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NUTRIENT RECOVERY IN A SMALL SCALE WASTEWATER TREATMENT PLANT IN COLD CLIMATE

Återvinning av näringsämnen i en småskalig avloppsanläggning i kallt klimat

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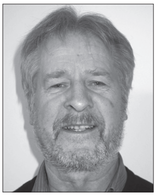

Abstract

An onsite wastewater treatment plant at Brändön, north of Luleå, receiving primarily treated wastewater from a village, was operated and investigated during one year. The wastewater flow was 0.5 m^3/d. The main treatment steps were a prefilter, mainly to distribute the flow, a vegetation filter consisting of two different clones of Salix and two phosphorus filters with Filtralite-P and blast furnace slag (BF slag) operated in parallel. The willow bed reduction of BOD_7 was in average about 80 % and of phosphorus (P) and nitrogen (N) 20–30 %. The main mechanism was believed to be filtration in the bed. The reduction through plant uptake was minor. The Filtralite-P filter reduced BOD_7, P and N with 67 %, 72 % and 20 %, respectively. The BF slag filter reduced P and N with 53 % and 3 %, respectively. The release of sulphuric compounds from the BF slag filter increased largely the BOD_7 content in the effluent. The Filtralite-P system achieved the requirements of the normal protection level given by the Swedish Environmental Protection Agency but not all of the requirements of the high protection level. The BF slag system did not fulfil the requirements of the two protection levels.

Key words – Blast furnace slag, cold-climate, domestic wastewater, filter, Filtralite-P, nitrogen, phosphorus, recovery, small-scale, willow

Sammanfattning

En småskalig avloppsanläggning har testats i Brändön norr om Luleå under ett år. 0,5 m^3/d slamavskiljt vatten från samhället pumpades till försöksanläggningen som bestod av ett förfilter för att sprida vattnet följt av en sälgbädd och två parallella fosforfilter med Filtralite-P och masugnsslagg. I sälgbädden reducerades BOD_7 med 80 % medan fosfor- och kväveinnehållet minskade med 20–30 %. Huvudsaklig mekanism bedömdes vara filtrering i bädden medan växtupptaget var av ringa storlek. Filtralite-P filtret reducerade BOD_7 med 67 %; fosfor och kväve med 72 % och 20 % respektive. Masugnsslaggen minskade fosforinnehållet med 53 % och kväveinnehållet med 3 %. BOD_7-innehållet ökade däremot påtagligt genom slaggfiltret beroende på reducerade svavelkomponenter som frigjordes från slaggen. Systemet med Filtralite-P som adsorbent uppfyllde Naturvårdsverkets krav på normal men inte på hög skyddsnivå. Systemet med BF slagg uppfyllde inte dessa krav.

Introduction

In Sweden, about 1 500 000 persons are connected to small-scale wastewater treatment units (SEPA, 2002) often consisting of sludge separation in a septic tank. A fraction of the treatment units has a soil treatment system following the septic tank. These small-scale treatment plants are responsible for 20 % of the gross anthropogenic phosphorus (P) discharge while municipal wastewater treatment plants with 85 % of the population connected, account for 15 % (SEPA, 2003). Swedish Environmental Protection Agency has recently published directives for small wastewater treatment systems (SEPA, 2006). The directives contain a demand of enabling recovery of wastewater nutrients and a specification of treatment efficiencies of the systems. The specification is given for two protection levels, normal and high. At the normal protection level, tot-P and BOD_7 reduction of the treatment system should be 70 and 90 %, respectively. At the high ditto, tot-P, BOD_7 and tot-N (nitrogen) reduction should be 90, 90 and 50 %. To approach these objectives, many small-scale wastewater treatment systems need to be updated. Thereby, the loading of watercourses with organic matter, P and N will be decreased and the recycling of P and N within the society can be improved.

In Sweden, short rotation willow coppice has been studied since the beginning of 1980 to enhance the pollutant removal, especially N, in wastewater treatment plants (Hasselgren, 1984; Hasselgren, 1999; EC 2003). Willow as a crop has a high biomass yield, high evapotranspiration rate and reported ability to take up heavy metals (Perttu & Kowalik, 1997). By using willow as fuel instead of coal or oil, CO_2 emissions can be reduced. Unfortunately vegetation filters have proven to have a low P removal capacity (Brix, 1994 & 1997). Further, energy forest coppicing is not recommended in northern Sweden (NUTEK, 1992). The retention of P in small wastewater treatment systems can be improved by the use of filter media. Several filter media e.g. blast furnace slag (BF slag) (Johansson, 1998) and Ca-enriched expanded clay (Filtralite-P) (Ádám et al., 2005; Jenssen et al., 2005; Heistad et al., 2006; Öövel et al., 2006) have demonstrated a high P sorption capacity. BF slag is a by-product from steel plants, whereas Filtralite-P is manufactured specially for P sorption in wastewater treatment plants. BF slag contains substances (e.g. sulphur and vanadium) which may cause problems while using it in wastewater application or as a soil conditioner (Tossavainen & Forssberg, 1999). High energy consumption during manufacturing of Filtralite-P is in a conflict with the aim of ecologically sustainable development. Further, both of the adsorbents release an effluent with high pH (Johansson, 1998; Hellström & Jonsson, 2005).

The objectives of this paper were:

- To estimate whether a willow vegetation filter for wastewater treatment can be established in cold-climate and to estimate the biomass production.
- To estimate the treatment efficiency of willow vegetation filter in terms of BOD_7 and nutrients N and P
- To determine the efficiency of BF slag and Filtralite-P for wastewater treatment in terms of P, N and organic matter
- To present effluent quality and reduction rates of the two treatment lines
- To describe operating experiences of the treatment plant

Materials and Method

Design and site conditions

A small on-site wastewater treatment plant comprising of a willow bed planted with two different clones "Karin" *(((Salix schwerinii* x *S. viminalis)* x *S. viminalis)* x *S. burjatica)* and "Gudrun" (*Salix dasyclados)* was constructed in the municipality of Luleå, in northern Sweden. The willow plantation was established using unrooted stem cuttings with the length of 20 cm at the middle of May. The density of plantations was 25 cuttings/m^2. The vegetation filter was followed by two parallel P filters comprising of BF slag and Filtralite-P (see Fig. 1).

The influent to the experimental treatment plant was a stream of primarily treated wastewater from a village. In order to simulate a flow pattern of one detached house, wastewater was pumped daily at 6–10 and 17–22. The pump had the same pumping cycle as the pumps of the nearby municipal wastewater treatment plant. The capacity of the pump was 0.25–0.4 l/s. The wastewater flow to the experimental treatment plant during the four months of operation was 600–900 l/d. Thereafter the flow decreased to 300–600 l/d with few exceptions.

