Danish guidelines for small-scale constructed wetland systems for onsite treatment of domestic sewage

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Abstract The Danish Ministry of Environment and Energy has passed new legislation that requires the wastewater from single houses and dwellings in rural areas to be treated adequately before discharge into the aquatic environment. Therefore official guidelines for a number of onsite treatment solutions have been produced. These include guidelines for soakaways, biological sand filters, technical systems as well as different types of constructed wetland systems. This paper summarises briefly the guidelines for horizontal flow constructed wetlands, vertical flow constructed wetlands, and willow systems with no outflow and with soil infiltration. There is still a lack of a compact onsite solution that will fulfil the treatment classes demanding 90% removal of phosphorus. Therefore work is presently being carried out to identify simpler and robust P-removal solutions.

Keywords Constructed wetland; horizontal flow; Phragmites; Salix; vertical flow; willow

Introduction
In 1987, the Danish parliament (Folketinget) passed the “Action Plan against Pollution with Nutrients of the Danish Aquatic Environment”, popularly known as the Action Plan for the Aquatic Environment. The objective of the plan was to reduce the total loading of the aquatic environment by nitrogen and phosphorus from agriculture, municipal and industrial discharge by 50% and 80%, respectively. The means of achieving the reductions included expansion of sewage treatment plants and efforts to ensure that the agricultural sector reduced their loss of nutrients to the aquatic environment. The target concerning reduction of phosphorus was largely met ten years later as a consequence of improved sewage treatment, but the discharge of nitrogen to the aquatic environment was still too high. Therefore a new action plan (Action Plan II) was stipulated in 1998, which among others included the establishment of wetlands on agricultural land to remove nitrogen (Ministry of Environment and Energy, 1997).

In step with the reduction in discharges from wastewater treatment plants and industry over the past 15 years, the relative impact of discharge from sparsely built-up areas and stormwater outfalls on watercourses and lakes has increased. The discharges from sparsely built-up areas – especially of organic matter and phosphorus – are responsible for many watercourses and lakes failing to meet their quality objectives. Therefore, in 1997 the Environmental Protection Act was amended with Act 325 of 14 May concerning wastewater treatment in rural areas (Ministry of Environment and Energy, 1997). The rural areas typically represent ordinary dwellings that lie outside the sewerage system catchment areas. The properties discharge their mostly ordinary domestic sewage via plants having a capacity of less than 30 person equivalents (PE) or have individual discharges. In 1998, there were a total of approx. 346,500 properties in the rural areas. These comprise houses located in summer cottage districts, allotment cabin districts, sparsely built-up areas, and villages. By far the majority (60%) of the registered properties in rural areas are located in sparsely built-up areas. Summer cottages also comprise a large group, accounting for approx. 30% of the properties. About half of all the properties.
discharge their wastewater via soakaways, i.e. that no discharge takes place to watercourses, lakes or the sea, and just under half of all the properties in rural areas discharge wastewater to watercourses, lakes or the sea. Permanent residences account for 90% of these properties (Ministry of Environment and Energy, 2000b).

The degree of treatment required in rural areas to improve the environmental state of inland waters, especially that of the small watercourses, is determined by regulations (Table 1). Act 325 of 14 May 1997 on Wastewater Treatment in Rural Areas (Ministry of Environment and Energy, 1997) defines four treatment classes that have to be met in rural areas. The treatment class depends on the quality objective of the receiving water body. The Counties specify in their Regional Plans the areas in which the treatment of wastewater from properties in rural areas is to be improved. In consultation with the municipal authorities, the County Council stipulates quality objectives for the individual recipient waters in its Regional Plan. The County Council identifies watercourses and lakes that are vulnerable to pollution and based on its knowledge of the environmental state and pollutional load on the individual recipient waters, assigns each individual recipient a maximal environmentally permissible level of pollution. The Danish EPA estimates that there are approx. 67,000 properties in rural areas nationwide that currently have individual discharges and which will have to improve wastewater disposal in the near future. The remaining properties can maintain the existing means of wastewater disposal without further improvement (Ministry of Environment and Energy, 2000a,b).

Removal of phosphorus (treatment classes OP and SOP) is required where the wastewater effluent is discharged into a lake or into a watercourse which later discharges into a lake. Nitrification (treatment classes SOP and SO) is required where the wastewater effluent is discharged into a watercourse with a water quality objective for salmon fish, and removal of organic matter (BOD) is always required, even if discharge is to the sea.

