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THE APPLICABILITY OF HYBRID SUBSURFACE FLOW CONSTRUCTED WETLAND SYSTEMS WITH RE-CIRCULATION FOR WASTEWATER TREATMENT IN COLD CLIMATES

ALAR NOORVEE

TARTU UNIVERSITY
PRESS

Institute of Geography, Faculty of Biology and Geography, University of Tartu, Estonia.

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Supervisor: Prof. Dr. Ülo Mander, Institute of Geography, University of Tartu, Estonia.

Opponent: Prof. Emer. Dr. Robert H. Kadlec, Department of Chemical Engineering, University of Michigan, USA.

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ORIGINAL PUBLICATIONS

Publication I
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Publication III
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ABSTRACT

In the current PhD dissertation the applicability and performance of two stage subsurface constructed wetlands (VSSF+HSSF filters) for wastewater purification in Estonia (cold climates) with re-circulation are assessed. In wastewater purification processes, oxygen supply and oxygen balance in the system are very important factors. The research conducted clearly demonstrated that the availability of oxygen is essential for purification processes. In cold climates another important factor influencing the performance of wastewater treatment is the effect of temperature. One possibility to assure sufficient aeration is to design a vertical subsurface flow (VSSF) wetland as the first stage of a constructed wetland. Since the aim of the VSSF filters is to enhance aeration of the wastewater, the design should be focused on the oxygen demand of the wastewater and on the aeration potential of the VSSF wetland. In cold climates, CWs are often designed with a reserve in order to compensate for lower temperatures during winter. Providing measures that can help achieve proper results without over-dimensioning would make CWs a much more attractive wastewater treatment technology. One possible operational method to compensate for the small area and short retention time is to re-circulate the wastewater. As the effluent is being re-circulated, additional oxygen for aerobic microbial activities can be transferred into the wastewater. Re-circulation also enhances contact between the pollutants and microorganisms. Another important reason for wastewater re-circulation is the low amount of organic matter remaining for denitrification of the nitrified wastewater. Wastewater re-circulation makes it possible to apply pre-denitrification.

It can be concluded that the re-circulation of wastewater in overloaded systems is a good solution to improve the aeration and overall purification efficiency of CWs. The re-circulation of the wastewater improves purification significantly. However, the small amount of re-circulated water (50 to 75% of the inflow) has only a small effect on purification efficiency when the system is heavily overloaded. In addition, small differences in re-circulation rate (about 10 to 20% more or less of the inflowing water) have insignificant effects on purification efficiency. The re-circulation rate has to be from 100 to 300 percent of the inflowing wastewater to achieve satisfactory results in terms of effective BOD and COD removal and nitrification/denitrification, as well as TSS removal. On the other hand, a high re-circulation rate (up to 600%) can have negative effects on TSS and P_{tot} removal. Unfortunately the LWA used as filter material in Kodijärve, Rämsi and Nõo CW rapidly lost its phosphorus adsorption and sedimentation properties. It is crucial to select a suitable filter material for phosphorus removal in subsurface constructed wetlands.

It can be concluded that the area of the VSSF filter should measure up to 2.5 m^2 pe^{-1} for effective organic matter removal and nitrification. Implementing re-circulation of over 100% results in an area need of 1.7 m^2 pe^{-1} for VSSF

filters. It is recommended to design the VSSF filters with a depth of 1.0 to 1.3 m. Taking into account both hydraulic loading and organic matter loading, the recommended area for HSSF filters is 3.0 to 5.0 m^2 pe^{-1} when they are placed as the second stage of the CW system.

1. INTRODUCTION

There is growing interest in wastewater purification with low cost technology. Constructed wetlands (CW) offer an economical and ecological alternative with lower operational costs and less energy demand compared to active sludge and other wastewater treatment technologies. The key factor is to meet the effluent standards in all water quality parameters. On the other hand, the CWs require more area to achieve the same performance, for example active sludge technology. Usually pre-treatment in a septic tank is required prior to channelling the wastewater into the CW. Different sources report an over 70% reduction in TSS, a 20 to 60% reduction in BOD_7 (Kuusik, 1995; Bounds, 1997) and a 10 to 20% reduction in N_{tot} and P_{tot} (Kuusik, 1995).

Oxygen supply and oxygen balance in the system are very important factors in wastewater purification processes. If the availability of dissolved oxygen in a wastewater treatment unit is high, then aerobic processes, such as the removal oxidation of organic compounds and nitrification, can occur properly (Noorvee *et al.*, 2005b; Publication I). Therefore supplementary measures must be adopted to increase the aerobic condition, such as direct bed aeration or aerobic pre-treatment systems (Harris & Mæhlum, 2003; Cooper, 2005).

In cold climates another important factor influencing the performance of wastewater treatment is the effect of temperature. Cold climates could be defined as climatic conditions where the daily average air temperature is below 0ºC over a longer period. In Estonia the winter period is defined as the period when average air temperature is below 0ºC and with the formation of snow cover. In mainland Estonia the duration of the winter period is usually 140 to 150 days, and the coldest month is usually January, with an average daily air temperature of –5.8 to –7.0ºC (Jaagus, 2001).

Low temperatures can significantly change the hydraulics and chemical and biochemical processes in constructed wetlands (Wittgren & Mæhlum, 1997; Mander & Mauring, 1997). It has generally been agreed that the major removal mechanisms for nitrogen in CWs are ammonification and nitrification/denitrification (Kadlec & Knight, 1996; Vymazal *et al.*, 1998). Processes such as nitrification and denitrification are known to be temperature dependent. It is known that the minimum temperatures for the growth of nitrifying bacteria *Nitrosomonas* and *Nitrobacter* are 5 and 4ºC respectively (Vymazal *et al.*, 1998). The extent of nitrogen and BOD_7 removal is more determined by the availability of dissolved oxygen in the treatment system. Whereas BOD_7 removal and nitrification need sufficient oxygen, denitrification occurs in the absence of oxygen. It is therefore important to take into account the oxygen demand of the inflowing wastewater in designing a wastewater treatment system (Noorvee *et al.*, 2005b; Publication I). Von Felde and Kunst (1997) have concluded that the size of constructed wetlands should be determined on the basis of the need for oxygen.

One means to assure sufficient aeration is to design a vertical subsurface flow (VSSF) wetland as the first stage of a constructed wetland (Noorvee *et al.*, 2005b; Publication I). VSSF wetland systems have a much greater oxygen transfer capacity than horizontal subsurface flow (HSSF) wetland systems (Cooper, 1999), and hence VSSF CW can achieve very good results in the removal of organic substances and enhance nitrification remarkably. Since the conditions in HSSF CWs are usually anoxic or anaerobic, combined HSSF and VSSF CWs can balance out each other's weaknesses, and it is possible to design a system that successfully removes BOD, total nitrogen, phosphorus and suspended solids (Cooper *et al.*, 1999).

Since the aim of the VSSF filters is to enhance aeration of the wastewater, design should focus on the oxygen demand of the wastewater and the aeration potential of the VSSF wetland. The maximum oxygen transfer rate of VSSF wetlands is generally considered to be 30 g O_2 m^{-2} d^{-1} (Vymazal *et al.*, 1998; Cooper, 1999). A review of the removal rates in wetland systems has shown that the aeration capability of VSSF wetlands can be 50 to 90 g O_2 m^{-2} d^{-1} (Cooper *et al.*, 1999). For more effective aeration, von Felde and Kunst (1997) recommend non-water-saturated conditions for VSSF filters. On the other hand, Green *et al.* (1997) describe a system where a water-saturated zone is retained at the bottom of the bed.

In cold climates, CWs are often designed with a reserve in order to compensate for lower temperatures during winter. Temperature effects can probably be partially compensated by greater hydraulic retention times (Mæhlum & Stålnacke, 1999). Over-design to compensate for uncertainty due to low temperatures raises construction and operating costs (Werker *et al.*, 2002). Different recommendations have been found for the sizing of CW systems in different countries. For example, Cooper (1999) recommends an area of 1 m^2 pe^{-1} for BOD removal only, and 2 m^2 pe^{-1} for BOD removal and nitrification for VSSFs. Austrian research recommends an area of 4 m^2 pe^{-1} for VSSFs, which assures year-round effective purification and nitrification (Langergraber *et al.*, 2006). Danish guidelines for small wastewater treatment systems suggest an area of 3.2 m^2 pe^{-1} for one-stage VSSFs (Brix & Arias, 2005). Typical hydraulic loading for VSSF CWs is 40 – 500 mm d^{-1} (Kadlec *et al.*, 2000). Paing *et al.* (2006) recommended 100...400 mm d^{-1} as optimal hydraulic loading for VSSF-s. Average recommended hydraulic loading for HSSF CWs varies from 20 to 100 mm d^{-1} and the recommended area from 2 to 10 m^2 pe^{-1} (Kadlec *et al.*, 2000). If the HSSF CW is used for secondary treatment (taking settled wastewater), the recommended area is 5 m^2 pe^{-1} (Cooper, 1999; Vymazal *et al.*, 1998), and for tertiary treatment 1 m^2 pe^{-1} (Vymazal *et al.*, 1998).

Providing measures that can help achieve proper results without over-dimensioning would make CWs a much more attractive wastewater treatment technology. Temperature effects can, for instance, be diminished using thermal insulation during wintertime, or by placing the distribution pipes of the VSSF

CW below the surface. This improves insulation, but complicates control of the system (Laber *et al.*, 2003). Another possible operational method to compensate for the small area and short retention time is to re-circulate the wastewater (Põldvere *et al.*, 2007; Publication V). As the effluent is being re-circulated, additional oxygen for aerobic microbial activities can be transferred into the wastewater. Re-circulation also enhances contact between the pollutants and microorganisms. In addition, as the suspended solids are predominantly removed by filtration, re-circulating the effluent increases the chances for the suspended solids to be trapped in the system (Sun *et al.*, 2003). These factors should account for the improvement of overall purification processes. Re-circulation has significantly enhanced the purification of landfill leachates (Connolly *et al.*, 2003; Zhao *et al.*, 2006). Values of water quality indicators, such as BOD and COD (Zhao *et al.*, 2004; Sun *et al.*, 2006; He *et al.*, 2006; Sun *et al.*, 1998; Del Bubba *et al.*, 2004), and concentrations of N_{tot} (Kanta-wanichkul *et al.*, 2001; Rustige & Platzer, 2001; Sun *et al.*, 2005; Arias *et al.*, 2005), NH_4-N (White, 1995; Sun *et al.*, 1998; Sun *et al.*, 2005; Zhao *et al.*, 2004; He, *et al.*, 2006; Sun *et al.*, 2006), P_{tot} (Farahbakhshazad & Morrison, 2003; Zhao *et al.*, 2004) and total suspended solids (Zhao *et al.*, 2004; He, *et al.*, 2006) have been reduced through the implementation of re-circulation. Several studies report enhanced aeration and increased O_2 consumption by microorganisms (Sun *et al.*, 1998; Sun *et al.*, 1999; Shi *et al.*, 2004). On the other hand, there are studies that point out no significant influence of re-circulation on the removal of P_{tot} (Brix & Arias, 2005; He *et al.*, 2006), and NH_4-N (Bahlo, 2000; Moreno *et al.*, 2002). However, in some countries the re-circulation of wastewater in subsurface flow filters has been included in the official guidelines on CWs (Bahlo, 2000; Brix & Arias, 2005).

The LWA-based hybrid CWs (VSSF and HSSF filters in series) for the treatment of domestic wastewater show equally high long-term efficiency in both summer and winter (Jenssen *et al.*, 1993; Mæhlum *et al.*, 1995; Mæhlum & Stålnacke; 1999, Jenssen *et al.*, 2005; Öövel *et al.*, 2007). In contrast, some studies report lower NH_4-N and P removal in subsurface flow wetlands in winter (Sikora *et al.*, 1995; Steer *et al.*, 2002), whereas Kushk *et al.* (2003) report on a significantly lower N removal in an experimental HSSF in winter.

Another important reason for wastewater re-circulation is the low amount of organic matter remaining for denitrification of the nitrified wastewater. In addition to the anoxic conditions, a carbon source is of the highest importance for the denitrifying bacteria (Laber *et al.*, 2003). A sufficient carbon source for denitrification can be provided either by adding an external carbon source (methanol for example) or by establishing a re-circulation of the nitrified effluent into the sedimentation tank. In order to achieve a high removal of N_{tot}, re-circulation of treated wastewater back to the inlet of the septic tank is suggested (Johansen *et al.*, 2002). Cooper *et al.* (1999) also recommended pumping effluent back from the outlet of the VSSF to improve denitrification.

The raw wastewater mixes with the nitrified water in the settling tank. The raw wastewater contains the necessary carbon source and anoxic conditions for denitrifying bacteria (Laber *et al.*, 2003). Re-circulation is also often used for denitrification in conventional biological sewage treatment systems (Cooper *et al.*, 1999). The re-circulation of wastewater for more effective denitrification is called pre-denitrification. Platzer (1999) and Laber *et al.* (1997) have shown that re-circulation rates of up to 200% of the incoming wastewater have yielded good results. Laber *et al.* (2003) indicate that in one-stage VSSF CWs, recirculation of 90–100% yields sufficient denitrification. Pre-denitrification can be dimensioned as the classic pre-denitrification in activated sludge plants (Platzer, 1999).

It is crucial to select a suitable filter material for phosphorus removal in subsurface constructed wetlands. For example, in light weight aggregates (LWA), Ca-minerals are a very important additive for the precipitation of phosphorus. In contact with water, this may yield a dramatic increase in pH, which may favour the precipitation of phosphates (Jenssen & Krogstad, 2003). Even if the medium with high P binding capacity has been selected, however, it will be saturated after a few years and something will have to be done to sustain P removal (Arias *et al.*, 2001). An obvious and sustainable solution would be a separate filter unit containing replaceable material with a high P-binding capacity (Brix *et al.*, 2001). Research with a filtering material with very promising phosphorus removal capacity has been conducted at the University of Tartu. The material is oil-shale ash from an oil shale ash plateau, which has shown very high P sorption capacity (98.4%) in batch experiments, and in field experiments P removal in the filter bed was 62–88% during the first 4 months (Vohla *et al*, 2005). Another means to achieve P_{tot} effluent standards is to use chemical precipitation, which can be installed in the septic tank (Brix & Arias, 2005).

In Estonia, standards for wastewater discharge from treatment plants of 2000 to 9999 pe (standards below 2000 pe are in most cases set at the same level) are as follows: $BOD_7 = 15$ mg l^{-1}, COD = 125 mg l^{-1}, TSS = 25 mg l^{-1}, $P_{tot} = 1.5$ mg l^{-1} (in sensitive waterbodies 1.0 mg l^{-1}) and for N_{tot} no standard has been set for treatment plants below 10,000 pe. In treatment plants over 10,000 pe, the standard for N_{tot} is 15 mg l^{-1}.

Objectives

The main objective of this PhD dissertation is to assess the applicability and performance of two-stage subsurface constructed wetlands (VSSF+HSSF filters) for wastewater purification in Estonia (cold climates). The sub-objectives for achieving the main goal are:

1) To evaluate the purification efficiency, mass removal rates and theoretical aeration capacity (oxygen transfer rate) of 1 full scale and 2 pilot scale hybrid subsurface constructed wetland systems in Estonia;
2) To assess the impact of water re-circulation on the purification performance of the systems;
3) To determine optimal loading and area parameters for two-stage hybrid subsurface wetlands in cold climate conditions;
4) To present design recommendations for hybrid subsurface constructed wetlands in Estonia.

