The role of SSVF and SSHF beds in concentrated wastewater treatment, design recommendation

M. Gajewska and H. Obarska-Pempkowiak

ABSTRACT

The return flows of reject water from sewage sludge dewatering alter the activated sludge process in a conventional WWTP and increase TN concentration in the final effluent from WWTP. The objective of the investigation carried out was to consider the application of multistage treatment wetland (MTW) for the treatment of reject water from sewage sludge dewatering in a centrifuge (RWC). This paper aims to present the design and performance of each stage of the treatment as well as the efficiency of total MTW. The full scale pilot plant for RWC, consisting of two vertical flow beds (SS VF) working in series, followed by an horizontal flow bed (SS HF), was built in 2008. The applied configuration ensured a very high removal efficiency of principal pollutant (COD – 76.0% and NH₄⁺-N – 93.6%). In the investigated facilities, the SS VF beds ensured an effective removal of nitrogen compounds, especially NH₄⁺-N, whereas the decomposition of hardly degradable Org-N and COD took place in SS HF. This research illustrates that the MTW could be successfully applied for the treatment of RWC.

INTRODUCTION

The most frequent sludge processing in a Wastewater Treatment Plant (WWTP) over 100,000 pe (person equivalent), covers a digestion process with biogas production and then mechanical dewatering, which generates highly polluted reject water (RW). The RW is characterized by a very high concentration of nitrogen, mainly in the form of NH₄⁺-N and organic matter as well as TSS. Another problem with RW management is connected with its irregular generation and a large fluctuation of pollutant concentrations, even from one WWTP (Janus & van der Roest 1997; Jeavons et al. 1998; Fux et al. 2002, 2003, 2006). In WWTPs with sewage sludge digestion, 15–20% of the nitrogen load is usually redirected with the RW. While the remaining COD after anaerobic digestion is generally quite low and poorly biodegradable, a separate treatment of the high nitrogen content in this stream can considerably reduce the total nitrogen concentration in the final effluent from WWTPs (Fux et al. 2005; Wett & Alex 2003; Fux et al. 2006; Gajewska & Obarska-Pempkowiak 2008).

The most promising way of handling reject water is to pre-treat it before it returns to the first stage of WWTP. High-tech solutions such as unconventional methods (ANAMMOX, SHARON, etc.), which are still very expensive, are usually applied. An alternative solution could be the application of Treatment Wetlands (TWs). TWs are successfully used to either treat or polish landfill leachate (which has similar properties as RW), which is inexpensive, simple in operation and has potential to remove not only organic carbon and nitrogen compounds, but xenobiotics and heavy metals as well (Peverly et al. 1995; Kowalik et al. 1996; Mæhlum 1998; Bulc 2006; Wojciechowska et al. 2010). Both surface and sub-surface flow (usually horizontal) TWs as well as those with several treatment stages with different flow conditions were applied in USA and Europe, including the temperate and sub-polar climate regions (Mæhlum 1998; Kozub & Liehr 1999; Rustige & Nolde 2007; Kinsley et al. 2007; Bulc 2006; Wojciechowska et al. 2010). The performance efficiency of the pilot TW for landfill leachate from Ljubljana (Slovenia) landfill site was investigated by Bulc (2006) within seven years of operation. The facilities, consisted of three interconnected beds with vertical and horizontal beds, covering 311 m² with intermittent
hydraulic load of 5 mm d⁻¹. It was indicated that removal efficiency for COD was 50%, BOD₅ = 59%, NH₄⁺-N = 51% and TP = 53% (Bulc 2006). Higher removal efficiency was demonstrated by Esvala Treatment Park which received landfill leachate from 5 ha landfill site near Oslo (Norway). Overall removal efficiency during the investigation carried out by Mæhlum (1998) was: for COD = 88%, BOD₅ = 91%, TN 83% and TP = 88%. Depending on pre-treatment and configuration of TWs applied for leachate treatment (in Poland and in Sweden) the removal of pollutants may vary for: COD from 5 to 66%, BOD₅ from 28 to 91% and NH₄⁺-N from 52 to 98% (Wojciechowska et al. 2010).

