The effect of pre-aeration on the purification processes in the long-term performance of a horizontal subsurface flow constructed wetland

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Abstract

Different conditions (water level, oxygen supply) prevailing in both beds of the Kodijärve double-bed horizontal subsurface flow (HSSF) constructed wetland (CW) (Southern Estonia; constructed in 1996, total area 312.5 m², 40 pe) provide the opportunity to compare how different operational methods have altered the efficiency of the purification processes inside the HSSF CW. In summer 2002 a vertical subsurface flow (VSSF) CW (total area 37.4 m²) was added as the first stage of the system. Data from 18 sampling wells installed in Kodijärve HSSF CW from two periods is compared: 1st period — January 2000—April 2002 (before the VSSF CW was built); 2nd period — October 2002–December 2004 (after the construction of the VSSF filter). The VSSF CW has remarkably improved aerobic conditions in both beds of the HSSF. Apart from total phosphorus concentrations in the right bed and nitrate nitrogen concentrations in the outflow of both beds, all of the water quality indicators (dissolved oxygen, total suspended solids, biological oxygen demand, ammonia nitrogen, nitrite nitrogen, total nitrogen and total iron) improved after the construction of the VSSF filter. Typically, purification processes in the HSSF CW were dependent on oxygen supply, which was partly influenced by the water level inside the filter beds.

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1. Introduction

Design and operational principles determine the effectiveness of purification processes in a wastewater treatment plant. It is necessary to develop different operational standards and optimization methods for different types of wastewater and different types of constructed wetlands (CW). It is possible to compare results from different operational methods and detect which could be best by implementing somewhat different operational methods inside a CW.

The Kodijärve CW is located in Southern Estonia and was built to treat the wastewater of a hospital (40 pe). The double-bed horizontal subsurface flow (HSSF) filter (total area of 312.5 m²) of the Kodijärve CW system was constructed in 1996. In summer 2002 an intermittently loaded double-bed vertical subsurface flow (VSSF) wetland (total area of 37.4 m²) was added as the first stage of the system for pre-aeration and
enhancing aerobic processes in the system. The HSSF CW is 1 m deep and isolated from the subsoil with a polyethylene liner. The HSSF CW is covered predominantly with *Phragmites australis* and *Scirpus sylvaticus* (Mander et al., 2001). In last years *Urtica dioica* and *Epilobium hirsutum* have been dominating. Eighteen sampling wells (9 on each bed) were installed 90 cm deep inside the HSSF filter beds in 1999 for the taking of water samples. The sampling wells provide a vertically integrated water sample. In the right (dry) bed of the HSSF CW, the water table is kept lower, and more aerobic conditions prevail, while in the left (wet) bed of the HSSF CW, the water table is constantly rising and the conditions have become more anaerobic (Noorvee et al., 2005). The VSSF filter is filled with crushed limestone, which has a very high hydraulic conductivity, and the filter is drained quickly, with no water-saturated layers remaining in the filter, and thus well-aerated wastewater flows rapidly to the HSSF filter.

The main objective of this study was to discover how pre-aeration due to the VSSF filter has affected the purification processes in the Kodijärve HSSF CW and to point out differences in purification efficiency in both beds of the HSSF filter before and after the establishment of the VSSF filter. It is important to indicate, that the water flow rate entering the system was significantly higher (*p* < 0.05) after the establishment of the VSSF filter (in average 3.2 m$^3$ d$^{-1}$ before the VSSF filter and 4.2 m$^3$ d$^{-1}$ after the VSSF filter was built). The second objective was to analyze how purification efficiency depends on the water level, oxygen supply and other parameters of the HSSF system. Another objective was to propose how the horizontal subsurface flow filters could be operated to achieve more effective purification of wastewater.

### 2. Methods

Water samples taken once a month (January 2000–December 2004) from the inlet and outlet of both VSSF and HSSF wetlands, as well as 17 water sample series sampled from each of the 18 sampling wells installed in both beds of the HSSF wetland (Fig. 1) were analyzed in the lab of Tartu Environmental Research Ltd (APHA, 1989) for pH, temperature, dissolved O$_2$, redox potential, total suspended solids (TSS), biological oxygen demand (BOD$_7$), ammonia nitrogen (NH$_4$–N), nitrite nitrogen (NO$_2$–N), nitrate nitrogen (NO$_3$–N), total nitrogen (Total N), phosphate phosphorus (PO$_4$–P), total phosphorus (Total P), sulphate (SO$_4$) and total iron (Total Fe). Changes in water quality in both beds of the Kodijärve HSSF CW (dissolved O$_2$, TSS, BOD$_7$, NH$_4$–N, NO$_3$–N, NO$_2$–N, Total N, Total P, and Total Fe) in two periods (1st period — January 2000–April 2002 before the VSSF CW was built; 2nd period — October 2002–December 2004 after the construction of the VSSF filter) were pointed out. The statistical analysis of changes in both beds of the HSSF filter was carried out for the combined average of sampling wells in each HSSF bed.

