2$/year. This could impact filter performance. However, the low load was due to a single unloaded period, so an important effect is unlikely. In the following 2 years, annual loads were normal with 95% and 104% (second and third year, respectively).

Major pollutants

Global performance of the whole filter

Hydraulic and pollutant loads were stochastic (normal for a CSO). Mass removal was calculated for major pollutants (Figure 5): TSS, total, dissolved and particulate COD (COD$_{tot}$, COD$_S$ and COD$_X$, respectively), and ammonium nitrogen (NH$_4$-N). Nitrate nitrogen (NO$_3$-N) and phosphate (PO$_4$-P) were studied, but these are not targeted by current CSO CW design.

TSS: High and stable removal rates were obtained (median: 96% with SD = 2.9), and outlet concentrations stayed around 10 mg/L. This result is consistent with other studies, e.g. Dittmer (2006) and Amaral et al. (2013).

COD: The removal rate (79%) was slightly lower than in CWs with a CSO tank (90%, Masi et al. 2017). Filtration was the dominant removal process and as such, higher inflow concentrations improved efficiencies (see also section ‘Influential factors for performance’). Low inlet concentrations led to low removal. A background concentration had already been described by Dittmer & Schmitt (2011), as the metabolic residue and inert COD from sediment mineralization. Furthermore, when separating the dissolved phase (COD$_S$) from the particulate phase (COD$_X$), dissolved COD removal is less efficient (37%). This is congruent with experiences from German Retention Soil Filters (RSFs or Retentionsbodenfiltern) (42%, Dittmer & Schmitt 2011).

NH$_4$-N: Inflow concentrations were expected of up to 9.9 mg/L for CSO (Gasperi et al. 2012). Measurements showed sometimes higher values (median: 13.8 mg/L EMC$_{in}$), because the industrial release contained slightly higher loads than typical stormwater. Removal performance was high (median: 72%), even if this includes also many loads above the design volume (1,160 m$^3$, which the wetland had to treat efficiently).

NO$_3$-N: Removal was not an aim. Measurements helped to follow nitrogen-related processes. Inlet concentrations were high due to industrial discharges. Effluent peaks were caused by the flush of nitrified ammonium. There was no sign of de-nitrification.

PO$_4$-P: Removal was negligible (8%) and often negative. However, total phosphorous was sampled for a low number of events where removal ranged around 45–75% ($N = 2$) in the second year of the analysis, with organic P concentrations below QL (i.e., only PO$_4$-P was detected). This indicates that organic P accumulates in the sludge, probably by filtration.

Table 1 | Hydraulic loads by filter side at the CSO CW at Marcy-L’Etoile. S: side with sand and zeolite; P: side with pozzolana

<table>
<thead>
<tr>
<th>Year</th>
<th>Events sampled</th>
<th>Filter material</th>
<th>Hydraulic load by event [m$^3$/m$^2$]</th>
<th>Total annual load (m$^3$/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Year 1</td>
<td>8</td>
<td>S</td>
<td>1.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Year 2</td>
<td>9</td>
<td>P</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Year 3</td>
<td>14</td>
<td>S</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 4 | Sludge sampling paths. Note that compost was avoided to be taken with the samples (bottom left corner).
Filter side comparison

The primary filter receives most solids due to sedimentation in the ponding water. Water in the secondary filter had only about 15% of inlet TSS concentration. This means that calculating the hydraulic load by filter side is not a good predictor of aging-related processes, because the solids that add to the sludge blanket are unevenly distributed between the primary and secondary filters. 

Regarding the two filter materials, differences were anticipated in dissolved pollutant removal due to different adsorption capacities and environments for biofilm development. Performance was determined for the sand and zeolite mixture and pozzolana (Figure 6). However, both for events below and above design load, the two filters performed well (p_value = 0.42, Student test). Pozzolana is a natural material, and shows differences in adsorption capacities depending on the region of origin. However, it has to be highlighted that the thickness of the active media for NH₄-N adsorption was 0.12 m zeolite against 0.60 m pozzolana. Pozzolana might offer a competitive alternative to the sand and zeolite mixture in certain cases (when available locally).