Following the adoption of Act 325 of 14 May 1997 on Wastewater Treatment in Rural Areas (Ministry of Environment and Energy, 1997) the Danish Ministry of Environment and Energy developed official guidelines for various treatment options for systems up to 30 person equivalents. The official guidelines include guidelines for soakaways or soil infiltration (Ministry of Environment and Energy, 1999d), guidelines for root-zone systems which are equivalent to horizontal subsurface flow constructed wetlands (Ministry of Environment and Energy, 1999c), and guidelines for biological sandfilters (Ministry of Environment and Energy, 1999b).

Soakaways are the preferred solution because of simplicity and because of the low price, but at many locations soil infiltration is not possible because of clayish soil conditions, high ground water tables or because of proximity to drinking water wells. At these sites, other treatment options must be used. These include: biological sand filters, different types of constructed wetlands, willow systems, collecting tanks, technical systems (mini treatment systems) as well as the connection to a sewerage system. Technical systems have to pass a fairly strict test to obtain an official certification to comply with the different treatment classes before they can be marketed in Denmark (Ministry of Environment and Energy, 1999a).

Table 1 Treatment classes (% removal) that has to be meet in rural areas

<table>
<thead>
<tr>
<th>Treatment class</th>
<th>BOD₅</th>
<th>Total-P</th>
<th>Nitrification</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOP</td>
<td>95%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>SO</td>
<td>95%</td>
<td>–</td>
<td>90%</td>
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<tr>
<td>OP</td>
<td>90%</td>
<td>90%</td>
<td>–</td>
</tr>
<tr>
<td>O</td>
<td>90%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
In the following the EPA guidelines for root-zone systems (horizontal flow constructed wetlands), vertical flow constructed wetlands, and willow systems will be briefly summarised. Guidelines for soakaways and biological sandfilters will not be described. The guidelines contain a summary of legislation and regulations, necessary pilot studies at the property before construction, pre-treatment demand, a technical description of how to design and build the systems including technical drawings detailing construction, and finally management demands. Soakaways fulfil the most stringent SOP treatment class. The only other treatment options that fulfil the SOP treatment demand are the willow systems and some of the technical solutions not described here. The root-zone systems (constructed wetlands with horizontally subsurface flow) only fulfil the ‘O’ treatment class (90% removal of BOD). Biological sandfilters and vertical flow constructed wetlands fulfil the ‘SO’ treatment class (95% removal of BOD and 90% nitrification).

Guidelines for root-zone systems
Root-zone systems will only meet the less stringent treatment class (O), i.e. 90% removal of BOD$_5$. Root-zone systems do not nitrify and the removal of phosphorus is also limited. The design and construction details of the root-zone systems described in the Danish guidelines is very similar to the systems described in the literature and in other guidelines (Cooper, 1990; Österreichisches Normeringsinstitut, 1997; Vymazal et al., 1998; Kadlec et al., 2000) Therefore, the guidelines will only be summarised briefly here. The main points of the guidelines are:

1. The sewage must be pre-treated in a two- or three-chamber sedimentation tank (minimum volume 2 m$^3$ for a single household with up to 5 PE)
2. The necessary surface area of the root-zone system is 5 m$^2$ per PE (minimum area for a single household is 25 m$^2$)
3. The minimum length of the root-zone system is 10 m
4. The bottom of the bed should have a slope of 10 o/oo from inlet to outlet, but the surface of the bed should have no slope
5. Bed depth should be 0.6 m at the inlet side of the bed and deeper towards the outlet
6. Inlet and outlet zones consist of a transverse trench filled with stones ensuring that no wastewater is exposed to the atmosphere
7. The root-zone system must be enclosed by a tight membrane (minimum 0.5 mm thickness)
8. The membrane must be protected by a geotextile or sand
9. The substrate must be uniform sand with a d$_{10}$ between 0.3 and 2 mm, d$_{60}$ between 0.5 and 8 mm, and the uniformity coefficient should be $<$ 4
10. The bed is planted with common reed (Phragmites australis)

The majority of root-zone systems in Denmark were built in the late eighties and in the beginning of the nineties, and these were almost exclusively constructed with soil as the bed substrate and for the treatment of wastewater from small villages (Brix 1998). The performance of these systems was good in terms of TSS and BOD removal, but no nitrification occurred and only a small fraction of phosphorus was eliminated. The new design where sand is used as the bed substrate (as described in the guidelines) is only used at very few sites because of the inability of the systems to nitrify and to remove phosphorus (Brix and Johansen, 1999; Brix et al., 2003).