About 0.5 m^3 of wastewater was pumped daily (time weighted average) to a distribution layer and a prefilter having a height of 1 m. The wastewater flowed vertically through the prefilter, and thereafter horizontally through the willow bed. In the P filters, wastewater flowed vertically. The willow bed and the P filters were watersaturated.

A drainage layer under the willow bed unit was built in order to avoid displacement forces lifting the bed. Two plywood boards of 30 cm height were placed vertically at the bottom of the willow bed in order to improve

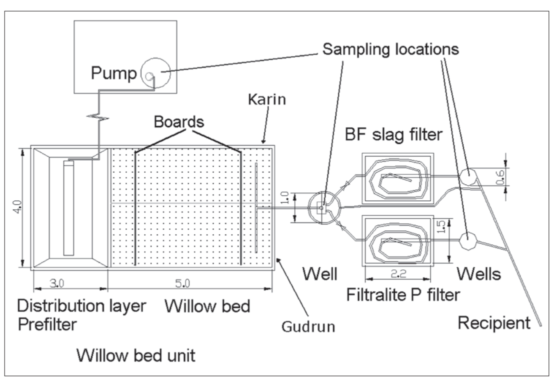

Fig. 1. *Layout of the experimental wastewater treatment plant.* Units are given in m.

Table 1. *Design parameters of the experimental treatment unit.*

	H [m]	A [m^2]	V [m^3]	Grain size [mm]	Surface loading [m/d]	Nominal retention time* [d]
Willow bed unit	–	32	26	–	–	20
Prefilter	1.0	4	20	16–32	0.1	–
Willow bed	0.8	22	16	4–8	0.2	–
BF slag filter	0.9	2.4	2.2	3–6	0.1	3.6
Filtralite P filter	0.9	2.4	2.2	0–4	0.1	3.6

* Calculated at a porosity of 40 % and with a flow of 0.5 m^3/d.

mixing of wastewater and precipitation in the bed. The location of the boards in the willow bed can be seen in Fig. 1. All of the three filters were insulated from the sides and the P filters at the top of the cases using 10 cm thick polystyrene insulation plates. Pipes were insulated using polystyrene pipe insulation and heating cable. One submersible heater was placed in each of the outdoor wells. A box in the distribution layer was covered with mineral wool wrapped in plastic.

Design data of the wastewater treatment plant can be found in Table 1. The volumes of the willow bed unit and each P filter were 26 and 2.2 m^3, respectively. The calculated retention times for the corresponding treatment processes were 20 and 3.6 d, assuming a porosity of 40 %.

Characteristics of phosphorus adsorbents

Filtralite-P is a Ca-enriched expanded clay commercially available. BF slag is a by-product from iron making. The BF slag used in the study originated from SSAB Merox AB in Oxelösund, Sweden. Both of the materials contain Ca and Mg. The bulk density of Filtralite-P and BF slag was 550 kg/m^3 and 1 300 kg/m^3, respectively. The filter porosity was 65 % in Filtralite-P and 40 % in the BF slag.

Measurements and analysis

Biomass production and nutrient content of willows

Half of the two sets of willow clones were harvested in the spring of the 2^{nd} year before the willows budded. The harvested stems were collected randomly from the experimental site and were weighted during the same day. A 200 g mixed sample of the collected stems was used for nutrient content analysis of the clones. The two samples were stored frozen prior to the analysis. Three stem samples of 50–70 g of each willow clone were chosen for dry mass (DM) analysis. The samples were chipped before drying at the temperature of 107°C for three days.

In the autumn of the 2^{nd} year, about 75 % of the stems were collected randomly before the leaf fall. The number of harvested and remaining stems was counted. Further, the number of first and second year harvested and remaining stems were counted. The weights of 1- and 2-year-old stems were measured during the same day as they were cut. A 200 g sample of the collected stems was used for nutrient content analysis of the clones. A sample of 100 g of each harvested stem type and a sample of 50 g of each willow leaf type were collected for DM analysis. The samples were dried at the temperature of 107°C till the dry weights were stable.

The analytical methods of DM, N and P content are presented in Table 2.

Wastewater

Sampling was done once a month in the pump well, in the well after the willow bed and in the wells after the P filters. All of the samples were grab samples and

Table 2. *Method of analysis.*

Type of sample	Parameter	Method of analysis
Willow stem	DM	SS-EN 12880
	Tot-P	SS-EN13346 mod / SS11885-1
	Tot-N	SS 02 81 01, ed. 1
Wastewater	Tot-P	SS 02 81 27
	PO_4-P	QuAAtro Applications No. Q-031-04
	Tot-N	SS 02 81 31
	NH_4-N	QuAAtro Applications No. Q-001-04 (multitest M9/M10)
	NO_3-N	QuAAtro Applications No. Q-003-04
	BOD_7	SS-EN 1899-1
	SO_4-S	Hach method DR-EL2
	SS	SS-EN 872
	Ca	Hach method 8204
	pH	WTW pH 330 meter

analysed with respect to tot-P, tot-N, NH_4-N, BOD_7, SO_4-S and Ca. After four months of operation, samples were analysed with respect to pH and SS. At four sampling occasions, the samples were analysed with respect to PO_4-P and NO_3-N. The samples were stored frozen prior to analysis. The flow from the pump was registered continuously.

The analytical methods of wastewater analyses are presented in Table 2.

Calculations

Loading rates

Nutrient loadings were calculated by multiplying average concentrations and the water volume that passed the willow bed between samplings during the growing period. At the end, the multiplications were added up. Irrigation rate was calculated by dividing the accumulated wastewater volume through the bed during the growing period with the number of the days of the growing period.

Biomass production

At the calculations of the biomass production during year 2, the fresh weight of stems was estimated to be 63 % of the total fresh above-ground biomass. The estimation was based on DM measurements in this study and a study of Ericsson (1994) where the DM weight of stems was about 69 % of the total above-ground DM biomass for the plants of age 2–3 years.

Nutrient uptake

Due to an error in analyses of the stem N content at the 1st sampling, the results of the 2nd sampling for the N content of 1-year-old stems were used in the calculation of the stem N uptake year 1.

Reduction rates

Reduction rates were calculated from the difference between the actual influent and effluent concentrations. Thus, the effects of retention times, precipitation or evapotranspiration were not taken into account at the calculation of the reduction rates.