2. METHODS

2.1. Site descriptions

In the current PhD dissertation, the following hybrid CW systems are analyzed:

1) Kodijärve hybrid CW
2) Nõo pilot-scale hybrid CW
3) Rämsi pilot-scale hybrid CW

2.1.1. Kodijärve hybrid constructed wetland system

The horizontal subsurface flow (HSSF) stage of the Kodijärve hybrid constructed wetland (CW) system (in South Estonia) was constructed in 1996 to treat the wastewater (dual-chamber septic tank outflow) of a hospital (40 population equivalents; pe). The double-bed HSSF filter is 1 m deep (312.5 m^2) had a PVC liner, was filled with coarse iron-rich sand and covered predominantly with *Phragmites australis* and *Scirpus sylvaticus* (Mander *et al.*, 2001). In recent years *Urtica dioica* and *Epilobium hirsutum* have been dominant (Noorvee *et al.*, 2007; Publication III).

As the Kodijärve HSSF CW had not achieved sufficient aeration capacity during its operational period since 1996, a vertical subsurface flow (VSSF) filter (two intermittently loaded crushed limestone filled beds with a total area of 37.4 m^2) was constructed between the septic tank and the HSSF filter in the summer of 2002 in order to enhance aerobic purification processes, especially nitrification (Noorvee *et al.*, 2005b; Publication I; Noorvee *et al.*, 2005a; Publication II; Noorvee *et al.*, 2007; Publication III). The beds of the VSSF CW are loaded intermittently. One bed (18.7 m^2) is loaded for a period of from one week to a month (depending on the sampling periodicity), while the other bed rests (Noorvee *et al.*, 2005b; Publication I; Noorvee *et al.*, 2005a; Publication II). Resting VSSF beds for several days prevents surface hydraulic and organic overloading, in order to avoid clogging (Weedon, 2003).

The VSSF beds were not planted. In Norwegian experiments with hybrid constructed wetlands, the expected positive effect of vegetation has not been convincingly demonstrated. The benefits of vegetation seemed to be insulation during wintertime, and aesthetics. (Mæhlum & Stålnacke, 1999).

The VSSF filter has a depth of 1.3 m and consists of three different crushed limestone layers. The bottom layer has the highest and the upper layer the lowest hydraulic conductivity (Noorvee *et al.*, 2005b; Publication I):

Bottom layer – stone size 16–40 mm;
Middle layer – stone size 5–20 mm;
Upper layer – stone size 4–8 mm.

Crushed limestone has a very high hydraulic conductivity, and the filter is drained quickly, with no water-saturated layers remaining in the filter, and thus well-aerated wastewater flows rapidly to the HSSF filter (Noorvee *et al.*, 2005b; Publication I; Noorvee *et al.*, 2005a; Publication II).

Since the phosphorus retention capacity of the HSSF wetland was reaching its limit, the filter material was exchanged in the summer of 2005, using light-weight aggregates (LWA with particle size of 2–4 mm) (Noorvee *et al.*, 2007; Publication III). Also, the possibility to re-circulate the water from the outflow well to the inflow well (to enhance nitrification-denitrification) was installed in the summer of 2005 (Figure 1).

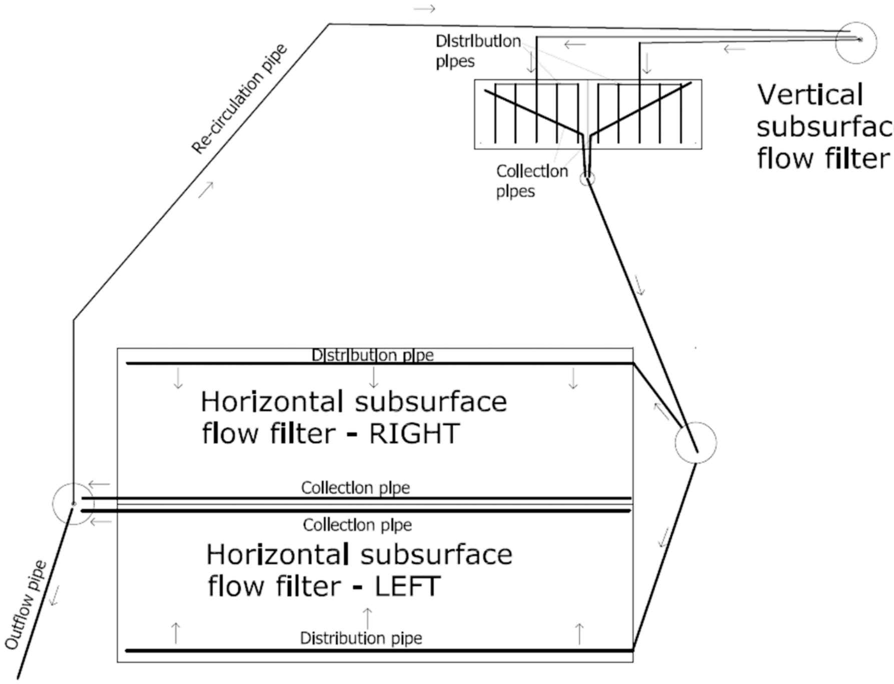

Figure 1. Schematic layout of the hybrid constructed wetland in Kodijärve, Estonia (after reconstruction in 2005).

2.1.2. Nõo pilot-scale hybrid CW

The Nõo pilot-scale CW (built in 2005) is located on the territory of the active sludge wastewater treatment plant (AWP) of Nõo village. The pilot-scale hybrid CW consists of two analogous parallel systems with different re-circulation regimes designed on the same principle: a vertical subsurface flow (VSSF) filter 0.7 m deep and with an area of 4 m^2, followed by a horizontal subsurface flow

(HSSF) filter 1 m deep and with an area of 10 m^2. The VSSF filters were constructed as one-bed units, and thus no resting of VSSF filters was possible. The filters were covered (air temperatures fell to –35°C) with 5 cm thick insulation slabs during winter. The systems were not planted, because of the short test period, which was insufficient for the proper growth of vegetation.

The wastewater (domestic wastewater combined with dairy and meat industry wastewater) is pumped into the CW before it reaches the grid of the AWP. The exact water volume is controlled by a timer-operated pump. First a certain amount of wastewater is pumped into a septic tank (2 m^3). After the septic tank, the wastewater is divided equally between both parallel experimental systems (Zaytsev *et al.*, 2007; Publication IV; Põldvere *et al.,* 200x; Publication V).

Table 1 reports the cross-section of the Nõo VSSF filters, which are constructed such that the bottom layer has the highest, and the upper layer the lowest hydraulic conductivity. The HSSF filters of both pilot scale CWs are filled with light weight aggregates (LWA) with particle size of 2–4 mm (Zaytsev *et al.*, 2007; Publication IV; Põldvere *et al.,* 200x; Publication V).

Table 1. Cross-sections of VSSF

Cross-section	**Nõo right system**	**Nõo left system**
Upper layer (20 cm)	crushed limestone Ø 2–8 mm	LWA Ø 2–4 mm
Middle layer (20 cm)	crushed limestone Ø 8–16 mm	LWA Ø 4–10 mm
Bottom layer (25 cm)	crushed limestone Ø 12–32 mm	LWA Ø 10–20 mm

It is possible to re-circulate wastewater from the outflow well of the VSSF filters (interim well) and from the outflow of the HSSF filters (outflow well) using timer-controlled pumps in both parallel CW systems (Figure 2).

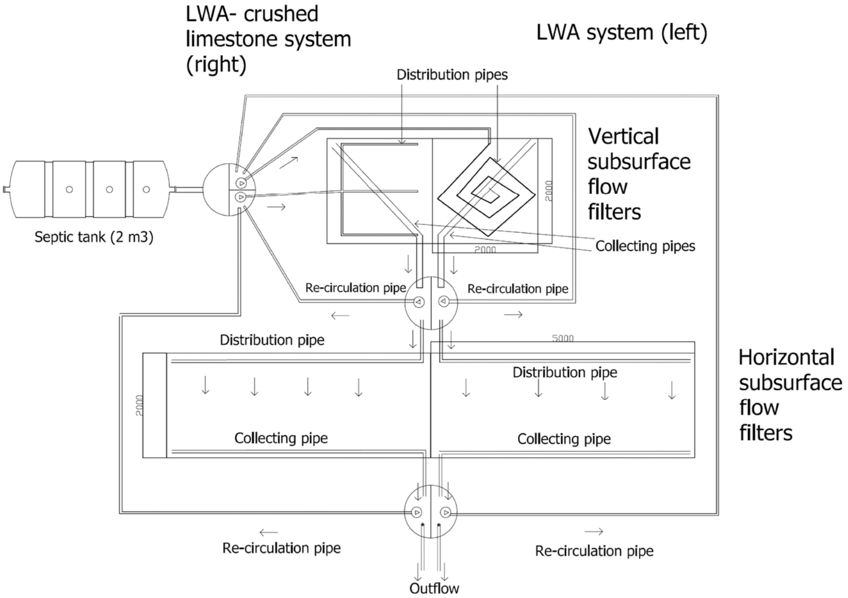

Figure 2. Schematic layout of the experimental pilot system of the hybrid constructed wetland in Nõo, Estonia. The parallel systems (right-left) are determined on the basis of the direction of wastewater flow.

2.1.3. Rämsi pilot-scale CW

The Rämsi pilot-scale CW (built in 2005) is located at a pig farm. The pilot-scale hybrid CW consists of two analogous parallel systems with different re-circulation regimes designed on the same principle: a vertical subsurface flow (VSSF) filter 0.7 m deep and with an area of 10 m^2, followed by a horizontal subsurface flow (HSSF) filter 1 m deep and with an area of 15 m^2. The VSSF filters were constructed as one-bed units, and accordingly no resting of VSSF filters was possible. The filters were covered with 5 cm thick insulation slabs during winter. The systems were not planted, because of the short test period, which was insufficient for the proper growth of vegetation (Põldvere *et al.,* 200x; Publication V).

The wastewater entering the CW is obtained by separating the liquid fraction from the solid fraction of the swine slurry in a separation well. A timer-operated pump pumps the desired amount of wastewater into the experimental system. The wastewater is first pumped into a septic tank (2 m^3). After the septic tank the wastewater is equally divided between both parallel experimental systems (Põldvere *et al.,* 200x; Publication V).

Table 2 reports the cross-section of the Rämsi VSSF filters, which are constructed such that the bottom layer has the highest, and the upper layer the lowest hydraulic conductivity. The HSSF filters of both pilot scale CWs are filled with light weight aggregates (LWA) with particle size of 2–4 mm (Põldvere *et al.,* 200x; Publication V).

Table 2. Cross-sections of vertical flow filters.

Cross-section	**Rämsi CW**
Upper layer (20 cm)	LWA Ø 2–4 mm
Middle layer (20 cm)	LWA Ø 4–10 mm
Bottom layer (25 cm)	LWA Ø 10–20 mm

It is possible to re-circulate wastewater from the outflow well of the VSSF filters (interim well), as well as from the outflow of the HSSF filters (outflow well) using timer-controlled pumps.

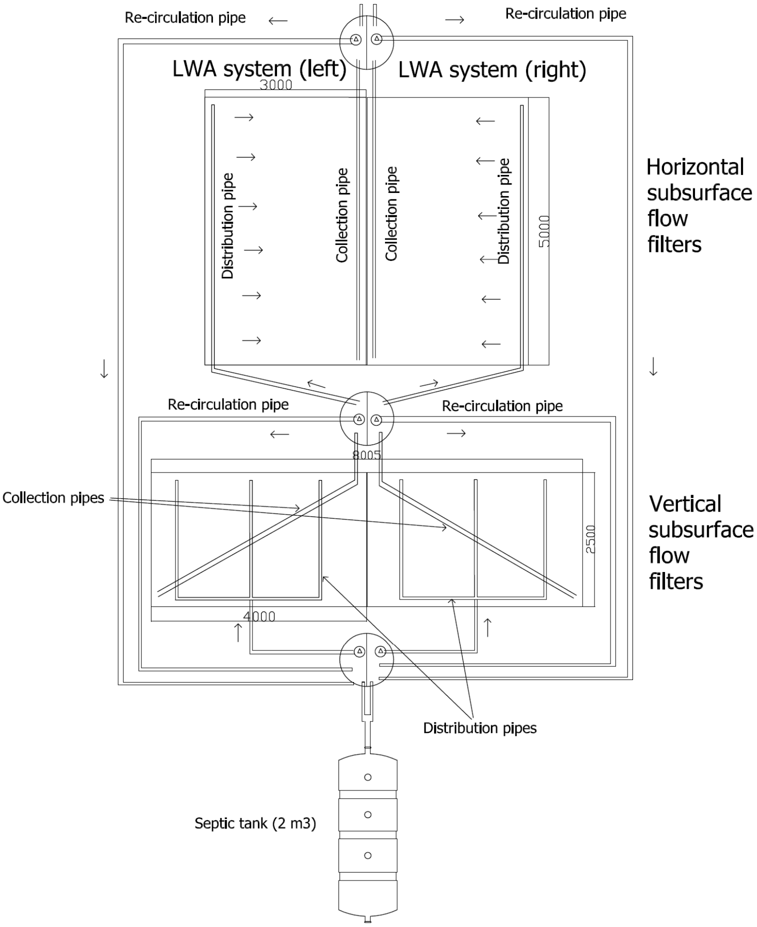

Figure 3. Schematic layout of the experimental pilot system of the hybrid constructed wetland in Rämsi, Estonia. The parallel systems (right-left) are determined on the basis of the direction of wastewater flow.

2.2. Hydraulic loading and waste water re-circulating regimes

In Kodijärve CW first research in connection with combined VSSF and HSSF systems was carried out in the years 2001 to 2003. During that period there was no possibility to re-circulate wastewater in the system. The research focused on the impact of the VSSF on the overall purification efficiency of the Kodijärve CW system. To demonstrate the impact of the VSSF wetland on the purification processes, two periods were compared: period 1 – one year before the VSSF system was built (October 2001 – August 2002) and period 2 – when the VSSF wetland was in operation (October 2002 – August 2003) (Noorvee *et al.,* 2005a; Publication II). The hydraulic loading rates of those two periods in the Kodijärve hybrid CW system are summarized in Table 3.

Table 3. Hydraulic loading rate (m^3 d^{-1} and mm d^{-1}) of Kodijärve CW (2001–2003).

Period	**Hydraulic loading rate**			
	m^3 d^{-1}	CW mm d^{-1}	VSSF mm d^{-1}	HSSF mm d^{-1}
1	3.3	10.4	–	10.4
2	6.6	18.6	328.6	19.7

After the reconstruction of the Kodijärve CW in 2005, different re-circulating regimes were tested during the experiments (November 2005 to December 2006), in order to determine optimal pollutant and hydraulic loading and water re-circulation rates for such systems. The Kodijärve CW system was the only system in which it was not possible to alter the hydraulic loading entering the system. The hydraulic loading rate depended on the water use in the hospital. At other experimental sites (Nõo and Rämsi), hydraulic loading and re-circulation rates were varied.

The hydraulic loading and re-circulation rates of 6 different operational regimes (November 2005…December 2006) in Kodijärve hybrid CW system are summarized in Table 4.

Table 4. Hydraulic loading rate ($m^3\ d^{-1}$ and $mm\ d^{-1}$) and re-circulating rates (% of hydraulic loading rate) of Kodijärve CW (2005–2006).