The objectives of the investigation carried out is to consider the application of sequential SS VF beds and an SS HF bed for the treatment of highly polluted wastewater, namely reject water from sewage sludge dewatering in a centrifuge (RWC). This paper aims to present the design and performance of each stage of the treatment as well as the total efficiency of pollutants removal.

**METHODS**

**Pilot treatment wetland – process design**

In 2008 a pilot TW was constructed in order to treat part of RWC at the municipal WWTP in Gdańsk. The design of the pilot TW was preceded by laboratory analyses of the RWC generated at the WWTP in Gdańsk (Obarska-Pempkowiak et al. 2010). The high variability of the concentrations of pollutants in time is characteristic for studied RWC (Gajewska & Obarska-Pempkowiak 2008). Maximum concentrations are often over 10 times higher than mean values, which substantially affects the median and standard deviations. The analysis of RWC composition indicate that the predominant pollutant is nitrogen, present mainly in the form of Kjeldahl nitrogen (ammonia + organic). Therefore, the assumption for the design of pilot treatment wetlands was that ammonia and organic nitrogen should be effectively removed. It was assumed that the pilot wetland would consist of two 1 m³ tanks working in series, where wastewater would be collected and equalized (Figure 1).

To investigate the role of SS VF and SS HF, it was decided that the pilot plant would consist of two SS VF beds and one SS HF (Figure 1). In order to design pilot SS VF-beds operating in a batch, it was assumed that the beds would treat the load of wastewater corresponding to 5 pe. The unit area of 2.5 m² pe⁻¹, and the daily pollutant loads of 120 g COD pe⁻¹ day⁻¹, 60 g TSS pe⁻¹ day⁻¹ and 12 g TN pe⁻¹ day⁻¹ were assumed and recalculated for the conditions of RWC (Table 1).

The filtration bed media was built with washed gravel with grain size between 4 and 8 mm and hydraulic conductivity of 4.2×10⁻² m s⁻¹. The beds were planted, in 2008, with Phragmites australis with 5 clumps per m² which was bought from special plantation (with well developed root zone system) to shorten the start-up period.
organics (BOD5 and COD), TSS and VSS (organic suspended solids on the basis of losses on ignition),

- nitrogen: total Kjeldahl nitrogen (TKN), ammonium ion and nitrates were analyzed.

Additionally, COD was analyzed after filtration (CODf) on a 0.45 μm pore size Millipore nitrocellulose filter.

Analyses were performed by independent laboratory (ISO certified) and all applied analytical procedures were in agreement with Polish Norms and guidelines given in the Polish Environmental Ministry Regulations of 24th July and 18th January 2009, and is comparable with APHA (2005) (Dziennik 2006). The cuvette test and analytical procedure recommended by Hach Chemical Company and Dr Lange GmbH was used for analysing COD, NH4+-N, NO3–-N. Biological Oxygen Demand was analysed by dilution method using OxiTop.

Removal efficiency was calculated as a concentration reduction according to the terminology frequently used in the literature (Kadlec & Knight 1996).

The results were evaluated using the StatSoft STATISTICA 8.0. The normality of variables was checked using the Shapiro-Wilk test with significance level α = 0.05. The data were distributed normally, for the predominant pollutants COD and TKN, within each separate year of sampling (2009 and 2010) (the summary of the tests parameters is provided in Table 2 below the RWC characteristic).

