POTENTIAL USE OF CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT IN NORTHERN ENVIRONMENTS

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ABSTRACT

Constructed wetlands consist of soil filled beds with aquatic plants. Wastewater is treated when flowing through these beds. It has been questioned if constructed wetlands will be able to operate when subjected to cold conditions in sub arctic regions. Experience from Norway indicates that significant biological activity occurs at temperatures between 0 and 5°C, and that high removal rates of nutrients and organic matter are achieved in ponds and soil amended with wastewater at these temperatures. Results from using constructed wetlands in Denmark, Sweden and North America show that winter performance is not significantly reduced as compared to other seasons, but in order to obtain high removal of organic matter and nitrogen in cold climates aerobic pretreatment is probably a prerequisite. Cold climates may also require careful installation of larger and deeper systems with a longer detention time. Results of 15 months operation of a Norwegian multi-stage constructed wetland pilot plant optimised for nutrient removal, show 55% nitrogen and 98% phosphorus removal. The large phosphorus removal is obtained by using sand with a high content of iron oxides and a fabricated porous medium that has a high phosphorus adsorption capacity. It remains to be seen if long term cost efficient phosphorus removal can be obtained in constructed wetlands. The results indicate that properly designed constructed wetlands can operate satisfactorily in a cold climate. When adequate design criteria are developed several possible applications exist for these simple low maintenance systems as main treatment system, or in conjunction with other treatment methods.

KEYWORDS

Ecological engineering; constructed wetlands; reed beds; wastewater treatment; cold climate; soil type; phosphorus removal; nitrogen removal; system design.

INTRODUCTION

There is a growing interest in natural systems for wastewater treatment and in particular for wetland systems. Natural systems have a minimal dependence on mechanical elements, hence, they are low cost and low maintenance, and often well suited for treatment of smaller wastewater flows. Natural systems include soil based or land-treatment systems such as slow rate and rapid infiltration and overland flow and the aquatic based systems as ponds, natural and constructed wetlands and aquatic plant treatment systems.

Wetlands have been defined as land where the water surface is at or above the ground surface for a long enough period of time each year to maintain saturated soil conditions and the growth of related vegetation.
Natural wetlands include marshes, swamps, bogs, fens and coastal marshes. Natural wetlands are not always available where treatment is needed, and treating wastewater in natural wetlands may involve environmental concerns. By the use of constructed wetlands (CW) the environmental concerns are less, and the systems can be built onsite, and more easily tailored to facilitate specific treatment needs. CW have shown abilities for reduction of pollutants from a variety of sources. In addition to their cost effectiveness, CW can provide aesthetic and recreational value to the landscape. These factors also encourage the use of CW. Currently CW are used for treatment of wastewater from single houses, villages and small towns, urban storm water runoff, different agricultural point and nonpoint pollution sources, landfill leachate and mine drainage, as well as treatment of water containing organic micropollutants (Hammer, 1989). CW also offer interesting possibilities combined with conventional mechanical treatment plants. This paper will focus on the use of CW for domestic wastewater treatment.

Northern environments are generally pristine and unpolluted and the ecosystems have a low diversity that is easily altered by human impact. Phosphorus is considered to be a main factor causing eutrophication in freshwater systems in Norway. Design of wastewater treatment facilities in these areas, especially those discharging to inland waterways, have to be adapted not only to the climate, but also to high purification standard. There is a natural and understandable scepticism to the use of CW for year round pollution abatement in cold climate because the plants are dormant for a long period of time and the systems are susceptible to freezing. Experience from the use of CW for year round treatment in cold climates is also limited. However, Reed et al. (1984) concluded, based on data from systems in Canada and north eastern USA, that CW were likely to be one of the most cost effective wastewater treatment alternatives in extremely cold climates.