Guidelines for vertical flow constructed wetlands
During the past few years investigations have been carried in order to develop a constructed wetland system that will meet the most stringent treatment class, i.e. 95% removal of BOD, 90% removal of total-P and 90% nitrification (Brix et al., 2003; Arias...
et al., 2003a, b). Previous studies have shown that compact subsurface flow constructed wetland systems with vertical flow may be able to fulfil these treatment demands. An experimental vertical flow constructed wetland system was established at a traditional municipal wastewater treatment plant so that the loading rate could be manipulated as desired, and a number of tests were conducted in order to establish the treatment capacity of vertical flow beds (Johansen et al., 2002). The studies also evaluated the effects of recycling of nitrified effluent back to the sedimentation tank in order to enhance denitrification in the sedimentation tank and the overall treatment performance of the system (Brix et al., 2002; Marti et al., 2003). These studies documented that the capacity of vertical flow constructed wetlands to remove BOD and to nitrify is very high and determined the area-demand of the system. The studies also proved that recycling of nitrified effluent to the sedimentation tank enhanced removal of nitrogen by denitrification and also improved and stabilised the overall treatment performance of the system.

Based on the initial experiences from the experimental system, a full-scale system for a single house with four persons was constructed. The system consists of a 2-m$^3$ three-chamber sedimentation tank, a level-controlled pump and a 15-m$^2$ vertical flow constructed wetland. Effluent from the system can be recirculated to the sedimentation tank to enhance removal of total-nitrogen by denitrification (Brix, 2003). The performance of the single-household system has been monitored under conditions with recirculation as well as without recirculation (Figure 1).

These studies have produced the necessary background documentation for the development of official guidelines for the design and construction of vertical flow constructed wetland system for use in the rural areas. The guidelines have just been published by the Ministry of the Environment (Brix and Johansen, 2004). The main points of the guidelines are:

- The sewage must be pre-treated in a two- or three-chamber sedimentation tank (minimum volume 2 m$^3$ for a single household with up to 5 PE)
- The necessary surface area of the vertical flow constructed wetland is 3 m$^2$ per PE (minimum size for a single household is 15 m$^2$)
- The effective filter depth is 1.0 m. The filter medium is sand with a d$_{10}$ between 0.25 and 1.2 mm, a d$_{60}$ between 1 and 4 mm, and the uniformity coefficient (U = d$_{60}$/d$_{10}$) should be less than 3.5. The contents of clay and silt (particles less than 0.125 mm) must be less than 0.5%

**Figure 1** General layout of a single-household vertical flow constructed wetland system
The filter bed must be enclosed by a tight membrane (minimum 0.5 mm thickness). The membrane must be protected by a geotextile on both sides. The bed is planted with common reed (Phragmites australis). The main function of the plants is to counteract clogging of the filter.

The sewage is distributed evenly over the surface of the bed by a network of pressurised distribution pipes. The distribution pipes are insulated against frost by a 0.2 m layer of coarse wood chips or sea shells on the surface of the filter. The loading frequency of the bed is typically 16–24 pulses per day, when half of the effluent water is recirculated within the system. The treated water is collected in an aerated system of drainage pipes placed in a 0.2 m layer of coarse gravel in the bottom of the filter.

Half of the effluent water from the filter is recirculated to the 1st chamber of the sedimentation tank or to the pumping well to enhance denitrification and to stabilise treatment performance of the system.

Vertical flow systems constructed according to the guidelines (Figure 2) will be able to fulfill the O and the SO treatment class, i.e. 95% removal of BOD and 90% nitrification. The vertical flow systems are not able to fulfil the treatment classes requiring removal of phosphorus. The possibility of developing a separate unit containing a P-binding material has been studied extensively both in the laboratory, in the experimental pilot-scale systems and in a full-scale system, and a calcite material was identified that had the right hydraulic properties and at the same time a high binding capacity for phosphorus (Brix et al., 2000; Arias et al., 2002; 2003a). However, unfortunately, the material is no longer commercially available and therefore it has not been possible to include it in the guidelines. The possibility of precipitation of phosphorus in the sedimentation tank by dosing of aluminium polychloride is presently being tested. Initial results are promising and suggest that the dosage needed is only 30 litres for a single-household system per year (Figure 3).