The normality of the variables was verified using the Lilliefors and $\chi^2$-tests. In most cases the variables were not normally distributed. Accordingly, the statistical analysis was carried out using non-parametric tests. In order to highlight significant changes in both beds of the HSSF filter between the two periods, a non-parametric Mann-Whitney *U* test was used. Non-parametric Spearman rank-correlation analysis was used to indicate the dependence of purification processes on water level, oxygen supply and other purification processes. Only significant dependences are pointed out (*p* < 0.001).

![Fig. 1. Diagram of the Kodijärve HSSF CW sampling points and 1–18 water sampling wells in the HSSF CW.](image-url)
The results of water samples taken are illustrated in the graphs along the different sampling points and inside the HSSF CW along the rows of sampling wells following the flow direction of the wastewater inside the HSSF filter beds (Fig. 1). In the 1st period the inflow to the CW is also the inflow to the HSSF filter. In the 2nd period the inflow to the CW is the inflow to the VSSF filter.

3. Results

3.1. Oxygen saturation rate and dissolved oxygen concentration

A significant increase in the oxygen saturation rate of the HSSF CW was observed in the 2nd period in both beds ($p<0.001$). During the 1st period the oxygen saturation rate in the wastewater was low (around 12% in the average), and it slowed down aerobic processes such as organic matter removal and nitrification. In the 2nd period the oxygen saturation achieved 40–60%, a level needed for the normal functioning of nitrifying bacteria (Vymazal, 2001).

The dissolved oxygen concentration is accordingly also significantly higher in both beds of the HSSF filter in the 2nd period ($p<0.001$). In the 1st period the dissolved oxygen concentration was on average 2.4 mg O$_2$ L$^{-1}$ in the right (dry) bed and 1.7 mg O$_2$ L$^{-1}$ in the left (wet) bed. In the 2nd period the dissolved oxygen concentration was on average 4.9 mg O$_2$ L$^{-1}$ in the right (dry) bed and 4.0 mg O$_2$ L$^{-1}$ in the left (wet) bed.

3.2. Water level

The left bed was wetter during the first period (average water level of all of the sampling points 32.6 cm below ground level) and remained so in the second period (32.5 cm below ground level). The right bed was with somewhat lower water level, especially in the first part of the filter, and was more dry (in the average 36.8 cm below ground level in the 1st period and 36.4 cm below ground level in the 2nd period). When we look at the average water level in both beds, there seems to be no important difference in the water level in both beds of the HSSF filter. However, when we consider the rows of sampling wells separately, there is a notable difference in water level. In the left bed the water level is quite even. In the right bed of the HSSF filter the first part (row 1–2–3) remains at the lower water level in both periods (Table 1). Accordingly, in the first part of the right bed the conditions were more aerobic than in the left bed. The average water level is higher in the right bed during the 2nd period and remained practically the same in the left bed. The somewhat higher water level in right bed can be explained by higher flow rates during the 2nd period and also by the possible clogging of the filter material (iron-rich sand). In the course of time the subsurface filter can become clogged with suspended solids, resulting in a decrease in the hydraulic conductivity of the filter (Kadlec and Knight, 1996). However, the Mann-Whitney $U$ test did not show any significant changes in water level within both beds between two periods.

Table 1 shows the differences in water level in both beds of the Kodijärve HSSF CW between 2 periods.

3.3. Total suspended solids

The main purification processes for the removal of suspended solids are sedimentation and filtration (Vymazal et al., 1998). An important component of the suspended solids in Kodijärve HSSF CW is iron sediment from the iron-rich sand used as filter material. In aerobic conditions iron is in the form Fe$^{3+}$. It changes to Fe$^{2+}$ in anaerobic conditions. Fe$^{2+}$ is soluble in water and normally no sediments are formed, however, if the wastewater contains sulphur, insoluble ferrous sulphide (FeS) is formed. The wastewater in Kodijärve CW contains sulphur, hence, FeS forming and sedimentation is affecting the suspended solids content in the wastewater and ferrous sediments are released from the system. Because of better aeration (increased dissolved oxygen concentration after the construction of the VSSF filter) and less reducing conditions in the 2nd period, there are less iron solids in the outflow of the HSSF in the 2nd period. A significant decrease in suspended solids was observed in the outflow of both beds in the 2nd period ($p<0.001$; Fig. 2). In the 1st period the removal of TSS in the right bed correlated with the oxygen saturation rate (Spearman rank correlation coefficient $R = -0.7$), water level ($R=0.6$), water temperature ($R=0.7$) and total Fe ($R=0.5$). In the outflow of the left bed, the removal of TSS in both periods correlated with total Fe content ($R=0.9$).
3.4. BOD$_7$