Results and Discussion

The average concentrations, in the influent wastewater of tot-P, tot-N, NH_4-N, BOD_7, pH and SS were 6.6, 43, 32, 146, 7.4 and 91 mg/l, respectively. There was no big difference between the average and median values of these parameters. The average values were within the range of the literature values of constructed wetland influent reported by Vymazal (2002). The bioavailable N (NH_4-N) was about 74 % of tot-N. The remaining part of N was organic bound and not available for plant uptake without ammonification. The influent was primarily treated wastewater, thus the nitrate content of the total N was negligible (3 %). The amount of bioavailable P (PO_4-P) in the influent was about 75 % of the tot-P.

Table 3. *Fertigation of willow bed during the growing period.* Year 1: 12.7.–18.10. and Year 2: 4.5.–6.9.

Year	Tot-N kg/ha	NH4-N kg/h a	Tot-P kg/ha	Wastewater loading mm/d
1	1678	1259	340	35
2	790	592	116	16

Willow bed

Fertigation of willow bed during the growth period

The load of tot-N, NH_4-N and tot-P was 1678, 1259 and 340 kg/ha, respectively, during the growing period of year 1. The corresponding values for year 2 was 790, 592 and 116 kg/ha, respectively (see Table 3).

Application of nutrients in this study was much higher than the plant demand. Estimations of N and P demand of *Salix* have been given by several authors (Hasselgren, 1984; Ericsson, 1992; Perttu, 1993; NUTEK, 1994; Hasselgren, 1999; Perttu, 1999 and Rytter, 2001). The plant demand of N and P was estimated to be 36–200 kg N/ha, a and 5–80 kg P/ha, a depending on local conditions (e.g. age of shoots, soil type, amount of biomass production). The optimum N: P-ratio for willows has been given by Perttu (1999), 100:14. In this study, the rate was higher 100:20 calculated from the loading rates.

Willows were irrigated with 35 mm/d of wastewater during year 1 and 16 mm/d during year 2 as can be seen in Table 3. The water demand of *Salix* grown in southern Sweden was studied by Lindroth and Halldin (1988). According to the study, the average water demand based on evaporation amounted to 3.5 mm/d during the growing period. In the present study, the irrigation rate was nine and four times higher than the demand during the first and second year, respectively. However, there are studies carried out in southern Sweden where irrigation rates higher than 3.5 mm/d have been successful (Hasselgren, 1984; Hasselgren, 1998; Hasselgren, 1999; EU 2003).

Table 4. *Stem biomass production and nutrient uptake by the willow stems.*

Year	ton DM/ha		kg tot-N/ha		kg tot-P/ha	
	Karin	Gudrun	Karin	Gudrun	Karin	Gudrun
1	1.4	1.2	7.5	4.6	2.2	1.9
2	8.5	8.1	46.5	44.6	9.7	9.7

Biomass production

The stem biomass production of Karin and Gudrun was 1.4 and 1.2 ton dry mass (DM)/ha for year 1. As for year 2, the corresponding values were 8.5 and 8.1 ton DM/ha (see Table 4). The biomass production of clone Karin was slightly higher than the one for clone Gudrun.

The difference in stem biomass production between the clones could be explained by the genetic differences between the clones. Gudrun is considered to be a slow starter whereas Karin is an opposite ditto (Weih & Nordh, 2002). At northern latitudes with short growing periods, plants starting to grow fast early in the season might gain a great advantage compared to those starting to grow slowly (Weih & Nordh, 2002). In this study, after three weeks of planting, most of the cuttings of Karin had produced above ground shoots whereas about half of the cuttings of Gudrun had not above ground shoots. Some of the Gudrun cuttings without above ground shoots were observed, and the cuttings were found to be free of shoots. About half of Gudrun was replanted with new cuttings and shoots of the new cuttings could be observed after some weeks.

The range of the stem biomass production of 1-year-old shoots found in similar studies in literature was 1.2–5.3 ton DM/ha (Hasselgren, 1984; Mortensen et al, 1998; Rytter, 2001; EC, 2003). Even though the nutrient and water demand of willows was met in this study, the stem biomass production for 1 year old shoots was at the low end of the range. The corresponding value for the stem biomass of the 2th year production was 3.7–17.7 ton DM/ha (Hasselgren, 1984; Mortensen et al, 1998; EC, 2003). The stem biomass production during year 2 in this study was in the middle of the range of the literature values.

According to Perttu (1983) and Ledin & Perttu (1989), temperature is normally the most limiting factor for plant growth at high northern latitudes. The growth rate is highly correlated with the temperature sum of the growth period. Thus, a possible reason for low stem biomass production during the first year and the biomass production comparable with other studies during the second year could be the average monthly temperatures during the experiment. The average temperature of May year 1 was 5°C which was 3°C lower than the May of the following year. Further, the temperature was well below the long time monthly average of 6.4°C (see Fig. 2). The average temperatures during the whole experiment were above the long time averages with 0.5–3.4°C, especially during July, August and September. According to Weih and Nordh (2002), an additional biomass gain late in the season hardly could compensate for the slow growth of slow starters early in the season.

The range of literature values above is from studies performed in southern Sweden (Lund and Roma) and in Denmark. The number of months with average temperature above 5°C during the years 1961–1990 is 7 in Lund, 6 in Roma and 5 in Luleå (SMHI, 1991). However, the stem production during the second year in this

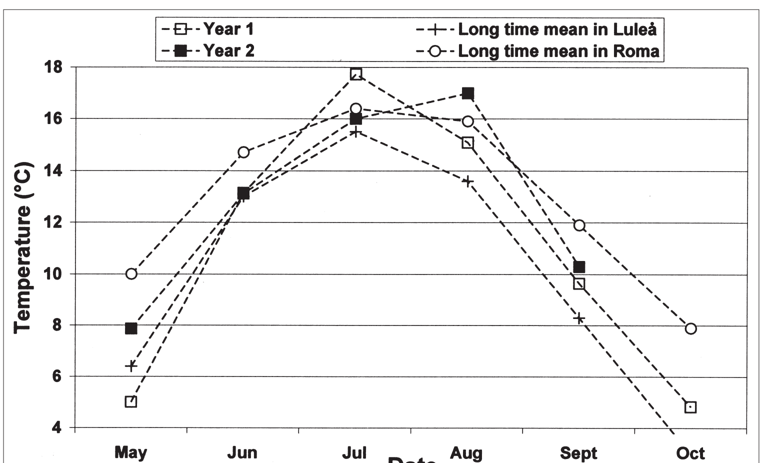

Fig. 2. *Monthly average temperatures at Kallax Airport, 19 km south of Brändön during the growing periods (year 1 and 2) with long time monthly averages in Luleå and Roma* (SMHI, 1991 and SMHI 2006).

study was at the same level as in the study by EC (2003) performed in Roma in which the production was about 9–10 000 kg/ha. Thus, the stem biomass production comparable with EC (2003) could be explained by an especially warm summer in Luleå. The temperature was 2°C above the long time average of June–August (SMHI, 2006) and the average temperatures of May, June, July and August in Luleå were similar to the long time averages in Roma (see Fig. 2).