**Guidelines for willow systems**

A novel constructed wetland system based on willows has been developed as a sewage disposal solution in rural areas (Gregersen and Brix, 2001; Brix and Gregersen, 2002). Main attributes of the willow wastewater cleaning facilities are that the systems have zero discharge of water (because of evapotranspiration) and part of the nutrients can be
recycled via the willow biomass. Furthermore, the harvested biomass may be used as a source of bioenergy. Two sets of guidelines have been published: one guideline is describing willow systems with no effluent (Gregersen et al., 2003a), and the other guideline is describing willow systems that are not contained in a membrane-enclosed bed and thus allow some soil infiltration (Gregersen et al., 2003b). The system with infiltration is intended to be used on clayish soils, where infiltration is low.

The willow wastewater cleaning facilities generally consist of c. 1.5 m deep high-density polyethylene-lined basins filled with soil and planted with clones of willow (Salix viminalis L.). The surface area of the systems depends on the amount and quality of the sewage to be treated and the local annual rainfall. For a single household in Denmark the area needed typically is between 120 and 300 m². Settled sewage is dispersed underground into the bed under pressure. The stems of the willows are harvested on a regular basis to stimulate the growth of the willows and to remove some nutrients and heavy metals.

Removal of water from the systems occurs by evaporation from the soil and plant surface and transpiration. The following factors are important for maximising evaporative loss of water: high energy input (solar radiation), high air-temperatures, low relative humidity in the air, exchange of air (wind), canopy resistance, stomata resistance, and leaf area index. Factors like the ‘oasis’ effect, which is the phenomenon where warmer and dry air in equilibrium with dry areas flows across an area of plants with a high water availability are important (Rosenberg, 1969). The vegetation experiences enhanced evaporation using sensible heat from the air as well as radiant energy, and air is cooled by this process. In addition, the so-called ‘clothes-line’ effect, where the vegetation height is greater than that of the surroundings (different roughness conditions), may increase evaporative water loss (Allen et al., 1998). This occurs where turbulent transport of sensible heat into the canopy and transport of vapour away from the canopy is increased by the ‘broadside’ of wind horizontally into the taller vegetation. In addition, the internal boundary layer above the vegetation may not be in equilibrium with the new surface. Therefore, evapotranspiration from isolated expanses, on a per unit area basis, may be significantly greater than the calculated potential evapotranspiration. Examples of the clothes-line or oasis effects would be evapotranspiration from a single row of trees surrounded by short vegetation or surrounded by a dry non-cropped field, or evapotranspiration from a narrow strip of cattails (a hydrophytic vegetation) along a stream channel.
The main characteristics of the willow systems are:

- For a single household system (5 PE), the sewage has to be pre-treated in a 2- or 3-chamber sedimentation tank with a minimum volume of 2 m³ before discharge into the willow system.
- Closed willow systems are generally constructed with a width of 8 m, a minimum depth of 1.5 m, and with 45 degree slopes on the sides.
- The total annual water loss from the systems is assumed to be 2.5 times the potential evapotranspiration at the location as determined by climatic parameters.
- The necessary area of the systems is determined by the amount of wastewater, the ‘normal’ precipitation, and the potential evapotranspiration at the location of the system.
- The bed is enclosed by a water tight membrane and wastewater is distributed underground within the system by a level-controlled pump.
- A drainage pipe is placed in the bottom of the bed. The pipe can be used to empty water from the bed if salt accumulates after some years.
- One third or one half of the willows are harvested every year to keep the willows in a young and healthy state with high transpiration rates.

The willow systems will meet all treatments classes including the most stringent SOP treatment class, i.e. 95% removal of BOD, 90% removal of phosphorus and 90% nitrification, as there is no outflow to any receiving water bodies (Figure 4).

Willow systems with soil infiltration are dimensioned in the same way as closed willow systems. The willows will evaporate all wastewater during the growing season, but during winter some wastewater will infiltrate into the soil. These systems also meet all treatments classes including the most stringent SOP treatment class, as there is no outflow to any receiving water bodies.

Conclusions

The Danish EPA has produced guidelines for a number of small-scale onsite treatment solutions for use in rural areas. If the guidelines are followed no monitoring of the systems is required, and the systems are expected to fulfill the treatment classes as described in the guidelines. There is still a lack of compact onsite solution that will fulfill the treatment classes demanding 90% removal of P. Soakaways and willow systems fulfill the requirement for removal of P, but in many places it is not possible to establish soakaways because of soil conditions or a high groundwater table, and willow systems require large...
areas. Therefore, at present the only option is small-scale technical systems with chemical precipitation of phosphorus. These systems are energy consuming and not very robust in terms of performance, and therefore work is presently being carried out to identify simpler and robust P-removal solutions.

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