The experience with CW for wastewater treatment has, however, been varied. In general, high removal of BOD, suspended solids and bacteria has been achieved, but the removal of nutrients has been highly variable. According to Schierup et al. (1990) Danish systems failure to reach expected performance goals can be attributed to: (i) the use of clay soils with low hydraulic conductivity leading to surface flow in subsurface flow systems and (ii) lack of sufficient nitrification resulting in low nitrogen removal rates.

Learning from previous experience, methods of improving and implementing CW can be deduced. This paper reviews some of the experiences from using CW in northern environments and discusses constraints and design improvements needed for subsurface horizontal flow CW (Fig. 1B) to operate in cold climate. Wastewater treatment options where CW constitute an important part of the treatment sequence are outlined, and preliminary data regarding treatment efficiency from an experimental multistage CW in Norway are presented.

CONSTRUCTED WETLANDS - THE CONCEPT

 Constructed wetlands consist of soil filled beds planted with various aquatic plants (emergent macrophytes). In Europe common reed (Phragmites) are found in most systems, whereas in the United States bulrush (Scirpus) and cattail (Typha) are the most common plant species (Conley et al., 1991). CW can be designed both as free water surface systems (FWS) and subsurface flow systems (SFS). In a FWS system (Fig. 1A) the soil is of low hydraulic conductivity and does not allow for significant flow through the root zone. The stalks provide a substrate for microbial growth which is thought to be responsible for an important part of the treatment processes. In addition, purification occurs by reactions in the water and the upper sediment zone. In SFS (Fig. 1B) water moves horizontally or vertically through the root zone. In the root zone impurities are removed by a complex variety of interacting microbial, chemical and physical processes. Organic matter and nitrogen (N) is mainly removed by biological mechanisms, while adsorption and precipitation reactions with the soil media account for removal of phosphorus (P). The actual role of the macrophytes in the removal processes varies according to the system design. Investigations have shown that systems with plants do achieve better purification performance than systems without plants (Gersberg et al., 1986).
A main concern is the emergent macrophytes’ ability to supply oxygen to the rhizosphere. The results are contradictory (Armstrong et al., 1990, Brix and Scierup, 1990). However, if the roots do not penetrate the bed fully (Reed, 1993) or if the plants are dormant, as in the winter, the plants cannot supply sufficient oxygen for complete biodegradation and subsequent nitrification. Aerobic pretreatment was therefore suggested in order to obtain sufficient purification in systems operating in cold climate (Jenssen et al., 1991b).

In the summer, plant uptake of nutrients and evapotranspiration reduce the discharge to the receiving waterbody (recipient). CW therefore have a naturally controlled discharge mechanism that is better matched to the water flow and pollutant vulnerability of the recipient than other treatment methods. A possible lower purification performance in the winter is therefore compensated by higher performance in summer and a more ecologically adapted discharge rate.

The macrophytes remove pollutants by directly assimilating them into their tissue, but if the plants are not harvested, absolute removal is not achieved by this mechanism. The main role of the macrophytes is therefore to act as a catalyst for purification reactions, by increasing the diversity of the environment in the root zone and promoting a variety of chemical and biochemical reactions that enhance purification.

Fig. 1. Typical arrangement of a constructed wetland with (A) free water surface flow and (B) subsurface horizontal flow (Brix and Schierup, 1989).

COPING WITH COLD CLIMATE

CW faces two main problems in cold climate: (i) hydraulic failure due to freezing or viscosity change of the wastewater and (ii) inadequate purification, due to low temperatures.

Freezing

CW have a large surface area and are usually shallow (depth < 0.8 m). The heat loss from an exposed system in winter climate can be considerable, and insulation may be needed. Heat loss can be reduced by several means; insulation of the supply systems, insulation of the CW system, or altered system design. Wastewater contains heat and our experience shows that the temperature of septic tank effluent in Norway seldom is below 5°C, even if the tank is not insulated. Energy loss prior to the discharge to the CW can therefore be minimised if the supply piping system and the pretreatment units are insulated.

