Zero-discharge of nutrients and water in a willow dominated constructed wetland

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Abstract A novel constructed wetland system has been developed to treat sewage, evaporate water and recycle nutrients from single households at sites where effluent standards are stringent and soil infiltration is not possible. Main attributes of the willow wastewater cleaning facilities are that the systems have zero discharge, the willows evapotranspire the water, and nutrients can be recycled via the willow biomass produced in the system. The willow wastewater cleaning facilities generally consist of c. 1.5 m deep high-density polyethylene-lined basins filled with soil and planted with clones of willow (*Salix viminalis* L.). The surface area of the systems depends on the amount and quality of the sewage to be treated and the local annual rainfall. For a single household the area needed typically is between 200–300 m^2. Settled sewage is dispersed underground into the bed under pressure. When correctly dimensioned, the willow 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 of the willows are harvested on a regular basis to remove nutrients and heavy metals and to stimulate the growth of the willows. Initial experiences from full-scale systems in Denmark show promising results.

Keywords Constructed wetland; evaporation; heavy metal; nutrient; recycling; Salix; water treatment; willow; zero-discharge

Introduction

Discharge of domestic sewage from single households to streams and lakes in the countryside is resulting in poor freshwater quality in many areas of Denmark. Therefore new legislation requires adequate treatment of sewage from single households. Soil infiltration is the preferred solution (EPA, 1999a) but at many locations this is not possible because of clayish soil conditions or high ground water tables. Other treatment solutions, like sand-filters and reed beds (EPA 1999b, c), may not provide the required treatment, and consequently other solutions are needed. This paper describes a willow-based constructed wetland system with no outflow, which has been developed to treat sewage and recycle nutrients from single households at sites where effluent standards are stringent and soil infiltration is not possible.

Willow plantations have been successfully used as recipients for municipal wastewater, sewage sludge and landfill leachate (e.g. Rosenqvist *et al*., 1997; Hasselgren, 1998, 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 facility described in this paper 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 (Figure 1).

A willow wastewater cleaning facility as constructed in Denmark generally consist of approximately 1.5 m deep high-density polyethylene-lined basins filled with soil and planted with clones of willow (*Salix viminalis* L.) (Figure 2). The surface area of the systems depends on the amount and quality of the sewage to be treated and the local annual rainfall,

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and range typically between 200–300 m^2 for a single household. Settled sewage is dispersed underground into the bed under pressure. When correctly dimensioned, the willow should – 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 (Figure 3).

Materials and methods

In 1997 six facilities receiving sewage from single households were constructed in Denmark to investigate the performance and operation of the systems. The surface areas of the systems varied between 150 and 500 m^2 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 in May as 20-cm cuttings with 5 cm above the soil surface. Wastewater discharges into the systems were monitored by flow meters in the pump lines and were also estimated based on water consumption in the households. The water levels within the willow beds were monitored with inspection wells placed vertically in the soil of the beds. Precipitation was measured at two sites and compared with data from the nearest meteorological station. For all sites precipitation data was available from meteorological stations. Water content in the saturated and non-saturated soils was measured by drying soil samples. Biomass production was measured by weighing the harvested biomass (stems after defoliation) and by weighing representative stems with leaves before defoliation. Stems and leaves were analysed for content of dry matter, total nitrogen, phosphorus, potassium, and the heavy metals cadmium, lead, mercury, zinc, nickel, copper and chromium. Soils were sampled and preserved for future analysis. Conductivity of the water in the beds was analysed to elucidate if accumulation of salts occur. At visits every month the willow health as indicated by the colour of leaves was evaluated. Furthermore, the number of plants, the number of stems per plant before and after the first, second and third harvests was counted, and the time of foliation and defoliation was recorded.