‘Box – and – Whiskers Plots’ have been chosen as a graphical interpretation of the statistical analysis. In applied graphical interpretation the box enclosed the middle 50%
Table 2 | continued

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (chamber I)</th>
<th>After chamber II</th>
<th>After SS VF I</th>
<th>After SS VF II</th>
<th>Effluent (After SS HF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD&lt;sub&gt;1&lt;/sub&gt;</td>
<td>734.9/720.3 ± 101.2</td>
<td>690.2/709.1 ± 99.3</td>
<td>443.7/421.4 ± 67.4</td>
<td>569.0/360.5 ± 61.3</td>
<td>209.2/210.4 ± 31.4</td>
</tr>
<tr>
<td></td>
<td>671.4 – 801.2</td>
<td>559.2 – 780.2</td>
<td>556.9 – 549.7</td>
<td>278.2 – 401.6</td>
<td>129.5 – 267.9</td>
</tr>
<tr>
<td>BOD&lt;sub&gt;3&lt;/sub&gt;</td>
<td>360.3/345.6 ± 65.3</td>
<td>295.2/298.1 ± 59.2</td>
<td>85.2/86.4 ± 18.2</td>
<td>51.0/50.2 ± 9.7</td>
<td>24.9/26.3 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>310.4 – 445.8</td>
<td>244.8 – 378.6</td>
<td>63.7 – 79.0</td>
<td>45.2 – 79.0</td>
<td>19.4 – 31.4</td>
</tr>
</tbody>
</table>

Influent – Shapiro-Wilk test for COD: \( W = 0.903 \) and \( p = 0.12 \) for TKN; \( W = 0.908 \) and \( p = 0.14 \)
after chamber II – Shapiro-Wilk test for COD: \( W = 0.909 \) and \( p = 0.33 \) for TKN; \( W = 0.912 \) and \( p = 0.38 \)