Operational regime	Hydraulic loading rate				Re-circulation rate
	$m^3\ d^{-1}$	CW $mm\ d^{-1}$	VSSF $mm\ d^{-1}$	HSSF $mm\ d^{-1}$	%
1	3.8	21.7[1]	203.2	24.3	0
2	5.3	30.1[1]	281.3	33.7	75
3	6.0	34.4[1]	322.1	38.5	150
4	5.6	17.0[2]	300.3	18.0	200
5	5.6	17.0[2]	300.3	18.0	250
6	7.0	39.9[1]	373.5	44.7	300

[1] One of the HSSF beds in use
[2] Both HSSF beds in use

At first it was planned to use both HSSFs during all of the operational regimes, but unfortunately we had some leakage problems during our experiments, and hence it was possible to use only one of the HSSFs in most of the operational periods.

The hydraulic loading and re-circulation rates of 6 different operational regimes in the Nõo pilot-scale hybrid CW system are summarized in Table 5, and the hydraulic loading and re-circulation rates of 6 different operational regimes in the Rämsi pilot-scale hybrid CW system are summarized in Table 6.

Table 5. Hydraulic loading rate ($m^3\ d^{-1}$ and $mm\ d^{-1}$) and re-circulating rates (% of hydraulic loading rate) of Nõo CW for both parallel systems.

Operational regime	Hydraulic loading rate				Re-circulation rates of Nõo CW[1]			
	$m^3\ d^{-1}$	CW $mm\ d^{-1}$	VSSF $mm\ d^{-1}$	HSSF $mm\ d^{-1}$	Left	Left	Right	Right
					From outflow well %	From interim well %	From outflow well %	From interim well %
1	0.73	52.1	182.5	73.0	35	0	25	0
2	0.37	26.4	92.5	37.0	35	0	25	0
3	0.29	20.7	72.5	29.0	0	50	0	75
4	0.22	15.7	55.0	22.0	85	0	0	70
5	0.30	21.4	75.0	30.0	300	0	150	150
6	0.20	14.3	50.0	20.0	150	150	300	0

[1] summarized re-circulation rates from the outflow and interim well were used in the correlation analysis

Table 6. Hydraulic loading rate (m^3 d^{-1} and mm d^{-1}) and re-circulating rates (% of hydraulic loading rate) of Rämsi CW for both parallel systems.

Operational regime	Hydraulic loading rate				Re-circulation rates of Rämsi CW[1]			
	m^3 d^{-1}	CW mm d^{-1}	VSSF mm d^{-1}	HSSF mm d^{-1}	Left	Left	Right	Right
					From outflow well %	From interim well %	From outflow well %	From interim well %
1	0.4	16.0	40.0	26.7	20	30	40	25
2	0.1	4.0	10.0	6.7	30	0	35	0
3	0.1	4.0	10.0	6.7	40	30	55	40
4	0.1	4.0	10.0	6.7	40	70	50	90
5	0.125	5.0	12.5	8.3	600	0	300	300
6	0.1	4.0	10.0	6.7	300	300	600	0

[1] summarized re-circulation rates from the outflow and interim well were used in the correlation analysis

2.3. Sampling and statistical analysis

In the research conducted between 2001 and 2003 at the Kodijärve hybrid CW, water samples were taken once a month from the inlet and outlet of both VSSF and HSSF wetlands and the outlet of the phosphorus removal bed. The water samples were analysed for pH, temperature, dissolved O_2, redox potential, conductivity, TSS, BOD_7, NH_4-N, NO_2-N, NO_3-N, N_{tot}, PO_4-P, P_{tot}, SO_4 and Fe_{tot}. (Noorvee *et al.*, 2005a; Publication II).

To demonstrate the impact of the VSSF wetland on the purification processes, two periods were compared: period 1 – one year before the VSSF system was built (October 2001 – August 2002), and period 2 – when the VSSF wetland was in operation (October 2002 – August 2003). In comparison, the purification efficiencies and removal rates of organic matter (after BOD_7), NH_4-N, N_{tot}, and P_{tot} were used as performance indicators. The normality of the variables was verified using the Kolmogorov-Smirnov, Lilliefors and Shapiro-Wilk tests. If the variables were not normally distributed, normalizing conversions were carried out. In order to compare the two periods, the Mann-Whitney U-test was used. The level of significance $\alpha = 0.05$ was accepted in all cases. (Noorvee *et al.*, 2005a; Publication II).

In the experiments with the implementation of re-circulation (November 2005…December 2006), water samples were taken from CWs once a week, from the outlet of the septic tank and the outlet of both VSSF and HSSF beds. Water samples were analyzed for pH, BOD_7, SS, COD_{Cr}, N_{tot}, NH_4-N, NO_2-N, NO_3-N, P_{tot}, temperature, redox potential and dissolved O_2. The Rämsi pilot-scale CW was partly frozen during the 2nd period in wintertime, and partly clogged during the 3rd and 4th periods. Hence less samples were taken in Rämsi. The data of 6 different operational regimes in the experimental systems of Kodijärve, Nõo and Rämsi is presented. In comparison, purification efficiencies (after BOD_7), COD_{Cr}, N_{tot}, NH_4-N, SS and P_{tot} were used as performance indicators (Põldvere *et al.*, 200x; Publication V). The mass removal rates of COD, BOD, N_{tot}, NH_4-N, P_{tot}, suspended solids are also presented.

The normality of the variables was verified using the Kolmogorov-Smirnov, Lilliefors' and Shapiro-Wilk's tests. Since the variables were not normally distributed, a non-parametric Kruskal-Wallis ANOVA test was performed. The level of significance $\alpha = 0.05$ was accepted in all cases (Põldvere *et al.*, 200x; Publication V).

Additionally, a non-parametric Spearman Rank Order Correlation coefficient was detected between the influencing factors (re-circulation regime, water temperature and hydraulic loading rate) and purification efficiencies of BOD_7, COD, N_{tot}, NH_4-N, SS and P_{tot} and theoretical aeration capacity. The level of significance $\alpha = 0.05$ was accepted in all cases (Zaytsev *et al.*, 2007; Publication IV; Põldvere *et al.*, 200x; Publication V).

2.4. Oxygen Demand

Oxygen demand (Od; g O_2 d^{-1}) was calculated according to the following equation (Cooper, 1999):

$$Od = [(BOD_{in} - BOD_{out}) + (NH_4\text{-}N_{in} - NH_4\text{-}N_{out})*4.3]*Q\ , \qquad (1)$$

where:

BOD_{in} = BOD_7 in the inflow (mgO_2 l^{-1});

BOD_{out} = effluent standard for BOD_7 in treatment plants <2000 pe (15 mg O_2 l^{-1});

NH_4-N_{in} = NH_4-N in the inflow (mg l^{-1});

NH_4-N_{out} = since there is no exact effluent standard for treatment plants smaller than 2000 pe in Estonia, the set target is that all of the NH_4-N should be removed (0 mg l^{-1});

Q – flow rate (l d^{-1}).

Although the NH_4-N target (0 mg l^{-1}) is very stringent, it helps to eliminate uncertainties, for example in ammonification, which could take place inside the system (Noorvee *et al.*, 2005a; Publication II).

2.5. Theoretical aeration capacity

The theoretical aeration capacity (oxygen transfer rate) (Ac; g O_2 m^{-2} d^{-1}) can be calculated according to equation (1), by dividing it with the area of the bed (Cooper, 1999):

$$Ac = [(BOD_{in} - BOD_{out}) + (NH_4\text{-}N_{in} - NH_4\text{-}N_{out})*4.3]*Q / A \qquad (2)$$

where:

BOD_{in} = BOD_7 concentration in the inflow (mgO_2 l^{-1});
BOD_{out} = BOD_7 concentration in the outflow (mgO_2 l^{-1});
NH_4-N_{in} = NH_4-N concentration in the inflow (mg l^{-1});
NH_4-N_{out} = NH_4-N concentration in the outflow (mg l^{-1});
Q = average wastewater flow (m^3 d^{-1}).
A = area of filter bed (m^2)

2.6. Purification efficiency and mass removal rate

The purification efficiency (Pe; %) of water quality indicators was calculated using the following equation (Kadlec and Knight, 1996):

$$Pe = (C_{in} - C_{out}) / C_{in}*100 \qquad (3)$$

where:

C_{in} = average value of inflow concentration (mg l^{-1})
C_{out} = average value of outflow concentration (mg l^{-1})

Mass removal (Mr; g m^{-2} d^{-1}) was calculated using the following equation (Kadlec and Knight, 1996):

$$Mr = [(C_{in} * Q_{in}) - (C_{out} * Q_{out})]/A \qquad (4)$$

where:

A = area of CW (m^2);
Q_{in} and Q_{out} = average values of water discharge in inflow and outflow (m^3 d^{-1});
C_{in} and C_{out} = average values of inflow and outflow concentrations (mg l^{-1})

3. RESULTS AND DISCUSSION

3.1. Kodijärve hybrid constructed wetland system 2001…2003

The VSSF CW built in 2002 for enhanced aeration demonstrated satisfactory results. Although the loading rates of organic matter, NH_4-N, N_{tot} and P_{tot} entering the CW doubled in period 2 (after the construction of the VSSF), the purification efficiency, except for P_{tot}, has increased. The mass removal rates of all parameters analyzed increased proportionally with increasing loading rates (Noorvee *et al.*, 2005a; Publication II) (Table 7).

There was a significant improvement in the removal of organic material after the VSSF system was constructed (Figure 4). The average purification efficiency and removal rate of organic matter in period 2 (during the operation of the VSSF) was significantly higher than in period 1. A slight but not significant improvement in the purification efficiency of NH_4-N was found, but the mass removal rate of NH_4-N improved significantly (Figure 4). On the other hand, no significant improvement in the purification efficiency of N_{tot} was observed in period 2, whereas mass removal rates increased significantly. Unfortunately the purification efficiency of P_{tot} decreased significantly, although the mass removal rate of P_{tot} improved significantly at the same time (Noorvee *et al.*, 2005a; Publication II) (Figure 4.).

Table 7. Loading rates, purification efficiency and mass removal rate of organic matter (after BOD_7), NH_4-N, N_{tot} and P_{tot} in Kodijärve CW in periods 1 (before the operation of the VSSF filter bed) and 2 (during the operation of the VSSF filter bed) (Noorvee *et al.*, 2005a; Publication II).

	Loading rate ($g\ d^{-1}$)		**Purification efficiency (%)**		**Mass removal rate ($g\ m^{-2}\ d^{-1}$)**	
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2
BOD_7	427	912	91.7	96.7	1.24	2.54
NH_4-N	234	567	57.2	60.0	0.44	1.22
N_{tot}	304	452	46.1	50.5	0.52	0.92
P_{tot}	42.5	81.9	77.2	61.6	0.05	0.17

Less effective nitrification indicated that the VSSF system is too small for 100% sufficient aeration, and therefore for complete nitrification (Noorvee *et al.*, 2005b; Publication I). The area of one bed is 18.7 m^2 (0.46 $m^2\ pe^{-1}$). On the other hand, the climatic conditions do not promote efficient nitrification, and nitrification efficiency tended to be somewhat lower during winter. The average removal efficiency of NH_4-N was 55.5% from October 2002 to March 2003, and 70.8% from April 2003 to October 2003 (Noorvee *et al.*, 2005a; Publication II).

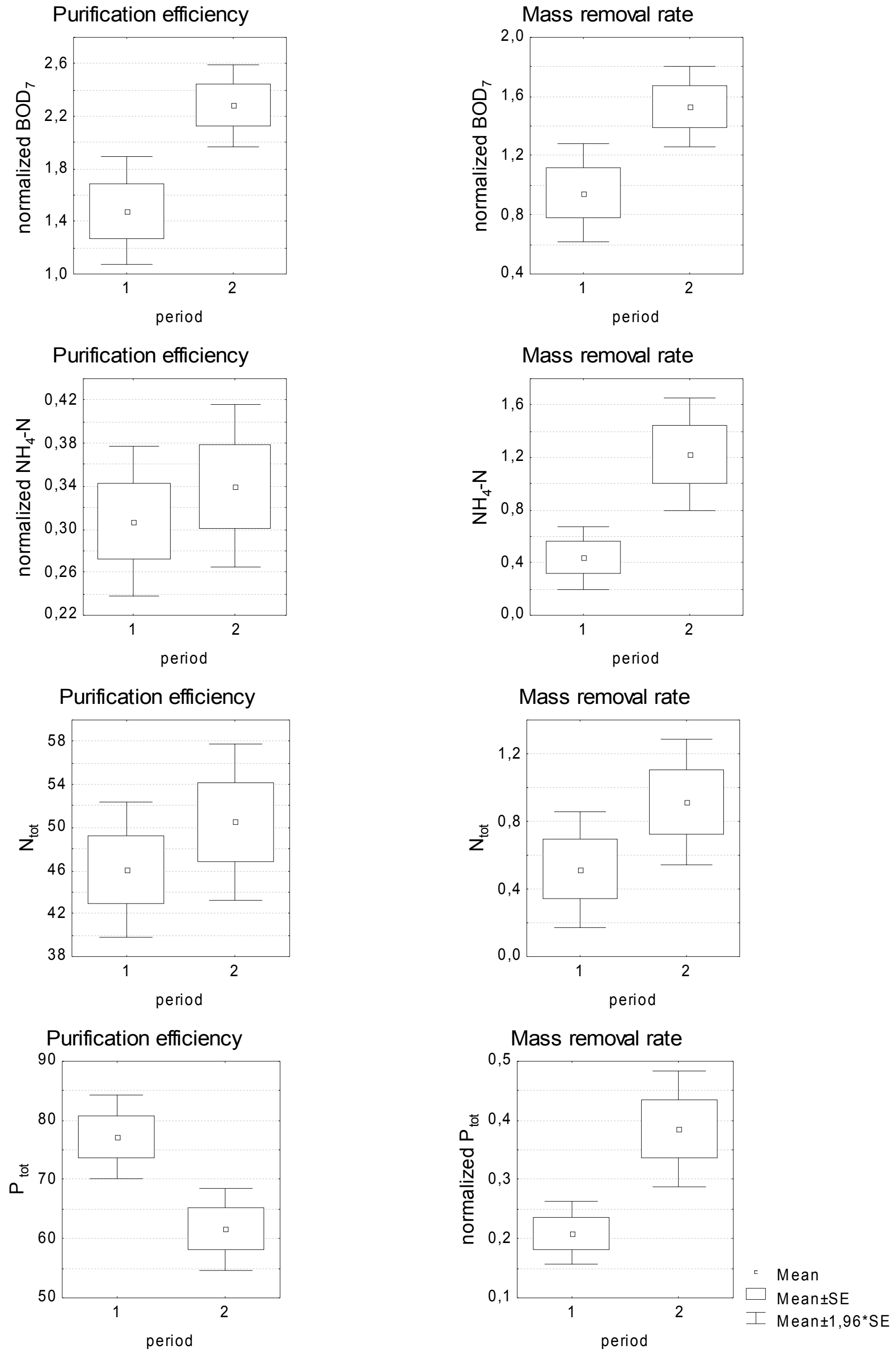

Figure 4. Purification efficiencies (%) and mass removal rates (g m^{-2} d^{-1}) of organic matter (after BOD_7), NH_4-N, N_{tot} and P_{tot} in periods 1 and 2 in Kodijärve CW (2001–2003). (Adapted from Noorvee *et al.*, 2005a; Publication II).

The construction of the VSSF filter also changed the conditions inside the HSSF CW. A significant increase in the oxygen saturation rate of the HSSF CW was observed in both beds in the 2nd period ($p<0.001$). During the 1st period the oxygen saturation rate in the wastewater was low (around 12% on average), and it retarded aerobic processes such as organic matter removal and nitrification. In the 2nd period the oxygen saturation reached 40–60% (Noorvee *et al.*, 2007; Publication III), which is the level needed for the normal functioning of nitrifying bacteria (Vymazal, 2001).