The CW can be insulated both by natural material (e.g. straw, ice, snow) and artificial material (e.g. rockwool, polystyrene foam). If the plant material is not harvested it will provide insulation, but this may not be sufficient, especially in the first years of operation when the layer of plant litter is thin. Additional insulation may therefore be necessary unless a snow cover arrives in early fall. Snow provides good insulation. In large parts of inland Norway and at higher altitudes, early snowfall will prevent the ground from freezing in normal years. The need for extra insulation will therefore only be occasional in these areas. Ice can also provide insulation. One possibility in cold climate is to construct the system so that the upper 10 - 30 cm can freeze, while the lower part of the system still has hydraulic capacity to conduct the applied...
water. This will call for deeper systems, with the obvious drawback that the water will flow through the system below the root zone. Another possibility is to build an ice cover above the top of the system by raising the water level when cold weather approaches. When a sufficiently thick ice cap is formed, the water level can be lowered so that the upper soil zone is unsaturated. This should produce adequate insulation, but requires a design with higher berms fencing the system.

The authors' experience with shallow trench and mound systems for wastewater infiltration in natural soils shows that these systems do not freeze even when exposed to very cold temperatures (-10 to -25°C) over several weeks and without any insulation except a soil cover of 40 cm. In Listowel, Canada, a FWS system was operated successfully by raising the water level and freezing an ice cap on the system over the winter (Herskowitz, 1986). The exact insulation needs for CW systems, given a specific set of winter conditions are not known. Work that clarifies insulation needs in order to provide adequate design criteria for cold climate conditions.

**Purification performance**

Chemical and biochemical reactions are temperature dependent; hence, the purification performance in cold climate can be questioned. In Table 1 the purification performance of some natural systems in cold climates is given.

**TABLE 1. Performance of Some Natural Systems for Wastewater Treatment in Cold Climate**

<table>
<thead>
<tr>
<th>Treatment plant</th>
<th>System type</th>
<th>T [°C]</th>
<th>D [days]</th>
<th>BOD [mg/l]</th>
<th>SS [mg/l]</th>
<th>Tot-N [mg/l]</th>
<th>Tot-P [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Listowel, Canada (4 years)</td>
<td>FWS</td>
<td>7</td>
<td>7</td>
<td>53/10</td>
<td>111/8</td>
<td>19/9</td>
<td>3.2/0.6</td>
</tr>
<tr>
<td>Moesgård, Denmark (9 years)</td>
<td>SFS</td>
<td>8</td>
<td>7</td>
<td>92/14</td>
<td>70/10</td>
<td>47/26</td>
<td>6.5/4.5</td>
</tr>
<tr>
<td>Rugballeård, Denmark (9 years)</td>
<td>SFS</td>
<td>8</td>
<td>916/3.6</td>
<td>108/53</td>
<td>89/44</td>
<td>20/4</td>
<td></td>
</tr>
<tr>
<td>Snogerød, Sweden (3 years)</td>
<td>SFS</td>
<td>8</td>
<td>5.6/1.2</td>
<td>—</td>
<td>10.6/5.3</td>
<td>3.5/1.2</td>
<td></td>
</tr>
<tr>
<td>Solborg; Norway (4 months)</td>
<td>FAP</td>
<td>5</td>
<td>54</td>
<td>330/66</td>
<td>79/32</td>
<td>52/37</td>
<td>9.5/3.3</td>
</tr>
<tr>
<td>Bardu, Norway (4 years)</td>
<td>RI</td>
<td>1</td>
<td>—</td>
<td>39/3.2</td>
<td>—</td>
<td>13/3</td>
<td>2/0.01</td>
</tr>
</tbody>
</table>

FAP=facultative aerated pond, RI=rapid infiltration, T=Mean annual temperature, D=Detention time, BOD=Biological oxygen demand, SS=Suspended solids, Tot-N=Total nitrogen, Tot-P=Total phosphorus, I=Influent, E=Effluent, COD (Chemical oxygen demand).

