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The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: New Danish guidelines

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Abstract

Official guidelines for the on-site treatment of domestic sewage have recently been published by the Danish Ministry of Environment as a consequence of new treatment requirements for single houses and dwellings in rural areas. This paper summarises the guidelines for vertical constructed wetland systems (planted filter beds) that will fulfil demands of 95% removal of BOD and 90% nitrification. The system can be extended with chemical precipitation of phosphorus with aluminium polychloride in the sedimentation tank to meet requirements of 90% phosphorus removal. The necessary surface area of the filter bed is 3.2 m^2/person equivalent and the effective filter depth is 1.0 m. The filter medium must be filtersand with a d_{10} between 0.25 and 1.2 mm, a d_{60} between 1 and 4 mm, and a uniformity coefficient ($U = d_{60}/d_{10}$) less than 3.5. The sewage is, after sedimentation, pulse-loaded onto the surface of the bed using pumping and a network of distribution pipes. The drainage layer in the bottom of the bed is passively aerated through vertical pipes extending into the atmosphere in order to improve oxygen transfer to the bed medium. Half of the nitrified effluent from the filter is recirculated to the first chamber of the sedimentation tank or to the pumping well in order to enhance denitrification and to stabilise the treatment performance of the system. A phosphorus removal system is installed in the sedimentation tank using a small dosing pump. The mixing of chemicals is obtained by a simple airlift pump, which also circulates water in the sedimentation tank. The vertical flow constructed wetland system is an attractive alternative to the common practice of soil infiltration and provides efficient treatment of sewage for discharge into the aquatic environment.

Keywords: Airlift pump; BOD; Constructed wetland; Guidelines; Nitrification; Nitrogen; On-site treatment; Phosphorus; *Phragmites*; Planted filter bed; Recirculation; Vertical flow

1. Introduction

About half of the properties in rural areas of Denmark discharge their mostly ordinary domestic sewage directly into watercourses, lakes, or the sea. This discharge of poorly treated sewage is responsible for many watercourses and lakes not presently meeting their quality objectives (Ministry of Environment and Energy, 2000). Therefore, national regulations have recently been adopted which define the permissible discharge of organic matter and nutrients from these

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properties (Ministry of Environment and Energy, 1997). The regulations stipulate four treatment classes that have to be met in different areas depending on the quality objective of the receiving water body. Removal of organic matter, measured as BOD_5, is always required to a level of 90 or 95% removal. Where the effluent is discharged into a lake or into a watercourse which later discharges into a lake 90% removal of phosphorus is required, and where the wastewater effluent is discharged into a watercourse with a water quality objective for salmon fish 90% nitrification is obligatory. There is no general requirement for the removal of nitrogen because of the high 'background' levels of nitrate in the aquatic environment as a consequence of drainage water from agricultural fields.

Following the adoption of the new regulations for wastewater treatment in rural areas, the Danish Ministry of Environment has developed official guidelines for various treatment options for systems up to 30 person equivalents (PE). Soakaways are the preferred solution because of simplicity and because of the low costs, but at many locations soil infiltration is not possible due to clayish soil conditions, high ground water tables or because of proximity to drinking water wells. At such sites, other treatment options must be used. These include on-site systems, such as biological sand filters, different types of constructed wetlands, willow systems, collecting tanks, technical systems (mini treatment systems) as well as the connection to a centralised large-scale sewage treatment system.

In the following, the official guidelines for vertical flow constructed wetlands (planted filter beds) will be summarised. The guidelines contain a summary of legislation and regulations, necessary pilot studies at the property before construction, pre-treatment demand, a technical description on how to design and build the systems including technical drawings detailing construction, and finally management demands. The vertical flow constructed wetland system described in the guidelines will fulfil the treatment classes requiring 95% removal of BOD_5 and 90% nitrification, but will not remove sufficient phosphorus to fulfil the demand of 90% removal of P. The system may, however, be extended with a simple chemical dosing system in the sedimentation tank to remove phosphorus.

2. Background

Since 2000 several 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_5, 90% removal of total-P and 90% nitrification (Brix et al., 2003; Arias et al., 2003a,b). These studies, as well as investigations performed in other countries, clearly demonstrated that vertical flow constructed wetland systems would be able to fulfil these treatment demands (Platzer, 1996; Laber et al., 1997; Cooper, 1999; Brix et al., 2002; Weedon, 2003). 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 documented that the capacity of vertical flow constructed wetlands to remove BOD_5 and to nitrify is very high and determined the area-demand of the system. It was documented that vertical flow beds are extremely effective in removing suspended solids and BOD_5, and they do also nitrify at high loading rates even during cold winters (Brix et al., 2002). The studies also evaluated the effects of recirculation of nitrified effluent back to the sedimentation tank in order to enhance denitrification in the sedimentation tank (Brix et al., 2002, 2003; Marti et al., 2003; Arias et al., 2005). A recycling rate of one to one, i.e. 100% recycling, resulted in about 50% denitrification. Recycling also improved and stabilised the overall treatment performance of the system. The removal of indicator bacteria in the system was about 2 log-units (Arias et al., 2003b).