Ideally, the purification processes in a hybrid constructed wetland should be implemented in such a manner that the oxygen that is supplied in the VSSF system will also mostly be used inside the VSSF system. Hence the anaerobic processes could function normally inside the HSSF filter. In Kodijärve the filter material of the VSSF CW – crushed limestone – is probably not the best filter material, because the wastewater flows very rapidly through the filter bed, and highly aerated wastewater flows into the HSSF filter, hindering anaerobic processes within the HSSF CW. It would probably be a better solution for the nitrification not to take place inside the HSSF CW, but already inside the VSSF filter, so the denitrification could take place in the HSSF filter. On the other hand, in the case of Kodijärve, better aeration in the HSSF has favoured phosphorus removal, because of the Fe- and Ca-rich sand used as filter material. Accordingly, the best solution would probably be to use a filter material that does not depend on oxygen supply for phosphorus removal and does not consist of iron as a phosphorus binding material. Del Bubba et al. (2003) clearly showed that sands with high Ca content are more suitable to be used in subsurface flow constructed reed beds for phosphorus removal (Noorvee *et al.*, 2007; Publication III).

3.2. Kodijärve hybrid constructed wetland system 2005…2006

Since it was not possible to change the hydraulic loading in the Kodijärve CW, the differences in system performance could only be controlled through re-circulation. Despite the fluctuation and raise of hydraulic loading and differences in water temperature in different operational regimes, the increase of re-circulation improved the purification efficiency in all water quality indicators except for N_{tot} and P_{tot} (Table 8 and Figure 5). We observed significant improvement in BOD_7 purification efficiency, comparing the last operational period with higher re-circulation to the first operational periods (Figure 5). Significant improvement in NH_4-N purification efficiency was also found between the 2nd and 6th operational periods. On the other hand, the P_{tot}

purification efficiency was significantly less effective in the 6th period than in the 3rd period (Figure 5).

However, in most operational regimes we did meet Estonian standards for wastewater discharge in terms of BOD_7, COD, and TSS. Unfortunately, the effluent standards were not met in terms of N_{tot} and P_{tot}. Although the nitrification occurred quite effectively in the 6th operational regime (average NH_4-N in the outflow 15.8 mg l^{-1}), the lack of carbon hindered denitrification, and high NO_3-N (over 20 mg l^{-1}) concentrations remained in the outflow. Accordingly, a better solution would be to pump the wastewater back into the septic tank, where more organic matter is available for denitrification, as reported also for example in Platzer (1999) and Brix & Arias (2005).

In the Kodijärve CW system the mass loading rate depended on whether both beds of the HSSF filter were in use or only on bed. Due to some water leakage problems (the PVC liner was broken), there was a possibility to use only one bed of the HSSF filters in most periods (Table 5). The mass removal rate approached the values of mass loading rate in periods with higher re-circulation.

Table 8. Mass loading rates (Lr; g m^{-2} d^{-1}), purification efficiencies (Pe; %) and mass removal rates (Mr; g m^{-2} d^{-1}) of the Kodijärve CW.

	1st regime			**2nd regime**			**3rd regime**		
	Lr	Pe	Mr	Lr	Pe	Mr	Lr	Pe	Mr
BOD_7	2.4	90.9	2.1	4.0	84.8	3.4	3.7	89.6	3.3
COD	4.7	73.5	3.5	8.3	74.0	6.1	7.1	78.4	5.6
N_{tot}	2.1	38.9	0.8	2.5	27.9	0.7	2.4	52.4	1.3
NH_4	1.9	56.2	1.1	2.1	30.7	0.6	2.1	55.0	1.2
P_{tot}	0.4	57.6	0.2	0.5	46.6	0.2	0.7	72.5	0.5
TSS	0.8	87.8	0.7	1.3	89.9	1.1	1.7	84.8	1.4
	4th regime			**5th regime**			**6th regime**		
	Lr	Pe	Mr	Lr	Pe	Mr	Lr	Pe	Mr
BOD_7	1.8	96.5	1.7	1.2	96.8	1.2	3.0	98.2	2.9
COD	4.7	82.3	3.8	3.1	81.0	2.5	5.9	83.4	4.9
N_{tot}	1.2	36.1	0.4	1.1	41.7	0.5	2.7	37.3	1.0
NH_4	1.0	58.6	0.6	1.0	61.5	0.6	2.2	71.7	1.6
P_{tot}	0.2	63.6	0.1	0.2	66.3	0.2	0.4	45.3	0.2
TSS	2.1	88.4	1.8	1.3	88.3	1.2	2.3	94.1	2.2

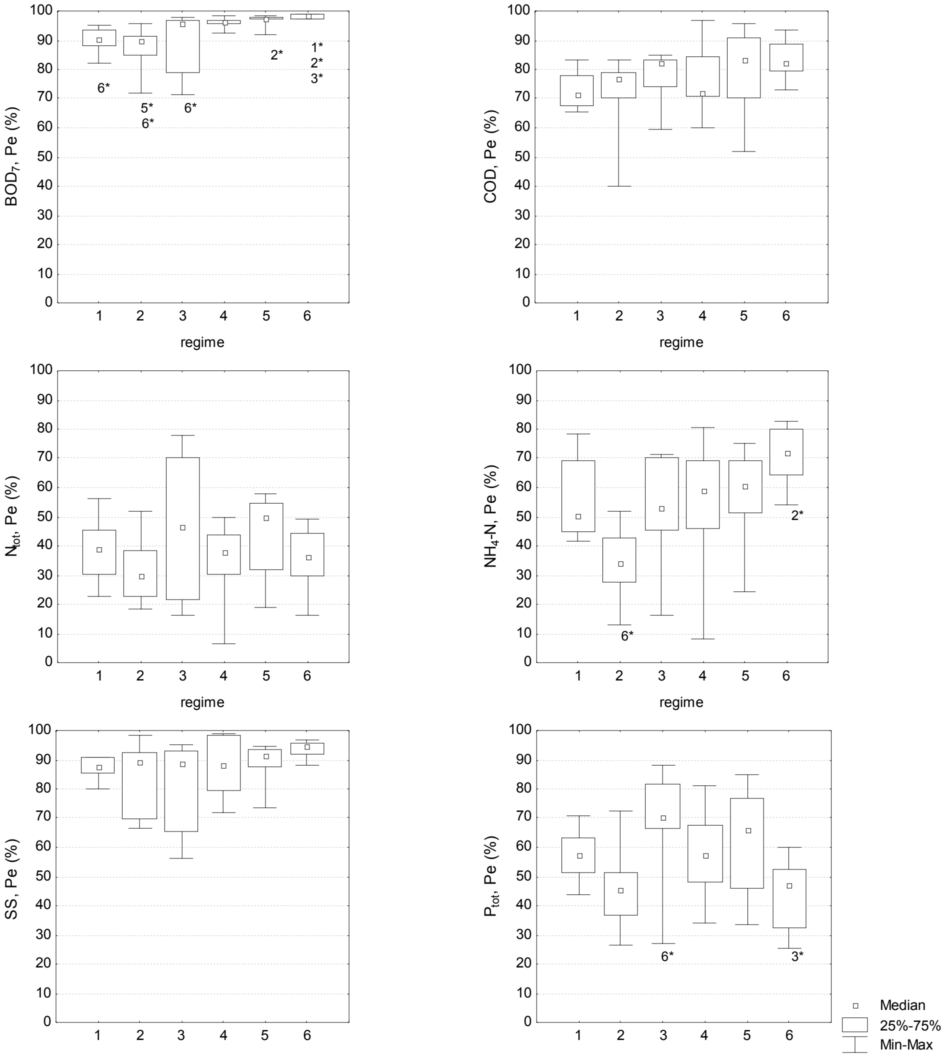

Figure 5. Purification efficiencies (Pe, %) of BOD_7, COD, N_{tot}. NH_4-N, suspended solids and P_{tot} in six different operational regimes in Kodijärve CW. 1* – $p<0.05$ with operational regime (regime number).

The Spearman Rank Order Correlation analysis showed a significantly positive correlation between re-circulation rates and the purification efficiencies of BOD_7, COD, NH_4-N and total suspended solids. A significantly positive correlation between water temperature and BOD_7 purification efficiency was also observable. However, no significant correlations were found between hydraulic loading (m^3 d^{-1}) and the purification performance of any parameters.

Also, a significantly positive correlation between the re-circulation rate and theoretical aeration capacity (oxygen transfer rate) of the Kodijärve VW VSSF was found, which indicates that water re-circulation can help improve aerobic purification processes (Table 9). However, the Kruskal-Wallis ANOVA test did not show any significant differences between theoretical aeration capacities in different operational periods.

Table 9. Oxygen demand and theoretical aeration capacity of the Kodijärve VSSF.

Operational regime	Oxygen demand	Aeration capacity
	g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}
1	94.4	61.4
2	105.5	47.6
3	114.4	63.6
4	95.0	48.8
5	120.0	76.7
6	110.8	87.8

3.3. Nõo pilot-scale hybrid CW

With the decrease in wastewater and pollutant load and the enhancing of wastewater re-circulation up to 300%, (Table 5, Figures 6 and 7) the purification efficiency increased significantly in most water quality indicators in both the right- and left-hand systems of the Nõo pilot-scale CW in the 6th period. The purification efficiency of BOD_7, COD_{Cr}, N_{tot} and NH_4-N increased in both the right-hand and left-hand systems of the CW (Zaytsev *et al.*, 2007; Publication IV; Põldvere *et al.*, 200x; Publication V).

In the left-hand system the purification performance was more effective than in the right-hand system. Better overall purification efficiencies in the water quality parameters were noted in the 2nd, 3rd, 4th and 5th periods, and only P_{tot} purification efficiency was better in the right CW in the 2nd, 3rd, and 4th periods, when the re-circulation from the outflow well was smaller (Table 10). The poorer purification efficiency in the right parallel indicates the influence of higher re-circulation in the left bed during the investigated periods (periods 1…4), and that LWA is a better filter material than crushed limestone in VSSFs, because of its higher porosity and longer residence time in the filter (Zaytsev *et al.*, 2007; Publication IV; Põldvere *et al.*, 200x; Publication V).

In the 6th operational period both sides of the parallel systems met Estonian wastewater effluent standards in the outflow in terms of BOD_7 (L = 3.7 and R = 4.5 mg l^{-1}), COD (L = 40.9 and R = 40.9 mg l^{-1}), N_{tot} (L = 13.9 and R = 15.6 mg l^{-1}), NH_4-N (L = 12.8 and R = 10.2 mg l^{-1}), and TSS (L = 16.1 and R = 15.5 mg l^{-1}). At the same time, the effluent standards of P_{tot} (L = 8.1 and R = 10.2 mg l^{-1}) were not met.

The Spearman Rank Order Correlation analysis shows a significantly negative correlation between the hydraulic loading (m^3 d^{-1}) and BOD_7, COD, N_{tot}, NH_4-N purification efficiency in both parallel CWs, as well as P_{tot} in the left-hand system. The higher re-circulation had a slightly negative effect on TSS and P_{tot} purification efficiency in the right-hand system. As expected, a significant positive correlation was found between the re-circulation rate and purification efficiency of BOD_7, COD, N_{tot} and NH_4-N in both parallel systems, as well as in the right-hand system, and also between the re-circulation rate P_{tot} purification efficiency. In both parallel systems, a significantly positive correlation with water temperature (°C) and BOD_7, COD, N_{tot}, NH_4-N purification efficiency was also observed.

Table 10. Purification efficiencies (Pe; %) of Nõo pilot-scale CW (L – left parallel; R – right parallel).

	1st regime		**2nd regime**		**3rd regime**		**4th regime**		**5th regime**		**6th regime**	
	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R
BOD_7	66.7	51.4	81.9	75.6	89.2	87.1	89.1	84.4	98.4	95.0	99.0	98.8
COD	64.1	51.1	78.3	72.1	85.5	83.5	83.4	82.4	94.1	92.1	93.1	93.1
N_{tot}	5.2	10.5	24.9	27.9	46.2	38.1	66.1	51.2	79.8	74.3	80.0	82.2
NH_4	–27.2	–23.7	17.7	13.5	51.8	36.1	66.5	51.9	75.7	70.6	79.4	83.6
P_{tot}	47.4	76.4	31.0	65.5	39.8	45.1	66.6	75.3	75.7	73.4	69.3	61.2
TSS	94.1	92.3	93.1	91.0	94.5	90.8	71.7	87.0	90.4	92.2	86.8	86.3

The mass removal rate (g m^{-2} d^{-1}) tends to decrease simultaneously with the decrease in pollutant loading rate (Table 11). In the 5th and 6th operational regime nearly all the pollutant loading was removed (more effectively in the left-hand system). The highest removal rates were achieved with the highest re-circulation rate, which indicates that the implementation of water re-circulation is a good solution to improve purification performance in overloaded systems. In the last 2 operational periods, purification efficiency was affected by the clogging of the pipes in HSSF filters, which caused a water level raise in the interim well and thus generated a water-saturated layer at the bottom of the VSSF filters (Põldvere *et al.*, 200x; Publication V). A water-saturated layer in the VSSF filter lengthens the residence time of water inside the filter, and less aerated water flows into the HSSF filter. On the other hand, the water-saturated layer can diminish aeration effectiveness.

We registered the negative purification efficiencies of NH_4-N in the 1st and 2nd operational regimes in both parallel systems of the Nõo CW. One possible explanation for the higher values of NH_4-N concentrations would be ammonification. Ammonification is a process whereby organic N is biologically converted into ammonia (Kadlec & Knight, 1996; Vymazal, 2001). This is, however, quite unlikely, because optimum temperatures for ammonification range from

40 to 60°C (Reddy & Patrick, 1984 cit. Vymazal, 2001), and water temperatures fell below 5°C during those operational regimes in the Nõo CWs. A more probable explanation is the release of NH_4-N from different sinks inside the system. For instance, Kadlec *et al.* (2005) demonstrated that ammonium is rapidly sorbed into wetland solids in the inlet region of the wetland, and subsequently gradually released back into the water to a considerable extent. The next downstream elements of solids then adsorb the release. This "park and go" path through the wetland has been termed "spiraling" in the literature (Kadlec *et al.*, 2005). The Nõo pilot-scale CW received high loadings during the first weeks of operation, and also the water temperatures fell below 5°C, hindering nitrification/denitrification processes. The sorbed NH_4-N was apparently subsequently released from the system.

Table 11. Mass loading rates (Lr; g m^{-2} d^{-1}), purification efficiencies (Pe; %) and mass removal rates (Mr; g m^{-2} d^{-1}) of the Nõo pilot-scale CW.

	1st regime			**2nd regime**			**3rd regime**		
	Lr	Mr L	Mr R	Lr	Mr L	Mr R	Lr	Mr L	Mr R
BOD$_7$	19.2	12.8	9.8	11.2	9.2	8.5	9.2	8.2	8.0
COD	35.7	22.9	18.3	19.8	15.5	14.3	16.7	14.3	14.0
N$_{tot}$	3.8	0.2	0.4	1.9	0.5	0.5	1.1	0.5	0.4
NH$_4$	2.4	–0.7	–0.6	1.4	0.2	0.2	1.0	0.5	0.4
P$_{tot}$	1.1	0.5	0.8	0.5	0.2	0.4	0.4	0.2	0.2
TSS	6.1	5.7	5.6	3.3	3.1	3.0	4.5	4.3	4.1
	4th regime			**5th regime**			**6th regime**		
	Lr	Mr L	Mr R	Lr	Mr L	Mr R	Lr	Mr L	Mr R
BOD$_7$	10.1	9.0	8.5	13.8	13.6	13.1	5.4	5.3	5.3
COD	16.9	14.1	13.9	24.3	22.9	22.4	8.4	7.8	7.8
N$_{tot}$	1.4	1.0	0.7	2.4	1.9	1.8	1.1	0.9	0.9
NH$_4$	1.2	0.8	0.6	1.7	1.3	1.2	0.9	0.7	0.7
P$_{tot}$	0.5	0.3	0.4	1.0	0.7	0.7	0.4	0.3	0.2
TSS	4.5	3.2	3.9	8.3	7.5	7.6	1.7	1.5	1.4

The theoretical aeration capacity (oxygen transfer rate) demonstrated a significantly positive correlation with water temperature in both parallel systems, as well as with hydraulic loading in the left-hand system. Table 12 presents the average theoretical aeration capacity in both parallel systems of the Nõo pilot-scale CW.