2010 \((n = 10)\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (chamber I)</th>
<th>After chamber II</th>
<th>After SS VF I</th>
<th>After SS VF II</th>
<th>Effluent (After SS HF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>546.1/526.4 ± 84.3</td>
<td>383.9/368.1 ± 67.4</td>
<td>161.6/151.2 ± 28.8</td>
<td>58.9/59.7 ± 10.3</td>
<td>26.2/24.9 ± 6.7</td>
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<tr>
<td></td>
<td>496 – 610</td>
<td>197.3 – 420</td>
<td>119.5 – 186.2</td>
<td>49.0 – 76.2</td>
<td>16.5 – 35.2</td>
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<tr>
<td>VSS</td>
<td>358/355.7 ± 66.4</td>
<td>193.3/194.8 ± 42.9</td>
<td>113.9/109.9 ± 26.6</td>
<td>40.7/44.3 ± 8.8</td>
<td>18.6/17.8 ± 7.7</td>
</tr>
<tr>
<td></td>
<td>246.3 – 420.3</td>
<td>117 – 252</td>
<td>80 – 152.6</td>
<td>34 – 60.2</td>
<td>14 – 30.5</td>
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<tr>
<td>TN</td>
<td>802.6/790.6 ± 51.1</td>
<td>647.7/643.9 ± 51.3</td>
<td>375.3/383.4 ± 42.5</td>
<td>269.6/268.1 ± 34.9</td>
<td>173/168.8 ± 21.1</td>
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<td></td>
<td>710.4 – 843.2</td>
<td>547.5 – 700.2</td>
<td>323.6 – 458.8</td>
<td>235.2 – 310.4</td>
<td>150.3 – 187.9</td>
</tr>
<tr>
<td>NH₄&lt;sup&gt;-N&lt;/sup&gt;</td>
<td>706.7/705.5 ± 33.7</td>
<td>573.2/586.54 ± 63.3</td>
<td>312.8/325.5 ± 39.8</td>
<td>217.2/210.6 ± 29.5</td>
<td>130.2/125.5 ± 20.2</td>
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<tr>
<td></td>
<td>640.6 – 730.5</td>
<td>509.3 – 675.4</td>
<td>270.4 – 389.3</td>
<td>165.3 – 247.8</td>
<td>100.2 – 154.6</td>
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<td>Org-N</td>
<td>95.5/93.1 ± 25.1</td>
<td>62.6/63.9 ± 21.7</td>
<td>51.4/55.2 ± 20.6</td>
<td>42.2/41.4 ± 17.1</td>
<td>31.5/34.8 ± 15.4</td>
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<td></td>
<td>54.9 – 122.5</td>
<td>21.5 – 88.8</td>
<td>18.5 – 84.2</td>
<td>15.1 – 73.9</td>
<td>13.2 – 66.9</td>
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<tr>
<td>NO₃&lt;sup&gt;-N&lt;/sup&gt;</td>
<td>0.3/0.4 ± 0.2</td>
<td>1.2/1.1 ± 0.2</td>
<td>2.4/2.4 ± 0.2</td>
<td>4.0/3.8 ± 0.2</td>
<td>6.0/5.5 ± 0.3</td>
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<td></td>
<td>0.2 – 0.4</td>
<td>0.9 – 1.5</td>
<td>1.5 – 3.3</td>
<td>3.0 – 5.0</td>
<td>4.2 – 8.3</td>
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<tr>
<td>COD</td>
<td>1,213.3/1,233.9 ± 87.4</td>
<td>987.5/978.3 ± 33.5</td>
<td>571.9/582.1 ± 33.9</td>
<td>421.6/440.7 ± 69.1</td>
<td>245.1/242.9 ± 29.5</td>
</tr>
<tr>
<td></td>
<td>1,093.9 – 1,400</td>
<td>899.2 – 1,008.2</td>
<td>528.4 – 640.4</td>
<td>348 – 500.2</td>
<td>183.6 – 267.3</td>
</tr>
<tr>
<td>COD&lt;sub&gt;1&lt;/sub&gt;</td>
<td>690.5/684.9 ± 47.3</td>
<td>578.2/584.5 ± 49.8</td>
<td>409.4/396.9 ± 28.1</td>
<td>188.6/186.5 ± 14.7</td>
<td>109.4/110.4 ± 12.6</td>
</tr>
<tr>
<td></td>
<td>601.8 – 712.6</td>
<td>521.5 – 670.6</td>
<td>350 – 458.2</td>
<td>170.3 – 223.7</td>
<td>90 – 134.6</td>
</tr>
<tr>
<td>BOD&lt;sub&gt;3&lt;/sub&gt;</td>
<td>435.7/429.1 ± 57.3</td>
<td>321.7/316.2 ± 29.4</td>
<td>50.3/54.7 ± 13.3</td>
<td>25.2/27.4 ± 7.2</td>
<td>18.6/18.0 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>320.4 – 500.7</td>
<td>270.8 – 346.2</td>
<td>40.2 – 65.2</td>
<td>21.3 – 32.1</td>
<td>10.6 – 25.4</td>
</tr>
</tbody>
</table>

Influent – Shapiro-Wilk test for COD: \( W = 0.915 \) and \( p = 0.36 \) for TKN; \( W = 0.923 \) and \( p = 0.44 \)
After chamber II – Shapiro-Wilk test COD: \( W = 0.956 \) and \( p = 0.66 \) for TKN; \( W = 0.940 \) and \( p = 0.58 \)

Significant differences in inlet concentrations of pollutants resulted from the improvements made in WWTP towards biogas production intensification. In the view of the RWC characteristic given above, the concentration of pollutants in studied pilot plant correspond very well to the data given by Janus & van der Roest (1997), Jeavons et al. (1998), and Fux et al. (2003, 2006).

The BOD<sub>3</sub>/COD and BOD<sub>3</sub>/TN ratios bring information about biodegradability, and they decrease with the decomposition process progress (Surnacz-Gór ska 2001). Additionally, in these studies BOD<sub>3</sub>/COD is presented as an indicator of easily degradable dissolved organic matter which is fundamental for effective removal of nitric nitrogen in denitrification process (Pagilla et al. 2008).