For the FWS in Listowel, which receive secondary effluent (Herskowitz, 1986), the winter performance was somewhat better than the summer performance for both BOD and SS, due to algae bloom in the summer. Algae bloom is not a problem in SFS. The N-removal rates in Listowel were up to twice as high in the summer as compared to the winter. For P the removal rates were about equal for summer and winter. During the monitoring of the Listowel system from 1980 to 1984, phosphate removal decreased, but for total-P and the other parameters given in Table 1 there was no trend towards decreasing removal rates with time.

The two Danish systems (Schierup et al., 1990) receive septic tank effluent. The good P-removal for the system at Rugballeård is attributed to the use of clayey soil and a very low hydraulic loading (0.02 m³/m²/d). The BOD and total-N removal is probably limited due to insufficient oxygen supply. Schierup et al. (1990) have investigated 109 CW systems in Denmark. They conclude that there are only small seasonal variations in BOD and SS removal. The Swedish plant at Snogerød (Gumbricht, 1991) is treating secondary effluent. Under the investigation period the plant had a moderate hydraulic loading (0.1 m³/m²/d). The N-removal efficiency during winter, was about 30%. According to Gumbricht (1991) other studies indicate N-removal capacities of about 40% at air-temperatures around zero.

The 15 year old facultative pond system at Solborg receives septic tank effluent and the first of three ponds is continuously aerated by flowforms (Jenssen et al., 1991b). The results in Table 1 show performance for
the period from December to March 1990, when the water temperature was below 1.5°C. According to Jenssen et al. (1991b), oxygen measurements and the decrease in COD in the pond system shows that biochemical reactions are occurring. The rapid infiltration system in Bardu (Jenssen et al., 1990) receives very dilute primary sewage. Average performance values for the first 3 years of operation are given. The seasonal variation in purification performance for this system is low. The results from Bardu and Solborg indicate that biochemical N-transformations occur at temperatures below 5°C in both systems.

Table 1 shows that substantial reduction of BOD and SS as well as nutrients is possible at low temperatures in natural systems. According to Wood (1990) the temperature of the wastewater appears to have little effect on effluent quality even when temperature changes from just above freezing in winter to 25°C in summer, because the total number of active bacteria in the soil rhizosphere increases in winter months as a result of reduced activity of the individual bacteria.

At Solborg especially, the detention time is very high. Increased detention times means larger and more expensive systems. This is probably necessary in order to obtain high performance in cold climate.

THE HAUGSTEIN FARM MULTI-STAGE WASTEWATER TREATMENT PLANT

The results presented above indicate that it should be possible to successfully use CW for wastewater treatment in cold climates. An experimental system was therefore constructed to treat the wastewater from two households at Haugstein farm 20 km east of Oslo, Norway. The layout of the system is shown in Figure 2. The system was built in November 1991 and the wetland units were planted with Phragmites australis and Typha latifolia in May 1992.

In order to improve the removal efficiency over traditional single unit CW systems, the Haugstein Plant is designed as a multi-stage system. A small aerobic pretreatment unit (vertical flow sandfilter, length 6.0 m, width 0.5 m and depth 0.7m) is constructed between the septic tank and the first wetland unit to provide aeration, removal of organic matter and nitrification. The second unit (CW1, 6 m x 10 m and 0.8 m deep) is primarily meant to be a denitrification unit, but contains a sand with a high potential for P-removal. The third unit (CW2, 4 m x 10 m and 0.9 m deep) contains the reactive porous media, LECA (0-4 mm), and is designed to function as the main P removal unit (LECA is a brand name and is produced in several European countries, e.g. A/S Norsk LECA, Oslo, Norway). Biological growth on particle surfaces (biofilm) can reduce the P-sorption capacity (Nilsson, 1990). The main P-removal unit is therefore located as the terminal step because application of low BOD water may reduce the biofilm production.