Table 12. Oxygen demand and theoretical aeration capacity of Nõo VSSF filters.

Operational regime	**Oxygen demand**	**Aeration capacity Right**	**Aeration capacity Left**
	g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}
1	110.4	40.1	64.6
2	58.7	24.7	35.1
3	46.1	28.8	31.0
4	52.9	31.2	34.4
5	57.7	49.4	43.0
6	26.5	24.8	24.0

In the 5th and 6th operational regime the total re-circulation rates were identical in both parallel systems, and only the pumping origin was changed – whether the water was pumped back only from the outflow well or from the interim and outflow well simultaneously (Table 5). In the Nõo CWs the change in re-circulating origin had no significant effect on purification performance.

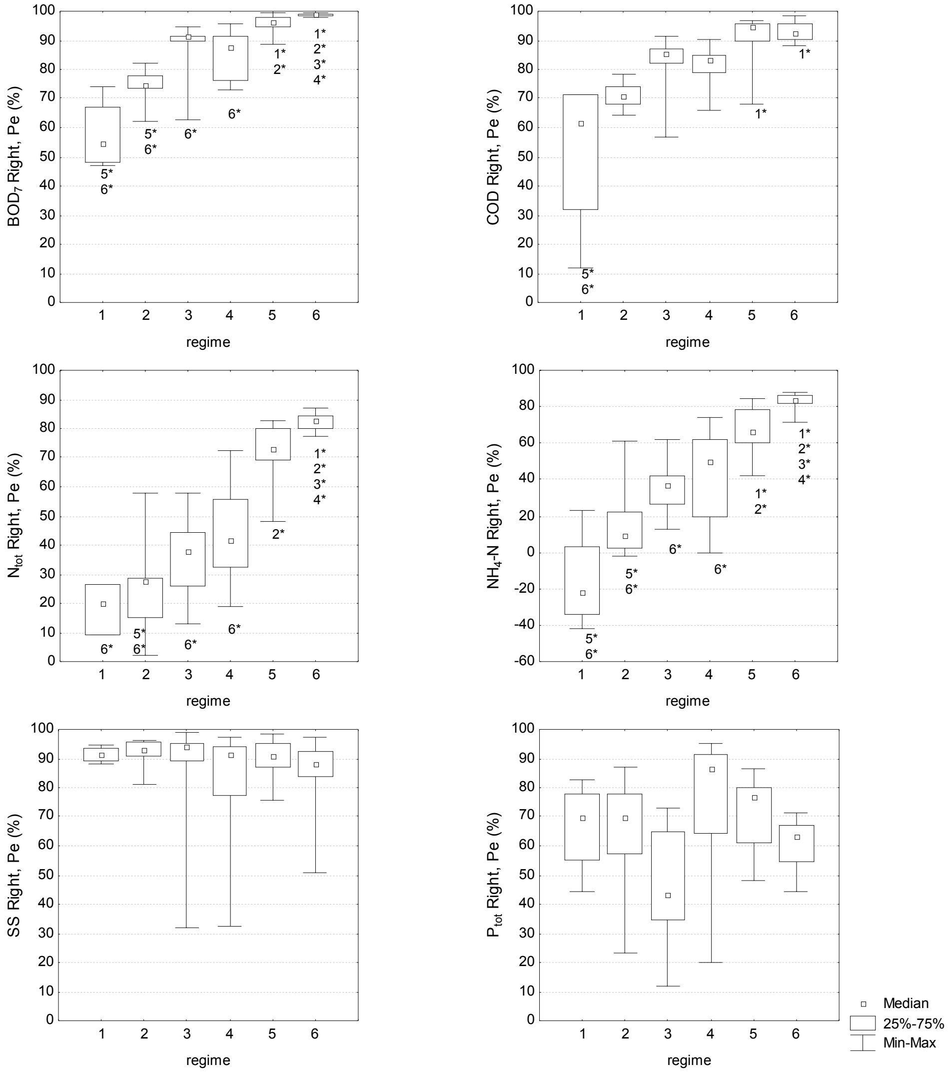

Figure 6. Purification efficiencies (Pe. %) of after BOD$_7$, COD, N$_{tot}$, NH$_4$-N, suspended solids and P$_{tot}$ in six different operational regimes in the right parallel system of the Nõo pilot-CW. 1* – p<0.05 with operational regime (regime number).

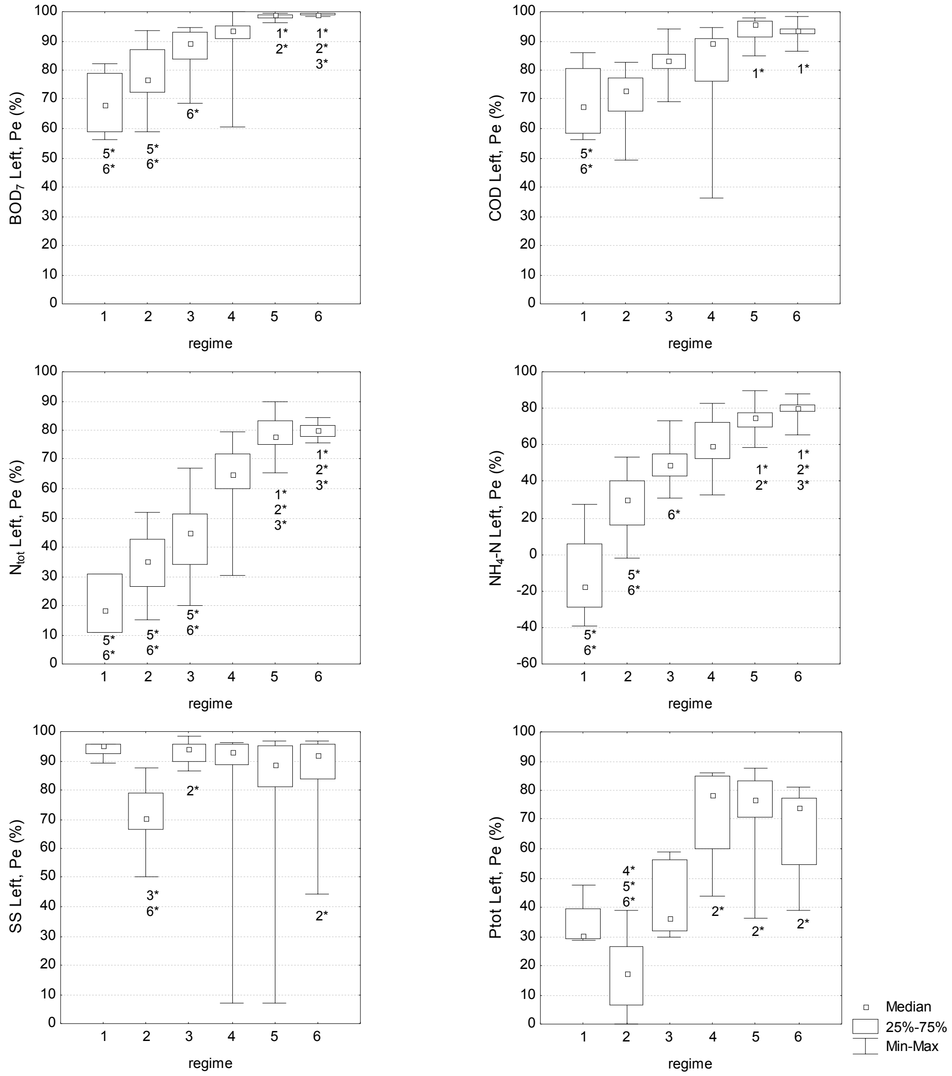

Figure 7. Purification efficiencies (Pe, %) of BOD_7, COD, N_{tot}, NH_4-N, suspended solids and P_{tot} in six different operational regimes in the left parallel system of the Nõo pilot-CW. 1* – $p<0.05$ with operational regime (regime number).

3.4. Rämsi pilot-scale hybrid CW

With the decrease in wastewater load and the enhancement of the re-circulation rate of treated wastewater up to 600%, the purification efficiency of the systems increased (Table 13, Figures 8 and 9). The purification efficiency of BOD_7, COD_{Cr}, N_{tot} and NH_4-N increased significantly in either the right- or left-hand systems of the CW. On the other hand, TSS purification efficiency did decrease significantly in the periods with higher re-circulation. Also, the efficiency of P_{tot} purification decreased in the 4th, 5th and 6th periods. However, the outlet concentrations from both parallel systems significantly exceeded standard values in the first periods, due to the systems' high loading with nutrients and organic matter (Põldvere *et al.*, 200x; Publication V). The effluent standards were also exceeded in the last operational periods. For example, in the 6th period the outflow parameters were as follows: BOD_7 (L = 38.0 and R = 84.1 mg l^{-1}), COD (L = 159.0 and R = 229.1 mg l^{-1}), N_{tot} (L = 58.9 and R = 69.2 mg l^{-1}), NH_4-N (L = 50.5 and R = 58.2 mg l^{-1}), P_{tot} (L = 59.5 and R = 46.6 mg l^{-1}) and TSS (L = 64.2 and R = 64.1 mg l^{-1}). At the same time, the effluent standards were not met.

In the right-hand parallel, better overall purification efficiencies in water quality parameters were noted in the 2nd, 4th and 5th periods (Põldvere *et al.*, 200x; Publication V).. In the right-hand parallel there were also higher re-circulation rates (Table 6). However, small differences in the re-circulation rate (Table 6) between both parallel systems in Rämsi CW during periods 1 to 4 did not have significant effects on the purification efficiency of the parallel systems.

The Spearman Rank Order Correlation analysis shows a significantly positive correlation in both parallel CWs with the re-circulation and purification efficiency of all analyzed wastewater parameters, except for TSS and P_{tot}. Higher re-circulation had a significant negative correlation with TSS and P_{tot} purification efficiency.

Table 13. Purification efficiencies (%) of the Rämsi pilot-scale CW (Pe – purification efficiency; L – left parallel; R – right parallel)

	1st regime		**2nd regime**		**3rd regime**		**4th regime**		**5th regime**		**6th regime**	
	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R	Pe L	Pe R
BOD_7	66.9	64.2	65.8	77.8	82.2	82.4	86.6	93.1	96.0	96.1	99.2	98.2
COD	60.7	58.0	60.8	68.1	78.6	77.7	87.3	90.8	95.1	95.5	97.8	96.8
N_{tot}	53.3	54.1	45.9	59.7	55.7	58.3	77.5	78.6	79.3	81.2	88.6	86.6
NH_4	56.9	50.7	43.3	52.8	52.8	56.8	75.2	75.8	78.7	80.3	87.3	85.3
P_{tot}	97.3	96.0	96.2	99.3	95.6	98.5	92.4	99.1	70.6	77.9	71.4	77.6
TSS	97.9	91.8	97.6	99.0	79.7	84.2	82.4	87.4	78.8	77.9	93.8	93.8

The mass removal rate (g m^{-2} d^{-1}) decreases simultaneously with the decrease in the pollutant loading rate (Table 14). In the 5th and 6th operational regime, nearly all of the pollutant loading was removed in both parallel systems. In the case of most pollutants, except for TSS and P_{tot}, the best results were achieved with the highest re-circulation rates. In the case of TSS and P_{tot} the highest mass removal rates were found in operational periods with the smallest re-circulation rates. The results show that higher re-circulation is a good solution for improving purification performance in overloaded systems. On the other hand, too high a re-circulation rate (in the case of Rämsi up to 600%) has a negative effect on TSS and P_{tot} removal. Inorganic chemical reactions such as phosphorus adsorption and precipitation, are normally rapid processes that are not greatly affected by increasing wastewater-media contact time. Therefore, the use of effluent re-circulation may have little impact on P_{tot} removal (Sun *et al.*, 2003). As found in Rämsi, the effect of re-circulation can even turn in the opposite direction.

Table 14. Mass loading rates (g m^{-2} d^{-1}) and mass removal rates (g m^{-2} d^{-1}) of the Rämsi pilot-scale CW (Lr – mass loading rate; Mr – mass removal rate; L – left parallel; R – right parallel)

	1st regime			**2nd regime**			**3rd regime**		
	Lr	Mr L	Mr R	Lr	Mr L	Mr R	Lr	Mr L	Mr R
BOD_7	88.3	59.1	56.6	22.8	15.0	17.7	15.4	12.6	12.7
COD	112.6	68.4	65.3	32.3	19.6	22.0	22.0	17.3	17.1
N_{tot}	8.1	4.3	4.4	2.1	1.0	1.3	1.2	0.7	0.7
NH_4	6.6	3.7	3.3	1.7	0.7	0.9	1.1	0.6	0.6
P_{tot}	3.1	3.0	2.9	0.6	0.6	0.6	0.5	0.5	0.5
TSS	8.7	8.5	8.0	2.1	2.0	2.1	0.9	0.7	0.7
	4th regime			**5th regime**			**6th regime**		
	Lr	Mr L	Mr R	Lr	Mr L	Mr R	Lr	Mr L	Mr R
BOD_7	29.9	25.9	27.9	23.3	22.3	22.4	18.6	18.5	18.3
COD	44.7	39.0	40.6	36.3	34.6	34.7	29.0	28.3	28.1
N_{tot}	2.4	1.8	1.9	2.1	1.7	1.7	2.1	1.8	1.8
NH_4	1.9	1.4	1.4	1.8	1.5	1.5	1.6	1.4	1.4
P_{tot}	1.2	1.1	1.2	1.0	0.7	0.8	0.8	0.6	0.6
TSS	2.0	1.7	1.8	1.5	1.1	1.1	4.1	3.9	3.9

The theoretical aeration capacity (oxygen transfer rate) had a significant positive correlation with hydraulic loading in both parallel systems. BOD_7, COD, N_{tot} purification efficiencies had a significantly negative correlation with hydraulic loading in both parallel systems and also NH_4-N purification efficiency in the right-hand system.

Table 15 reports the oxygen demand of the wastewater loads and the theoretical aeration capacity of the system. Since the calculation of the theoretical aeration capacity is based on the assumption that NH_4-N is removed in “classical” nitrification/denitrification processes, the values of aeration capacity assume that all of the ammonia is nitrified. However, other processes are also reported, which could explain the very high NH_4-N removal rates and thus very high theoretical aeration capacity values in the 1st operational regime in the Rämsi CW. Examples of potential alternative processes that are relevant to treatment wetlands are (Tanner et al., 2002): Oxygen-limited autotrophic nitrification-denitrification, anaerobic ammonium oxidation (ANAMOX) and heterotrophic nitrification.