The influent wastewater had a temperature of 6–15°C during the experiment. It could be possible that the heat released from the wastewater had prolonged the growing period. In Fig. 3 willows in October year 1 can be seen. Willows growing in the surroundings have had leaf fall while the willows in the experimental site were still green.

The willows studied were planted almost ten times more densely than the recommendation of 20 000 plants/ha (Willebrand et al., 1993). The denser spacing might have increased the biomass production in this study according to findings of Willebrand et al. (1993). However, Kopp et al. (1997) received opposite results of the studied spacings of 0.3 x 0.3 (111 111), 0.3 x 0.9 (37 037) and 0.6 x 1.1 m (15 151 plants/ha). In that study, the differences in biomass production between the spacings were not found to be statistically significant.

In this study, the irrigation rate was > 15 mm/d and thus exceeded the evaporation rate during the growing period. Studies have shown an inhibitory effect of the high irrigation rate (10 mm/d and higher) on biomass production (Kowalik & Randerson, 1994; Hasselgren, 1998 and Hasselgren, 1999) explained by that the root zone became anaerobic. However, an inhibitory effect of the high irrigation rate may not have existed in this study since the flow was horizontal in the willow bed and the water table was 10–25 cm below the soil surface.

Fig. 3. *Willow plants with leaves in October after three months of growth.* The surrounding willows have had the leaf fall. The black pipes are 50 cm tall.

Nutrient uptake

The N uptake by Karin and Gudrun stems was 7.5 and 4.6 kg/ha, respectively, during year 1. The corresponding values for the P uptake were 2.1 and 1.9 kg/ha as can be seen in Table 4. The nutrient uptake of the clones during year 2 increased due to the higher biomass production. The N uptake in stems of Karin and Gudrun then was 46.5 and 44.6 kg/ha, respectively. There was no difference in the stem P uptake between the clones. The uptake was about 9.7 kg/ha. The stem nutrient uptake by the clone Karin was higher than by the clone Gudrun during the experimental period. Further, the assimilation of N and P in stems was about 2 % of the loaded amounts during the growth period.

The higher N uptake by the clone Karin stems was not solely due to a higher stem biomass production but higher N content in the stems. The N content of the stems was about 0.5 % in Karin and 0.4 % in Gudrun. There was no great difference in the stem P content between the clones. This content was about 0.1 %.

In literature, stem N uptake by 1- and 2-year-old willows was 9–36 kg N/ha, a (Mortensen et al., 1998; Rytter, 2001) and 27–149 kg N/ha, a (Ericsson, 1994; Mortensen et al., 1998; Aronsson et al, 2001; Rytter, 2001). The N uptake by willow stems produced year 1 was below the literature range, and the uptake by the stems produced year 2 was within the literature range in this study, but at the low end. The lower N uptake in this study compared to literature values was due to both lower stem biomass production and lower N content of the stems. Literature values for stem N content of 1-year-old and 2-year-old willows were of 0.4–1.15 % (Obarska-Pempkowiak, 1994; Mortensen et al., 1998; Rytter, 2001) and 0.53–0.74 % (Mortensen et al, 1998; Rytter, 2001), respectively.

Effluent quality

The reduction rates of tot-N, NH_4-N and tot-P of the willow bed during the experimental period are given in Fig. 4. The tot-N and tot-P reduction rates were 10–60 % with a few exceptions. The reduction of NH_4-N was 10–40 % during the experimental period. At the sampling occasions of 5.8., 15.11. and 4.1., the higher reduction rates were due to influent concentrations higher than the average concentrations when the corresponding effluent was expected after 2–3 weeks. Further, the low reduction rates at 21.4. sampling was due to an influent diluted by melting snow. No obvious changes in the treatment efficiencies of NH_4-N, tot-N and tot-P were found between summer and winter conditions.

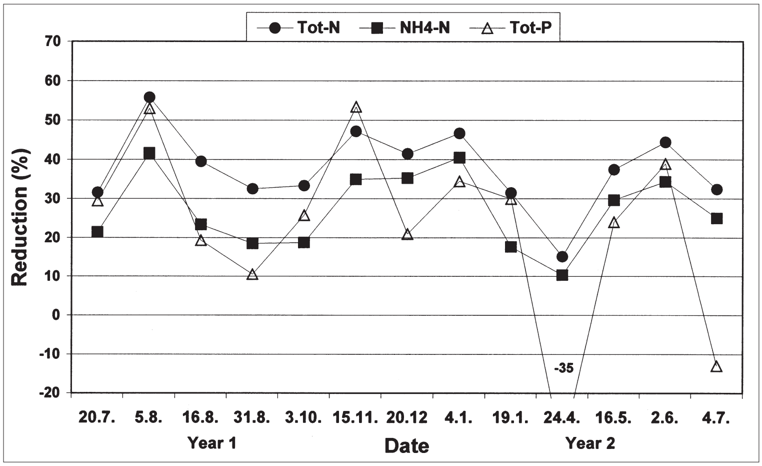

Fig. 4. *Tot-N, NH_4-N and tot-P reductions in the willow bed.*

Note: At the sampling occasions of 5.8., 15.11. and 4.1., the influent concentrations were much higher than the average concentrations for all three parameters. The corresponding effluent was expected 2–3 weeks later. The lower reduction rates of tot-N and tot-P at the 24th of April were due to an influent diluted by melting snow.

The pretreatment step may not have been effective in nitrifying the wastewater ammonium due to a low contact time and insufficient spreading of wastewater over the prefilter. Thus, there were not prerequisites for a high N reduction through denitrification. The main mechanism of N reduction may have been separation of particulate matter since the NH_4-N reduction of the tot-N ditto was about 70 % and the reduction rate was about the same regardless the time of the year. Further, the mean SS reduction in the willow bed was high (93 %).

The removal of P in the willow bed may have occurred through mechanical filtration of particulate P. Due to the neutral pH of the effluent wastewater and the fact that macadam was used as substrate P removal may not have occurred through adsorption reactions to a large extent.

The average reduction rates of tot-N, NH_4-N and tot-P were 40, 28 and 27 %, respectively. N and P removal efficiency given by literature (Hasselgren, 1984; Hasselgren, 1999 and Mant et al., 2003) was 58–95 % and 90–97 %, respectively. The lower N and P reduction rates in this study could be explained by high loading rates of the nutrients exceeding the nutrient demand of the willows. A study of Hasselgren (1999) supports this explanation. In that study, the irrigation rates were adapted to the evaporation rate and to the nutrient demand which resulted in treatment efficiencies of N and P of about 80 % and 95 %, respectively.

Tot-N, NH_4-N and tot-P concentrations in the effluent, as can be seen in Fig. 5, did not vary to a great extent during the experiment, even though influent concentrations doubled (not shown). Tot-N and NH_4-N concentrations in the effluent were 20–37 and

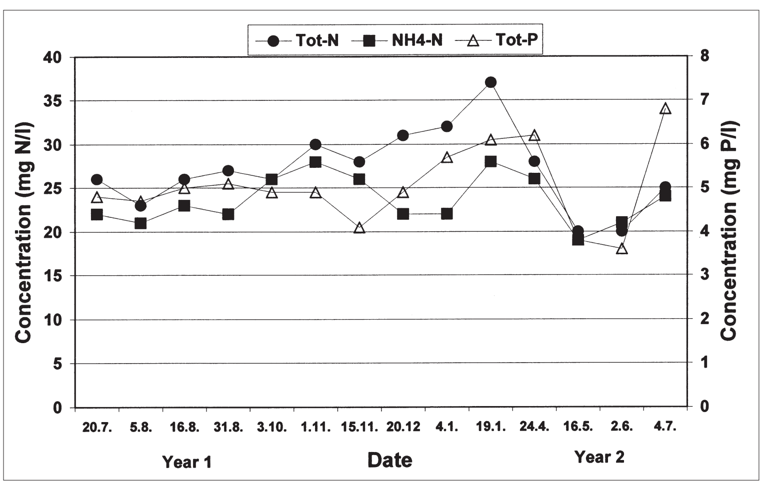

Fig. 5. *Tot-N, NH_4-N and tot-P concentrations in the effluent of the willow bed during the experiment.*

19–28 mg/l during the experimental period. Tot-P concentration varied between 3.6 and 6.8 mg/l. A single peak of tot-N content in the effluent (19.1.) could be due to an influent of high strength that entered the willow bed some weeks earlier. During the experiment, the highest tot-N content in the influent was measured at the 4th of Jan., and it was 60 mg/l. Further, the snow melting occurred at the end of April. The corresponding effluent was leaving the willow bed some weeks later which can be seen as low effluent concentrations at 16.5. The average tot-N, NH_4-N and tot-P concentrations in the effluent were 26, 23 and 4.8 mg/l.

In a study by Mant et al. (2003), wetland systems with willows were irrigated with wastewater. According to Mant et al. (2003), suitable volumes of wastewater were added each week over period of 19 weeks with the mean concentrations of ammonium N and P same as in this study. N and P concentrations in the effluent were 6–25 mg/l and 1–4 mg/l, respectively. Thus, the effluent concentrations of N and P in this study were about within the same ranges but at the higher end.

The BOD_7 reduction rates and the BOD_7 content in the influent and effluent is presented in Fig. 6. The BOD_7 reduction was high and between 80–90 % with few exceptions even at a high loading rate of 80 g/d. There was no great variation in the reduction rates during the experimental period. The BOD_7 content in the influent was fluctuating; 80–368 mg/l. The BOD_7 concentrations in the effluent was fluctuating during the first month and was 26–44 mg/l. Thereafter, the concentration decreased with time from 20 mg/l to about 10 mg/l till the end of the experiment. The average BOD_7 reduction rate and concentration in the effluent was 86 % and 26 mg/l.

There was a pattern where reduction rates were following the influent concentrations. The high reduction rate during the 5th of August year 1 could be due to a high BOD_7 content in the influent. The following reduction rate was low which could be due the high strength influent that had entered the treatment plant about a week earlier. The decrease in the reduction rate at 24.4. sampling could be due to the influent being diluted by water from snow melting.

The removal efficiencies of BOD found in literature for similar willow-wastewater irrigation systems were 74–98 % (Hasselgren, 1984; Kowalik & Randerson, 1994; Hasselgren, 1999; Mant et al., 2003). In this study, the reduction rates were within this interval during the whole experimental period. In a study performed by Mant et al. (2003), a wetland system with willows and a control without willows were irrigated with wastewater. In that study, the BOD reduction was high in both of the systems, and at a level of 90 % which indicates that a high reduction of organic matter can be achieved without vegetation effects. The BOD_7 removal of this study may have occurred through a mechanical filtration of organic matter since the reduction of SS was high (93 %). Further, a part of the reduction may have occured through a biofilm on the substrate grains and on the willow roots that developed with time as the concentration in the effluent decreased during the experiment.

In this study, the BOD_7 concentration in the effluent was within a range (7–44 mg O_2/l) given by the study of Mant et al. (2003).

Phosphorus adsorbents

Phosphorus removal

The P reduction rates and the effluent concentrations of tot-P for both of the adsorbents are presented in Fig. 7. For the Filtralite-P and the BF slag filters, the tot-P re-

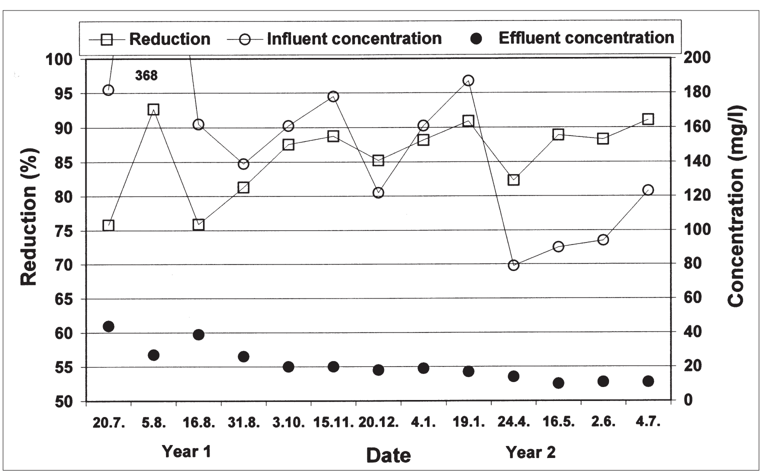

Fig. 6. *The reduction and the effluent concentrations of BOD_7 in the willow bed during the experiment.*

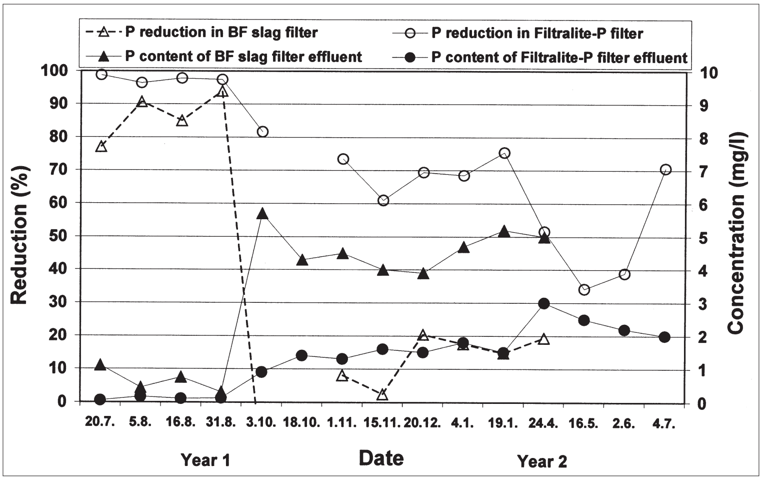

Fig. 7. *The reduction and the effluent concentrations of tot-P in the adsorbents.* The open marker denotes the reduction rate and the closed marker the effluent concentration.

duction was 96–99 and 77–93 %, respectively, in the beginning but decreased rapidly within a few months of operation to the level of 60–74 and 2–20 %. This high reduction in the beginning could be due to a maintenance work in the filters which was done during August of year 1. At that time, the wastewater flow to the filters decreased. In September, when the filters were in normal operation, the decrease of reduction rates and the increase in effluent concentrations could be seen at the following sampling. After three months of operation, the effluent tot-P concentration of the BF slag filter was above 4 mg/l and the reduction rate below 20 %. After nine months, the BF slag material was considered P saturated since the tot-P reduction rate was stable and below 20 %. The filter was reducing particulate P as the tot-P and PO_4-P concentrations in the effluent were about the same. Therefore, operation of the BF slag filter was terminated. The reduction rate of the Filtralite-P filter was decreasing with time but not as drastically as in the BF slag filter. The two low reduction rates in the spring of year 2 (35–40 %) were due to a influent wastewater that was diluted by water from snow melting. The tot-P concentrations of the Filtralite-P filter effluent increased from 0.1 to about 2 mg/l at the end of the experimental period. When the operation of the BF slag filter was terminated, the Filtralite-P filter gave a P reduction of 35–50 %, and the effluent had a content of 2–3 mg tot-P/l. The mean tot-P concentration in the effluent of the Filtralite-P and BF slag filter was 1.3±0.9 mg/l and 3.3±2.1 mg/l, respectively.

The Filtralite-P filter was more effective in reducing P than the BF slag filter. This could be due to the smaller grain size of the Filtralite-P compared to the BF slag as the substrate with a smaller particle size will have larger a surface area increasing the potential for direct reaction with phosphates. This could be the case for the adsorbents in this study as the PO_4-P reduction was higher in the Filtralite-P filter (45 %) than in the BF slag ditto (15 %). A higher P sorption in a BF slag filter with smaller grain size was observed in a study of Hylander et al. (2006). The main mechanism of P removal in the adsorbents could be a formation of Ca-phosphates as the PO_4-P reduction was more than 50 % of the tot-P ditto. A part of the P was removed through mechanical filtration of particulate P as the tot-P reduction was higher than the PO_4-P ditto. Further, more extensive mechanical filtration of particulate P may have occurred in the Filtralite-P filter than in the BF slag ditto since SS reduction was higher in the former one.

P removal is related to highly alkaline conditions and large amounts of soluble calcium (Johansson, 1998). The average pH in the effluent of Filtralite-P was 9.7 and about one unit higher than in the one of the BF slag filter. Moreover, the average calcium concentration in the effluent of Filtralite-P (79 mg/l) was higher than in the effluent of BF slag filter (56 mg/l). These conditions created better prerequisites for P removal in the Filtralite-P filter than in the BF slag ditto.

Jenssen et al. (2005) presented a summary of efficiencies of constructed wetlands in Norway with a pretreatment biofilter. The substrate in the wetland systems was Filtralite-P and the total wetland area varied between 7–12 m^2/pe. For 10 of these 13 wetlands the removal efficiency of P was above 93 % and the effluent concentration 0.01–0.6 mg tot-P/l. Higher P removal in these systems compared to this study can be addressed to a higher volume of P adsorbent per person in the Norwegian systems.

In a study of Asuman Korkusuz et al. (2005), removal of P in a BF slag-based wetland planted with reeds was studied. The wetland was loaded with 0.10 m/d municipal wastewater. The average P removal and P concentration in the effluent was 45 % and 3.3 mg/l, respectively, and these figures are at the same level as in this study.

The amount of sorbed P by the filter media when the operation of the filter was terminated is given in Table 5. The Filtralite-P material had sorbed 378 mg P/kg when the operation of the filter was terminated. The corresponding value for the BF slag filter was 64 mg P/kg after operation of 9 months. The higher P loading rate of the Filtralite-P filter is due to longer operation of the filter than the BF slag ditto. When the operation of the BF slag filter was terminated, the Filtralite-P filter had sorbed 171 mg P/kg material. Thus, the longer operation time of the Filtralite-P filter can not explain the higher P sorption of this filter compared with BF slag ditto.

The P sorption by the BF slag and by the Filtralite-P filter was lower than the ones found in the literature (Yamada et al., 1986; Lee et al., 1997; Johansson, 1998; and Ádám et al., 2005). A possible reason for lower sorption values in this study compared with the literature can be due to the differences in the experimental method. The studies in the literature are often batch experiments or column experiments using artificial P solutions which give too high estimates of sorption capacities (Drizo et al. 2002). Further, the Filtralite-P material in this study was not completely P saturated since the influent concentrations were higher than the effluent ditto. A sorption value of 52 mg P/kg Filtralite-P was presented for a wetland system treating wastewater from a school (Ádám et al., 2006). In that study, the filter material was not saturated with P as the inlet concentrations were higher than the outlet ones.

Prior to the willow planting, wastewater was pumped to the willow bed unit. A valve was leaking wastewater that was drained off from the area through the BF slag filter and partly through the Filtralite-P filter. Further, the willow bed was not covered with an impermeable layer. Water from snow melting and rainfall from the willow bed entered the P filters in pulses. These factors may have caused partial washing away of vital substances for P sorption reducing the P removal capacity. A possible washing out was reported by Hellström & Jonsson (2005) where a Filtralite-P filter had a sorption value of about 100 mg P/kg substrate when indications of saturation in the bottom of the filter were reported. In that study, the P load on the filter bed was 30 % of the design capacity and only 5 % of the assumed P sorption capacity had been utilised. Alkalinity and calcium concentrations had decreased significantly after one and half a year operation possible due to a leakage in a storage tank into the treatment plant.

Table 5. *P sorption by the filter medium when the filter operation was terminated.* BF slag filter operated 9 months and Filtralite-P filter 13 months before the termination.

	BF slag	Filtralite-P
Phosphorus load, g	510	620
Sorbed tot-P, g	180	460
mg P/kg filter material	64	378
mg P/m^3 filter material	83	208

Nitrogen removal

Tot-N reduction in both of the filter varied to a great extent. The reduction rates in Filtralite-P and the BF slag were –7 to 52 and –52 to 22 %, respectively. When the flow to the filters was reduced (August of year 1), a tot-N reduction of 40–50 % and 10–20 % occurred in the Filtralite-P filter and the BF slag filter, respectively. Otherwise, the tot-N reduction in the filters was lower and below 30 % in the Filtralite-P filter and below 10 % in the BF slag ditto (with one exception). The tot-N reduction was higher in the Filtralite-P than in the BF slag ditto with few exceptions. The average tot-N reduction rates in the BF slag and the Filtralite-P filters were 3 and 20 %, respectively.

The tot-N concentration in the BF slag and the Filtralite-P effluents varied between 21–35 and 13–32 mg/l, respectively. There was a decrease in the tot-N effluent concentrations for both filters when the flow was reduced. Otherwise, no obvious pattern could be found for the fluctuations of the effluent tot-N concentrations. The average tot-N concentrations in the BF slag and the Filtralite-P filter effluent were 28 and 22 mg/l. The average NH_4-N concentration was about 78 % of the average tot-N effluent concentration for both of the filters.

The main mechanism for N reduction in the filters could be mechanical filtration of particulate N since SS reduction occurred in both filters. Further, it could explain the higher N reduction in the Filtralite-P filter since the grain size of the Filtralite-P material was smaller and the SS reduction in the Filtralite-P filter was higher. Since NH_4-N reduction occurred in both of the filters, the N reduction in the filters may also be due to other mechanisms. When the flow to the filters was reduced (during August year 1), the tot-N reduction was the highest during the whole experimental period in both of the filters. The NH_4-N reduction in the Filtralite-P was at the same highest compared to the whole experimental period. The pH in the effluent in both of the effluents was above 10. This indicates that a part of the N may have been reduced in the filters through volatilization of ammonium, and most intensively when the retention time of the filters was reduced (August year 1).

The reduction of tot-N by the BF slag and the Filtra-

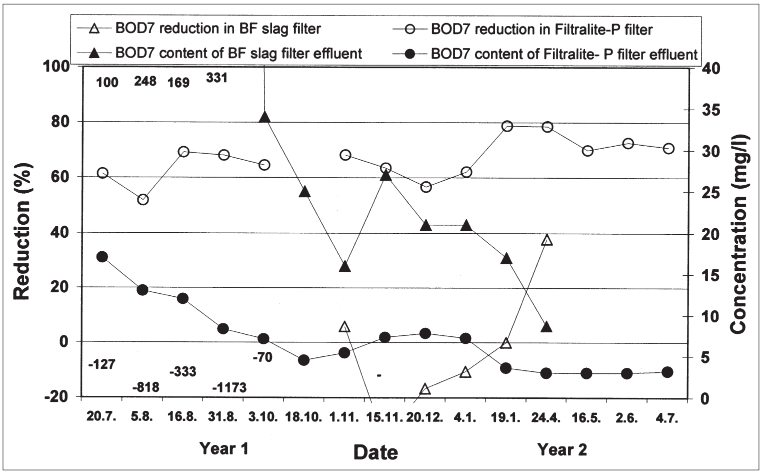

Fig. 8. *The reduction and the effluent concentrations of BOD_7 of the P filters during the experiment.*

lite-P filter was lower than in other P sorption filters in the studies of Hellström & Jonsson (2005) and Öövel et al. (2006). The reduction of NH_4-N by the Filtralite-P filter in this study was about as high as in the study of Hellström & Jonsson (2005). Further, the average tot-N and NH_4-N concentrations in the effluent of the Filtralite-P were similar to the ones in the study of Hellström & Jonsson (2005).

BOD_7 removal

As can be seen from Fig. 8, the Filtralite-P filter was more effective in reducing BOD_7 than the BF slag filter. During the experimental period, the BF slag filter was releasing an effluent with a higher BOD_7 concentration than in the influent with few exceptions. The BOD_7 content in the effluent could be up 17 times higher than the in the influent. Similar phenomena could not be seen in the Filtralite-P filter. The high BOD_7 reduction in the BF slag filter at 24.4. sampling could be due to a sample diluted by water from snow melting. The Filtralite-P filter had a BOD_7 reduction that varied between 50 and 80 % during the experiment.

The high BOD_7 reduction rates in the Filtralite-P could be due to fine filter material which was effective in filtering the particulate organic matter. Thus, the mechanical filtration was the main mechanism of BOD_7 removal in the Filtralite-P filter.

The effluent BOD_7 concentrations in the Filtralite-P filter decreased during the experiment from 17 mg/l to 3 mg/l till at the end of the experiment. The same trend could be seen in the effluent BOD_7 content of the BF slag filter. The concentrations decreased from about hundred mg/l to about ten mg/l. High influent BOD_7 concentrations were coupled with high effluent ditto in both of the filters.

According to Kanschat (1996), the BF slag consists of 1–2 % reduced sulphuric compounds which may be oxidised and leached out. The high BOD_7 content in the effluent of the BF slag filter could be due to a high release of reduced sulphuric compounds from the BF slag material as the effluent SO_4-S concentrations of BF were high at the same time (150–500 mg/l). The effluent SO_4-S concentrations of the Filtralite-P filter were 6–55 mg/l and the concentrations of the influent wastewater was 36–51 mg/l. The effluents of the adsorbents were exceeding the SO_4-S limit of Swedish drinking water which is 33 mg/l.

The average and median reduction of BOD_7 in the BF slag filter was –231 and –35 %, respectively. The average and median reduction in the Filtralite-P filter was about 70 %. The average and median BOD_7 concentrations of the BF slag effluent were 111 and 26 mg/l. The corresponding values of the Filtralite-P effluent were 4.1 and 5.4 mg/l. The BOD_7 reduction and the average BOD_7 effluent concentration of the Filtralite-P were at the same level as in the study of Öövel et al. (2006).

Overall function of the treatment plant

Effluent quality

The average effluent concentrations of tot-P, tot-N NH_4-N, BOD_7, pH and SS in the effluent with the average reduction rates of the parameters in the two treatment systems are presented in Table 6. The average tot-P, tot-N NH_4-N, BOD_7, pH and SS concentrations in the Filtralite-P effluent were 1.3, 22, 20, 7.6, 9.7 and 2.6 mg/l, respectively. The corresponding values for the BF slag effluent were 3.3, 28, 25, 85, 8.8 and 3.5 mg/l, respectively. The Filtralite-P treatment system was more

Table 6. *Average reduction rates and effluent quality of the present study with the reduction rates given by SEPA (2006) for two protection levels.*

	System	Tot-P	Tot-N	NH_4-N	BOD_7	pH	SS
Average concentration (mg/l)	BF slag	3.3±2.1	28±5	25±3	85±108	8.8±0.2	3.5±1.4
	Filtralite-P	1.3±0.9	22±6	20±4	7.6±4.2	9.7±0.3	2.6±1.0
Average reduction rate (%)	BF slag	53	38	25	48	–	95
	Filtralite-P	83	51	39	95	–	96
Reduction rate by SEPA (%)	Normal level	70	–	–	90	–	–
	High level	90	50	–	90	–	–

– = not given

effective than the BF slag ditto in removing these wastewater compounds. This was especially apparent for tot-P and BOD_7. Further, there was a great variation in the reduction rates of the BF slag system; the system could occasionally have negative reduction rates of tot-N, NH_4-N and BOD_7.

Swedish Environmental Protection Agency has recently published directives for small wastewater treatment systems (SEPA, 2006). The directives contain a demand of enabling recovery of wastewater nutrients and a specification of treatment efficiencies of the systems. The specification is given for two protection levels, normal and high. These treatment efficiencies of the protection levels can be seen with the average pollutant reductions in the studied systems in Table 6. The BF slag system did not fulfil the requirements of the normal or the high protection level. The Filtralite-P system could fulfil the reduction rates of the normal and two of the three reduction rates in high protection level.

Operation experience

The treatment plant has been operating since the beginning of July 2005. Soon after the introduction of the treatment plant, a perforated pipe with 4 mm holes in the distribution layer of the willow bed was clogged by the solids of the wastewater. The perforated pipe was replaced by a box with V-formed weirs where waste water overflowed to the prefilter. No clogging of the willow filter or the adsorbents could be observed. After some months of operation, a precipitate appeared at the bottom of the outlet (sloping 1–2 ‰). With time the thickness of the precipitate layer was increasing, and after a year and half of operation, the thickness was about 20 % of the inner diameter of the pipe.

Frost killed most of the top shoots of the hybrids during the late autumn of year 1. However, the growth continued next spring with new shoots, see Fig. 9. Problem with weed were not experienced mainly due to the nature of the substrate in the willow bed. Some single weed plants appeared at the prefilter and at the edges of the willow bed during the experiment. At the end of the second growth period, willow stems shadowed by other willows became long and thin due to a dense planting. This effect can make them susceptible for heavy rains and snow fall. Thus, dense spacing of willows should be avoided.

The willow bed was not covered with an impermeable layer. The effect of it could be seen as an increase in the flow from the willow bed to the P filters during snow melting and precipitation which resulted in decreased retention times of the willow bed and of the P filters. It was hard to quantify the effect of the decreased retention times on the treatment efficiencies.

The BF slag effluent was strongly coloured to yellow, especially in the beginning of the experimental period. At the same time, sulphuric odours were experienced at the effluent. Similar phenomena could not be observed at the effluent of the Filtralite-P filter.

Even though the pipelines were placed in the depth of ground frost, no freezing problem occurred due to use of

Fig. 9. *New shoots with frozen ones – the clone Gudrun.*

different kinds of insulation materials, heating wire and submersible heaters.

Conclusions

The willow vegetation filter could be established in cold climate. Even though most of the willow shoots experienced frost damages at the end of the year 1, both of the clones produced about equal high stem biomass of 8 ton DM/ha during year 2. The high biomass production was most likely due to temperatures higher than long-time monthly averages during the growth period and to a high fertigation rate.

The reduction of BOD_7 of the willow filter was in average about 80 % and the average reduction of tot-P and tot-N was about 20–30 %. The main removal mechanism was mechanical filtration. The low nutrient removal rate was due to a loading rate exceeding several times the nutrient demand and a low nitrification rate of the prefilter.

The Filtralite-P filter was more effective in reducing P, N and organic matter measured as BOD_7 than the BF slag filter. The average reduction rates of the previous parameters in the Filtralite-P filter were 72, 20 and 67 %, respectively. The corresponding values for the BF slag filter were 53, 3 and –231 %, respectively. The negative reduction of BOD_7 of the BF slag filter was coupled with a high release of sulphuric compounds.

The overall reduction rates of tot-P, tot-N and BOD_7 in the Filtralite-P system were 83, 51 and 95 %, and the corresponding values for the BF slag system were 53, 38 and 48 %, respectively. Thus, Filtralite-P system achieved the requirements of the normal protection level given by Swedish Environmental Protection Agency but not all of the requirements of the high ditto. The BF slag system did not fulfil the requirements of the two protection levels. The average concentrations of tot-P, tot-N and BOD_7 in the Filtralite-P filter effluent were 1.3, 22 and 7.6 mg/l. The corresponding values for the BF slag filter effluent were 3.3, 28 and 85 mg/l.

No clogging problems occurred in the treatment plant besides in a perforated pipe at the beginning of the experiment. No freezing of the pipes took place due to heating and insulation of the treatment plant. Due to a coarse mineral substrate, no great weed problems existed in the willow bed. Dense spacing of willows should be avoided in order to produce more stable willow stands for heavy precipitation. In order to avoid clogging of the outlet pipe from the P filter, the slope of the outlet pipe should be more than 1–2 ‰. The willow bed and the P filters should be constructed in such manner that neither drainage water nor precipitation may enter the units to a great extent.

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