LECA 0-4 mm has a hydraulic conductivity of 1200 m/d, and a P-adsorption capacity exceeding 4 kg/m³, estimated by a batch experiment using phosphate solution (Jenssen et al., 1991a). This unique combination of a high hydraulic conductivity and high P-adsorption capacity makes the LECA interesting as a P-adsorbent in onsite wastewater treatment systems.

Depth of the CW systems is recommended not to exceed 60 cm. In order to allow for freezing of the upper layer and still have sufficient hydraulic capacity the CW units at Haugstein are deeper. The estimated detention time is 14 days based on the design flow rate. The system operates by gravity, and has no moving parts except for two tipping buckets registering inflow and outflow. Samples of septic tank effluent, and effluent from the sandfilter and the two wetland units, have been collected monthly. Routinely they have been analysed for, pH, electrical conductance, BOD, COD, SS, NH₄-N, NO₃-N, Tot-N, PO₄-P, Tot-P and Cl according to Norwegian standards for water analysis.
Results and discussion

The removal rates of the Haugstein system are shown in Table 2.

TABLE 2. Removal (%) and Effluent Concentrations [mg/l] of Ammonia (NH₄), Nitrate (NO₃) and Chloride (Cl)* in Different Stages of the Haugstein Multi-Stage Plant

<table>
<thead>
<tr>
<th></th>
<th>COD [%]</th>
<th>BOD [%]</th>
<th>Tot-N [%]</th>
<th>Tot-P [%]</th>
<th>NH₄ [mg/l]</th>
<th>NO₃ [mg/l]</th>
<th>Cl [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand filter</td>
<td>64</td>
<td>63</td>
<td>3</td>
<td>37</td>
<td>77</td>
<td>12</td>
<td>51</td>
</tr>
<tr>
<td>CW1</td>
<td>-27</td>
<td>8</td>
<td>43</td>
<td>50</td>
<td>36</td>
<td>2</td>
<td>43</td>
</tr>
<tr>
<td>CW2</td>
<td>38</td>
<td>17</td>
<td>9</td>
<td>11</td>
<td>15</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>Total</td>
<td>76</td>
<td>88</td>
<td>55</td>
<td>98</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/E [mg/l]</td>
<td>246/60</td>
<td>191/24</td>
<td>99/45</td>
<td>11/0,2</td>
<td>91/15</td>
<td>0,14/14</td>
<td>51/36</td>
</tr>
</tbody>
</table>

Removal and effluent concentrations are adjusted for dilution due to precipitation based on the Cl- concentration. I=Influent (Septic tank effluent), E=Effluent

The main removal of organic matter occurs in the sandfilter. COD increases through the CW1 unit and the BOD decreases slightly. The increase in COD is probably due to discharge of organic matter that is slowly biodegradable, e.g., humic acids, originating in this unit. It is also worthy to note that BOD in the order of 2-7 mg/l is produced within a CW due to decomposition of plant litter and other naturally occurring organic materials (Reed, 1993). This may contribute to the low BOD reduction in CW1. The main removal of nutrients occurs in CW1. The influent of nitrogen to CW1 has been dominated by ammonia. The present results do not reveal whether the N-reduction is due to ammonia adsorption or nitrification and subsequent denitrification in CW1.
The overall removal for P (98%) is promising, but the system has only been operating for 15 months, and half of that time without plants. How the development of a root biomass will influence P-removal is uncertain. Anoxic or anaerobic conditions prevail in a CW, except for close to the roots (Hofmann, 1991). In winter when the plants do not provide oxygen, the system might turn anaerobic. P-release is often associated with anaerobic conditions, but for the Haugstein plant, which has been in operation through two winter seasons, a fairly constant P-removal independent of season is observed (Fig. 3). Because of the high P-removal in CW1, the long-term P-removal of the LECA in CW2 has not been challenged. In theory the total service life for P-removal for the Haugstein plant is more than 2 decades, but, for the reasons mentioned above, this may be much shorter. If the P-removal drops below acceptable levels, replacement of the LECA or possibly the sand in CW1 will remediate the situation. The removed LECA constitutes a suitable soil conditioner, especially for heavy clay soils. The value of the used LECA as a P-fertiliser depends on the bioavailability of the associated P. Whether or not this will be a cost efficient P-removal method depends on the longevity of the LECA as a P-adsorbent, and its subsequent fertiliser value. Another means for remediation of decreasing P-removal capacity is to allow one CW unit to dry and rest. This has shown to increase the P-removal capacity of soil infiltration systems (Sawhney and Hill, 1975).