In an LWA, Ca-minerals are a very important additive for the precipitation of phosphorus. In contact with water, this may yield a dramatic increase in pH, which may favour the precipitation of phosphates (Jenssen & Krogstad, 2003). No great changes in pH in the Rämsi CWs were registered. In addition, calcium present in the wastewater itself can promote phosphorus precipitation (Maurer *et al.*, 1999). This is probably the explanation for the very effective phosphorus removal in the pilot-scale system at the Rämsi pig farm (average P_{tot} over 150 mg l^{-1} in the inflow and below 8 mg l^{-1} in the outflow in operational periods 1–4). Since the pig fodder also contains Ca-minerals (according to the pig farm data, average Ca content is 11.3 g/kg, it also contains phosphorus (average 8.6 g/kg), some of the Ca is excreted with the slurry. The Ca inside the wastewater probably allows the phosphorus to precipitate as Ca-phosphate (Põldvere *et al.*, 200x, Publication V).

Table 15. Oxygen demand and theoretical aeration capacity of Rämsi VSSF filters.

Operational regime	**Oxygen demand**	**Aeration capacity Right**	**Aeration capacity Left**
	g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}	g O_2 m^{-2} d^{-1}
1	290.9	160.1	167.2
2	75.3	48.9	42.0
3	49.6	44.5	39.4
4	95.1	74.9	74.4
5	76.5	61.5	64.1
6	59.2	47.8	45.8

In the 5th and 6th operational regime, also in the Rämsi pilot system, the total re-circulation rates in both parallel systems were identical, and only the back-pumping origin changed – the water was only pumped back from the outflow well or from the interim and outflow well simultaneously (Table 6). In the Rämsi CWs the change in the origin of re-circulation showed no significant effects on purification performance.

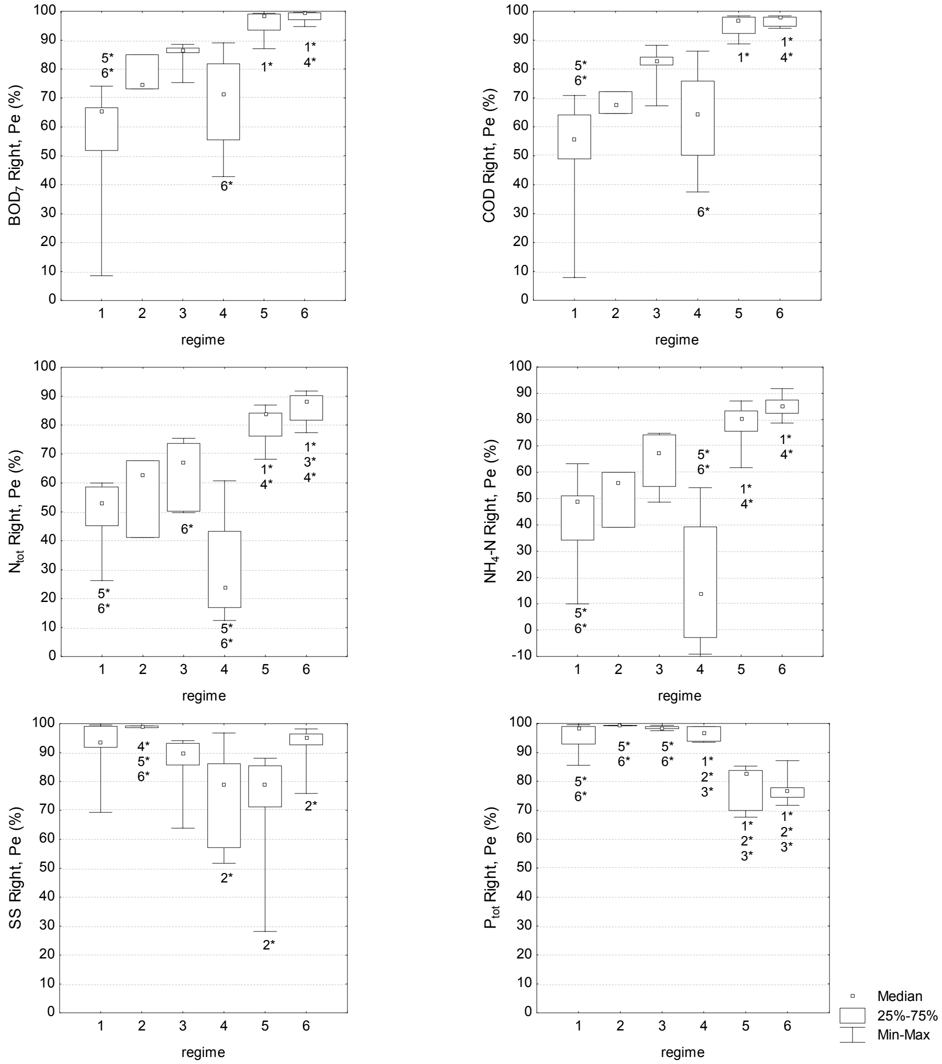

Figure 8. Purification efficiencies (Pe, %) of BOD$_7$, COD, N$_{tot}$, NH$_4$-N, suspended solids and P$_{tot}$ in six different operational regimes in the right parallel system of the Rämsi pilot-CW. 1* – $p<0.05$ with operational regime (regime number).

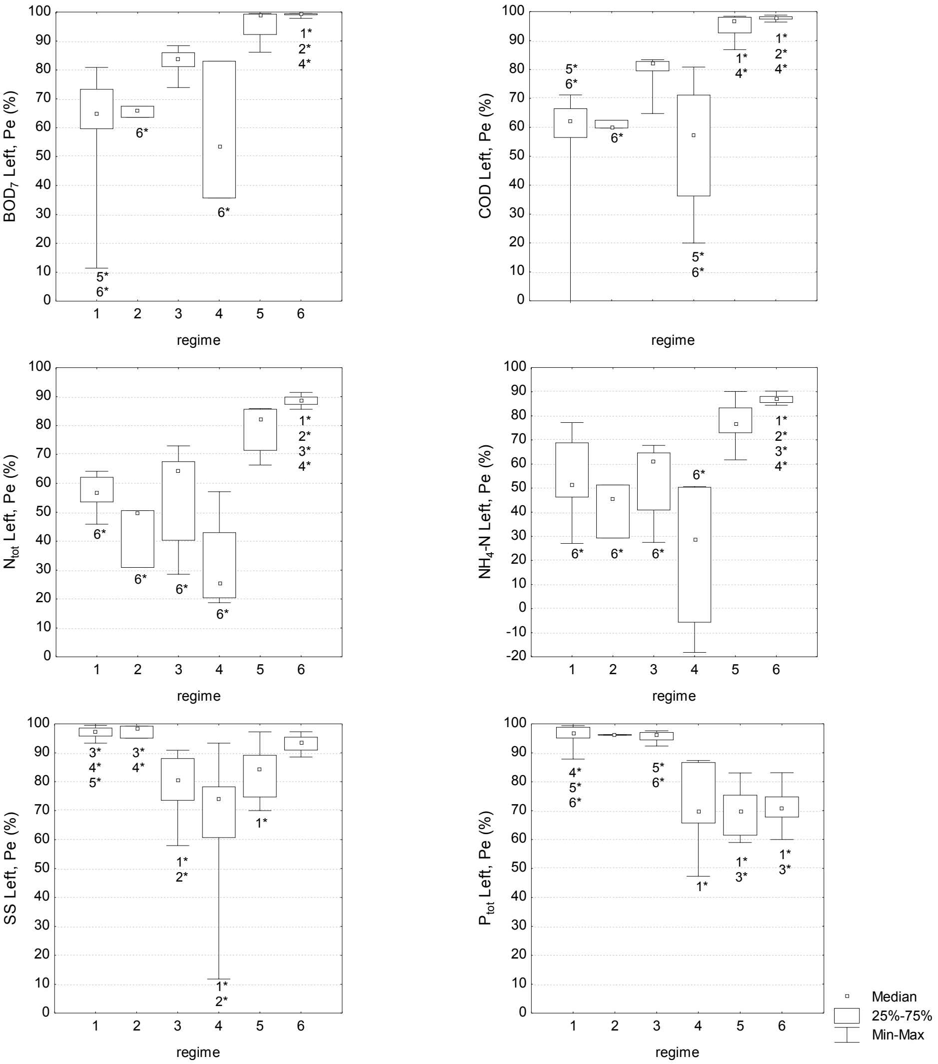

Figure 9. Purification efficiencies (Pe, %) of BOD_7, COD, N_{tot}, NH_4-N, suspended solids and P_{tot} in six different operational regimes in the left parallel system of the Rämsi pilot-CW. 1* – $p<0.05$ with operational regime (regime number).

3.5. Design recommendations

Two-stage hybrid CW systems (VSSF+HSSF filters) can be designed solely on the basis of the oxygen demand of the wastewater. The experiments showed theoretical aeration capacity of up to more than 100 g O_2 m^{-2} d^{-1}. However, designing a VSSF without taking into account the re-circulation rate, the theoretical aeration capacity of the VSSF system should be assumed to be 30 g O_2 m^{-2} d^{-1}. If re-circulation over 100% is considered in the design, the theoretical aeration capacity can easily be assumed to increase up to 45 g O_2 m^{-2} d^{-1}.

The oxygen demand can be calculated based on the following equation, which has been modified from Cooper (1999) (equation 1):

$$Od = (BOD_{in} - BOD_{out} + 0.9 * N_{tot-in} * 4.3) * Q \qquad (5)$$

where:

BOD_{in} = BOD_7 in the inflow (mgO_2 l^{-1});
BOD_{out} = effluent standard for BOD_7 (15 mg O_2 l^{-1});
N_{tot-in} = N_{tot} in the inflow (mg l^{-1});
Q – flow rate (l d^{-1}).

Since no NH_4-N analyzes are usually performed in the monitoring of wastewater treatment plants in Estonia, N_{tot} is used in the modified equation. The coefficient 0.9 characterizes the average content of NH_4-N in N_{tot} amount in domestic wastewater. The established target is that all of the NH_4-N should be removed, and this helps to reduce uncertainties, for example from possible ammonification and sorbed ammonia releases from the surface of the filtering material.

Assuming the theoretical aeration capacity to be 30 g O_2 m^{-2} d^{-1}, the area needed for VSSF filters can be calculated using the following equation (Noorvee *et al.*, 2005a, Publication II):

$$A = OD/VA , \qquad (6)$$

where:

A – the area needed (m^2);
OD – the oxygen demand of the wastewater entering the wetland system (g O_2 d^{-1});
VA – aeration potential of a VSSF wetland (30 g O_2 m^{-2} d^{-1}).

In Estonia, the average water flow (Q) for small wastewater treatment systems is considered to be 100 l pe^{-1} (Kuusik, 1995). The average pollutant loading for BOD_7 is considered to be 60 g d^{-1} pe^{-1}, and 12 g d^{-1} pe^{-1} for N_{tot}. Accordingly, the average concentrations are 600 mg l^{-1} for BOD_7 and 120 mg l^{-1} for N_{tot}. Assuming that about 40% of BOD and 10% of N_{tot} can be removed via pre-treatment in a septic tank, the concentrations flowing into the VSSF filter will on average be 360 mg l^{-1} for BOD_7 and 108 mg l^{-1} for N_{tot}. Using equations 5 and 6, it can be concluded that the area of the VSSF filter should measure up to 2.5 m^2 pe^{-1} for effective organic matter removal and nitrification. Implementing re-circulation of over 100% results in an area need of 1.7 m^2 pe^{-1}.

In our experiments, the Kodijärve VSSF filter had a depth of 1.3 m and the VSSF filters of Nõo and Rämsi a depth of 0.7 m. Since the Kodijärve VSSF filter had a significantly higher theoretical aeration capacity, we can conclude that VSSF filters with greater depth can improve aeration even if the filtering material is crushed limestone instead of LWA. Accordingly, it is recommended to design the VSSF filters with a depth of 1.0–1.3 m.

Based on the experiments, the optimal hydraulic loading of VSSF filters should be 50–300 mm d^{-1}. Taking the example of water flow of Q= 100 l pe^{-1} the minimal hydraulic loading rate 50 mm d^{-1} results in an area need of 2 m^2 pe^{-1}.

Based on the experiments, the optimal hydraulic loading for HSSF filters should be 20–30 mm d^{-1}, which results in an area of 3.3–5 m^2 pe^{-1}. Mass removal rates of BOD_7 in the HSSF filters of the experimental systems varied from 0.2–8.0 g m^{-2} d^{-1}, being lowest when not much organic matter was left to be removed after the VSSF filters. Assuming the capability for the removal of BOD_7 is, based on the experiments conducted, on average 4.0 g m^{-2} d^{-1}, and that that 60–80% of BOD can be removed in a VSSF filter, the concentrations flowing into the VSSF filter will on average be 72–144 mg l^{-1}. Accordingly, the area requirement of an HSSF filter will be 1.8–3.6 m^2 pe^{-1}. Taking into account both hydraulic loading and organic matter loading, the recommended area for HSSF filters is 3.0–5.0 m^2 pe^{-1}.

4. CONCLUSIONS

The research conducted in the Kodijärve hybrid CW in the years 2001–2003 clearly demonstrated that the availability of oxygen is essential for purification processes, which is obviously expressed in the differences in wastewater purification between the periods before the VSSF CW was constructed and after the construction of the VSSF CW. The Kodijärve HSSF CW proved that HSSF filters cannot remove enough BOD and nitrogen, even if the hydraulic loading rate is below designed values and the duration of water residence in the system is greater.

Better aeration can significantly improve purification. The VSSF CW built in 2002 for enhanced aeration demonstrated satisfactory results. Although the purification efficiencies did not improve significantly after the establishment of the VSSF in Kodijärve CW, the mass removal rates of BOD, N_{tot} and NH_4-N did increase significantly in proportion with increasing loading rates. In any case, VSSF systems with an area 0.5 m^2 pe^{-1} are probably too small for sufficient aeration and therefore for complete nitrification. Unfortunately, insufficient carbon for denitrification is retained in the Kodijärve HSSF wetland. In order to provide a sufficient carbon source for denitrification and improve overall purification processes, it was decided to implement re-circulation in the system.

The reconstruction of the Kodijärve CW system and the establishment of the pilot-scale CW systems in Nõo and Rämsi in 2005 provided information on the effect of re-circulation on the performance of such hybrid CW systems.

The Kodijärve VSSF is filled with crushed limestone, which has a very high hydraulic conductivity, and the filter drains rapidly, with no water-saturated layers remaining in the filter. The aeration capacity of this VSSF system has shown remarkable results, and with re-circulation rates of 300% the aeration capacity has been 87 g O_2 m^{-2} d^{-1}. Re-circulation improved the purification performance in terms of all water quality indicators other than N_{tot} and P_{tot}. The main reason for the less effective N_{tot} removal was the continuing insufficient carbon for denitrification.

As expected, the purification efficiency in both Nõo and Rämsi CWs had a significant negative correlation with hydraulic loading entering the CW system, and hence also with the mass loading rate of the water quality indicators. Accordingly, the experimental systems in Nõo and Rämsi were heavily overloaded in the 1st operational period and also overloaded in the following operational periods (in terms of both hydraulic, nutrient and organic matter load). Since oxygen supply is essential for effective wastewater purification, an oxygen deficiency occurs in overloaded systems.

It can be concluded that the re-circulation of wastewater in overloaded systems is a good solution for the improvement of the aeration and overall purification efficiency of CWs. The re-circulation of the wastewater improves purification significantly. However, the small amount of re-circulated water (50…75% of the inflow) has only a small effect on purification efficiency when the system is heavily overloaded. In addition, small differences in re-circulation rate (about 10…20% more or less of the inflowing water) have insignificant effects on purification efficiency. The re-circulation rate must be from 100 up to 300 percent of the inflowing wastewater to achieve satisfactory results in terms of effective BOD and COD removal and nitrification/denitrification, as well as TSS removal. On the other hand, too high a re-circulation rate (up to 600%) can have negative effects on TSS and P_{tot} removal (when the filter material acts as a phosphorus precipitating substrate). At the same time, the high re-circulation rate can still have positive effects on the purification performance in terms of processes that depend on oxygen supply. In terms of applying pre-denitrification, a better solution would be not to pump the wastewater back into the inflow well, but instead to pump it into the septic tank, where more organic matter is available for denitrification. Since the change in the re-circulating origin (interim + outflow well or only the outflow well) showed no significant effects on purification performance, the use of re-circulation from the interim well seems to be irrelevant in terms of additional improvement of purification performance, and back-pumping only from the outflow well is more adequate.