Phosphorus removal in vertical flow constructed wetlands is very limited, and it is not possible to obtain a sand bed medium that has a sufficient high capacity to bind phosphorus for a prolonged period (Arias et al., 2001; Del Bubba et al., 2003; Arias and Brix, 2005). Therefore, the phosphorus binding capacities of various artificial media have been assessed in the laboratory in an attempt to find a medium that could be used to bind phosphorus. The idea was to establish a separate exchangeable filter unit after the constructed wetland system to remove phosphorus from the effluent (Brix et al., 2001; Arias et al., 2003a). A suitable calcite material was identified, but the full-scale tests showed that removal initially was good, but after a few months, the filters were saturated with phosphorus and there were problems with clogging. It has not subsequently been possible to solve the inherent problems with this material. Instead phosphorus removal can be obtained by simple precipitation with an aluminium compound in the sedimentation tank prior to the wetland.

Based on the initial experiences from the experimental systems, a full-scale system was constructed treating the sewage from a single household with four persons. 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, 2003a). Phosphorus was initially removed by a separate exchangeable filter-unit containing calcite. However, because of the problems mentioned above, this system was abandoned, and phosphorus is now removed by chemical precipitation in the sedimentation tank. The performance of the single household system has been monitored under conditions with recirculation as well as without recirculation, and has documented the importance of recirculation for the treatment performance. The experiences from this full-scale system as well as the laboratory- and pilot tests described above 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 recently been published by the Ministry of Environment and Energy (Brix and Johansen, 2004; Brix and Arias, 2005).

3. The guidelines

3.1. Scope of the guidelines

The guidelines are to be used for systems up to 30 person equivalents (PE) and only for wastewater with a composition similar to normal household sewage. Rain and storm water may not be discharged into the system together with the household sewage. The vertical flow constructed wetland system will fulfil the treatment classes requiring 95% removal of BOD_5 and 90% nitrification or effluent concentrations of <10 mg l^{-1} for $BOD_{5(modified)}$ and <5 mg l^{-1} $NH_4{}^+$-N. The system will only fulfil the treatment classes requiring 90% removal of phosphorus or a total-P effluent concentration <1.5 mg l^{-1} if extended with chemical precipitation in the sedimentation tank. It is assumed that pollutant loadings per PE are 60 g day^{-1} of BOD_5, 13 g day^{-1} of nitrogen and 2.5 g day^{-1} of phosphorus. The water discharge is assumed to be 150 l PE^{-1} day^{-1}.

3.2. Pre-treatment requirements

The sewage must be pre-treated in a two- or three-chamber sedimentation tank (septic tank) prior to discharge into the vertical flow wetland to minimise the risk of clogging of pipes and the vertical filter (Fig. 1). For single household systems with up to 5 PE, the total volume of the tank must be 2 m^3. For larger systems, the volume must be enlarged in proportion to the number of PE connected. For two-chamber tanks, the volume of the first chamber should be 70–90% of the total tank volume, and for three-chamber tanks, the volume of the first chamber should be 50–70% of the total volume. The remaining volume should be distributed evenly between the second and third chamber. The sludge must be removed from the tank once a year to maintain a sufficient sludge removal capacity.

3.3. System operation and layout

In vertical flow constructed wetlands the wastewater is loaded onto the surface of a planted filter bed (Fig. 2). The necessary surface area of the filter bed is 3.2 m^2/PE. The pollutants are removed or transformed by the microorganisms that are attached to the filter-sand and the root system of the plants. It is important that the filter is not saturated or covered with water in order to secure a high oxygen level in the filter (Brix and Schierup, 1990). The bed is planted with common reed (*Phragmites australis*). The main function of the plants is to counteract clogging of the filter. The standing aboveground biomass also insulates the filter against freezing during winter (Brix, 1994, 1997). The treated wastewater is collected in a system of passively aerated drainage pipes placed in the bottom of the filter. Half of the effluent is recirculated to the sedimentation tank or the pumping well in order to enhance denitrification and to stabilise performance of the system.

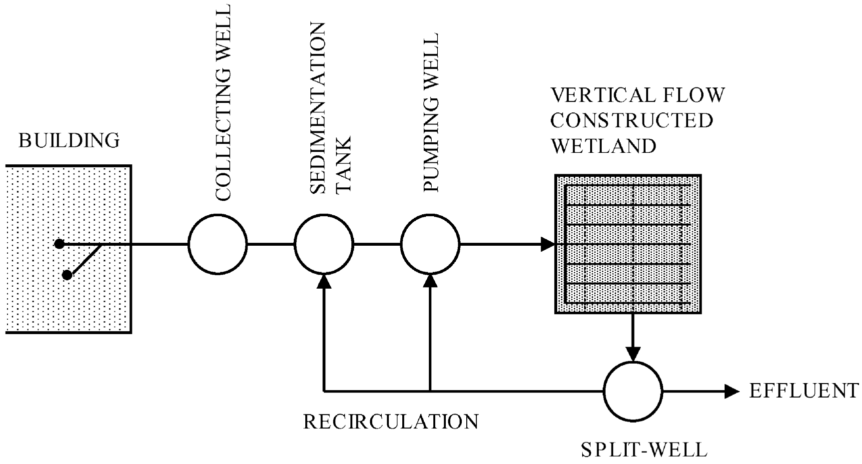

Fig. 1. General layout of a single household vertical flow constructed wetland system. All household wastewater is collected and passed through a 2-m^3 sedimentation tank before discharged by pumping to the planted filter bed. Half of the effluent from the wetland is returned to the sedimentation tank, or alternatively to the pumping well, to enhance removal of nitrogen and stabilise performance of the system.

3.4. Standard system for a single 5 PE household

A vertical flow system for a single household should have a total surface area of 16 m^2 (Fig. 3). The total filter depth is 1.4 m and consists of drainage layer of 0.2 m, a 1.0 m layer of filtersand, and an insulation layer of 0.2 m (Fig. 4). A 0.2 m high embankment is established around the filter bed to prevent surface water from the surroundings entering the 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 drainage layer is built up of coarse gravel (Ø 8–16 mm) in which a number of 70 mm diameter drainage pipes are placed. The drainage pipes are connected on one side to a 90–120 mm collection pipe that discharges the effluent from the bed to the effluent well. The drainage system is passively aerated by vertical pipes extending 0.3 m over the filter bed surface (Fig. 5).

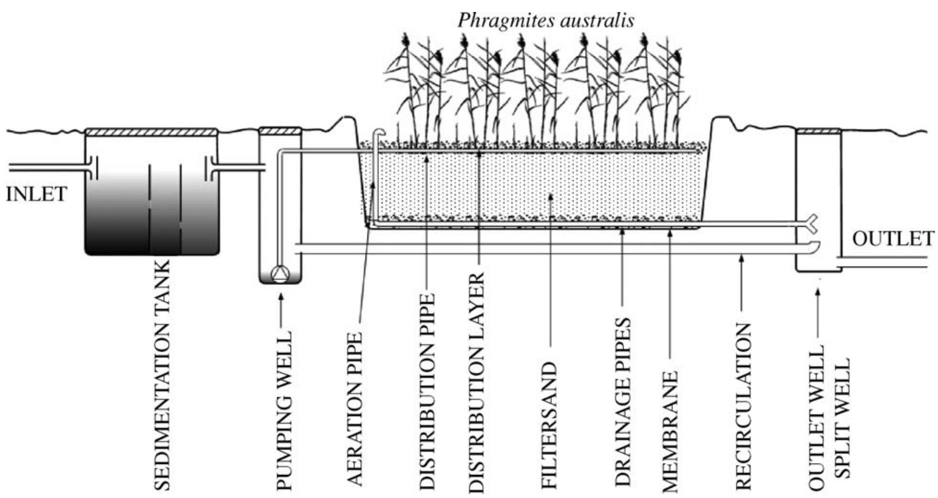

Fig. 2. Layout of a vertical flow constructed wetland system for a single household. Raw sewage is pre-treated in a 2 m^3 sedimentation tank. Settled sewage is pulse-loaded onto the surface of the bed by a level-controlled pump. Treated effluent is collected in a system of drainage pipes, and half of the effluent is recirculated back to the pumping well (or to the sedimentation tank).

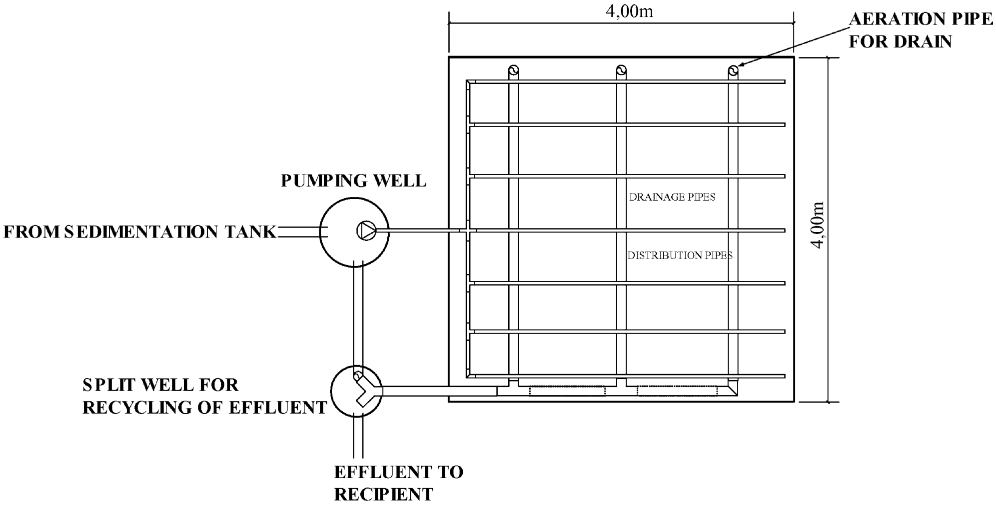

Fig. 3. Overview of a vertical flow constructed wetland for a single 5 PE household showing the network of distribution pipes and drainage pipes.

3.5. Filter medium

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 (Fig. 6). The contents of clay and silt (particles less than 0.125 mm) must be less than 0.5%. In practice, only washed sand materials can be used. The effective filter depth is 1.0 m and the surface of the filter should be level. The filtersand is separated from the drainage layer in the bottom of the bed either by the placement of an open geotextile between the two layers or by a layer of graded gravel that will prevent the filtersand from penetrating and blocking the drainage layer. It is important not to compact the filtersand during construction. Therefore, the use of heavy machinery is not allowed within the bed during construction.

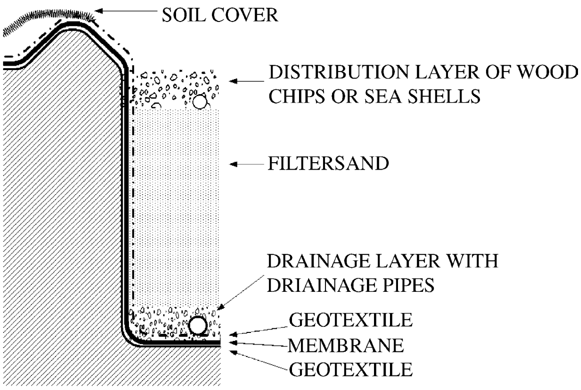

Fig. 4. Detail of the side of the filter bed showing the position of the membrane and geotextiles. The membrane should be covered by soil in order to protect it from UV-radiation.

3.6. Distribution system

The sewage is distributed evenly over the surface of the bed by a network of pressurised distribution pipes. The distribution pipes should have a diameter of 32–45 mm and should have 5–7 mm holes placed in the bottom of the pipes for every 0.4–0.7 m. It is important that the whole distribution system is placed under pressure for a period that is long enough to secure an even distribution of water over the entire bed surface. In practice, the volume pumped should be at least three times the volume of the distribution pipe system. If 32 mm diameter distribution pipes are used for a single household system, the volume of the distribution system will be approximately 20 l. Therefore, the volume of water pumped to the system at every pulse should be at least 60 l. This means that the loading frequency at a normal loading rate for a household will be 8–12 pulses/day, and when half of the effluent water is recirculated in the system, 16–24 pulses/day. The distribution pipes are insulated against freezing by a 0.2 m layer of coarse wood chips or sea shells placed on the surface of the filter.

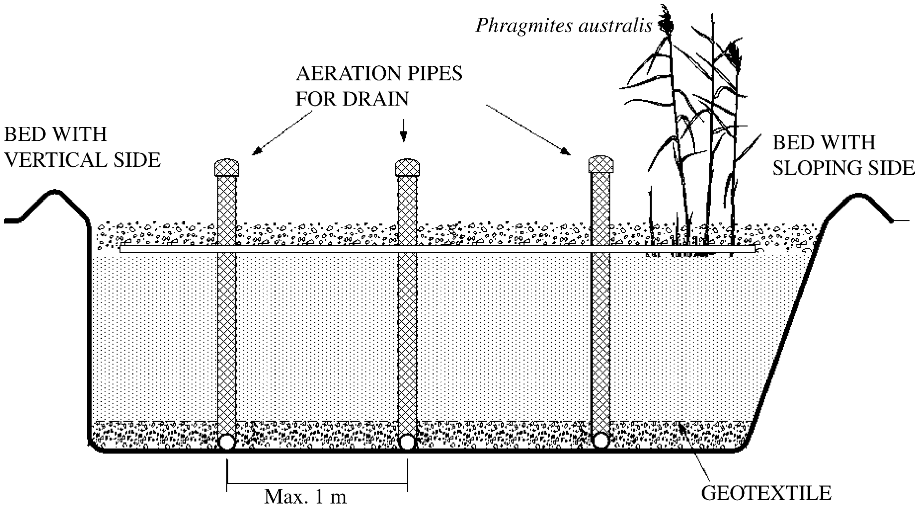

Fig. 5. Vertical cut through a filter bed showing the position of the distribution system and drainage system. The drainage pipes must be aerated by vertical pipes extending into the atmosphere. The filter bed can be built with vertical sides (shown at the left) or sloping sides (shown on the right).

3.7. Effluent recirculation

Half of the effluent water from the filter is recycled to the first chamber of the sedimentation tank or to the pumping well to enhance denitrification and to stabilise treatment performance of the system. A split well containing two V-notch weirs is placed at the outlet of the system, and the overflow from one weir is recirculated by gravity preferentially to the first chamber of the sedimentation tank. If this is not possible because of the local site conditions, recirculation can be done to the pumping well. It is important that the V-notch weirs are placed at the same level in order to distribute the water evenly between recirculation and effluent. The weirs should also be easily accessible for cleaning and maintenance.

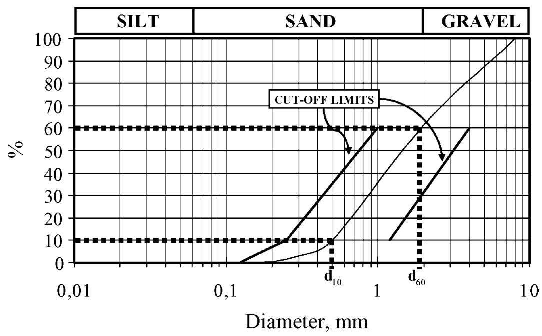

Fig. 6. The filtersand should have a d_{10} between 0.25 and 1.2 mm, a d_{60} between 1 and 4 mm, and the uniformity coefficient ($U = d_{60}/d_{10}$) should be less than 3.5. The grain distribution curve should be located between the two cut-off lines in the diagram.

3.8. Planting

The bed is planted with the common reed, *P. australis*, in a density of approximately 4 plants/m^2. The best planting time is April–May, but planting can be done all year round except is periods with risks of severe frost. The best result is obtained if potted seedlings are used, but pieces of rhizomes might also be used (Brix, 2003b).

3.9. Systems larger than 5 PE

For systems with capacities larger than 5 PE, the size of the filter bed is increased in proportion to the loading (Fig. 7). For systems larger than 15 PE, it is preferred to divide the system into two equal-sized beds loaded in parallel. It is very important to make sure that the pump capacity is increased in proportion to the size of the systems in order to assure an even distribution of water across the entire bed surface.

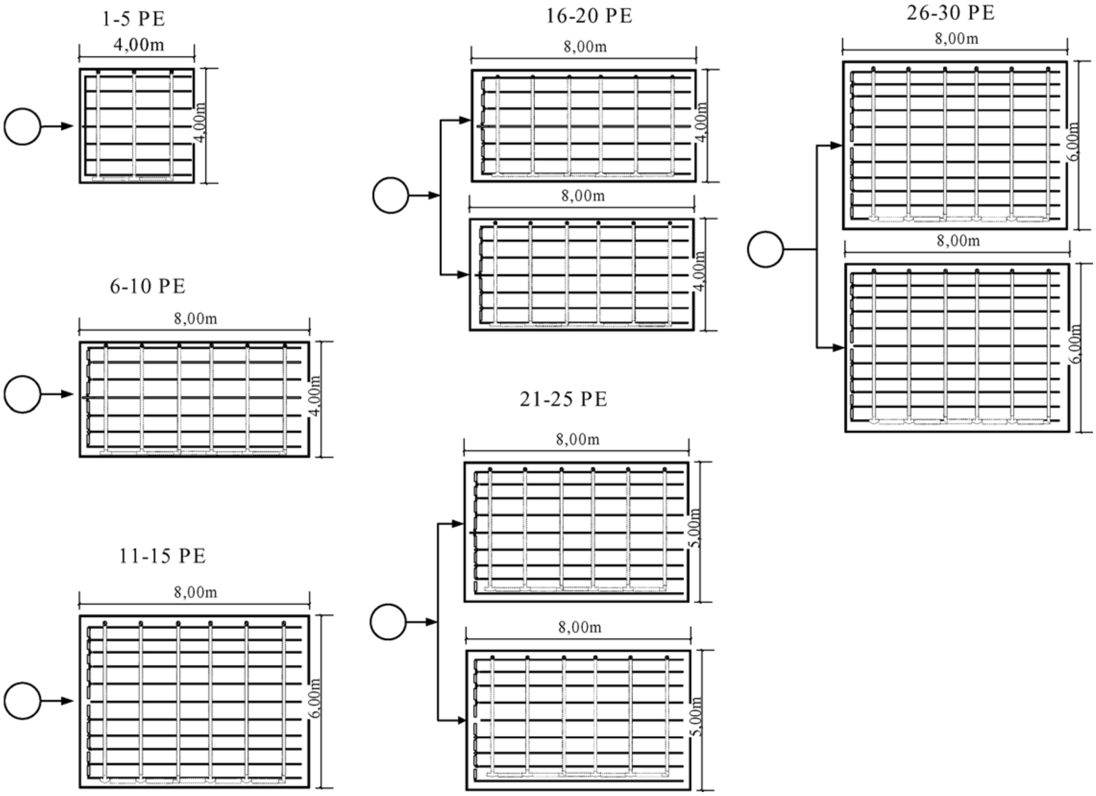

Fig. 7. Layout of vertical flow constructed wetland systems for capacities up to 30 PE. Systems with capacities larger than 15 PE should be divided into two parallel beds.

3.10. Phosphorus removal

The removal of phosphorus in the vertical flow constructed wetland system described here will be fairly low, typically 20–30%. If higher removals are required, this can be achieved by chemical precipitation in the sedimentation tank (Fig. 8). A very simple solution has been developed using addition of aluminium polychloride in small doses in the sedimentation tank. The dosing system consists of a timer-controlled dosing pump and a small aeration pump installed in a separate well next to the sedimentation tank. The aluminium polychloride is dosed into the outlet of an airlift pump placed in the third chamber of the sedimentation tank. The airlift pump is circulating water at a low rate from the third chamber to the first chamber, and is at the

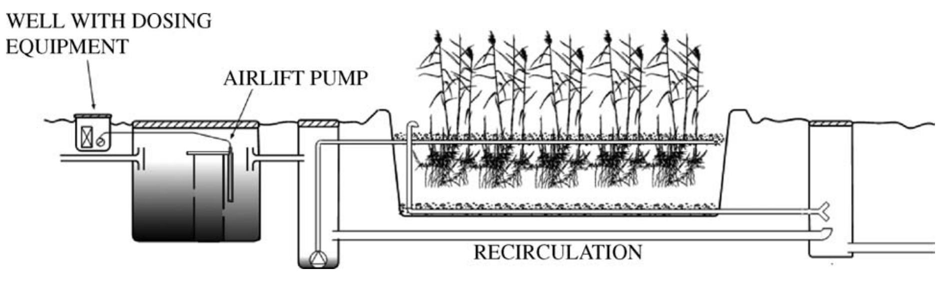

Fig. 8. Vertical flow constructed wetland system extended with chemical precipitation of phosphorus in the sedimentation tank.

same time mixing the aluminium polychloride with the wastewater, without disturbing the sludge in the bottom of the tank. The use of chemicals is about 30 l/year for a single household.

3.11. Management requirements

Sludge must be emptied from the sedimentation tank once per year to secure a well-functioning removal of settleable and floating material prior to the filter bed. The distribution pipes should be cleaned and flushed once per year to remove sludge and biofilm that might have blocked some of the holes. The V-notch weirs distributing water between effluent and recirculation should be inspected and cleaned at regular intervals, e.g. every third month. During the first growing season, it is important to remove any weeds that might compete with the planted reeds. The reeds should not be harvested during autumn because the plant material will help insulate the filter against frost during winter. It might, however, stimulate the growth of the plants if the aboveground dead plant material is removed in the early spring. If it happens that the vertical filter clogs because of overloading, the system should be taken out of operation for a period of several weeks and allowed to dry out. If this does not help, it might be necessary to remove and replace the upper 10 cm of the filtersand.

4. Performance of single household systems

Until now, there is very limited information on the actual performance of systems designed and constructed according to the guidelines. The design and

Table 1
Performance data (mean ± 1 S.D.) of some single-house vertical flow constructed wetlands

System	Parameter	Inlet ($mg\,l^{-1}$)	Outlet ($mg\,l^{-1}$)	Removal (%)
VF1[a] (without recirculation)	TSS	85 ± 28	8 ± 3	91
	BOD_5	254 ± 123	19 ± 4	92
	NH_4-N	105 ± 45	23 ± 17	78
	$NO_2 + NO_3$-N	<0.1	40 ± 13	–
	Total-N	125 ± 51	72 ± 28	43
	Total-P	17.2 ± 7.0	13.0 ± 6.6	25
VF1 (with 100% recirculation)	TSS	68 ± 22	3 ± 1	96
	BOD_5	100 ± 35	11 ± 3	89
	NH_4-N	45 ± 13	7 ± 1	85
	$NO_2 + NO_3$-N	0.13 ± 0.09	36 ± 4	–
	Total-N	57 ± 13	44 ± 5	23
	Total-P	5.2 ± 1.7	5.7 ± 1.2	0
VF2[b]	TSS	88 ± 8	7 ± 5	92
	BOD_5	507 ± 395	7 ± 2	98
	NH_4-N	242 ± 75	59 ± 11	76
	$NO_2 + NO_3$-N	0.1 ± 0.1	141 ± 40	–
	Total-N	350 ± 5	190 ± 37	46
	Total-P	20.6 ± 7.5	7.5 ± 4.8	64
VF3[c]	TSS	124 ± 135	4 ± 3	97
	BOD_5	320 ± 139	2 ± 1	99
	NH_4-N	18 ± 22	0.4 ± 0.2	98
	$NO_2 + NO_3$-N	0.5 ± 0.5	8.0 ± 2.6	–
	Total-N	30 ± 23	9 ± 3	63
	Total-P	4.6 ± 3.6	4.5 ± 2.6	2

The inlet samples were taken as grab samples after the sedimentation tank. *Note:* The systems were not constructed and loaded according to the presented guidelines (see text for details).

[a] 15 m^2 system receiving sewage from a household with five persons monitored for a period without recirculation ($n = 10$) and a period with recirculation ($n = 4$) to the first chamber of the sedimentation tank.

[b] 17 m^2 system receiving only grey water from a household with four persons ($n = 3$).

[c] 8 m^2 system receiving only grey water from a household with four persons ($n = 3$).

construction of most of the systems in operation deviates significantly from the design described in the guidelines. Table 1 summarises performance data for some of these. In some instances the filtersand is significant coarser than prescribed resulting in water penetrating through the filter too fast with low nitrification rates as a result. Also, the depth of the filter bed is usually less than 1 m as prescribed by the guidelines. It is well known from several studies that most of the removal actually takes place in the upper few centimetres of the filter. However, the hydraulics of operational systems might not be perfect, and so there is a risk that water bypasses thin filters very fast because of non-homogeneity or channels in the filter material. Two of the systems presented are loaded by gravity (VF2 and VF3), and hence water is not distributed as effectively over the surface of the beds as it is for the pump loaded system. Two systems receive only grey water (VF2 and VF3), and only one of the systems has the possibility of recirculation of water to the sedimentation tank (VF1). It can be seen from Table 1 that recirculation of water results in lower effluent concentrations, and hence better performance. The inlet concentration also decreases, but this is artificial because of the dilution from the recirculated effluent water to the sedimentation tank. Sewage from single households often is very concentrated, and the concentration of ammonium nitrogen can be higher than 100 mg l^{-1}. In such cases, the dilution by recirculation is important to achieve low effluent concentrations. None of the systems presented have been extended with precipitation of phosphorus.

5. Discussion

When the guidelines produced by the Danish EPA are followed by the constructor, there are no requirements for the house owners to monitor performance. The systems are presumed to fulfil the outlet criteria as stated in the guidelines. The surface area of the vertical flow constructed wetland described in the Danish guidelines is smaller (3.2 m^2/PE) than the common applied area of 5 m^2/PE, which is used in Austrian guidelines (Österreichisches Normeringsinstitut, 1997). Austrian guidelines include nitrification (NH_4-N < 10 mg l^{-1}) but not phosphorus. The German guidelines concern on-site constructed wetland systems up to 50 PE and municipal systems up to 1000 PE (ATV, 1998). The guidelines are only valid for removal of organic matter (outlet demand: BOD_5 < 40 mg l^{-1}; COD < 150 mg l^{-1}) and it is stated that the surface area should be >2.5 m^2/PE. The low area need of vertical flow system to achieve simultaneous removal of BOD and nitrification is presently being recognised by several studies (Cooper, 1999, 2004; Platzer, 1999). It is possible to achieve full nitrification as well as BOD and TSS removal in vertical flow beds sized at 2 m^2/PE or less when treating domestic sewage. However, bed clogging might be a problem, particularly if the beds are operated without a resting period (Platzer and Mauch, 1997; Langergraber et al., 2003). In order to achieve a good performance and at the same time to prevent clogging, it is important that the bed medium allows the passage of the wastewater through the bed before the next dose arrives whilst at the same time holding the liquid back long enough to allow the contact with the bacteria growing on the media. The presence of the planted reeds will by their movement and growth help preventing clogging, but it is of prime importance that the texture of the bed medium is right. It is also important that the oxygen transfer rate to the bed medium is high, both from the atmosphere through the bed surface, but also from below via the aerated drainage layer. The design described in the Danish guidelines has integrated all these issues, which together with the effluent recirculation in the system will maximise treatment capacity and secure a good and sustainable performance.

References

ATV, 1998. Arbeitsblatt ATV-A 262. Grundsätze für Bemessung, Bau und Betrieb von Pflanzenbeeten für kommunales Abwasser bei Ausbaugrößen bis 1000 Einwohnerwerte. ATV-DVWK Deutsche Gesellschaft für Wasserwirtschaft und Abfall e.V., Hennef.

Arias, C.A., Brix, H., 2005. Phosphorus removal in constructed wetlands: Can suitable alternative media be identified? Water Sci. Technol. 51 (9), 267–273.

Arias, C.A., Brix, H., Johansen, N.H., 2003a. Phosphorus removal from municipal wastewater in an experimental two-stage vertical flow constructed wetland system equipped with a calcite filter. Water Sci. Technol. 48 (5), 51–58.

Arias, C.A., Brix, H., Marti, E., 2005. Recycling of treated effluents enhances removal of total nitrogen in vertical flow constructed wetlands. J. Environ. Sci. Health Part A – Toxic/Hazard. Subst. Environ. Eng. 40 (6–7), 1431–1443.

Arias, C.A., Cabello, A., Brix, H., Johansen, N.H., 2003b. Removal of indicator bacteria from municipal wastewater in an experimental two-stage vertical flow constructed wetland system. Water Sci. Technol. 48 (5), 35–41.

Arias, C.A., Del Bubba, M., Brix, H., 2001. Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. Water Res. 35, 1159–1168.

Brix, H., 1994. Functions of macrophytes in constructed wetlands. Water Sci. Technol. 29 (4), 71–78.

Brix, H., 1997. Do macrophytes play a role in constructed treatment wetlands? Water Sci. Technol. 35 (5), 11–17.