### RESULTS AND DISCUSSION

Influent concentration 2009 and 2010

The characteristic RWC, means with standard deviation and medians as well as the range with regard to studied parameters were shown for 2009 and 2010, separately (Table 2). (between 25 and 75% quartile) of the data, the median value is drawn as a small square inside the box. Vertical lines (whiskers) extending from each end of the box represent the range of not-outliers values. The dots represent outliers and the cross external values.
The BOD$_5$/COD ratio of RWC discharged to the first SS VF was 0.25–0.32, which is characteristic for mature landfill leachate (with a ratio of 0.5–0.3), where the easily biodegradable organics (BOD$_5$) have been already consumed (Surmacz-Górskaa 2001; Bulc 2006; Wojciechowska et al. 2010). Obtained in this study ratios were slightly higher than the one given by Fux et al. (2006), which was equal to 0.2 for the reject water from the WWTP in Minworth, Great Britain (Table 3). Furthermore low BOD$_5$/COD ratio reflects low degradability of the organic compounds as it is found in methanogenic sanitary landfill, characterized by low concentration of volatile fatty acids and relatively high concentration of humic compounds (Kjeldsen et al. 2002; Wojciechowska et al. 2010).

The BOD$_5$/TN ratio was equal to 0.37 and 0.54 in 2009 and 2010 respectively and the BOD$_5$/COD$_t$ varied from 0.48 to 0.51. The values of BOD$_5$/COD$_t$ confirmed that a half of the dissolved COD was in the form of easily degradable organic matter. Together with very low BOD$_5$/TN ratios can indicate that the content of easily degradable organics was probably not sufficient, due to very high content of NH$_4^+$/N for conventional pathways of nitrogen removal.

**Removal efficiency and effluent concentration**

Comparing the efficiency of pollutant removal in 2009 and 2010, only small improvements can be observed (up to 5%) in 2010 with the exception of Org-N and NH$_4^+$/N (Table 2 and Figure 2).

Since the values of pollutants concentration varied at the influent as well as effluent, the removal efficiency in subsequent stages fluctuated to great extent, which is clearly shown in Figure 2. The boxes between 25% and 75% quartile, which represented the removal efficiency e.g. in terms of Org-N, indicate both variation in time (in two years of investigation), as well as in subsequent stages of treatment process.

Operation of pilot TW, with regard to the study parameters, was not influenced by temperature, since the investigations were carried out only during vegetation season. In contrast to the information given in literature, in this study transpiration and precipitation did not influence significantly the entire system operation removal (Bulc 2006). Detail assumption of these processes in terms of studied pilot plant working condition were described by Obarska-Pempkowiak et al. (2010).

Although, the ratios (BOD$_5$/COD, BOD$_5$/TN and BOD$_5$/COD$_t$) seemed to be inadequate for biological treatment, a quite effective removal of pollutants was observed in the entire TW: over 96% for TSS and over 70% for COD. Since the BOD$_5$ removal efficiency was over 90.0% and the COD$_t$ removal was slightly lower than the COD removal, it can be assumed that part of particulate COD was transformed into easily biodegradable organic matter. During the treatment in the facility, the analysed ratios of BOD$_5$/COD, BOD$_5$/TN and BOD$_5$/COD$_t$ decreased significantly and were equal to 0.09 and 0.17 and 0.1 respectively in the effluent for 2009 (Table 3). Such low ratios of BOD$_5$/COD and BOD$_5$/COD$_t$ indicate the presence of organic matter in a hardly decomposable form (namely recalcitrant compounds). Although the BOD$_5$/TN ratio decreased significantly a very high nitrogen concentration was observed in the effluent. The main form of TN in the effluent was ammonia nitrogen, with concentration variations from 99.6 to 198.6 mg L$^{-1}$. The concentration of ammonia nitrogen in the raw sewage discharged to a WWTP usually do not exceed 90 mg L$^{-1}$, thus the return flow of RWC treated in the pilot TW should not cause any negative impact on the WWTP operation and final effluent quality.