In the last 2 operational periods, the purification efficiency in Nõo was affected by the clogging of the pipes in HSSF filters, which caused a water level rise in the interim well and thus generated a water-saturated layer at the bottom of the VSSF filters. The maximum aeration capacity values in Nõo were lower than in Kodijärve and Rämsi CWs, which indicates that better aeration results are gained in VSSF systems with no water-saturated layers remaining in the system.

Unfortunately the LWA used as filter material in Kodijärve, Rämsi and Nõo CWs rapidly lost its phosphorus adsorption and sedimentation properties. In an LWA, Ca-minerals are a very important additive for the precipitation of phosphorus, and this was insufficient in the experimental CWs in Kodijärve, Rämsi and Nõo. It is therefore very important to find a suitable filter material for phosphorus removal via adsorption or precipitation. Another possibility to assure sufficient phosphorus removal (<1.5 mg l^{-1} in the outflow) is to use chemical precipitation inside the septic tank.

It can be concluded that the area of the VSSF filter should measure up to 2.5 m^2 pe^{-1} for effective organic matter removal and nitrification. Implementing re-circulation over 100% results in an area need of 1.7 m^2 pe^{-1} for VSSF filters. It is recommended that the VSSF filters be designed with a dept of 1.0 to 1.3 m. Taking into account both hydraulic loading and organic matter loading, the recommended area for HSSF filters is 3.0 to 5.0 m^2 pe^{-1}, when they are placed as a second stage of the CW system.

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SUMMARY IN ESTONIAN

Kombineeritud kahe-astmeliste pinnasfiltersüsteemide rakendatavus külma kliima tingimustes

Seoses reoveepuhastuse arendamisega on kasvanud huvi odavamate reoveepuhastustehnoloogiate rakendamiseks. Tehismärgalasüsteemid on üheks võimalikuks reoveepuhastustehnoloogiaks, mis võimaldab reovee puhastamist väiksemate hoolduskuludega ja madalama energiatarbega, kui aktiivmuda tehnoloogial baseeruvad reoveepuhastid või teised reoveepuhastusmeetodid. Samas vajavad aga tehismärgalasüsteemid samasuguse puhastusefekti saavutamiseks suuremat pindala kui näiteks aktiivmudapuhastid. Reeglina rakendatakse enne reovee tehismärgalasüsteemi juhtimist eelpuhastust septikus, kus eemaldatakse suur osa hõljuvainetest, aga ka orgaanikast ja väiksemal määral taimetoitainetest.

Reoveepuhastusprotsesside toimimiseks on väga oluliseks aspektiks hapniku varustatuse tagamine. Üheks võimaluseks tehismärgalasüsteemide hapnikuga varustatuse tagamiseks on vertikaalse läbivooluga pinnasfiltri (VF) rajamine märgalasüsteemi esimeseks etapiks. Kuna VF-ide rajamise peamine eesmärk on reovee õhustamine, siis peab selliste süsteemide projekteerimiseks lähtuma puhastussüsteemi siseneva reovee hapnikutarbest.

Külmas kliimas (regioon, kus keskmine ööpäevane õhutemperatuur jääb pikemaks perioodiks alla 0°C) on teiseks oluliseks puhastusprotsesse mõjutavaks teguriks temperatuur. Seetõttu projekteeritakse külmas kliimas sageli tehismärgalasüsteeme varuga, et tagada süsteemide parem töökindlus ka talveperioodil. Varuga süsteemide rajamine muudab aga puhastussüsteemi rajamise kallimaks. Seetõttu on oluline leida meetmeid, mis võimaldavad tehismärgalasüsteeme rajada ilma varuta. Üheks võimaluseks on seejuures reovee tagasipumpamise rakendamine, et vähendada lühemast vee viibeajast tingitud mõjusid. Kui vett ringi pumbata, antakse süsteemi täiendavat hapnikku aeroobsete mikrobioloogiliste protsesside toimumiseks. Lisaks sellele pikendab vee ringluse rakendamine mikroorganismide ja reovee kontaktaega. Lämmastikuärastuse seisukohast on vee ringluse tagamisel oluline mõju ka nn eel-denitrifikatsiooni läbiviimise seisukohast. Kuna orgaanika laguneb aeroobsetes protsessides kiiremini, kui toimub nitrifikatsioon, siis jääb lämmastikuärastuse teise etapi – denitrifikatsiooni tarbeks reovette liiga vähe orgaanikat (heterotroofse denitrifikatsiooni käigus tarbitakse orgaanilist materjali). Eel-denitrifikatsioon tähendab seda, et vesi pumbatakse tagasi reoveepuhasti sissevoolu, kus see seguneb värske reoveega, kus on piisavalt süsinikku denitrifikatsiooni toimumiseks.

Käesolevas töös hinnati kahe-astmeliste kombineeritud pinnasfiltersüsteemide (VF + horisontaalse läbivooluga pinnasfilter (HF)) rakendatavust suhteliselt pika ja külma talvega piirkondades, kus asub ka Eesti.. Süsteemide puhul rakendati tagasipumpamist, et tagada eel-denitrifikatsiooni toimimist ning analüüsida tagasipumpamise mõju teiste reoveeparameetrile puhastusefektiivsusele. Uuritavateks süsteemideks olid Kodijärve hooldekodu tehismärgalapuhasti (VF-i pindala 2 x 18,7 m^2 + HF 2 x 156,25 m^2), Nõo katsesüsteem Nõo aktiivmudapuhasti territooriumil (kaks paralleelset pinnasfiltersüsteemi pindalaga: VF 4 m^2 + HF 10 m^2) ning Rämsi katsesüsteem OÜ Heko Põld seafarmi territooriumil (kaks paralleelset pinnasfiltersüsteemi pindalaga: VF 10 m^2 + HF 15 m^2).

Töö tulemused näitavad, et VF-i rajamine HF-i ette tõstab oluliselt süsteemi hapnikuga varustatust ning parandab seeläbi reoveepuhasti tulemuslikkust. Aeratsioonimäärad ulatusid VF-ide puhul isegi üle 100 g O_2 m^{-2} d^{-1}. Paremad aeratsiooni näitajad saavutati VF süsteemides, kus filtri põhja ei moodustunud veega küllastunud kihti. HF-id seevastu ei taga piisavat hapnikuga varustatust ning ei suuda seetõttu sageli tagada piisavat puhastusefekti enamike parameetrite osas. Eeskätt lämmastikuärastuse osas jääb jõudlus madalaks.

Töö tulemuse näitavad, et tagasipumpamise rakendamisel on oluline positiivne mõju puhastusprotsesside efektiivistamisele ja tagasipumpamine aitab puhastusefektiivsust parandada ka süsteemi ülekoormuse korral. Väikesel tagasipumpamise määral (50...75% sissevoolava vee vooluhulgast) on siiski väheoluline mõju puhastusprotsessidele, kui süsteemid on ülekoormatud. Väikesed erinevused tagasipumpamise määras on (10...20%) on aga sisuliselt ebaolulised. Tagasipumpamise määr peab ulatuma 100...300%, et saavutada nõutud puhastusefekt orgaanika, KHT ja nitrifikatsiooni/denitrifikatsiooni osas. Samas liiga kõrge tagasipumpamise määr (kuni 600%) võib omada hoopiski negatiivset mõju hõljuvainete ja üldfosfori puhastusefektiivsusele, parandades seejuures endiselt orgaanika ja lämmastiku puhastusefekti. Kahjuks kaotas süsteemides filtermaterjalina kasutatud FIBO kergkruus oma fosfori sidumisvõime kiiresti. Üldfosfori nõuetekohaste väärtuste saavutamiseks (<1,5 mg l^{-1}) on vajalik endiselt sobiva filtermaterjali leidmine, mis tagaks piisava fosfori sidumise kas läbi adsorptsiooni või sadestamise. Teiseks võimaluseks nõutud väljundparameetri saavutamiseks on keemilise sadestamise rakendamine septikus.

Töö tulemuste põhjal võib kinnitada, et taoliste süsteemide projekteerimisel võib lähtuda vaid süsteemi siseneva reovee hapnikutarbest. VF-i pindala määramisel peab lähtuma aeratsioonivõime näitajast 30 g O_2 m^{-2} d^{-1}, kui tagasipumpamist ei rakendata. Kui tagasipumpamist on kavas rakendada üle 100% sissevoolava reovee vooluhulgast, võib aeratsioonivõime näitajana arvestada kuni 45 g O_2 m^{-2} d^{-1}. Ilma tagasipumpamiseta peaks VF-i pindala ulatuma 2,5 m^2 ie^{-1} ja tagasipumpamise määra >100% rakendamisel 1,7 m^2 ie^{-1}. VF-i sügavus peab olema 1,0...1,3 m. Lähtudes sobivast hüdraulilisest koormusest ja orgaanika puhastusmäärast HF-ide puhul, peab arvestama HF-i pindalaks 3,0...5,0 m^2 ie^{-1}.

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III

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V

Põldvere, E., **Noorvee, A**., Karabelnik, K., Maddison, M., Nurk, K., Zaytsev, I.
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THE PERFORMANCE OF PILOT SCALE LWA-BASED HYBRID SOIL FILTERS IN ESTONIA

E. Põldvere[1*], A. Noorvee[1], K. Karabelnik[1], M. Maddison[1], K. Nurk[1],
I. Zaytsev[1] andÜ. Mander[1]

[1] Institute of Geography, University of Tartu, 46 Vanemuise St., Tartu 51014, Estonia

*Corresponding author: E-mail: anai@ut.ee, Tel +372 5289197, Fax: +372 7366676

ABSTRACT

Two pilot scale experimental hybrid soil filters (SF) filled with light weight aggregates (LWA) were established during the summer of 2005 for the treatment of different types of wastewater, with the aim of developing compact hybrid constructed wetlands (CW) for use in cold climates. Both SFs are designed on the same principle: a vertical subsurface flow filter followed by a horizontal subsurface flow filter. Six different operational regimes (varying loading rates, intervals of loading, recirculation regimes and regimes of hydraulic retention time) were tested during the experiments. Water samples were taken from both SFs once a week (November 2005…December 2006). With the decrease in wastewater and pollutant load and the larger re-circulation of wastewater, purification efficiency increased in terms of most water quality indicators.

Keywords: Aeration; constructed wetland, design; hybrid soil filter; LWA; re-circulation.

1. INTRODUCTION

Two pilot scale experimental hybrid soil filters (SF) were established during the summer of 2005 for the treatment of different types of wastewater, with the aim of developing compact hybrid constructed wetlands (CW) for use in cold climates. The idea of compact systems is to sustain systems with lower building costs [1]. In cold climates, CWs are often designed with a reserve in order to compensate for lower temperatures during winter. Over-design to compensate for uncertainty due to low temperatures raises construction and operating costs [2]. Providing measures that can help achieve proper results without over-dimensioning would make CWs a much more attractive wastewater treatment technology. One possible operational method to compensate small area and short retention time is to re-circulate the wastewater. As the effluent is being re-circulated, additional oxygen for aerobic microbial activities can be transferred into the wastewater. Re-circulation also enhances contact between the pollutants and microorganisms. In addition, as the suspended solids are predominantly removed by filtration, re-circulating the effluent increases the chances for the suspended solids to be trapped in the system [3]. These factors should account for the improvement of overall purification processes.

The main aim of our studies was to determine optimal loading, design parameters, management schemes and operational regimes for LWA-based two-stage hybrid wetlands in cold climate conditions for the treatment of wastewater of various origin and quality, without the conventional biological treatment (before the SF).

2. MATERIAL AND METHODS

2.1. Site description

Two pilot scale experimental hybrid SFs for the treatment of different types of wastewater were established in Southern Estonia during the summer of 2005. Both pilot scale SFs in Nõo and Rämsi consist of two parallel systems with different operating regimes designed on the same principle: a vertical subsurface flow filter (VF) 0.7 m in depth followed by a horizontal subsurface flow filter (HF) 1 m in depth. The systems were not planted, because of the short test period which was not sufficient for the proper growth of vegetation. Therefore they do not fulfil the strict definition of a wetland, and we used the term “soil filter”. The filters were covered with 5-cm-thick insulation slabs during winter. Table 1 reports the average inflow and water quality parameters in both SFs during 6 operational regimes.

Table 1. Average values of the concentrations (m/L) of studied water quality parameters (bold – minimal; bold and underlined – upper value) in the inflow of the studied SFs during sequential operational regimes.

Period	**SF**	**Q ($m^3 d^{-1}$)**	**pH**	**Temp C^0**	**Average water quality parameters (mg/L) in the inflow**					
					BOD_7	**TSS**	**COD_{Cr}**	**N_{tot}**	**NH_4-N**	**P_{tot}**
1	Nõo	**0.73**	7.4	6.5	405	132	745	72	52	**20**
Nov-Dec	Rämsi	**0.4**	**6.6**	5.1	5519	541	7039	507	412	191
2	Nõo	0.37	**7.6**	**3.9**	425	126	750	71	52	21
Jan-Mar	Rämsi	**0.10**	6.3	**2.7**	5700	523	8068	527	431	158
3	Nõo	0.29	7.4	7.4	446	219	808	**55**	**47**	21
Mar-May	Rämsi	**0.10**	6.2	8.2	**3838**	**220**	**5512**	**305**	**265**	**120**
4	Nõo	0.22	**7.0**	16.4	644	287	1077	92	78	31
May-Jul	Rämsi	**0.10**	**5.8**	**18.1**	**7483**	504	**11180**	**594**	**474**	**297**
5	Nõo	0.30	7.2	**16.9**	**646**	**387**	**1136**	**112**	**81**	**45**
Aug-Oct	Rämsi	0.13	5.7	17.3	4656	291	7267	426	368	194
6	Nõo	**0.20**	7.2	8.3	**376**	**118**	**590**	78	62	26
Oct-Dec	Rämsi	**0.10**	6.4	8.7	4655	**1032**	7246	517	396	208

The Nõo experimental SF is located on the territory of the active sludge wastewater treatment plant (AWP) of Nõo village. The wastewater (domestic wastewater combined with dairy and meat industry wastewater) is pumped into the SF before it reaches the grid of the AWP. The exact volume of water is controlled by a timer-operated pump. A certain amount of wastewater is first pumped into a septic tank (2 m^3), where the hydraulic retention time (HRT) was, by period, 1, 3, 3, 5, 3 and 5 days respectively. After the septic tank, the wastewater is divided equally between both parallel (left-hand and right-hand) experimental systems (area of VF: 2 x 4 m^2; area of HF: 2 x 10 m^2). Treated wastewater is directed by gravity flow to Nõo stream.

The Rämsi experimental SF is located at a pig farm. The wastewater entering the SF is obtained by separating the liquid fraction from the solid fraction of the swine slurry in a separation well. A timer-operated pump pumps the desired amount of wastewater into the experimental system. The wastewater is first pumped into a septic tank (2 m^3), where the hydraulic retention time (HRT) was, by period, 3, 10, 10, 10, 8 and 10 days respectively. After the septic tank the wastewater is divided equally between both parallel experimental systems (area of VF 2 x 10 m^2; area of HF 2 x 15 m^2). Treated wastewater is directed to a natural ditch by gravity flow.