Performance below and above the design load

For solids and organics, mass removal performance stayed stable with p_value = 0.51 (Figure 7). An exception was dissolved COD (COD_S) with an apparent performance drop.

In the case of nutrients, extreme loads impacted performance after high inflow volumes (Figure 8). Median mass removal lowered by 23% and 14% for ammonium and phosphorous, respectively.

Influential factors for performance

Environmental conditions affect biomass both inter- and intra-event. The PCA showed COD removal variability according to several parameters, as shown by Figure 9. The plane defined by F1 and F2 explained 62.5% of the total variance in the dataset. The duration and the cumulative PET of the inter-event as well as the inlet COD_S concentration impacted outlet total COD concentration. A multiple linear regression was set (Equation (1)), leading to a fit shown on Figure 10.

\[
\text{COD}_{\text{out}} = 0.19 \text{Duration} + 0.21 \text{COD_S} + 0.10 \text{PET} + 23.56
\] (1)
Figure 7 | In-and outlet EMCs and median mass removal performance ($\eta$) for solids and organics by load. Left: events below, and right, events above the design load (2.3 m). N: number of events.

Figure 8 | In-and outlet EMCs and median mass removal performance ($\eta$) for nutrients by load. Left: events below, and right, events above the design load (2.3 m). N: number of events.

Figure 9 | Principal components (PC) explaining the variability of COD outlet concentrations, based on 24 events. Focusing on the left panel, the analysis highlighted the influence of inflow dissolved COD concentrations and the sum of potential evapotranspiration (PET). Inter-event duration (expressed in days) was marked as less influential, but eventually it is shown to take effect through PET (expressed in mm for the whole inter-event duration).
where Duration is the length of the inter-event expressed in days and PET is the cumulative value of PET in millimetres for the whole inter-event.

**Micropollutants**

**Metals and metalloids**

A group of 25 metals and metalloids was studied in dissolved and particulate phases (Table 2). Of these, cadmium, nickel and lead are ‘priority substances’ by the EU Water Framework Directive (2000/60/EC). An Environmental Quality Standard (EQS) sets a concentration limit for the receiving water that should be abided, after discharge (immission). Concentrations are 0.08–0.25 µg/L, 4 µg/L and 1.2 µg/L for Cd, Ni and Pb, respectively.

In storm-generated flows (third campaign, end of feeding), most metals were bound with particles. This is in accordance with Dembélé et al. (2009), who found particulate forms representing 55–85% of the total from a similar residential catchment. Compared to a wet weather discharge study covering explicitly urbanized areas (Becouze-Lareure et al. 2016), concentrations were low. Concerning removal efficiency (Table 3), four compounds have good performance both at the beginning and at the end of the event: Al, Ti, Cr and Ba. For five others (Mn, Fe, Cu, Zn, Sr), release was observed at the beginning of the feeding, whilst removal efficiencies were improved (some up to 90%) after extreme load volumes passed the filter. Priority substances (Ni and Pb) were not quantified at the beginning of the event. The explanation of system behaviour will need further research. Focus should be given to the detailed composite sampling of regular events, with pH and possibly redox measurements.

**PAHs**

PAHs primarily exist adsorbed to soil particles due to their chemical properties (Prabhukumar & Pagilla 2010). Mean total PAH concentration was about 1.3 µg/L, mostly bound to particulates. This is lower than concentrations found in highway runoff, reported to be 3–5 µg/L by Terzakis et al. (2008) and similar to residential area runoff, reported to be 1.2 µg/L by Ruban et al. (2005). Compounds are listed in Table 4. Inflow PAHs were above five times the QL (and analysed) only for three pollutants. Removal

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**Table 2** | Inlet metal and metalloid concentrations at Marcy-L’Etoile. ‘’’ below QL