In the Kodijärve HSSF filter, the organic carbon content is determined by the amount of carbon entering the system with wastewater and the carbon available from the decomposition of plants that are covering the filter. Removal of organic matter can occur both aerobically and anaerobically. In wastewater treatment, more intense...
organic matter removal takes place through aerobic processes. Anaerobic degradation of organic compounds is much slower than aerobic degradation (Vymazal et al., 1998). Accordingly, the removal of organic matter can be weakened when there is insufficient oxygen. The removal of organic matter in the Kodijärve HSSF CW was better in the 2nd period, for example in the right bed row 1–2–3, than in period 1 (Fig. 2). However, in the left (wet) bed the amount of organic matter was much lower during period 2. In addition, the purification efficiency of the left bed rose remarkably in the 2nd period (97%) compared to the 1st period (77%), whereas in the right bed the increase was not as high (98% in the 2nd period and 91% in the 1st period). The Mann-Whitney U test showed a significant increase in organic matter removal in the 2nd period in the outflow of both beds \((p=0.002\) in the right bed and \(<0.001\) in the left bed). Spearman rank-correlation analysis showed that in the 2nd period the removal of organic matter in both beds was correlating with water temperature \((R=-0.7)\).

### 3.5. Total N

The removal of nitrogen in constructed wetlands takes place mainly by ammonification, microbial nitrification/denitrification, plant uptake and adsorption. The most important processes for nitrogen removal in constructed wetlands are microbial nitrification/denitrification (Vymazal et al., 1998). The total nitrogen content decreased in both beds of the Kodijärve HSSF CW in the 2nd period. We observed a significant decrease in total N in the sampling wells, as well as in the outflow concentrations of the left bed \((p=0.002;\) Fig. 2). On the other hand, there was no significant, but only a slight change in the outflow concentrations of the right bed \((p=0.066)\). The total N removal in the 2nd period correlated with water temperature in both beds \((R=-0.7\) in the right bed and \(R=-0.8\) in the left bed), on BOD\(_7\) concentration \((R=0.6\) in the right bed and \(R=0.7\) in the left bed) and with the oxygen saturation rate in the left bed \((R=-0.8)\). In addition, the concentrations in the outflow are more balanced between both beds in the second period (Table 2). There was an increase in purification efficiency in the left bed, from 40% in the 1st period to 51% in the 2nd period.

#### 3.6. NH\(_4\)–N

There is significantly less ammonia–nitrogen in the sampling wells and outflow of the left bed in the 2nd period \((p<0.001)\). On the other hand, there is even more NH\(_4\)–N in the sampling wells of the right (dry) bed. However, there is also remarkably (not significantly — \(p=0.059\)) less ammonia in the outflow of the right bed (Fig. 2). In the 2nd period, NH\(_4\)–N removal correlated with water temperature in both beds \((R=-0.7\) in right bed and \(R=-0.8\) in left bed), on BOD\(_7\) \((R=0.6\) in right bed and \(R=0.7\) in left bed), and with the oxygen saturation rate in the left bed \((R=-0.8)\).

#### 3.7. NO\(_3\)–N and NO\(_2\)–N

In the 2nd period, the VSSF CW increased the amounts of NO\(_3\)–N \((7.1±7.3\,\text{mg N L}^{-1})\) and NO\(_2\)–N \((0.3±0.4\,\text{mg N L}^{-1})\) entering the HSSF system (Fig 2). This indicates that the nitrification process is occurring in the VSSF system. Additional nitrification occurred inside the HSSF filter because well-aerated wastewater flowed into the HSSF filter in the 2nd period. Further, more oxygen entering the system in the HSSF filter was available for nitrification during the 2nd period, since the organic matter was already decomposed mostly inside the VSSF filter. Nitrification took place more

### Table 2

Inflow to the Kodijärve CW, changes in the outflow of both beds of the HSSF CW and purification efficiencies of the whole CW during periods 1 and 2.