Table 2 reports the cross-section of the VFs, which is constructed such that the bottom layer has the highest, and the upper layer the lowest hydraulic conductivity. The HFs of both pilot scale SFs are filled with light weight aggregates (LWA) with particle sizes of 2–4 mm, which were chosen because of their porosity and good P removal ability [4].

Table 2. Cross sections of vertical flow filters.

Cross-section	**Nõo right system**	**Nõo left system and both left & right systems in Rämsi**
Upper layer (thickness 20 cm)	Crushed limestone Ø 2–8 mm	LWA Ø 2–4 mm
Middle layer (20 cm)	Crushed limestone Ø 8–16 mm	LWA Ø 4–10 mm
Bottom layer (25 cm)	Crushed limestone Ø 12–32 mm	LWA Ø 10–20 mm

The received pollutant loading (Table 1) was high, but the aim of our studies was not to over-dimension the systems. Therefore there was the possibility of re-circulating wastewater from the outflow well of the VFs (interim well) and from the outflow of the HFs (outflow well) using timer-controlled pumps in both SF systems. The wastewater re-circulating regimes are presented in Table 3.

Table 3. Re-circulating regimes (% of hydraulic loading rate), bold – upper value.

	Recirculation regimes of Nõo SF*				**Recirculation regimes of Rämsi SF***			
Opera-tional regime	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**
	From interim well %	**From interim well %**	**From outflow well %**	**From outflow well %**	**From interim well %**	**From interim well %**	**From outflow well %**	**From outflow well %**
1	0	0	25	**35**	25	**30**	**40**	20
2	0	0	25	**35**	0	0	**35**	30
3	**75**	50	0	0	**55**	40	**40**	30
4	**70**	0	0	**85**	**90**	70	**50**	40
5	**150**	0	150	**300**	**300**	0	300	**600**
6	0	**150**	**300**	150	0	**300**	**600**	300

* summarized recirculation rates from the outflow and interim well were used in the correlation analysis

2.2. Sampling

Water samples were taken from both SFs once a week (November 2005…December 2006), from the outlet of the septic tank and the outlet of both VSSF and HSSF beds. Water samples were taken 8 times in the 1st period, 11 (Nõo) and 3 (Rämsi) times in the 2nd period, 9 (Nõo) and 7 (Rämsi) times in the 3rd period, 9 (Nõo) and 6 (Rämsi) times in the 4th period, 9 times in the 5th period, and 11 times in the 6th period. Rämsi was partly frozen during the 2nd period (in winter), and partly clogged during the 3rd and 4th periods. Water samples were analyzed for pH, BOD$_7$, SS, COD$_{Cr}$, N$_{tot}$, NH$_4$-N, NO$_2$-N, NO$_3$-N, P$_{tot}$, temperature, redox potential and dissolved O$_2$.

2.3. Statistical analysis

This paper presents data and compares the purification efficiencies of 6 different operational regimes in the experimental systems. All parameters were verified for normality (Kolmogorov-Smirnov, Lilliefors' and Shapiro-Wilk's tests). Since the variables were not normally distributed, a non-parametric Spearman Rank Order Correlation coefficient was detected between influencing factors and purification efficiencies of BOD_7, N_{tot}, NH_4-N and P_{tot}. The level of significance of $\alpha = 0.05$ was accepted in all cases. We used *Statistica 7.0* for the data analysis.

3. RESULTS

3.1. Nõo SF

With the decrease in wastewater and pollutant load and the greater re-circulation of wastewater, purification efficiency (Table 4) increased in terms of most water quality indicators. For instance, the purification efficiency of BOD_7, COD_{Cr}, N_{tot} and NH_4-N increased in both the right-hand and left-hand systems of the SF. The significantly lower purification efficiency of P_{tot} during the 3rd operational regime probably reflects the influence of the lower water temperature and the switching of the recirculation from the outflow well to the interim well (Table 3). This could have an effect on the reaction balances in the vertical filter, because enhanced inflow of O_2-rich water from the interim well may suppress the solubility of CO_2. Thus the average CO_2 concentration could become the limiting factor in the geochemical pathway that leads to the final sedimentation of P [5].

The left-hand system of both parallels showed more stable purification efficiency in comparison with the right-hand systems of the SFs. Better overall purification efficiencies in the water quality parameters were noted in the 2nd, 3rd, 4th and 5th period, and only P_{tot} purification efficiency was better in the right SF in the 2nd, 3rd, 4th period, when the re-circulation from the outflow well was smaller (Table 3), and also different VF materials ($CaCO_3$-rich limestone) were used. The poor purification efficiency in the right parallel indicates the influence of higher re-circulation in the left bed during the investigated periods, and that LWA is a better filter material than crushed limestone in VFs, because of its higher porosity and longer residence time in the filter. We registered higher pH values in the outflow of the right SF in the 1st, 2nd, 3rd and 4th periods (average values of periods: 8.8, 8.3, 8.1, 8.1), and after that, in the 5th and 6th period, the results were not as high, with average values of 7.6 and 7.7 for the periods in question (Table 1).

Table 4. Hydraulic retention time (HRT) and purification efficiency of organic matter (after BOD$_7$), COD, total suspended solids, N$_{tot}$, NH$_4$-N and P$_{tot}$ in Nõo SF, bold – upper value.

Period	**Parallel**	**HRT (day)**	**Purification efficiency at outflow of Nõo SF (%)**					
			BOD$_7$	**TSS**	**COD$_{Cr}$**	**N$_{tot}$**	**NH$_4$-N**	**P$_{tot}$**
1	Right	6	51	92	51	**11**	**–24**	**76**
	Left	6	**67**	**94**	**64**	5	–27	47
2	Right	11	76	91	72	25	14	**66**
	Left	11	**82**	**93**	**78**	**28**	**18**	31
3	Right	10	87	91	84	38	36	**45**
	Left	**13**	**89**	**95**	**86**	**46**	**52**	40
4	Right	14	84	**87**	82	51	52	**75**
	Left	14	**89**	72	**83**	**66**	**67**	67
5	Right	4	95	**92**	92	74	71	73
	Left	**5**	**98**	90	**94**	**80**	**76**	**76**
6	Right	6	99	86	93	**82**	**84**	61
	Left	**7**	99	**87**	93	80	79	**69**

The Spearman Rank Order Correlation analysis shows a significantly negative correlation between the inflow (Q) and BOD$_7$, COD, N$_{tot}$, as well as NH$_4$-N purification efficiency in both parallel SFs. In the left-hand system of the SF we also found a significant negative correlation between inflow (Q) and P$_{tot}$ purification efficiency. As expected, we found a significant positive correlation between the re-circulation rate and purification efficiency of BOD$_7$, COD, N$_{tot}$ and NH$_4$-N in both parallel systems. In the left-hand system, we also observed a significantly positive correlation with inflow temperature (^{o}C) and BOD$_7$ purification efficiency. The comparison between two parallel systems is not direct, because of the difference in VF filter media (Table 2).

3.2. Rämsi SF

With the decrease in wastewater load and the application of treated water with a re-circulation rate of 300–600%, purification efficiency increased (Table 5).

The purification efficiency of BOD$_7$, COD$_{Cr}$, N$_{tot}$ and NH$_4$-N did increase in the right- and left-hand systems of the SF. TSS purification efficiency did not vary significantly. Only the efficiency of P$_{tot}$ purification decreased in the 5th and 6th periods, when HRT also decreased. However, the outlet concentrations from both parallel systems significantly exceeded standard values in the first periods, due to the high loading of the systems with nutrients and organic matter.

In terms of purification efficiency, the right-hand parallel was more stable than the left-hand system. Better overall purification efficiencies in water quality parameters were noted in the 2nd, 4th and 5th periods. In the right-hand parallel there were also higher re-circulation rates (Table 3). The highest average pH values (9.2) were measured from the outflow of the right-hand parallel in the 2nd period. The smallest average pH values (7.6) were measured from the outflow of the left-hand system in the 6th period (Table 1).

The Spearman Rank Order Correlation analysis shows a significantly positive correlation in both parallel SFs with re-circulation and BOD_7, COD, N_{tot} and NH_4-N purification efficiency, which was expected. There was also a significantly negative correlation with re-circulation and TSS, as well as P_{tot} purification efficiency in both SFs.

Table 5. Hydraulic retention time (HRT) and purification efficiency of organic matter (after BOD_7), COD, total suspended solids, N_{tot}, NH_4-N and P_{tot} in Rämsi SF, bold – upper value.

Period	**Parallel**	**HRT (day)**	**Purification efficiency at outflow of Rämsi SF (%)**					
			BOD_7	**TSS**	**COD_{Cr}**	**N_{tot}**	**NH_4-N**	**P_{tot}**
1	Right	14	64	92	58	**54**	51	96
	Left	**16**	**67**	**98**	**61**	53	**57**	**97**
2	Right	70	**78**	**99**	**68**	**60**	**53**	**99**
	Left	**73**	66	98	61	46	43	96
3	Right	49	82	**84**	78	58	**57**	**99**
	Left	**56**	82	80	**79**	58	53	96
4	Right	39	**93**	**87**	**91**	**79**	**76**	**99**
	Left	**45**	87	82	87	78	75	92
5	Right	10	96	78	**96**	**81**	**80**	**78**
	Left	10	96	**79**	95	79	79	71
6	Right	13	98	94	97	87	85	**77**
	Left	13	**99**	94	**98**	87	**87**	71

4. DISCUSSION AND CONCLUSIONS

The main reasons for the unsatisfactory results during the first periods (operational regimes) were the overloaded systems (in terms of both hydraulic, nutrient and organic matter load). Likewise, the communities of micro-organisms were not sufficiently developed in the filter material. Nitrification occurs after carbon is reduced, and therefore that is only possible if there is enough oxygen available in the system after COD (BOD) elimination [6]. Insufficient oxygen content is considered to be one of the most important factors influencing nitrogen removal. Therefore supplementary measures must be adopted in order to increase the aerobic condition, such as direct bed aeration or aerobic pre-treatment systems [7].

The re-circulation of wastewater in overloaded systems is a good solution for the improvement of the aeration and overall purification efficiency of CWs. The high re-circulation rate of the wastewater significantly improves purification. However, the small amount of re-circulated water (25…50% of inflow) has only a small effect on purification efficiency when the system is heavily overloaded. The re-circulation rate must be at least 100…200 percent of the inflowing wastewater to achieve satisfactory results in terms of effective BOD and COD removal and nitrification. The removal efficiency of BOD_7 equally depends on the enhancement of the recirculation rate and the lowering of the hydraulic loading rates, whereas the purification efficiencies of N compounds were related to the increase in recirculation [5]. Differences between the two parallel systems in Nõo could be caused by the relatively poor properties of limestone compared to LWA in terms of aeration and insulation, which enhance the effects of other factors such as hydraulic loading rate and temperature regime. The Limestone-LWA system probably retained P through sedimentation reactions with Ca, whereas the LWA system retained P in redox-potential dependent reactions of P with soil Fe and Al [5].

It is crucial to select a suitable filter material for phosphorus removal in subsurface constructed wetlands. Unfortunately the LWA used as filter material in the Rämsi and Nõo pilot scale SFs rapidly lost its phosphorus adsorption and sedimentation properties. In LWAs, Ca-minerals are a very important additive for the precipitation of phosphorus. In contact with water, this may yield a dramatic increase in pH (pH up to 12), which may favour the precipitation of phosphates [4]. We did not register great changes in pH in Nõo and Rämsi SFs. In addition, calcium present in the wastewater itself can promote phosphorus precipitation [8]. This is probably the explanation for the very effective phosphorus removal in the pilot-scale system at Rämsi pig farm. Since the pig fodder also contains Ca-minerals (according to the pig farm data, average Ca content is 11.3 g/kg), it also contains phosphorus (average 8.6 g/kg), and some of the Ca is excreted with the slurry. The Ca inside the wastewater probably allows the phosphorus to precipitate as Ca-phosphate.

Our study gives us forward guidelines to develop systems that match Estonian legislation, when treated wastewater is channelled into a body of water (the subsequent reuse of treated wastewater is not common in Estonia). Those experimental SFs showed that pre-treatment of the wastewater must be sufficient (to prevent clogging), the re-circulation rate has to be at least 100–200% of the inflowing wastewater and the filter material (various alternatives) must support the purification process. On developing compact hybrid constructed wetlands we will also follow other studies [9] that provide comparable data. One way to make P removal more efficient is to use a reagent dosing system in the sedimentation tank [10].

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CURRICULUM VITAE

ALAR NOORVEE

Sünniaeg: 16. 01.1980.
Aadress: Alkranel OÜ, Riia 15b, 51010 Tartu, Eesti
Kontakt: Tel: +372 55 40 579; Faks: + 372 7366 676; e-post: alar@alkranel.ee

Haridus

1998 – Tartu Raatuse Gümnaasium
2002 – Tartu Ülikool Bioloogia-geograafia teaduskond. Keskkonnatehnoloogia. *BSc.*
2003 – Tartu Ülikool Bioloogia-geograafia teaduskond. Keskkonnatehnoloogia. *MSc.* (magistritöö „Puhastusprotsessid Kodijärve vertikaalvoolulises pinnasfiltris”)

Teenistuskäik

Alates oktoober 2005 TÜ Tehnoloogiainstituut, spetsialist.
Alates november 1999 Alkranel OÜ, tegevjuht, keskkonnakonsultant.

Publikatsioonid

Noorvee, A., Repp, K., Põldvere, E. and Mander, Ü. 2005. Aeration effects and the application of the k–c* model in a subsurface flow constructed wetland. Journal of Environmental Science and Health, Part A – Toxic/Haz. Subst. & Environmental Eng., A, 40, (6/7), 1445–1456.

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Põldvere, E., Noorvee, A., Karabelnik, K., Maddison, M., Nurk, K., Zaytsev, I. and Mander, Ü. 200x. Performance of pilot scale LWA-based hybrid constructed wetlands for wastewater treatment. (Submitted).

CURRICULUM VITAE

ALAR NOORVEE

Date of birth: 16.01.1980.
Address: Alkranel Ltd, Riia 15b, 51010 Tartu, Estonia.
Contact: Ph: +372 55 40 579; Fax: + 372 7366 676; e-mail: alar@alkranel.ee.

Education

1998 – Tartu Raatuse Gymnasium.

2002 – University of Tartu, Faculty of Biology and Geography, Institute of Geography. Environmental technology. *BSc.*

2003 – University of Tartu, Faculty of Biology and Geography, Institute of Geography. Environmental technology. *MSc.* (master thesis "Purification processes in the vertical flow constructed wetland in Kodijärve, Estonia").

Professional employment

Specialist at the University of Tartu, Institute of Technology, 2005 – present.
Managing director, environmental consultant at Alkranel Ltd, 1999–present.

Publications

Noorvee, A., Repp, K., Põldvere, E. and Mander, Ü. 2005. Aeration effects and the application of the k–c* model in a subsurface flow constructed wetland. Journal of Environmental Science and Health, Part A – Toxic/Haz. Subst. & Environmental Eng., A, 40, (6/7), 1445–1456.

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DISSERTATIONES TECHNOLOGIAE CIRCUMIECTORUM UNIVERSITATIS TARTUENSIS

1. **Sille Teiter.** Emission rates of N_2O, N_2, CH_4 and CO_2 in riparian grey alder forests and subsurface flow constructed wetlands. Tartu, 2005.
2. **Kaspar Nurk.** Relationships between microbial characteristics and environmental conditions in a horizontal subsurface flow constructed wetland for wastewater treatment. Tartu, 2005.
3. **Märt Öövel.** Performance of wastewater treatment wetlands in Estonia. Tartu, 2005.