<table>
<thead>
<tr>
<th></th>
<th>Dissolved (µg/L)</th>
<th>Particulate (µg/L)</th>
<th>Dissolved (µg/L)</th>
<th>Particulate (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Li</td>
<td>–</td>
<td>–</td>
<td>8.3</td>
<td>0.7</td>
</tr>
<tr>
<td>B</td>
<td>–</td>
<td>–</td>
<td>73.6</td>
<td>8.0</td>
</tr>
<tr>
<td>Al</td>
<td>424.7</td>
<td>302.9</td>
<td>12.2</td>
<td>–</td>
</tr>
<tr>
<td>Ti</td>
<td>14.3</td>
<td>–</td>
<td>2.0</td>
<td>–</td>
</tr>
<tr>
<td>V</td>
<td>–</td>
<td>–</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Cr</td>
<td>4.2</td>
<td>3.6</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Mn</td>
<td>14.2</td>
<td>12.9</td>
<td>17.2</td>
<td>6.5</td>
</tr>
<tr>
<td>Fe</td>
<td>394.8</td>
<td>247.5</td>
<td>63.6</td>
<td>9.3</td>
</tr>
<tr>
<td>Co</td>
<td>–</td>
<td>–</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Ni</td>
<td>–</td>
<td>–</td>
<td>5.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Cu</td>
<td>24.7</td>
<td>19.3</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Zn</td>
<td>54.4</td>
<td>44.7</td>
<td>54.6</td>
<td>13.0</td>
</tr>
<tr>
<td>As</td>
<td>–</td>
<td>–</td>
<td>2.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>
efficiencies were calculated only for these as shown in Figure 11.

Seven PAHs are considered as priority substances in the Water Framework Directive (Table 5). Many high-molecular-weight PAHs (benzo (b) fluoranthene, benzo (a) pyrene, benzo (k) fluoranthene, benzo (g,h,i) perylene) are known or suspected carcinogens, and many low-molecular-weight PAHs (naphthalene, anthracene: high solubility and volatility) are acutely toxic to aquatic organisms (Smith et al. 2000). None of these seven substances exceeded their EQS, not even in the effluent water.

### Sludge

#### Sludge blanket

The campaign followed 3 years of operation, during which F1 and F2 received 82.5 and 102.3 m³/m² of water, respectively, and with switched priority. Sludge maps (Figure 12) show inhomogeneous distribution: sludge is thicker close to the inlet and absent from the other end of the filter.

The sludge volume after 3 years was 24 m³ in F1 and 26 m³ in F2 (Figure 13). If this sludge had been uniformly distributed, this would correspond to 3.2 cm/year accumulation in F1 and 3.5 cm/year in F2. The values correspond to about 0.35 mm of sludge for one m³/m² of hydraulic load, but this may vary between different CSO sites.
The change of sludge volume between the two campaigns explains short term functioning with regards to filter priority and regeneration. The imposed load on the whole filter was extremely high: about 12 m$^3$/m$^2$ of water, corresponding to around 6 months of normal operation. However, settled water carries only about 15% of TSS, therefore the solid load is equivalent to what a single sided-filter had received from about 22 m$^3$/m$^2$ of hydraulic load for F1 (primary side, inlet flow) and only 2 m$^3$/m$^2$ for F2 (secondary side, cross-connection flow only). The increase of sludge volume in F1 was 4.8 m$^3$. By contrast, decrease was 2.1 m$^3$ in F2.

Concerning distribution, sludge settled in a semi-circle: more concentrated close to the inlet, less near the middle of the filter. Close to F1 inlet, sludge depth grew by 21%.

**Dry and organic matter content**

To better understand sludge accumulation and decomposition dynamics, dry and volatile matter contents are crucial parameters. Sludge sampling imposed an idea about mineralization in a mature filter. Figure 14 shows that sludge on F1 contained more water than F2 and had higher volatile matter content (6 days after the 8 m$^3$/m$^2$ load). This is consistent with previous observations: inlet water contains an important amount of fresh organic matter (OM) which settles quickly on F1, but the secondary filter (F2) wears a more mature blanket.

According to Molle et al. (2005), sludge mineralization is governed by drying and the OM content, which is degradable. OM in the sludge of mature CWs treating municipal wastewater is between 30 and 50%. At Marcy-L’Etoile, this value ranged around 30–40%.

**Sludge and micropollutants**

Samples were analyzed for metals and metalloids and PAHs. Concerning PAHs, 11 of the 18 analyzed substances were detected (Figure 15). Except for naphthalene, the detected PAHs are very hydrophobic: their solubility in water is low and their octanol/water partition coefficients (log Kow) are between 4.46 and 6.78 (Nagpal 1995). This indicates a potential for adsorption on suspended matter and, consequently, their presence in any sludge.