<table>
<thead>
<tr>
<th></th>
<th>Inflow to the CW(^a)</th>
<th>Inflow to HSSF</th>
<th>Outflow left (wet bed)</th>
<th>Outflow right (dry bed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st per mg L(^{-1})</td>
<td>2nd per mg L(^{-1})</td>
<td>1st per mg L(^{-1})</td>
<td>2nd per mg L(^{-1})</td>
</tr>
<tr>
<td>TSS</td>
<td>54.8</td>
<td>36.2</td>
<td>35.2</td>
<td>44.9</td>
</tr>
<tr>
<td>BOD(_7)</td>
<td>113.5</td>
<td>118.4</td>
<td>35.3</td>
<td>26.7</td>
</tr>
<tr>
<td>NH(_4)–N</td>
<td>85.9</td>
<td>75.8</td>
<td>49.5</td>
<td>53.3</td>
</tr>
<tr>
<td>NO(_2)–N</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>NO(_3)–N</td>
<td>14.5</td>
<td>11.5</td>
<td>7.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Fe(_{tot})</td>
<td>1.3</td>
<td>0.7</td>
<td>0.5</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Significant differences are indicated with bold \(p\) values (average flow rate in 1st period 3.2 m\(^3\) d\(^{-1}\) and in 2nd period 4.2 m\(^3\) d\(^{-1}\)).

\(^a\) In 1st period the inflow to the CW is also the inflow to the HSSF filter.
effectively in the right (dry) bed than in the left (wet) bed of the HSSF filter in both periods. The outflow concentration of NO$_3$–N was higher than the inflow concentration during the 2nd period in both beds. Additionally, nitrification was completed in the 2nd period inside the HSSF, since the NO$_2$–N concentration declined towards the outflow of both beds of the HSSF filter. The very high outflow concentration of NO$_2$–N in the 1st period proves the lack of oxygen in the system before the VSSF was built, accordingly, nitrification was not complete and high NO$_2$–N concentration was found in the outflow (Table 2).

Nevertheless, there remains a problem with denitrification and the NO$_3$–N concentrations remain high in the outflow of the HSSF. During the 2nd period we found a significant ($p=0.005$) increase in NO$_3$–N in the outflow of the left (wet) bed. In the 2nd period the NO$_3$–N removal correlated with water temperature in the left bed ($R=0.6$), on BOD$_7$ ($R=-0.6$), with oxygen saturation rate ($R=-0.8$) and with water level ($R=0.5$).

3.8. Total P

In the Kodijärve HSSF CW, iron-rich sand is used as filter material, and phosphorus is bound mostly to iron oxides. But the iron phosphate that is formed is only stable in aerobic conditions. The iron phosphate breaks down to Fe$^{2+}$ and PO$_4^{3-}$ in anaerobic conditions, and phosphorus is released from the sediments. In the right (dry) bed, where the conditions have always been more aerobic, P retention capacity is weakened significantly and there is an increase in total P in the outflow of the right (dry) bed in the 2nd period ($p=0.006$). In the left bed the conditions are more aerobic during the 2nd period and there is a significant decrease in total P in the outflow ($p=0.01$; Fig. 2). According to Spearman rank-correlation analysis, the total P removal in the 2nd period correlated with water temperature in both beds ($R=-0.7$), with BOD$_7$ ($R=0.7$ in right bed and $R=0.8$ in left bed) and with the oxygen saturation rate in the left (wet) bed ($R=-0.7$).

Table 2 shows the differences in outflow concentrations and purification efficiency in both beds of the Kodijärve HSSF CW between 2 periods.

4. Discussion

Aeration of the inflowing wastewater is essential. If the water table in the HSSF CW is kept low, aeration by air diffusion can be quite effective. On the other hand, if the water table is kept higher, additional aeration is obligatory. Insufficient oxygen content is considered to be one of the major factors influencing nitrogen removal, for instance. Therefore, supplementary measures must be adopted to increase the aerobic condition, such as direct bed aeration or aerobic pre-treatment systems (Harris and Maehlum, 2003; Cooper, 2005).

If there is pre-aeration before an HSSF CW, it is probably a good solution to keep the water table high in the HSSF in order to guarantee more effective nitrogen removal. Pre-aeration gives enough oxygen for oxidation processes, so supplemental aeration in the HSSF filter is not needed. For instance, in period 2, the oxygen saturation in the HSSF filter reached 40–60%, which is the level needed for normal functioning of nitrifying bacteria (Vymazal, 2001). Thus it is possible to maximally use the volume of the HSSF filter.

