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KRISTJAN KARABELNIK

Advanced design and management of hybrid constructed wetlands: environmental and water purification effects

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Department of Geography, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia.

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

Opponent: Professor Otto R. Stein, Department of Civil Engineering and the Center for Biofilm Engineering, Montana State University, Bozeman, USA

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Author's contribution

Publication I: The author designed the batch-operated CW system and is partly responsible for the fieldwork and data collection (about 70%), analysis (100%), and for writing the manuscript (about 90%).

Publication II: The author is partly responsible for the fieldwork and data collection (about 40%) and analysis (about 40%), and for writing the manuscript (about 40%).

Publication III: The author is one of the designers of the compact filter systems and is partly responsible for the fieldwork and data collection (50%), analysis (about 90%), and for writing the manuscript (about 70%).

Publication IV: The author is one of the designers of the compact filter systems and is partly responsible for the fieldwork and data collection (50%) and for writing the manuscript (about 10%).

Publication V: The author is partly responsible for the fieldwork and data collection (about 20%) and for writing the manuscript (about 10%).

ABBREVIATIONS

ASTP	activated sludge wastewater treatment plant
BOD_7	biological oxygen demand (7 days)
COD_{Cr}	chemical oxygen demand (dichromic)
CW	constructed wetland
FS	filter system
GHG	greenhouse gases
HLR	hydraulic loading rate
HF	horizontal (subsurface) flow
LWA	light weight aggregates
NH_4-N	ammonium nitrogen
NO_2-N	nitrite nitrogen
NO_3-N	nitrate nitrogen
N	nitrogen
N_{tot} or TN	total nitrogen
P	phosphorus
PE	purification efficiency
pH	measure of the acidity or basicity of a solution
PO_4-P	phosphate phosphorus
P_{tot} or TP	total phosphorus
Q	discharge volume
StDev	standard deviation
SO_4	sulphate ions
TSS or SS	total suspended solids or suspended solids
VF	vertical (subsurface) flow

ABSTRACT

The removal of organic matter and nitrogen in a CW is highly dependent on the availability of dissolved oxygen in the treatment system. Therefore it is of great importance to develop methods to enhance oxygen supply in the CW matrix. This PhD dissertation focuses on the methods used to enhance oxygen supply in CWs, such as VF systems, systems with effluent recirculation, systems with fluctuating water level, tidal-flow systems and batch-operated systems. The performance of batch-operated CWs is compared to that of conventional CWs is studied. In addition, different aspects of advanced management of hybrid constructed wetlands, such as importance of filter materials and appropriate loading rates and regimes, are studied and discussed.

In the first part of the study, a pilot scale experimental batch-operated LWA FS was established for the treatment of municipal wastewater, with the main objective of evaluating the performance of the experimental batch-operated FS on the basis of performance indicators. During the experiments, the effect of different operational regimes on the purification efficiency of the filter system was also investigated. The highest purification efficiencies of 96% and 51% for BOD_7 and N_{tot}, respectively, were achieved when a recirculation rate of 200% was applied in conjunction with a hydraulic retention time of ~2 days. The highest organic matter removal rate of the experimental FS, K_{BHT}=0.19 m d^{-1}, is approximately two times higher than the removal rate of typical horizontal-flow CWs. The highest aeration capacity of 21.1 gO_2 m^{-2} d^{-1} is, however, somewhat lower than the average aeration capacity of VF CWs, and is substantially lower than the aeration capacity of a VF filter with re-circulation or tidal-flow systems. As the aeration capacity of the system partly depends on the oxygen demand of inflow wastewater, it is necessary to carry out studies of shorter HLRs in order to optimize the performance of experimental batch-operated FSs. We believe that the performance indicators should be interpreted regarding the low inflow concentrations of wastewater, and as the shorter hydraulic retention times could be applied during the future studies, the performance indicators of batch-operated FS are expected to improve substantially.