The content of E. Coli in the effluent has varied between 0 and 75 per 100 ml, and shows a very efficient removal of bacteria in this wastewater treatment system. In Fig. 3 the overall purification performance for the winter months (December through March) is compared to the performance during the other seasons.

The Haugstein multi-stage treatment plant has been successful so far. However, the removal of BOD and N is only 88 and 55%, respectively. It is possible that the oxidation of organic matter as well as nitrification in the wetland units will increase as the plant cover matures. Better nitrification in the pretreatment filter should also increase the potential for N removal in subsequent wetland units provided that the plants and wastewater can supply sufficient organic matter for the denitrification. In the future we therefore expect better BOD and N-removal and a slowly decreasing P-removal.

The system at Haugstein farm was insulated by 15 cm of straw during the winters of 1992 and 1993. This has been sufficient to prevent hydraulic problems due to freezing, but the upper 10 to 20 cm of CW1 and CW2 froze during January 1993. The winters of 1992 and 1993 have been warmer than usual. On the other hand a good snow cover has also been absent through most of the winter months. Colder temperatures than in 1993 without an additional snow cover could therefore have caused hydraulic problems.
APPLICATIONS OF CW

The results presented above indicate that CW can be designed to operate satisfactorily in cold climate. This opens interesting possibilities for application of these simple low maintenance systems, both as a main treatment system and in conjunction with other treatment methods. However, the experience with constructed wetlands in cold climate still is very limited, and widespread application is not recommended until adequate design criteria for cold climate has been developed.

One of the main advantages of CW is the simplicity, hence, the method is well suited for onsite use when minimal maintenance is a requirement. Where high P-removal is needed it is still uncertain if CW will be cost efficient. When the discharge is to the ocean, where N-removal is more important, CW should be considered as alternative to other treatment methods, especially for single homes, villages and tourist facilities. However, CW has also been successfully applied for treatment of effluent from tourist facilities in high alpine regions (Navara, 1992).

CW constitute an interesting alternative for upgrading of existing sewage treatment plants, especially when better N or pathogen removal is required. In addition the CW will have ability to reduce the content of suspended material and act as buffer in periods of maintenance problems of the preceding units. This makes CW especially interesting for upgrading of effluent from smaller activated sludge units with chemical precipitation. A filter for polishing the effluent from activated sludge plants is often necessary to reduce Turbidity (Odegaard, 1992). By polishing the effluent in a CW a high quality effluent that is low in N, SS and bacteria should be possible to obtain.

CONCLUSIONS

Biological degradation occurs at low temperatures (< 5 °C). Results from Europe and North America indicate that CW can perform well in a temperate climate with cold winters, if properly constructed and insulated, but work to determine the need for insulation is required. Existing systems show that the purification performance does not decrease substantially during the winter, but larger systems with a longer detention time (lower loading rate) and aerobic pretreatment is probably a prerequisite in cold climate. More knowledge about purification processes and long term performance at low temperatures is needed, in order to refine design criteria for systems operating under cold conditions.

A second generation CW system with aerobic pretreatment and two consecutive wetland units has shown 55% N-removal and 98%-P-removal. The P-removal is obtained by using porous media with high P-adsorption capacity, but a longer testing period is required to prove if cost efficient P-removal can be obtained in a CW.

There are several possible applications for CW in northern climate, both as a main treatment system and in conjunction with other treatment methods. These applications should be explored.

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