The volume of biological reactors used for wastewater treatment is a very important factor, because it determines hydraulic retention time (HRT) (Garcia et al., 2004a). When, for example, a filter material for phosphorus sorption is used, it is of the highest importance to use the volume of the material maximally, so that there are no “dead zones” in the filter system. Bypasses (dead zones in the vicinity of inflow pipes; Alas, 2006) and differences in granular medium size within the filter beds (see Garcia et al., 2004b) may also be the reason for the somewhat lower removal efficiency in our system.

Oxygen diffuses through water-saturated soil many times more slowly than through air, due to the smaller diffusion coefficient in water, but also because of the low solubility of oxygen in water (Mitsch and Gosselink, 2000). Thus aerobic purification processes, especially nitrification, are slowed down in the left (wet) bed of the HSSF CW (Noorvee et al., 2005). This can be observed in the differences in purification efficiencies between the left (wet) bed and right (dry) bed in the 1st period, since oxygen diffusion through soil was an important oxygen supplier before the construction of the VSSF filter.

Furthermore, the higher water table and more anaerobic conditions in the HSSF favour denitrification. Denitrification is also dependent on the amount of organic matter. In Kodijärve the organic matter is removed rapidly, and there remains very little organic matter for denitrification. In addition to the anoxic conditions, a carbon source is of the highest importance for the denitrifying bacteria (Laber et al., 2003). Therefore the recirculation of wastewater is recommended. With recirculation, the wastewater mixes with raw wastewater in the inflow of the wastewater treatment system, where enough organic matter for effective denitrification is present. Re-circulation is often used for denitrification in conventional biological sewage treatment systems (Cooper et al., 1999). The recirculation of wastewater...
for more effective denitrification is called pre-denitrification. Platzer (1999) and Laber et al. (1997) have shown that recirculation rates of up to 200% of the incoming wastewater have given good results. Laber et al. (2003) indicate that in one stage VSSF CW recirculation of 90–100% gives sufficient denitrification. Pre-denitrification can be dimensioned as the classic pre-denitrification in activated sludge plants (Platzer, 1999). The recirculation rate of 100–150% of the inflowing wastewater is based on the experiences of active sludge treatment plants. Further investigations will show how high the recirculation rate should be in Kodijärve CW in order to achieve results meeting purification standards set in Estonia.

Ideally, the purification processes in a hybrid constructed wetland should be implemented in such a manner that the oxygen that is supplied in the VSSF system will also mostly be used inside the VSSF system. Hence the anaerobic processes could function normally inside the HSSF filter. In Kodijärve the filter material of the VSSF CW – crushed limestone – is probably not the best filter material, because the wastewater flows very rapidly through the filter bed, and highly aerated wastewater flows into the HSSF filter, hindering anaerobic processes within the HSSF CW. Vertical flow CWs often have problems of maldistribution of wastewater over the surface and the inadequate pollutants microorganisms contact, as the wastewater normally passes through bed matrices fairly quickly (Sun et al., 2003). It would probably be a better solution for the nitrification not to take place inside the HSSF CW, but already inside the VSSF, so the denitrification could take place in the HSSF. On the other hand, in the case of Kodijärve, better aeration in the HSSF has favoured phosphorus removal, because of the iron-rich sand used as filter material. Accordingly, the best solution would probably be to use filter material that does not depend on oxygen supply for phosphorus removal and does not consist of iron as phosphorus binding material. Del Bubba et al. (2003) clearly showed that sands with high Ca content are more suitable to be used in subsurface flow constructed reed beds for phosphorus removal.

5. Conclusions

We can conclude that the establishment of the VSSF CW has remarkably improved aerobic conditions in both beds of the HSSF filter. The dissolved oxygen content increased significantly in both filter beds ($p < 0.001$). Except for total P concentrations in the right (dry) bed and NO$_3$–N concentrations in the outflow of both beds, all of the water quality indicators improved after construction of the VSSF bed. No significant seasonal effects on purification efficiency of the water quality indicators were found.

Since the phosphorus retention capacity of the HSSF wetland is reaching its limit, the filter material of the HSSF was replaced, using light-weight aggregates (LWA) in July 2005. Once the media is saturated with P, the entire system would need to be removed and replaced in order to restore P removal performance. The LWA used as filter material hopefully also offers better results in phosphorus removal. Also, recirculation of water to enhance denitrification is implemented. For better denitrification, 75–150% of the wastewater will be pumped back from the outflow of the HSSF to the inflow well of the system. The water level in the HSSF will be raised in order to achieve full use of the volume of the filter material in the HSSF CW, and accordingly longer residence time and more effective purification.

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