During the second part of the study, four parallel pilot-scale experimental compact filter systems were established in order to study the treatment capacity of hydrated oil shale ash (an industrial by-product) and Filtralite® in compact highly loaded filter systems for the reduction of BOD and COD values and nutrient concentration in household greywater. The systems were tested at two different HLRs over a nearly two-year period. All of the Filtralite® systems performed significantly better than the oil shale ash system, showing a median COD reduction of 83–88%, whereas the system with 4–10 mm crushed Filtralite® performed significantly better than others filled with Filtralite®. The oil shale ash system clearly outperformed the Filtralite® systems, with a mean reduction of P_{tot} in the oil shale ash filter system of 89%, achieving a median effluent concentration of 0.55 mgP L^{-1} compared to the respective 40–44% and

2.9–3.3 mgP L^{-1} for Filtralite® systems. It was also noticeable that most of the organic matter, TSS and even N_{tot} and P_{tot} was removed in VF filters. When operating the filter systems under ~2.5 times higher loading rates, there were no significant differences in organic matter, TSS and N_{tot} removal efficiencies. The results provide encouragement for the application of similar full-scale systems in places where space for the establishment of CWs is limited, in areas that are far from central sewage systems and/or where there is a lack of potable water. The system's effluent can be reused for toilet flushing or irrigation. In hybrid filters, the preferred filter material for the VF filter could be crushed Filtralite® with a fraction of 4–10 mm, while for the HF filter the suggested material would be hydrated oil shale ash sediment. The improvements of the filter system regarding pumping pressure and distribution system should, however, also be considered before designing a prototype.

In addition to the positive effect of the intermittent loading of CWs on oxygen transfer and purification efficiency, the environmental impact through possible changes in GHG emissions should also be taken into account. Measurements of GHG emissions in three types of CWs in Estonia indicate that intermittent loading to CWs significantly enhanced N_2O fluxes, but did not influence CO_2 and CH_4 fluxes. Further research is needed to determine the relationships between different operational regimes and the environmental impacts regarding the GHG emissions.

1. INTRODUCTION

In the past two decades, CW technology has been developed to a considerable extent, and the CW approach to wastewater treatment has become widespread throughout the world as an ecological alternative to conventional wastewater treatment systems. In addition to the well-known application of CWs for domestic wastewater treatment, the possible employment of CWs for greywater treatment has also been studied intensively during the past decade.

1.1. The use of CWs for greywater treatment

Water shortage has been recognized as one of the main problems in many countries (Li et al., 2010). In the developing world, insufficient water supply and poor sanitation facilities cause thousands of deaths each day, while in developed countries water wastage is often the norm and ineffective septic and wastewater treatment systems cause the pollution of lakes, rivers and groundwater (Finley et al., 2009). Moreover, there are many remote unsewered areas that need to treat wastewater in challenging climatic and spatial conditions and with limited energy and water supply (Brissaud, 2007; Kadlec and Wallace, 2008).

Household wastewater is mainly divided into greywater and blackwater (Otterpohl et al., 1999; Palmquist and Hanaeus, 2005). Greywater is traditionally defined as wastewater that is produced in a household, and excludes toilet wastes (Liu et al., 2010). There is usually no separation between greywater and blackwater, so both streams are mixed and treated together (Gross et al., 2007). Since greywater is less contaminated than blackwater, the purification of greywater is much faster and easier (Revitt et al., 2011). One option for the design of sustainable wastewater treatment systems involves the separate treatment of greywater in a combined filter system, although in order to develop a compact filter system, high loading rates need to be applied. Since in contrast to blackwater, greywater usually contains a minority of nutrients and more than 50% of organic matter from household wastewater, systems that can remove organic matter are needed in order to facilitate the discharge or reuse of the greywater (Li et al., 2009). Therefore the design of the system and the selection of filter materials are of crucial importance (Adam et al., 2007; Kõiv et al., 2010).

Greywater quantity varies from one household to another, but normally constitutes 50–80% of total household wastewater (Eriksson et al., 2002; Li et al., 2009, 2010; Leal et al., 2007). It also depends on the development status of the countries: in developing countries the average per capita production of greywater per capita is 20–30 L d^{-1}, whereas in developed countries it is as high as 90–120 L d^{-1} (Li et al., 2009). There is also a high variation in greywater composition, which varies greatly depending on lifestyle characteristics such as family size, the age of the residents, their eating and washing habits and the detergents used for dishwashing and washing machines (Rasmussen et al., 1996; Eriksson et al., 2002).

Greywater normally includes wastewater from bathroom sinks, baths and showers, but also wastes from laundry facilities and dishwashers (Gross et al., 2007). Some authors exclude wastes from dishwashers and kitchen sinks because it is full of grease and food particles, and is therefore much more difficult to treat (Al-Jayyousi, 2003). In our research, kitchen and laundry wastewater is included.

There are many fields of application for the reuse of purified greywater, such as toilet flushing, garden/crop watering, irrigation, groundwater volume enlargement and the washing of roads and walls (Friedler and Hadari, 2006; Eriksson et al., 2009; Scheumann et al., 2008; