

NATIONAL EXPERIENCES



DANISH EXPERIENCES WITH WASTEWATER TREATMENT IN CONSTRUCTED WETLANDS

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ABSTRACT

Constructed wetlands have been in use in Denmark since 1983. The initial systems were soil-based reed beds constructed according to the root-zone concept. These systems perform satisfactorily concerning removal of TSS and BOD, but removal of nitrogen and phosphorus and nitrification do not meet present standards. Presently more focus is put on two-stage systems and vertical flow systems because of the higher treatment capacity and better removal efficiency of these systems. This paper summarises the experiences with the different types of constructed wetlands that are in use in Denmark. Besides the soil-based constructed reed beds, a two-stage system consisting of a horizontal subsurface flow bed followed by a vertical flow bed for nitrification is described. A compact vertical flow system equipped with a separate calcite filter for removal of phosphorus and with recirculation of nitrified effluent to the sedimentation tank is described. A deep vertical flow system with crushed marble constructed to treat combined sewer overflow is described, and finally a new evaporative system based on evapotranspiration by willows is described.

KEYWORDS

Constructed wetland; reed bed; root-zone system; treatment wetland; vertical flow; willow.

INTRODUCTION

Full-scale constructed reed beds have been in operation in Denmark since 1983 where the root-zone-method was introduced from Germany (Brix, 1987b). Since then, several hundred systems have been constructed, and during the past year new system designs have been developed. The present paper attempt to summarise the Danish experiences with constructed wetlands. The overall experience with soil based reed beds constructed according to the root-zone concepts has already been described in detail elsewhere (Brix, 1998), and therefore these experiences will only be summarised here based

largely on this publication. In the last sections of the paper some of the newest developments within the constructed wetland systems in Denmark are described.

HISTORY OF THE USE OF CONSTRUCTED WETLANDS IN DENMARK

The initial Danish concept for the construction of reed beds has largely been a copy of the German ideas and recommendations, introduced in 1983 (Brix, 1987b). This includes the inlet arrangement, area required, soil physical composition and the two preferred wetland plants: *Phragmites australis* (the Common Reed) and *Typha latifolia* (Broad-Leaved Cattail). Several municipalities accepted the theoretical assumptions for the operation of this kind of macrophyte-based wastewater treatment system concerning the reduction of BOD₅ and removal of total-N and P, heavy metals and indicator bacteria. For all the parameters an efficiency better than 90% was claimed when a reed bed surface area of 3 to 5 m² PE⁻¹ (PE = person equivalent) was assumed (Kickuth, 1980; Kickuth, 1982). These claims were largely based on data from a system in Othfresen in Germany, but the validity of these data has later been seriously questioned (Brix, 1987a). After a few years it became obvious that the initial claims concerning treatment performance were not fulfilled (Schierup et al., 1990). And contrary to earlier belief, the growth of the reed did not increase the hydraulic conductivity of the substrate (Brix and Schierup, 1990; Haberl and Perfler, 1990). Therefore experiments with new designs based on gravel and vertical flow were initiated (Johansen and Brix, 1996; Brix and Johansen, 1999; Brix et al., 2001b; Johansen et al., 2002; Brix et al., 2002; Arias et al., 2002; Cabello et al., 2002). Also, specific systems were developed to remove phosphorus (Brix et al., 2000; Arias et al., 2001; Gervin and Brix, 2001; Brix et al., 2001a; Brix et al., 2001b; Johansen et al., 2002; Arias et al., 2002). In the late nineties a new type of constructed evaporative wetland with no outflow based on willows was introduced as a treatment solution particularly in rural areas (Gregersen and Brix, 2001).

EXPERIENCES WITH THE ROOT - ZONE METHOD

In the following text the term reed bed will be used to describe systems constructed according to the root-zone concept, i.e. soil based systems with intended subsurface flow (Figure 1).

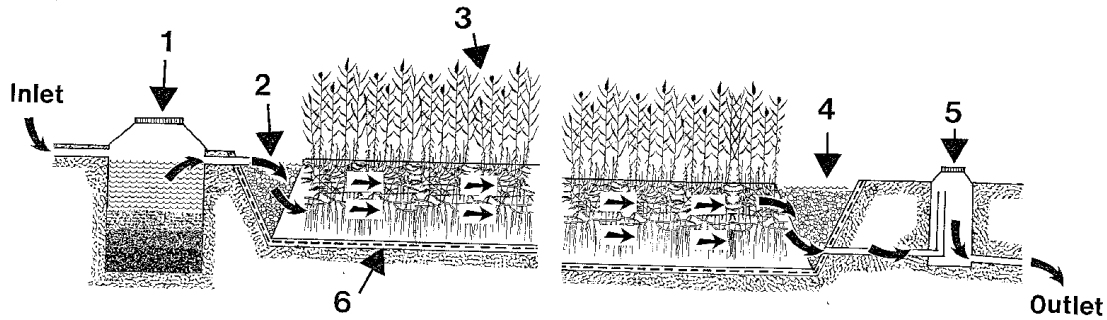


Figure- 1

Typical arrangement of a Danish reed bed constructed according to the root-zone concept. 1. Sedimentation tank; 2. Stone-filled inlet distribution trench; 3. The common reed, *Phragmites australis*; 4. Stone-filled outlet collection trench; 5: Outlet regulation well. From Brix (1987b)

In all Danish reed beds the wastewater is pre-treated before inlet to the reed bed. Generally, the pre-treatment takes place in two- or three-chamber settling tanks. The earliest systems were more or less square. However, as overland flow appeared to be a common problem in these systems, the 2nd generation systems were designed with a low aspect ratio (length:width ratio) and thus have very long inlet trenches and a comparably short passage length. A low aspect ratio was thought to overcome the problem of surface flow. However, the design with very long inlet trenches caused problems with the distribution of water in the inlet trench. Therefore in the next generation systems the inlet trench was subdivided into two or more separate units that could be loaded separately in order to get better control on the distribution of water.

All constructed reed beds have been excavated to a depth of 0.6-1 m. In most cases a water tight membrane of polyethylene, PVC, or clay has been placed at the bottom of the excavation in order to prevent seepage and contamination of the groundwater. In a small number of reed beds (especially those on clayish soils) the membrane has been omitted. In most cases local soil has been used as the medium in the reed beds, but in a few cases the soils have been amended with sand, organic material or chalk in an attempt to improve the hydraulic permeability or the ability to retain phosphorus. The latest designs are established with coarse sand as the medium in order to secure a high hydraulic conductivity.

The pre-treated sewage is generally led to a stone-filled inlet trench by one or more water pipes in order to secure a good distribution of the sewage in the trench. In many cases the inlet is distributed through a drainage pipe buried in the inlet trench. By this

design a free water surface at the inlet trench can be completely omitted. At the outlet a similar stone-filled trench is used to collect water from the reed bed. Normally it is possible to regulate the water level in the reed bed by a special arrangement in an outlet well.

The constructed reed beds are usually planted with *Phragmites australis* (the Common Reed). In the initial systems clumps or rhizomes of *Phragmites* from local wetlands were planted. However, today most beds are planted with potted seedlings which are commercially available from nurseries. In some of the initial systems, the cattails *Typha latifolia* and *Typha angustifolia* were planted close to the inlet trench, but also other species like *Iris pseudacorus* (Yellow Flag) and *Carex acutiformis* (Lesser Pond Sedge) have been planted in sections of the reed beds. Normally, the total amount of wastewater (full capacity) has been supplied to the bed right from the beginning.

Number Danish constructed reed beds

Through a questionnaire to the 275 municipalities in Denmark and companies designing constructed wetland treatment systems in 1997, information on 134 constructed reed beds have been collected. About two-third of those are public systems owned by the municipalities and the remaining are privately owned (Schierup et al., 1990; Brix, 1998). While the number of publicly-owned reed beds probably is correct, the number of privately-owned reed beds is a minimum estimate since private systems are not necessarily registered by local authorities.

The number of systems constructed since 1983 is shown in Figure 2. It should be noticed that the interest in the technique was high shortly after the introduction of the technology in Denmark in 1983. The high interest prevailed until 1988 where the number of new constructions decreased. This decrease was related to a new central legislation - "the Water Environment Plan" - which defined new requirements to nutrient removal for large producers of wastewater (>5 000 PE). In the following years until 1992, the municipalities therefore had to concentrate their investments on the major sources of wastewater, and less emphasis was put on small on-site systems. Furthermore, the fact that the earlier systems did not fulfil the initial expectations to nutrient removal resulted in a generally decreasing interest in constructed reed bed systems. Since 1996 the number of new constructions has been small, and a number of the earliest systems have been closed down, mainly because of new nitrification requirements.



Figure- 2

Number of reed beds constructed in Denmark in the period 1983-1996. From Brix (1998)

The reed beds are generally used to treat wastewater from small wastewater producers (size: 10-500 PE). About 50% of all constructed reed beds are smaller than 1 000 m² and serve less than 200 PE (Brix, 1998). The number of small reed beds (less than 100 m²) is probably much higher since the exact number of privately-owned reed beds is not known. Only one system is larger than 10 000 m² (surface area 13 000 m²). This system has been constructed to treat the secondary effluent from a larger village with 6 000 PE.

The vast majority of the Danish reed beds are constructed to treat domestic sewage from small villages in rural areas and as on-site systems for single households and farms. Often small villages have combined sewerage systems, i.e. the reed beds receive rainwater as well as domestic sewage, although newly sewered villages have separate systems. Constructed reed beds are, however, also used to treat wastewater from schools and institutions, camping sites, leachate from solid waste deposits, run-off from roads, and effluent from some industries (mainly food-processing factories). A few systems function as a tertiary step after conventional wastewater treatment systems.

Outlet criteria for Danish constructed reed beds

Until recently there were no general discharge standards for small wastewater treatment systems in Denmark. However, all public reed beds and most of the privately-owned systems have well defined discharge standards. The criteria may include demands on 90 or 95% removal of BOD, 90% removal of phosphorus and 90% nitrification, depending

on the receiving waters. In addition, there may be standards for suspended solids, temperature, pH and oxygen saturation. For systems serving more than 30 PE, the effluent quality must be monitored at regular intervals, normally on a monthly basis, although 4-8 samples per year is regarded as adequate for very small systems. The inlet and effluent quality control samples are usually taken during a 24-hour period proportional to volume flow. Quality control analyses normally include measurements of pH, total suspended solids (TSS), biochemical oxygen demand (BOD₅), dissolved oxygen, chemical oxygen demand (COD), total nitrogen (total-N), nitrite and nitrate (NO₂+NO₃), ammonium nitrogen (NH₄-N), total phosphorus (total-P) and orthophosphate (PO₄-P).

Performance of the Danish reed beds

Inlet and outlet quality data from the Danish systems have been collected in a central database at the Department of Plant Ecology, University of Aarhus. The database contains the analytical results from more than 5000 samples from nearly 100 systems. In the following sections the data for TSS, BOD₅, N-fractions and total-P will be summarised largely based on Brix (1998).

Total Suspended Solids (TSS)

The influent concentrations of TSS to the reed beds were very variable <2 to 3 800 mg/l (median 75 mg/l) depending on the type of wastewater and the efficiency of the mechanical pre-treatment. In spite of high concentrations in the inlet, the concentrations in the effluent were consistently low (median value 7.6 mg/l). Effluent concentrations exceeding 10 mg/l were often connected with production of algae in systems with open water in the effluent channel. The effluent concentrations of TSS were independent of the inlet concentrations as well as of the TSS mass loading rate and the hydraulic loading rate.

Biochemical Oxygen Demand (BOD₅)

The median inlet concentration of BOD₅ was 94 mg/l varying between less than 10 to >8 000 mg/l. About a third of all systems had median effluent concentrations of <5 mg/l, 80% had <10 mg/l, and 98% had median effluent BOD₅ concentrations of <20 mg/l. The effluent concentration of BOD₅ was largely independent on inlet concentration as well as on the mass loading and the hydraulic loading rate. The BOD₅ mass loading rate of the systems varied between <1 to 23 g BOD₅ m⁻² day⁻¹ (average 5 g m⁻² day⁻¹).



Phosphorus

The inlet concentration of total-P varied between 0.04 and 175 mg/l (median 7.4 mg/l), and the effluent concentration between 0.01 and 55 mg/l (median 4.8 mg/l). The effluent concentrations of total-P were linearly related to the inlet concentrations. The regression coefficient indicates a mean removal efficiency of total-P of ~54%. However, the scatter around the line is immense, and in most of the systems the removal of total-P was less, maybe 20-30%. However, some systems had much better. There were no clear relationships between the effluent concentrations of total-P and the mass loading rate, and the percent removal was independent of inlet concentration. The results show that the removal of total-P varies between systems, probably as a consequence of differences in system design (e.g. type and P-binding capacity of substrate used in the beds).

Nitrogen

A linear relationship between inlet and effluent concentrations of total-N was observed. The regression coefficient indicates a mean removal efficiency of ~50% for total-N. There were no clear relationships between the effluent concentration of total-N and the mass loading rate, and the removal efficiency was independent of inlet concentration. The median inlet and outlet concentrations of total-N were 35 mg/l (range 2.1 - >300 mg/l) and 20 mg/l (range 0.7-198 mg/l), respectively. Nitrogen occurs primarily as $\text{NH}_4\text{-N}$ in the inlet and outlet water, the median inlet and outlet concentrations being 25 and 12 mg/l, respectively. In general the removal of $\text{NH}_4\text{-N}$ was low in the reed beds, and the effluent concentrations of NH_4 were dependent on the inlet concentrations. As expected, most reed beds had low inlet concentrations of $\text{NO}_2\text{+NO}_3$ (median 1 mg/l). A number of systems, including most of the systems designed as a tertiary stage after a conventional wastewater treatment system, had higher inlet concentrations of NO_3 , and in those systems there was a tendency to lower effluent concentrations as a consequence of denitrification. Under optimal conditions, ammonium should be nitrified during the passage of the reed beds, and the produced NO_2 and NO_3 subsequently denitrified. Nitrification seems to be the process limiting nitrogen removal.

PH

There was no tendency to a pH reduction during the passage through the reed beds, which in case could have influenced the stability of precipitated phosphorus compounds within the systems. The median pH in both inlet and outlet was ~7.6, and the inlet pH varied more than the effluent pH. A decrease in pH could have resulted from

nitrification. However, the buffer capacity of the water is normally high and a decrease in pH due to nitrification may not be detected. In all systems the average effluent pH during the whole period of operation was >7 .

System performance in relation to age

The reed bed at the village Sdr.Thise, treating the sewage from a 120 PE village, is used as an example of the development in performance in relation to system's age. The results from this system are some of the best of the Danish systems. The bed was established in 1985, and consists of a 560 m² one-unit bed planted with *Phragmites australis* (clones imported from Germany). The depth of the bed is 60 cm. The medium in the bed is the local soil (loam). The sewerage system in the village is a combined system receiving municipal sewage as well as rainwater. The water is pre-treated in a three-chamber settler before the reed bed. The effluent standards for the system is confined to BOD₅ (<15 mg/l). The data presented here are based on 24-hour composite influent and effluent samples taken proportional to flow.

The hydraulic loading rate of the system varies with the season, generally being highest during winter and spring where the system is receiving a fair amount of rainwater in addition to the sewage. This huge variability in hydraulic loading rate (average ± 1 standard deviation: 11.8 ± 11.8 cm day⁻¹) affects the strength of the wastewater in the inlet. Thus, high hydraulic loading rates usually occur in concert with rather dilute wastewater. The overall performance data of the system is presented in Table 1 and Figures 3 to 6.

Table - 1

Average inlet and outlet concentrations and removal rates at the constructed reed bed at Sdr. Thise during the period 1985-2000

Parameter	Inlet	Outlet	Removal
pH	7.8 ± 0.4	7.6 ± 0.2	-
TSS (mg/l)	329 ± 272	18 ± 16	94%
BOD ₅ (mg/l)	215 ± 145	12 ± 12	95%
COD (mg/l)	549 ± 358	78 ± 58	86%
Total-N (mg/l)	54.6 ± 18.9	11.7 ± 12.3	46%
NH ₄ -N (mg/l)	35.0 ± 15.5	22.6 ± 11.1	36%
NO ₂ +NO ₃ -N (mg/l)	1.9 ± 1.3	3.2 ± 3.7	-
Total-P (mg/l)	13.2 ± 5.3	9.0 ± 7.0	32%

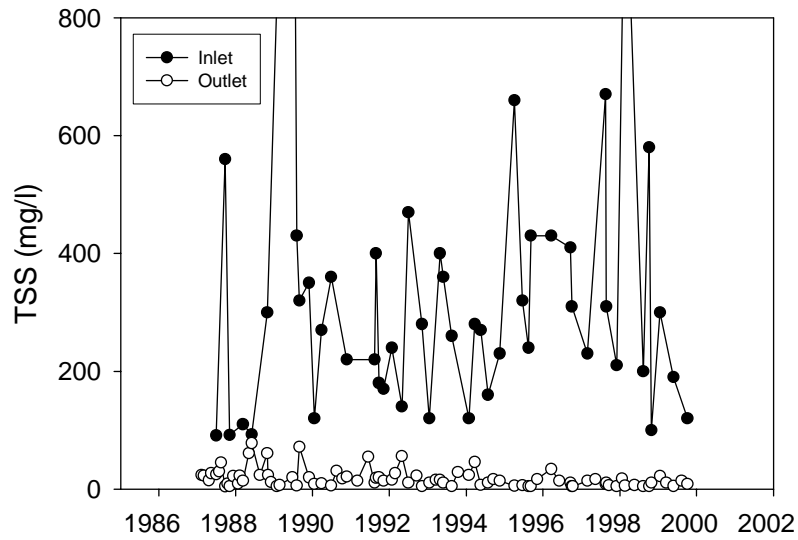


Figure- 3

Inlet and outlet concentrations of total suspended solids in the constructed reed bed at Sdr. Thise

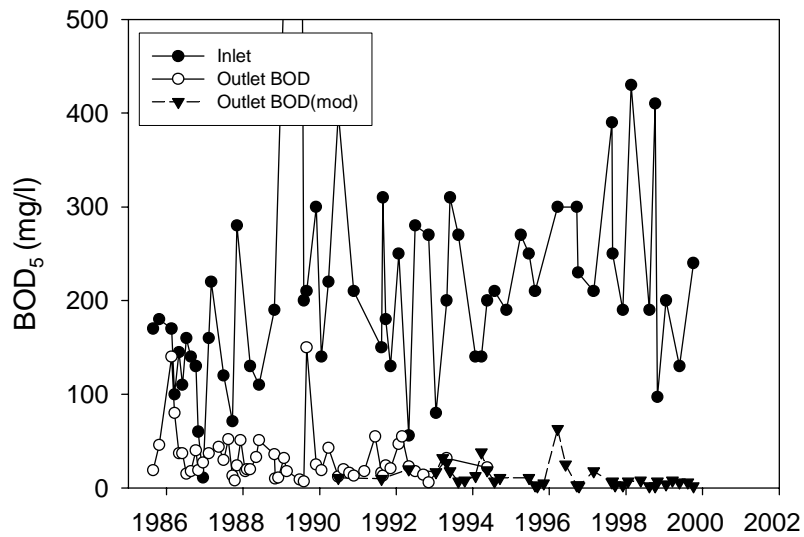


Figure- 4

Inlet and outlet concentrations of biochemical oxygen demand in the constructed reed bed at Sdr. Thise

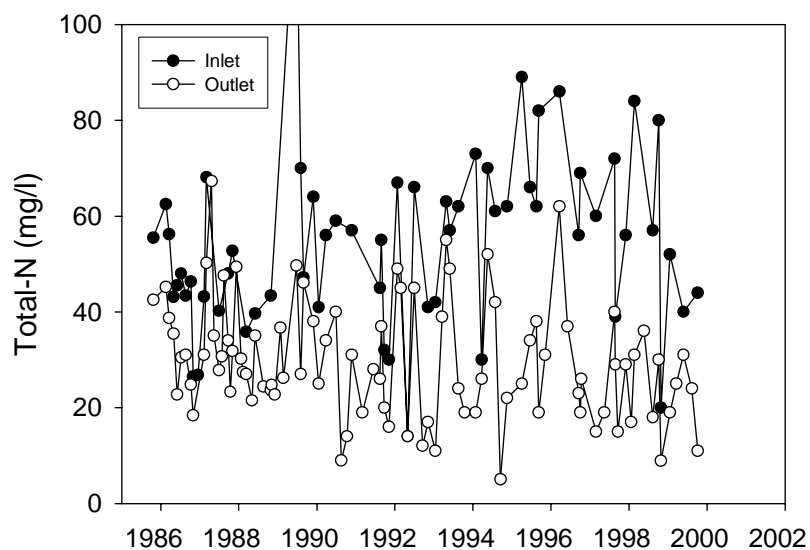


Figure- 5
Inlet and outlet concentrations of total nitrogen in the constructed reed bed at Sdr. Thise

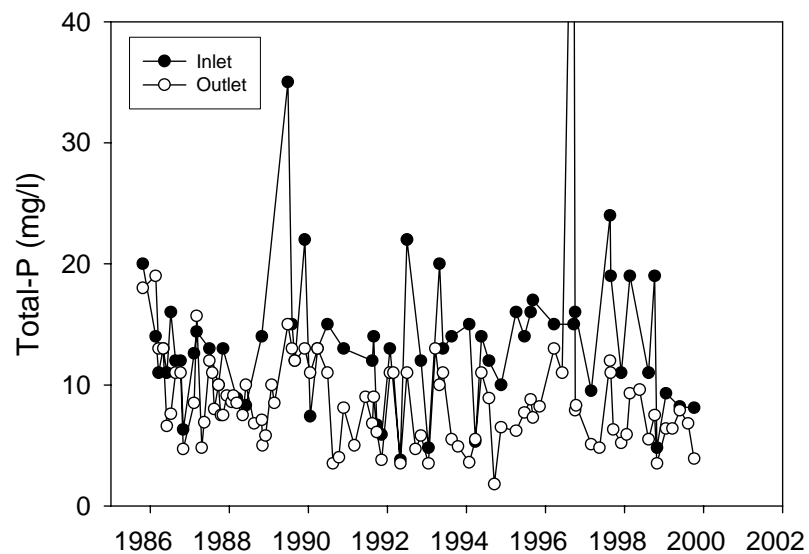


Figure- 6
Inlet and outlet concentrations of total phosphorus in the constructed reed bed at Sdr. Thise



Total suspended solids and BOD₅ were removed effectively in the system (Figs. 3 and 4). However, the removal of nitrogen and phosphorus was poor (Figs. 5 and 6). Most nitrogen in the inlet was in the form of ammonium, and the nitrification in the system was very poor. The general pattern shown here is typical of most of the soil-based constructed reed beds in Denmark. The performance with respect to TSS and BOD₅ is excellent after an initial running-in-phase of variable duration, whereas the performance with respect to N and P is ~30-40% removal. In more recent systems constructed with better hydraulic control with sand or gravel as the medium, the treatment performance develops much faster (within a few months).

Soil-based systems do fulfil the general effluent standards for TSS and BOD₅ after only one growing season. However, the performance does continue to improve with time. This development of performance with time is especially pronounced for P and N. In soil-based systems a great proportion of the wastewater bypasses the bed as surface flow because of low soil hydraulic conductivity. However, in concert with the development of vegetation a layer of dead plant material (litter) is produced on the surface of the beds. The continuous development in treatment performance seen is probably associated with the thickness of this layer of litter, which is providing a great surface area for attached microbial growth. It is likely that the performance of these systems will continue to improve in the future in concert with the development of the litter layer. Despite the fact that the temperature of the water varies by more than 10 degrees between summer and winter in the Danish constructed reed beds, there is no seasonal variation in treatment performance (Brix, 1998).

Dimensioning criteria for Danish reed beds

The criteria for the dimensioning of most Danish reed beds were originally based on the design principles presented by Kickuth (1982). The basis for the design model was some measurements in the constructed reed bed at Othfresen, Germany. The measurements in the Othfresen system indicated that the degradation of organic material can be described by first-order reaction kinetics. The model was based upon measurements which has later been criticised especially due to the physical construction of the Othfresen system and due to measurements in the systems undertaken by other institutions (Brix, 1987a).

The design principles used in the dimensioning model consists of (i) calculation of the necessary bed volume based on first-order reaction kinetics for the degradation of organic matter (measured as BOD₅), and (ii) calculation of the bed dimensions (length,

width, slope) based on Darcy's law and the hydraulic conductivity in the rhizosphere of the wetland plants (Brix, 1987b). The dimensioning model assumes plug flow without dispersion. Kickuth (1982) stated that the hydraulic conductivity in a reed bed with initial low hydraulic permeability after three years would increase to 10^{-3} m s^{-1} due to the formation of coarse pores as a consequence of decaying roots and rhizomes. However, this statement, which is a prerequisite for getting the wastewater in contact with the soil, has not been supported by others.

Performance evaluation

The quality control analyses from the large number of Danish constructed reed beds show that satisfactory removal efficiency only exists for suspended solids and BOD₅. However, as the reed beds are exclusively used for small to medium sized communities where the discharge standards are (or have been) confined to BOD₅ and TSS, the reed beds generally perform satisfactorily in the context of meeting the discharge standards. A few systems have been closed because of their lack of nitrification, and a few have been extended with a nitrification step in order to meet nitrification standards.

TWO-STAGE CONSTRUCTED REED BEDS

All the systems described so far are soil-based horizontal subsurface flow systems planted mainly with *Phragmites australis*. The treatment efficiency in these systems is generally good in terms of suspended solids and BOD removal, but poor in terms of nutrient removal and ability to nitrify the effluent. Nowadays there is also a demand for nitrification (and enhanced nutrient removal) in many locations, even for small wastewater producers. Therefore, a new two-stage design was developed attempting to meet these requirements.

During the past few years a great emphasis has been put on constructed wetlands with vertical-flow (Brix and Johansen, 1999). In an intermittently-loaded vertical-flow system substrate oxygenation is increased several-fold compared to horizontal subsurface flow systems (Brix and Schierup, 1990). During the loading period air is forced out of the substrate and during the drying period atmospheric air - and hence oxygen - is drawn into the pore spaces of the substrate. Furthermore, diffusive oxygen transport to the substrate is enhanced during the drying period, as the diffusion of oxygen is approximately 10 000 times faster in air than in water. Therefore, vertical-flow systems are generally able to provide good nitrification of the wastewater. However, loading only mechanically pre-treated wastewater onto a vertical flow bed possesses a potential risk of clogging the bed.



Based on the present experiences with various designs of constructed wetland treatment systems and on experiences from traditional trickling filter technologies, a two-stage constructed wetland system capable of providing nitrification as well as a better removal of total nitrogen and phosphorus compared to conventional reed beds was developed (Johansen and Brix, 1996; Brix and Johansen, 1999). The first systems constructed according to this concept have been built in Poland (Ciupa, 1995; Ciupa, 1996).

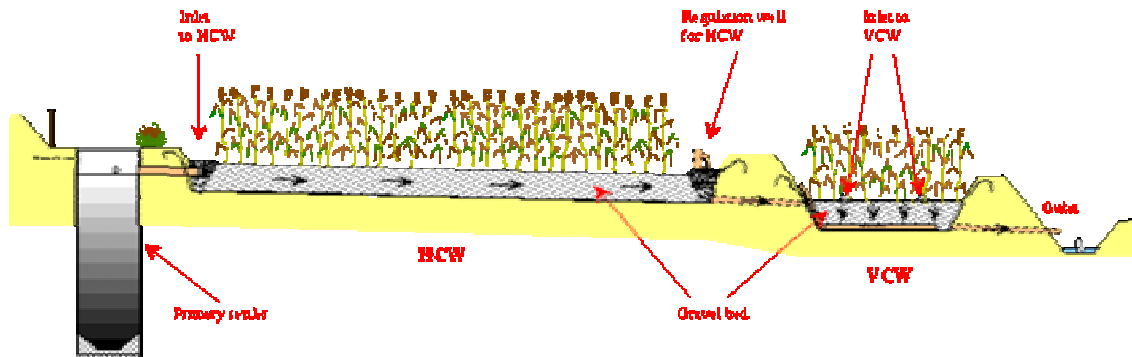


Figure- 7

Sketch of a two-stage constructed wetland consisting of a sand-based horizontal subsurface flow unit for degradation of BOD followed by a pulse-loaded vertical-flow unit for nitrification. Enhanced nitrogen removal can be achieved by recycling of the nitrified effluent to the first stage and hence get denitrification there.

System design

The concept of the system is as follows (Fig. 7): (1) A mechanical pre-treatment step (usually a two- or three-chamber settler) for removal of large particles and settleable material; (2) A horizontal subsurface flow sand or gravel-based constructed reed bed (HCW) for TSS and BOD removal (and denitrification if recirculation is applied); (3) An intermittently-loaded vertical-flow constructed wetland (VCW) for nitrification; and (4) an option for recirculation from the VCW to the inlet of the HCW where the nitrified nitrogen can be denitrified (total-N removal). Phosphorus will be adsorbed to the substrate. However, if necessary, precipitation chemicals (e.g. FeCl_3) can be added before the VCW for enhanced P-removal. The precipitates will then accumulate in the VCW which is kept aerobic.

Dimensioning process

Dimensioning of the two-stage constructed wetland treatment system is based on obtained performance data from other full scale constructed wetland systems, as well as experience of traditional trickling filter technologies. The dimensioning process involves the following steps (Johansen and Brix, 1996; Brix and Johansen, 1999):

1. Estimate the amount and characteristics of the wastewater to be treated as well as the desired outlet quality.
2. Estimate the load into the HCW based on knowledge of reduction in the chosen mechanical pre-treatment step.
3. Estimate the surface area of the HCW needed using empirically-determined first-order degradation rate constants (k_{BOD}) and background BOD concentrations (C^* , see Kadlec & Knight (1996).
4. Check if the area-specific oxygen demand of the wastewater is below a certain empirically determined oxygen transfer rate (Z_{BOD} , $\text{g O}_2 \text{ m}^{-2} \text{ day}^{-1}$). If necessary, enlarge the surface area.
5. Calculate the width and the slope of the HCW using Darcy's law. The depth of the bed is set to 0.6 m, the maximum difference in elevation between inlet and outlet to 0.3 m, the hydraulic conductivity of the medium must be >200 and $<1000 \text{ m day}^{-1}$, and the texture of the medium should fulfil the following criteria: $d_{10}>0.3 \text{ mm}$ and $d_{60}/d_{10}<4$. A safety factor of 25% is added to the width.
6. Calculate the length of the bed based on the necessary surface area and the width. The length should be $>15 \text{ m}$ to reduce the probability of short-circuiting.
7. Calculate the total area of the bed including the 25% safety factor.
8. Calculate the effluent concentrations from the HCW.
9. Calculate the oxygen demand (BOD degradation, nitrification) of the effluent from the HCW based on concentrations of BOD and ammonium. The concentration of BOD in the effluent from the HCW must be $<30 \text{ mg/l}$.
10. Calculate the surface area of the VCW needed, assuming that the surface aeration rate is $30 \text{ g O}_2 \text{ m}^{-2} \text{ day}^{-1}$ (amount of oxygen available for degradation of BOD and for nitrification). Add 25% safety area.
11. Calculate the outlet concentrations from the VCW. If the bed is one metre deep, a nitrification efficiency of 85% can be expected when the bed is intermittently loaded.
12. Check if the outlet criteria for NH_4 and total-N are fulfilled; if not, recycling to the HCW is necessary
13. Choose an appropriate recycling rate (50 to 100%), and calculate the new load to the HCW (point 2)



14. Continue from point 2 as before. Assume that the nitrified nitrogen (nitrate) contribute to the degradation of BOD by $2.4 \text{ kg O}_2 \text{ per kg NO}_3$.

When recirculation is included in the process, the dimensioning is an iterative process, and the calculations should be carried through the points 2 to 14 at least three times.

Alternative a spreadsheet can be set up doing the calculations. The described two-stage constructed wetland is able to fulfil requirements of TSS and BOD removal as well as requirements for nitrification and total-N removal. The system can be designed for enhanced P-removal by selecting special P-adsorbing media in the beds, or by adding precipitation chemicals to the wastewater and use the beds for accumulation of the precipitated phosphorus.

Experiences from a two-stage system – Bjødstrup-Landborup

The following describes the performance of a 55 PE full-scale system (Bjødstrup-Landborup) designed according to the above principles. The bed consists of a 22 m^3 settler, a 456 m^2 HCW followed by a 35 m^2 VCW. The effluent from the HCW are pulse-loaded onto the VCW by a siphon system installed between the HCW and the VCW.

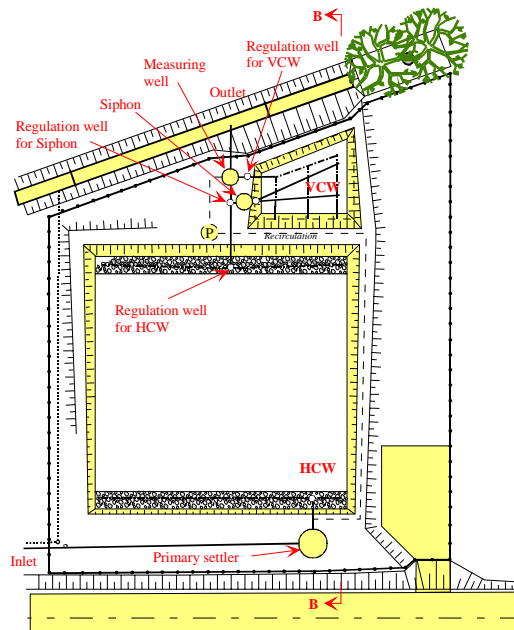


Figure- 8

Surface view of the 55 PE two-stage constructed wetland system at Bjødstrup - Landborup

Effluent is not recirculated in the system. The water passes through the system by gravity only, as there is no electricity installed at the site. The filter depth of the vertical bed is only 0.6 m because of restrictions in the hydraulic gradient at the site. This also means that during sampling (24-h sampling) a weir is installed in the outlet well to allow impounding of water for sampling. This impounding during sampling raises the water level in the vertical filters and saturates the lower 0.3 m. Hence, the filter does not function as desired during sampling. Unfortunately, the weir is often left in place even in periods between sampling, and therefore the desired nitrification activity is not obtained. However, during intensive measuring periods where the vertical filter has been drained, the vertical filter does nitrify.

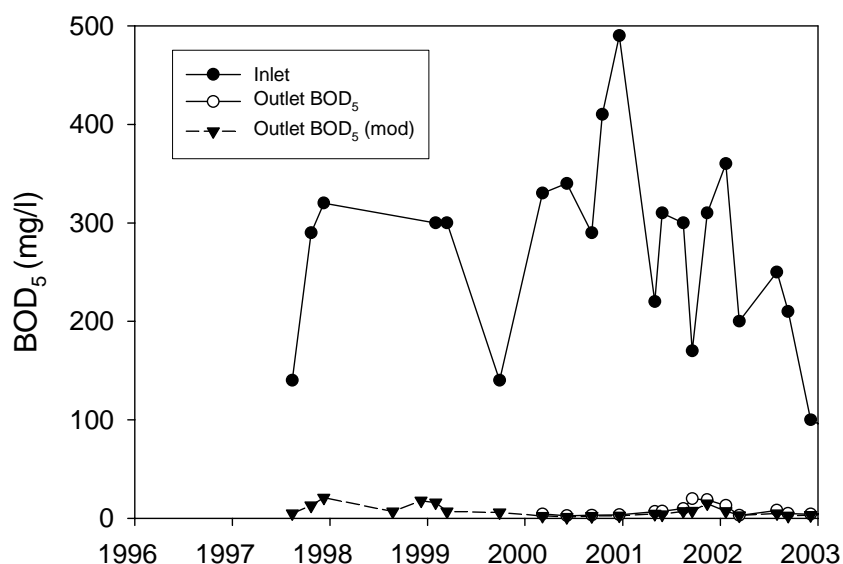


Figure- 9
Inlet and outlet concentrations of BOD₅ at the 55 PE two-stage constructed wetland at Bjødstrup-Landborup

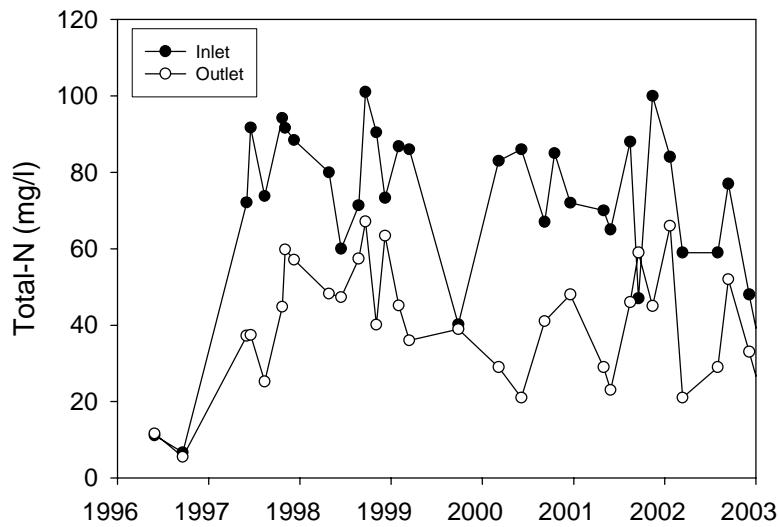


Figure- 10
Inlet and outlet concentrations of total-nitrogen at the 55 PE two-stage constructed wetland at Bjødstrup-Landborup

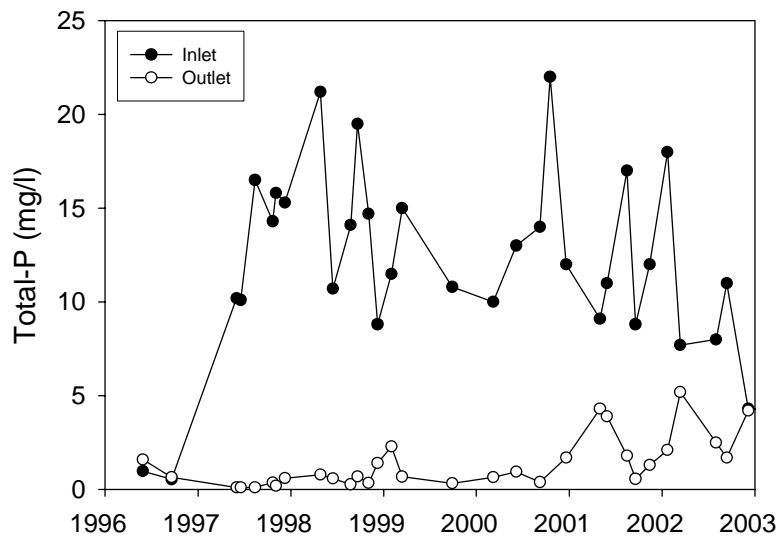


Figure- 11
Inlet and outlet concentrations of total-phosphorus at the 55 PE two-stage constructed wetland at Bjødstrup-Landborup

The medium used in the bed is a iron-containing sand, and therefore the removal of phosphorus has been good the initial years. However, the past two years the effluent concentration is increasing probably because the medium is getting phosphorus saturated (Figure 11).

COMPACT VERTICAL FLOW CONSTRUCTED WETLANDS

Outlet criteria for single households are becoming still more stringent and often include demands for nitrification as well as removal of total-phosphorus before discharge. The preferred disposal solution in rural areas in Denmark is soakaways (soil infiltration). But at many sites it is not possible to use soakaways because of clayish soil conditions or high water tables. There is therefore a need to find new and cost-effective on-site technologies. In order to develop a new constructed wetland system that will remove 95% of BOD, 90% phosphorus and 90% nitrification, a number of studies have been performed in an experimental vertical flow system. The system is extended with a specific filter unit containing calcite for removal of phosphorus and recirculation of effluent to the sedimentation tank. The results of the experimental plant showed that very efficient removals of TSS, BOD, phosphorus, indicator bacteria as well as nitrification could be obtained in a vertical flow system using very small areas (Johansen et al., 2002; Brix et al., 2002; Arias et al., 2002; Cabello et al., 2002). The studies in the experimental system showed that vertical flow constructed wetland systems have a high capacity to remove BOD and to nitrify the wastewater using a relatively small area ($<2 \text{ m}^2/\text{person}$). Recycling of effluent to the sedimentation tank improved and stabilised the performance of the system and enhanced the removal of nitrogen by denitrification. Phosphorus can be removed in a separate filter unit with calcite. The residence time in the calcite filter has to be sufficient for the binding processes to occur. At high hydraulic loading rates the filter showed decreased performance and symptoms of clogging.

The single step vertical flow CW has several advantages compared to a horizontal subsurface flow system, and is very cost effective compared to multi step system. The vertical flow beds can be loaded at very high hydraulic loading rates without jeopardising the treatment performance. Based on the data from the 1½ years of testing and operation of the experimental plant, a compact commercial design of vertical constructed wetlands for single houses was developed.



A compact vertical flow system at “Mosehuset”

The vertical flow system at Mosehuset was built in May. The plant operates for a single house with a family composed of two adults and two children. The design of the compact vertical flow system is shown in Figure 12. The system at Mosehuset consists of a 2-m³ three-chamber sedimentation tank, a level-controlled pump, a 15-m² vertical flow constructed wetland followed by a filter-unit containing calcite for the removal of phosphorus. Effluent from the system can be recirculated to the sedimentation tank to enhance removal of total-nitrogen by denitrification. The performance of the single-household system has been monitored under conditions with recirculation as well as without recirculation (Figure 13).

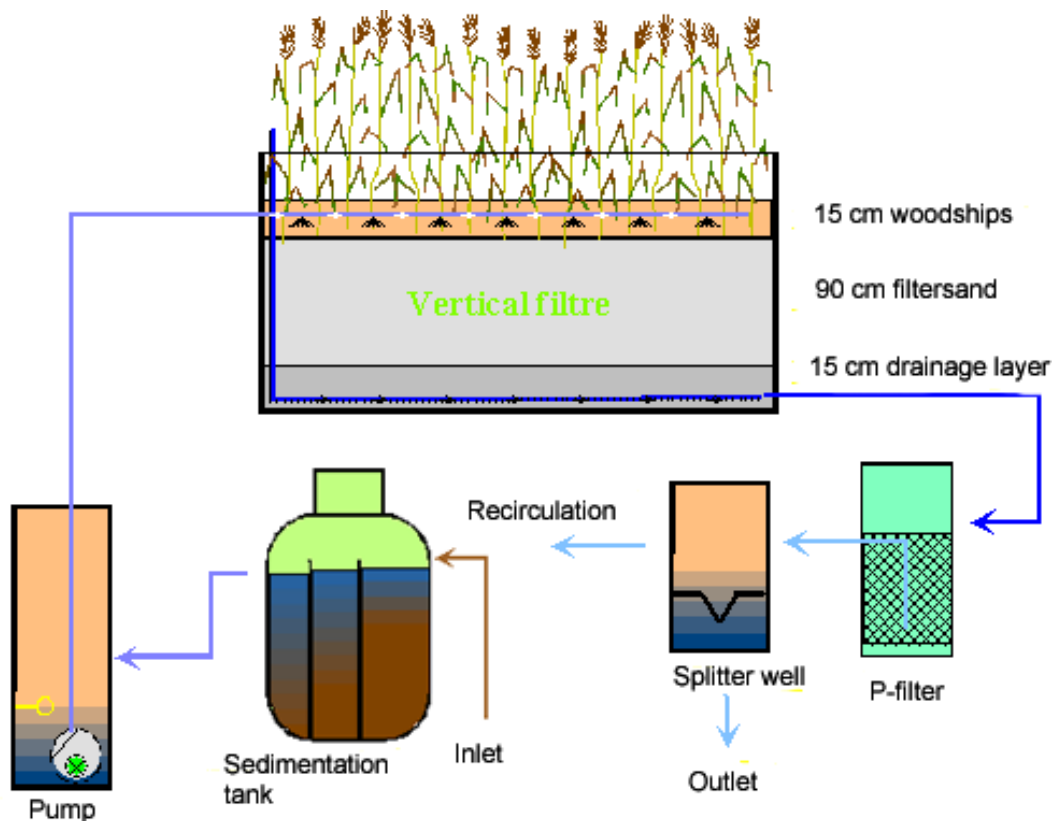


Figure-12

Sketch of design of a compact vertical flow constructed wetland with recirculation and a phosphorus filter. The system consist of a sedimentation tank, a level controlled pump for dosing of sewage onto the vertical bed, a calcite based filter unit for removal of phosphorus, a spiller well for regulation of recirculation of effluent to the sedimentation tank.

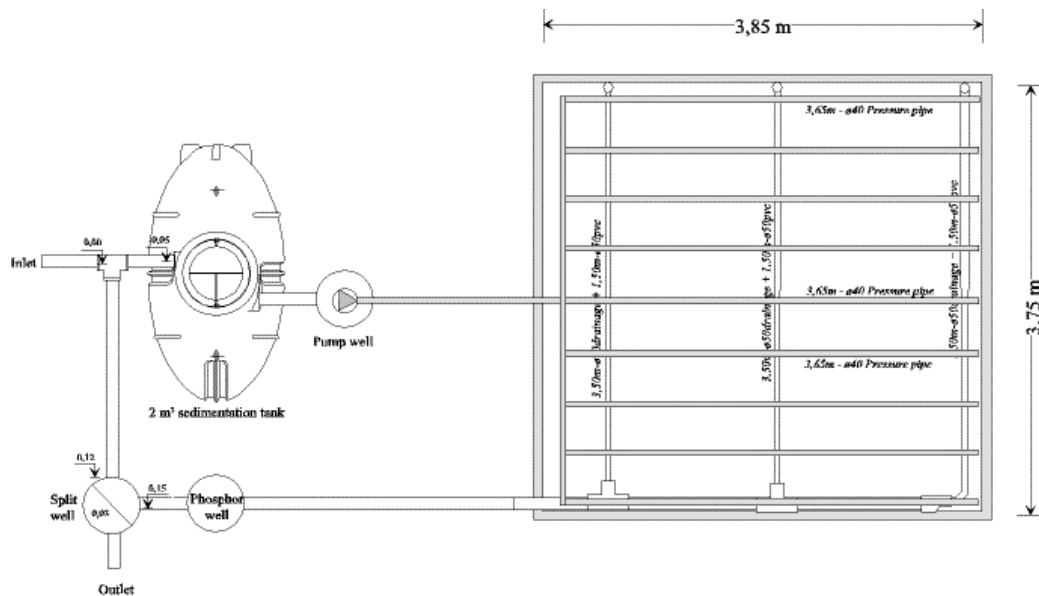


Figure- 13

Technical drawing of the vertical flow system at “Mosehuset”. Raw domestic sewage is conducted to a 2-m³ three-chamber sedimentation tank. A pump feeds the effluent to the 14,4 m² vertical bed of. The wastewater trickles and flows through the P-filter. A splitter well regulates recirculation rate

Performance of the compact vertical flow system at Mosehuset

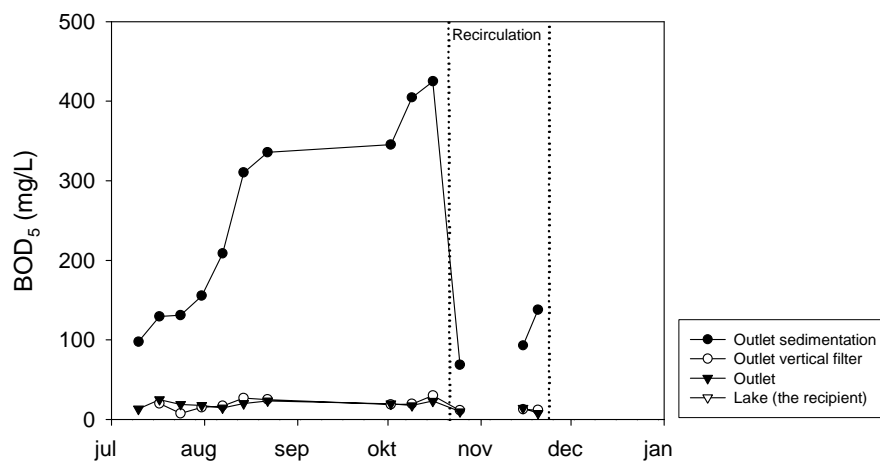


Figure - 14

Performance of the compact vertical flow system at Mosehuset during the initial months

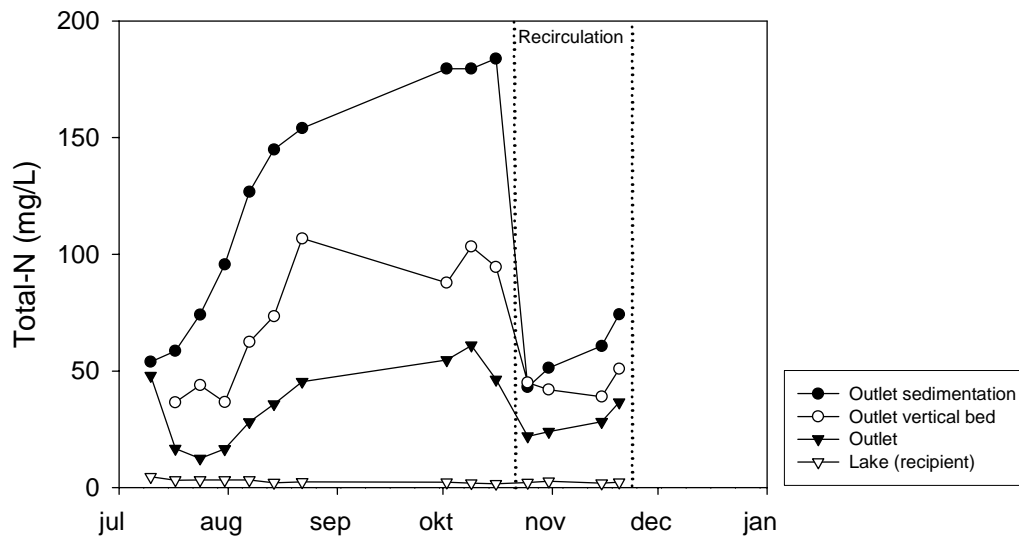


Figure - 15
Performance of the compact vertical flow system at Mosehuset during the initial months

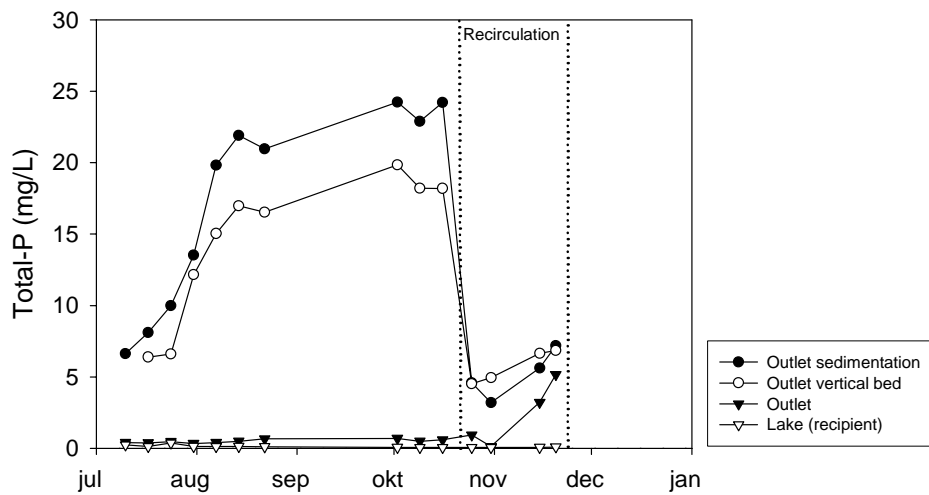


Figure-16
Performance of the compact vertical flow system at Mosehuset during the initial months

The removal performance of the full scale single household system fulfils the most stringent standards in rural areas, i.e. 95% removal of BOD, 90% nitrification and 90% removal of phosphorus – when recirculation is used (Figs. 14-16). The position of the phosphorus filter in the system is not optimal because recirculation in the system increased the water flow through the filter and hence decreased the residence time. In future constructions the P-filter should be placed at the outlet to avoid the effects of recirculation. The results also indicated that the size of the filter unit should be extended to achieve sufficient capacity for removal of phosphorus for a period of one year. The vertical flow system is small and compact and the removal performance is robust. The cost of construction for a single-house system is at the same level as the costs of a soak-away system. The Danish Environmental Protection Agency is presently producing official guidelines for the construction and establishment of vertical flow constructed wetland systems in rural areas.

ZERO-DISCHARGE WILLOW SYSTEMS

Willow plantations have been successfully used as recipients for municipal wastewater, sewage sludge and landfill leachate (Rosenqvist et al., 1997; Hasselgren, 1998; Hasselgren, 1999; Venturi et al., 1999). By these techniques the resources in the wastewater, namely water and nutrients, are used for biomass production, but excess nutrients and water are discharged to receiving water bodies. The treatment concept in the willow wastewater cleaning facilities is that all the nutrients contained in the sewage are used to produce plant biomass and all the water is evapotranspired to the atmosphere by the willows. Hence there will be no outflow from the systems (Gregersen and Brix, 2000; Gregersen and Brix, 2001; Brix and Gregersen, 2002).

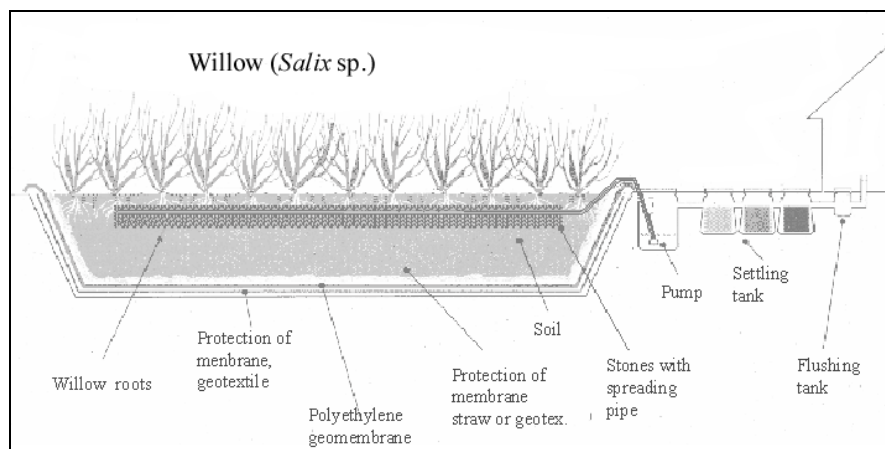


Figure- 17
Cross-section through a willow wastewater cleaning facility



System design

A willow wastewater cleaning facility as constructed in Denmark generally consist of approx. 1.5 m deep high-density polyethylene-lined basins filled with soil and planted with clones of willow (*Salix viminalis* L.) (Fig. 17). The surface area of the systems depends on the amount and quality of the sewage to be treated and the local annual rainfall, and range typically between 150 to 300 m² for a single household. Settled sewage is dispersed underground into the bed under pressure. When correctly dimensioned, the willows will – on an annual basis - evapotranspire all water from the sewage and rain falling onto the system, and take up all nutrients and heavy metals from the sewage. The stems and leaves of the willows are harvested every third year (one third of the bed area is harvested every year) to keep a healthy vegetation and a high production of bark, which is known to contain high concentrations of phosphorus and heavy metals (Sander and Ericsson, 1998). Consequently, a bed should always contain one and two year old willow plants that can evapotranspire water.

Experiences with zero-discharge willow systems

At present there are more than 100 zero-discharge willow systems in operation in Denmark, mainly serving single households in the rural areas. In the following experiences from six systems, that were constructed in 1997 will be summarised (Gregersen and Brix, 2000; Gregersen and Brix, 2001). The six facilities receive sewage from single households. The surface areas of the systems are between 150 and 500 m² depending on number of inhabitants connected, their water consumption and the local precipitation. Three different clones of *Salix viminalis* ('Björn', 'Tora' and 'Jorr') were planted as 20-cm cuttings with 5 cm above the soil surface. Wastewater discharges into the systems and precipitation were monitored as well as the water levels within the willow beds.

One of the most important aspects of the willow wastewater cleaning facilities is their ability to evapotranspire all the sewage discharged into the systems as well as the rain falling onto the systems. Table 2 presents data on the estimated evaporation from the six systems the two initial years of operation (from Gregersen and Brix (2001)). The wastewater loading into the systems was 450 to 600 mm per year. During the second year the precipitation was approximately 400 mm higher than the 'normal' 30-year average (1150 mm). Facilities No. 1 and 5 had relatively poor growth of willow because of vigorous growth of weeds in the beds. Facility No. 6 had some surface water flowing into the system because of construction problems. The high rate of precipitation the second year resulted in completely saturated conditions (water on the

bed surface) in some of the systems, and hence the systems were hydraulically overloaded.

Table- 2
Estimated evaporation rates (mm per year) for six willow wastewater cleaning facilities in Denmark during the first (April 1997 to March 1998) and the second year (April 1998 to March 1999) of operation (from Gregersen and Brix, 2001)

Facility	Year 1	Year 2
1	980	1470
2	1270	2090
3	1140	1650
4	1130	1690
5	980	1660
6	1020	1880

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 a vegetation of plants with a high water availability. 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 ‘clothesline’ effect, where the vegetation height is greater than that of the surroundings (different roughness conditions), may increase evaporative water loss. This occurs where turbulent transport of sensible heat into the canopy and transport of vapour away from the canopy is increased by the 'broadsideing' 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 the isolated expanses, on a per unit area basis, may be significantly greater than the calculated potential evapotranspiration. Examples of the clothesline 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.

Data on biomass production and the contents of nutrients and heavy metals in the stem and leaves of one-year and two-year old shoots was collected in facility No. 4. Here the plantation consists of 3 rows of the clone ‘Jorr’, 2 rows of the clone ‘Bjørn’, and 2 rows



of the clone 'Tora' (Table 2). Unfortunately we have no accurate measurement of the nutrient and heavy metal discharged into the system. Using 'normal' contents in 'normal' household wastewater, i.e. 30 mg/l total-N, 10 mg/l total-P (Henze, 1982), and 30 mg/l K, it can be seen that the amount of N, P and K in the harvestable biomass almost exactly balances the amount discharged into the system with the sewage. Only for P the amount discharged into the system was approx. 30% higher than the amount in the harvestable biomass. The balance for P will however depend on the use of phosphate-containing detergents in the specific household. For heavy metals, it is not possible, based on the available data, to evaluate the mass balance. But usually sewage from single households contains low levels of heavy metals. 'Normal' levels of heavy metals in domestic sewage have been reported to be Cd: 2 $\mu\text{g l}^{-1}$; Pb: 40 $\mu\text{g l}^{-1}$; Zn: 130 $\mu\text{g l}^{-1}$; Cu: 40 $\mu\text{g l}^{-1}$; Ni and Cr: 15 $\mu\text{g l}^{-1}$; and Hg: 1 $\mu\text{g l}^{-1}$ (Henze, 1982). If these levels are used to make up the mass balance, it can be calculated that some accumulation of heavy metals may occur in the system over time. However, it is known that the uptake of heavy metals by willows depends on the levels in the soil as well as on the clone (Landberg and Greger, 1994; Landberg and Greger, 1996; Greger and Landberg, 1997; Greger, 2000), and therefore removal by harvesting may be higher than indicated by the present data. A worst case scenario, based on the present removal data and the concentration levels cited above, shows that after 25 years of operation the heavy metal levels in the soil will not exceed the present legislative standards for use of soil for agricultural purposes (Cd: 0.5 mg kg^{-1} dry matter; Pb: 40 mg kg^{-1} dry matter; Zn: 100 mg kg^{-1} dry matter; Cu: 40 mg kg^{-1} dry matter; Ni: 15 mg kg^{-1} dry matter; and Cr: 30 mg kg^{-1} dry matter).

It is likely that the contents of salts in the system will increase over time, but the rate of increase is unknown and will depend on the amount of salts in the sewage and hence the habits of the sewage producers. If the contents of salt in the system increase to unacceptable levels it is possible at some later stage to discharge the salt-containing water from the system.



Figure- 18

Three-year-old willow wastewater cleaning facility showing one year old stems (at the right) and two year old stems (at the left) at three year old root stocks. From Gregersen and Brix (2001)

The initial experiences from the Danish systems show that it is important to keep a new-established bed free from weeds the first year after planting. Vigorous growth of weeds will significantly reduce the production of willow stems the first year. Usually the willow stems are cut the first year to increase the number of stems per plant, but if the willows have had a low number of stems the first year they will also have a low number in the second and following years. Hence biomass production will be lower and evapotranspiration and nutrient uptake will be affected. It is therefore urgent to keep the facilities free of weeds the first year. The second year the willows will outcompete the weeds if kept clean the first year.

The parameters of importance when designing a willow wastewater cleaning facility include: (1) the exact amount of wastewater during the first year of operation; (2) the amount of rainfall at the site of construction, and (3) the ability of the selected willow clones to evapotranspire water and accumulate nutrients and heavy metals in the aboveground harvestable biomass. To exemplify: In an area where the annual mean precipitation is 700 mm per year, it is assumed that the willow can evapotranspire 1200 mm per year. The difference between precipitation (700 mm) and evapotranspiration (1200 mm), i.e. 500 mm or 500 l m^{-2} , is equal to the amount of sewage that can be loaded into the system on an annual basis. Assuming a water discharge rate of 100 l per person per day or 36,500 l per person per year, it can be calculated that the surface area needed to evapotranspire the sewage equals $36,500 \text{ l year}^{-1}$ divided by $500 \text{ l m}^{-2} \text{ year}^{-1} =$



73 m² per person. The seasonal variation in precipitation and evapotranspiration must also be considered as the system should have volume (depth) enough to be able to store the sewage and rain during winter. In addition, the amount of nutrients discharged into the system should balance the amount that can be removed by harvesting aboveground biomass.

Our data show that when optimal growth of willow is achieved during the first year of operation the evapotranspiration in the system may increase by at least 300 mm under Danish conditions the following year, i.e. from 1200 mm to 1500 mm per year. Therefore, willow wastewater cleaning facilities designed for 2-3 persons may be able to receive higher amounts of sewage than designed for the following years. However, there is still some uncertainty about the long-term performance of the systems, particularly the potential accumulation of salts and the sustained health of the willows. Research is presently being carried out to evaluate these aspects and to further optimize the systems.

SEWER OVERFLOW TREATMENT

Lake Utterslev is situated in a densely built-up area of Copenhagen, and is heavily eutrophicated from combined sewer overflows. At the same time the lake suffers from lack of water. Constructed wetland systems have been successfully established to treat combined sewer overflows and urban stormwater. In 1998 the Municipality of Copenhagen developed and constructed a wetland system to treat the combined sewer overflow before discharge into the marsh (Gervin and Brix, 2000; Gervin and Brix, 2001). This was done in order to reduce the loading of phosphorus in particular to the marsh, and at the same time retain the supply of water to the marsh. Besides treating combined sewer overflows, the constructed wetland is used to clean lake water in 'dry' periods when there are no sewer overflows.



Figure- 19

Location of the circular constructed wetland system (CW) in Utterslev marsh From (Gervin and Brix, 2001)

The constructed wetland is located in the natural littoral zone of one of the lakes in an existing reed swamp (Fig. 19). The system is designed as a 90 m diameter circular bed partly buried in the swamp and is separated from the rest of the swamp by a polyethylene membrane (Fig. 20). The membrane is placed 3 m beneath the water level of the lake on the underlying clay layer. The two meter deep bed substrate consists of a mixture of gravel and crushed marble, which has a high binding capacity for phosphorus (Brix et al., 2000). The surface level of the bed medium is located one meter beneath the water level of the lake. The plant is surrounded by a dike of earth, and is planted with reeds (*Phragmites australis*). The surface area of the plant is 5 000 m², and the storage capacity for water in the system, including the void volume of the bed medium, is 6 500 m³. The inlet-pipes are buried in a dike leading to the centre of the plant, from where the influent water is distributed over the surface of the bed. The system is intermittently loaded with combined sewer overflow water or lake water, and after percolation through



the bed medium, the water is collected in a network of drainage pipes at the bottom of the bed and pumped to the lake.

A buried in-line retention basin built into the sewerage system is located immediately upstream of the constructed wetland system. The basin withholds the "first flush" of the combined sewer overflow, and therefore the water going into the wetland during overflow events is rather dilute. During periods with no overflow events, the system is used to clean lake water. The fully automated loading cycles result in alternating wet and dry periods.

Several built-in attributes of the system contribute to enhance the nutrient removal performance. The bed medium is relatively deep (2 m) and contains crushed marble, which has a high binding capacity for phosphorus (Brix et al., 2000). The vertical-flow regimen secures a good contact between water and bed medium, and the intermittent loading creates alternating wet and dry periods which increase oxidation of organic compounds and nitrification in the bed medium.

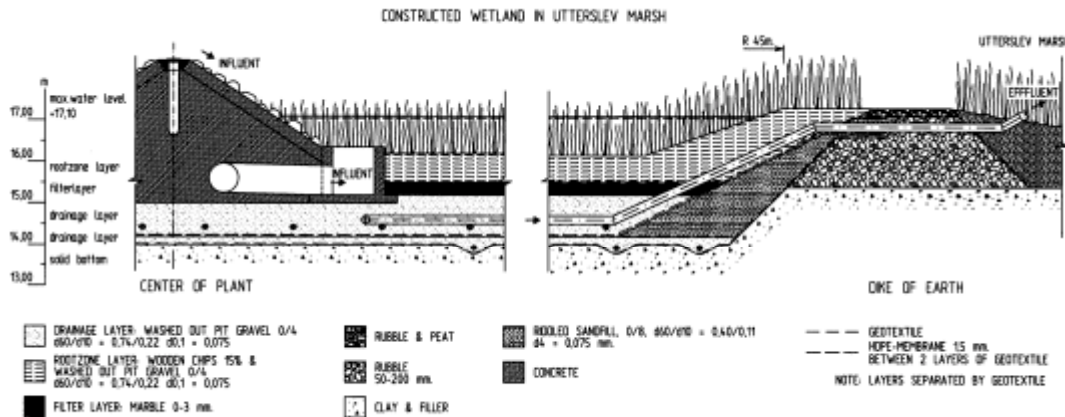


Figure- 20

Cross-section through the circular constructed wetland system at Utterslev marsh

Treatment performance

The initial period of operation has been a running-in period, where the focus has been to study the effects of residence time on removal performance. In the period from October 1998 to January 1999 only lake water with low contents of nutrients were treated in the system as there were no overflows from the sewer system until June 1999. In the period from October 1998 to the first of January 2000 a total of 125 000 m³ of water were

treated in the system (115 000 m³ in 1999). The inflows consisted of c. 50 loadings of lake water (42 loadings in 1999), and 16 loadings of sewer overflows. The performance when treating lake water was tested by analysis of 24 in- and outlet samples. The performance when treating sewer overflows was tested by analysis of 12 inlet and 16 outlet samples. At two of the overflow events samples were taken of the outlet water after 3, 5 and 7 days, respectively, to evaluate the effects of residence time.

Inlet concentrations of phosphorus in the lake water varied between 0.08 and 0.37 mg/L during winter, but were higher (0.12 to 0.78 mg/L) during summer because of release of phosphorus from the lake sediments during anoxic conditions in the lake. However, effluent concentrations from the constructed wetland system were consistently low (0.03-0.04 mg/L) resulting in high removal rates that were largely independent on inlet concentration. Concentrations of phosphorus in the sewer overflows were higher (0.9 to 3.2 mg/L) than concentrations in lake water, but effluent concentrations were still low, and removal efficiencies greater than 97%. The retention times studied (3, 5 and 7 days) did not have any consistent effect on effluent phosphorus concentration. A total mass balance showed that 86 kg of phosphorus, corresponding to 96% of the loading, were removed by the constructed wetland system during 1999.

The concentrations of nitrogen in the lake water were generally low and occurred nearly exclusively as organic nitrogen. The total nitrogen content was reduced by c. 25% and some nitrification occurred in the system. The combined sewer overflows contained more nitrogen than lake water and mainly as organic-N and NH₄. This was effectively removed in the system as a consequence of nitrification-denitrification processes. The denitrification rate was higher when treating overflows compared to lake water, probably because of the higher nitrogen contents in the sewer overflow. However, the higher content of organic matter, and the degradability of the organic matter may also have affected the denitrification process. It was not possible to observe a significant relation between the residence time and the denitrification rate for any of the types of water. The effluent concentrations of ammonium were consistently low, and as a consequence of the nitrification process in the system some nitrate was present in the effluent.

The COD (Chemical Oxygen Demand) concentrations in the lake water were very low in winter, but increased during summer as a consequence of the presence of algae. This could also be seen in the contents of TSS, which varied between <5 mg/L during winter to 48 mg/L in August (yearly average 13 mg/L). The COD contents in the sewer overflows were consistently higher (up to 294 mg/L at one occasion) as was the contents of TSS (average 90 mg/L). Effluent concentrations of COD were generally



low, but were higher during summer than during winter. Effluent concentrations of TSS were below the detection limit (5 mg/L) in 22 out of 24 samples.

The constructed wetland system clearly reduces the discharge of phosphorus and other pollutants contained in the sewer overflows to the Utterslev marsh. Furthermore, the constructed wetland removes phosphorus from the lake water when no overflows occur. Therefore, the establishment of the wetland no doubt contributes to improve the environmental conditions of Utterslev marsh. The initial experiences with the constructed wetland at Utterslev marsh document that a constructed wetland can be designed and operated to effectively remove phosphorus and other pollutants from polluted water. The lifetime of the system is not known, but estimates based on the phosphorus sorption capacity of the bed medium of the constructed wetland indicate that the phosphorus removal can be sustained for several decades.

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