Results

Water balance

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

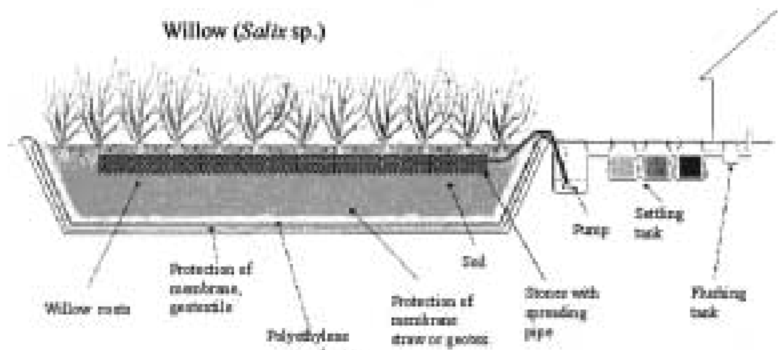

Figure 1 Cross-section through a willow wastewater cleaning facility

Figure 2 Excavation for establishment of willow wastewater cleaning facility showing placement of geotextile and high-density polyethylene membrane

falling onto the systems. Table 1 presents data on the estimated evaporation from the six systems in the two initial years of operation. 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 (1,150 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.

Biomass production and contents of nutrients and heavy metals

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^{-1} total-N, 10 mg l^{-1} total-P (Henze, 1982), and 30 mg l^{-1} 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

Table 1 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

Facility	Year 1	Year 2
1	980	1,470
2	1,270	2,090
3	1,140	1,650
4	1,130	1,690
5	980	1,660
6	1,020	1,880

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 µg l^{-1}; Pb: 40 µg l^{-1}; Zn: 130 µg l^{-1}; Cu: 40 µg l^{-1}; Ni and Cr: 15 µg l^{-1}; and Hg: 1 µg 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 know that the uptake of heavy metals by willows depends on the levels in the soil as well as on the clone (Greger and Landberg, 1995; Landberg and Greger, 1996), 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).

Accumulation of salts

Conductivity of the water within the beds was analyzed and the data do not as yet show an increase in conductivity. However, it is very 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 may be possible at some later stage to discharge the salt-containing water from the system.

Discussion

The first experiences indicate that willow wastewater cleaning facilities have the ability to evapotranspire all water, and recycle nutrients and heavy metals from household wastewater by uptake in willow stems and leaves. Composting biomass from willow wastewater cleaning facilities and using it as a soil amendment could bring nutrients back to the food chain. Using harvested biomass for energy purposes could reduce emission of carbon dioxide to the atmosphere because it replaces fossil fuels. By extracting heavy metal from the ashes it may be possible to make a source of fertilizer with a high content of potassium. Potassium is a limiting resource in organic farming.

Table 2 Biomass of three clones of willow (*Salix viminalis*) at a willow wastewater cleaning facility (facility No. 4) September 1998, after two growing seasons. Some growth occurred after harvesting

		"Bjørn"			"Jorr"			"Tora"	
	Stem	**Leaves**	**Total**	**Stem**	**Leaves**	**Total**	**Stem**	**Leaves**	**Total**
Biomass (tonnes DM ha^{-1})	9.4	1.4	**10.8**	10.0	2.1	**12.1**	10.1	1.5	**11.6**
Nutrients (kg ha^{-1})									
N	120	50	**170**	102	68	**170**	89	48	**137**
P	26	7	**33**	27	11	**38**	26	4	**30**
K	85	62	**147**	121	92	**213**	123	75	**198**
Heavy metals (g ha^{-1})									
Cd	1.7	0.2	**1.9**	3.6	0.3	**3.9**	3.4	0.3	**3.7**
Pb	0.4	0.3	**0.7**	0.5	0.7	**1.2**	–	0.4	**–**
Zn	201	25	**226**	206	49	**255**	253	32	**285**
Cu	15	3	**18**	23	6	**29**	15.6	4.4	**20**
Ni	1.9	0.1	**2.0**	1.6	0.3	**1.9**	1.3	0.1	**1.4**
Cr	7.7	0.6	**8.3**	19.6	1.3	**20.9**	9.3	0.6	**9.9**
Hg	0.2	0.1	**0.3**	0.2	0.2	**0.4**	0.2	0.1	**0.3**

Figure 3 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

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 1,200 mm per year. The difference between precipitation (700 mm) and evapotranspiration (1,200 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 l $year^{-1}$ divided by 500 l m^{-2} $year^{-1}$ = 73 m^2 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 1,200 mm to 1,500 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.

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