Brix, H., 2003a. Danish experiences with wastewater treatment in constructed wetlands. In: Dias, V., Vymazal, J. (Eds.), Proceedings of the First International Seminar on the Use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands. Ministerio das Cidades, Ordenamento do Território E Ambiente, Lisboa, Portugal, May 8–10, pp. 327–361.

Brix, H., 2003b. Plants used in constructed wetlands and their functions. In: Dias, V., Vymazal, J. (Eds.), Proceedings of the First International Seminar on the Use of Aquatic Macrophytes for Wastewater Treatment in Constructed Wetlands. Ministerio das Cidades, Ordenamento do Território E Ambiente, Lisboa, Portugal, 8–10 May, pp. 81–109.

Brix, H., Arias, C.A., 2005. Danish guidelines for small-scale constructed wetland systems for onsite treatment of domestic sewage. Water Sci. Technol. 51 (9), 1–9.

Brix, H., Arias, C.A., Del Bubba, M., 2001. Media selection for sustainable phosphorus removal in subsurface flow constructed wetlands. Water Sci. Technol. 44 (11–12), 47–54.

Brix, H., Arias, C.A., Johansen, N.H., 2002. BOD and nitrogen removal from municipal wastewater in an experimental two-stage vertical flow constructed wetland system with recycling. In: Proceedings of the Eighth International Conference on Wetland Systems for Water Pollution Control, Arusha, Tanzania, 16–19 September, pp. 400–410.

Brix, H., Arias, C.A., Johansen, N.H., 2003. Experiments in a two-stage constructed wetland system: nitrification capacity and effects of recycling on nitrogen removal. In: Vymazal, J. (Ed.), Wetlands—Nutrients, Metals and Mass Cycling. Backhuys Publishers, Leiden, The Netherlands, pp. 237–258.

Brix, H., Johansen, N.H., 2004. Retningslinier for etablering af beplantede filteranlæg op til 30 PE. Økologisk Byfornyelse og Spildevandsrensning. Miljøstyrelsen (in Danish) 52, 1–48.

Brix, H., Schierup, H.-H., 1990. Soil oxygenation in constructed reed beds: the role of macrophyte and soil atmosphere interface oxygen transport. In: Cooper, P.F., Findlater, B.C. (Eds.), Constructed Wetlands in Water Pollution Control. Pergamon Press, London, pp. 53–66.

Cooper, P., 1999. A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. Water Sci. Technol. 40 (3), 1–9.

Cooper, P., 2004. The performance of vertical flow constructed wetland systems with special reference to the significance of oxygen transfer and hydraulic loading rate. In: Proceedings of the Ninth International Conference on Wetland Systems for Water Pollution Control, Avignon, France, September, pp. 153–160.

Del Bubba, M., Arias, C.A., Brix, H., 2003. Phosphorus absorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. Water Res. 37, 3390–3400.

Johansen, N.H., Brix, H., Arias, C.A., 2002. Design and characterization of a compact constructed wetland system removing BOD, nitrogen and phosphorus from single household sewage. In: Proceedings of the Eighth International Conference on Wetland Systems for Water Pollution Control, Arusha, Tanzania, 16–19 September, pp. 47–61.

Laber, J., Perfler, R., Haberl, R., 1997. Two strategies for advanced nitrogen elimination in vertical flow constructed wetlands. Water Sci. Technol. 35 (5), 71–77.

Langergraber, G., Haberl, R., Laber, J., Pressl, A., 2003. Evaluation of substrate clogging processes in vertical flow constructed wetlands. Water Sci. Technol. 48 (5), 25–34.

Marti, E., Arias, C.A., Brix, H., Johansen, N.H., 2003. Recycling of treated effluents enhances reduction of total nitrogen in vertical flow constructed wetlands, vol. 94. Publicationes Instituti Geographici Universitatis Tartuensis, pp. 150–155.

Ministry of Environment and Energy, 1997. Act No. 325 of 14 May 1997 on Wastewater Treatment in Rural Areas (in Danish).

Ministry of Environment and Energy, 2000. Aquatic Environment 1999. State of the Danish Aquatic Environment. Environmental Investigations No. 3.

Österreichisches Normeringsinstitut, 1997. Bepflanzte Bodenfilter (Pflanzenkläranlagen) Anwendung, Bemessung, Bau und Betrieb. ÖNORM B 2505.

Platzer, C., 1996. Enhanced nitrogen elimination in subsurface flow artificial wetlands—a multi stage concept. In: Proceedings of the Fifth International Conference on Wetland Systems for Water Pollution Control, Universität für Bodenkultur Wien, Vienna, Austria.

Platzer, C., 1999. Design recommendations for subsurface flow constructed wetlands for nitrification and denitrification. Water Sci. Technol. 40 (3), 257–263.

Platzer, C., Mauch, K., 1997. Soil clogging in vertical flow beds. Mechanisms, parameters, consequences and solutions. Water Sci. Technol. 35 (5), 175–181.

Weedon, C.M., 2003. Compact vertical flow constructed wetland systems—first two years' performance. Water Sci. Technol. 48 (5), 15–23.