For metals and metalloids, 25 substances were analysed (Figure 16). Rb, Sb, Se, Tl and U remained below the detection limit.
Compared to the thresholds posed by French regulation concerning wastewater sludge recovery (Table 6), sludge at Marcy-L’Etoile could be used for manuring or composting. However, most overflows the filter received were dominated by industrial release instead of stormwater; therefore, no general conclusion is drawn here about the safety of the use of CSO CW sludge in agricultural practice.

### Table 6 | French regulation for 3 PAHs and 6 metals concerning sludge recovery compared to the values found at Marcy-L’Etoile

<table>
<thead>
<tr>
<th>Water quality constituent</th>
<th>Limit values (mg/kg DM)</th>
<th>Mean values (mg/kg DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoranthene</td>
<td>5.0</td>
<td>0.20</td>
</tr>
<tr>
<td>Benzo(b)fluoranthene</td>
<td>2.5</td>
<td>0.09</td>
</tr>
<tr>
<td>Benzo(a)pyrene</td>
<td>2.0</td>
<td>0.07</td>
</tr>
<tr>
<td>Cd</td>
<td>10</td>
<td>0.67</td>
</tr>
<tr>
<td>Cr</td>
<td>1,000</td>
<td>38.1</td>
</tr>
<tr>
<td>Cu</td>
<td>1,000</td>
<td>181.6</td>
</tr>
<tr>
<td>Ni</td>
<td>200</td>
<td>43.3</td>
</tr>
<tr>
<td>Pb</td>
<td>800</td>
<td>19.4</td>
</tr>
<tr>
<td>Zn</td>
<td>3,000</td>
<td>361.5</td>
</tr>
<tr>
<td>Cr + Cu + Ni + Zn</td>
<td>4,000</td>
<td>643.9</td>
</tr>
</tbody>
</table>

### CONCLUSIONS AND OUTLOOK

French-type vertical flow CSO CWs perform well and have proven to be robust in removing major pollutants. Mass removal during events below the design load (2.3 m$^3$/m$^2$) was 97% for TSS, 80% for COD and 85% for NH$_4$-N. Performance drops were observed only at extreme volumes with a return period over 2 years (about 12 m$^3$/m$^2$ hydraulic load). However, as inter-event regeneration and intra-event removal cannot be separated, it is important that pollutant loads have to be in balance with the time available for regeneration. Otherwise filters will be prone to premature aging (clogging) and might perform below...
expectations, especially at cold temperatures (slow nitrification).

The comparison of the filter sides with different filter materials showed identically good removal efficiency for the sand and zeolite mixture and natural pozzolana. Pozzolana might be an alternative to sand and zeolite mixtures when locally available. According to filter priority, sludge accumulation was prominent close to the inlet of the primary filter. Sludge was absent at the cross connection (far from the inlet point). This means the cross-connection can be placed just over the filter surface if its location is far from the inlet. A low cross-connection level might enable frequent feeding on the secondary side and avoid drought stress on it, without compromising regeneration.

The analysis of COD removal performance confirms dependency on environmental parameters and on the concentration of the dissolved fraction in the inlet. Total outlet COD concentration can be calculated from dissolved inlet COD, inter-event duration and PET and a constant background concentration of the dissolved fraction in the inlet. Total outlet COD loads, with pH and possibly redox measurements.

The focus should be on detailed composite sampling of regular population number. The equation could be taken into account at the step of CSO CW dimensioning.

It was shown that CSO CWs remove effectively some micropollutants, both from the group of PAHs (benzo(a) pyrene, phenanthrene, naphthalene) and metals (Al, Ti, Cr and Ba). For Mn, Fe, Cu, Zn and Sr, higher outlet concentrations were observed at the beginning of the feedings. This might indicate the release of metals after solid mineralization in the inter-event periods. However, due to the low number of the analysed samples (N = 2–6), and the nature of the inflows (often an industrial release substituted the surface runoff part), a conclusion which is detailed and discusses the other metals and metalloids listed in this paper will need further research. The focus should be on detailed composite sampling of regular loads, with pH and possibly redox measurements.

REFERENCES


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