**Subsequent stages removal efficiency**

The role of mechanical stage of the treatment was both equalizing and, most importantly, trapping the particulate during sedimentation (Table 2). The removal efficiency at ‘the sedimentation stage’ was equal to: 23.6% and 33.8% for TSS, and 23.8 and 44.1% for VSS. The most significant was the Org-N removal: 77.9% in 2009 and 50.2% in 2010. The organic matter removal in terms of COD was low in 2009 and equal 9.7% and increased in next year to 20.2%.

The discharging of RWC into the SS VF I resulted in the increased nitrate concentration thus the operation efficiency of both SS VF beds was negative in terms of nitrate. Both

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (after chamber I)</th>
<th>After chamber II</th>
<th>After SS VF I</th>
<th>After SS VF II</th>
<th>Effluent (after SS HF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>BOD$_5$/TN</td>
<td>0.37</td>
<td>0.41</td>
<td>0.21</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>BOD$_5$/COD</td>
<td>0.29</td>
<td>0.25</td>
<td>0.11</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>BOD$_5$/COD$_t$</td>
<td>0.48</td>
<td>0.42</td>
<td>0.21</td>
<td>0.14</td>
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<td>2010</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>BOD$_5$/TN</td>
<td>0.54</td>
<td>0.49</td>
<td>0.14</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>BOD$_5$/COD</td>
<td>0.35</td>
<td>0.32</td>
<td>0.09</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>BOD$_5$/COD$_t$</td>
<td>0.51</td>
<td>0.44</td>
<td>0.14</td>
<td>0.13</td>
<td>0.12</td>
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</table>
TSS and VSS were removed in SS VF I bed with effectiveness over 65.0%, and BOD$_5$ with over 70.0%, which were the highest during all the stages of the treatment. Similar findings were reported by Kayser et al. (2001), Molle et al. (2005) who investigated SS VF beds with intermittent loadings of wastewater. They found a especially good environment for the mineralization of organic compounds and oxidation of nitrogen compounds in these beds and...
assumed that during ‘resting’ periods, the accumulated organic matter was decomposed, which protects the beds against clogging. The half of demonstrated effectiveness varied from 42.1% to 52.3% in 2009, and from 40.9% to 49.0% in 2010 for the ammonium nitrogen (Figure 2). During the treatment in SS VF I, the analyzed ratios of BOD₅/COD, BOD₅/TN and BOD₅/COD₁ decreased rapidly up to 50% of their initial values, and were equal to: 0.09–0.11, 0.14–0.21 and 0.14–0.21 respectively (Table 3).

After SS VF II, the analysed ratios of BOD₅/COD, BOD₅/TN and BOD₅/COD₁ were similar to the initial ones, which can suggest that both organic matter and nitrogen were consumed proportionally.

In the case of SS HF the removal efficiency of COD was the highest and equal to 47.6% in 2009, and 44.8% in 2010. Similar very high NH₄⁺-N as well as Org-N reduction was observed which was accomplished with over 40% efficiency removal of TN at this stage of the treatment. According to many authors long retention time and anoxic condition in SS HF beds favour the degradation of hardly degradable organic matter and many toxic compounds such as THM, detergents or PAHs (Peverly et al. 1995; Kadlec & Knight 1996; Kadlec 2003; Weis et al. 2004). The results achieved in this study confirmed that SS HF bed was designated for suspended solids removal – over 60% in 2009 and over 70% in 2010. The average retention time of 10 days favours the decomposition of organic matter, even in the form of hardly degradable form. The efficiency removal of the investigated organic fraction was equal to: 44.2–47.2% for COD, 41.6–43.6% for COD₁, 47.6–55.3% for BOD.

The dimensioning and role of SS VF and SS HF beds

The application of a TW for concentrated wastewater treatment, especially RWC is quite a new attempt, that is why there is a lack of publications on the subject. Thus, the achieved results will be compared with the appropriate data for sewage and leachate treatment.

In the pilot plant TW, the SS VF stages were very effective in the TSS removal, 90.0% up to these stages, and further SS HF improved only about 7.0% to 97.0% for total treatment process (Table 2). The contribution of SS VF in nitrogen removal was the most crucial and the efficiency was over 72.0% and 85.9% after SS HF. About 50% of the discharged COD and about 85% of the BOD₂ were removed in the sequential SS VF beds. These findings are in accordance with data given by Mæhlum (1998) and Wojciechowska et al. (2010). While they are much better when comparing with removal efficiency reported by Bulc (2006) for TW with similar configuration working for landfill leachate in Slovenia.

In order to dimension the vertical stage, the assumption of 2.5 m² pe⁻¹ (after the load recalculation) was attempted. In the first stage, 60% of the total area was calculated, and 40% in the second one. According to Cooper et al. (1997), the unit area of SS VF bed designed for organic matter removal only should be about 1.0 m² pe⁻¹, whereas for efficient nitrification it should be over 2.0 m² pe⁻¹. According to Langergraber (2007), the effluents of one-stage SS VF beds in a unit area equal to 4 m² pe⁻¹ and organic matter load equal to 20 g m⁻² day⁻¹ can meet rigorous Austrian effluent standards (below 90 mg L⁻¹ of COD and 25 mg L⁻¹ of BOD₅), regardless of the season of a year and air temperature. For Molle et al. (2005), two sequential SS VF beds, periodically supplied with raw sewage, provide effective treatment to the following level: COD – 60 mg L⁻¹, TSS – 15 mg L⁻¹, Kjeldahl nitrogen – 8.0 mg L⁻¹. The treatment effectiveness of the analysed facilities working in the same way was very high: over 91.0% for COD, 95.0% for TSS and 85.0% for Kjeldahl nitrogen.

In the applied configuration, the last stage of the treatment was carried out in SS HF (0.78 m² pe⁻¹), which ensured the most effective removal of Org-N, nearly 40%, and almost 50% of COD, which at this stage of the treatment were present in a hardly degradable form. The operation efficiency of SS HF beds for landfill leachate is strongly dependant on hydraulic regime as it was indicated by Wojciechowska et al. (2010). Although working with the same medium SS HF beds showed different efficiency removal of pollutants since one of them was exposed to surface runoff. In the contrast to the findings presented by Bulc (2006), addition of surface runoff due to precipitation caused decrease of removal effectiveness up to 30% for organics and up to 15% for TN in case of SS HF beds investigated in Poland by Wojciechowska et al. (2010).

CONCLUSIONS

This research illustrates that the MTW could be successfully applied for the treatment of highly contaminated wastewater (reject water from centrifuge – RWC).

The applied configuration, of two SS VF beds working in series, followed by an SS HF, ensured a very high removal efficiency of predominant pollutants (COD – 76.0% and NH₄⁺-N – 93.6%). The surface runoff after precipitation event cannot contribute to the presented overall performance in virtue of the pilot TW being constructed above
ground. The unit processes responsible for pollutants reduction in the pilot TW are still under investigation.

However, during the studied period in the investigated facilities, the SS VF beds ensured an effective removal of nitrogen compounds, especially NH$_4^+$-N, whereas SS HF ensured a good environment for the decomposition of hardly degradable Org-N and COD.

The analyses of the achieved results proved that the sewage with a very low concentration of easily degradable organic matter like RWC (BOD$_5$/COD ratio 0.3) could be successfully treated in the MTW, and the ratio decreasing to 0.1 after the treatment. It can be assumed that the majority of the final COD concentration is due to the presence of recalcitrant substances.

The return flow of RWC treated in the pilot MTW did not cause any impact on WWTP operations and minimized the impact on the final effluent.

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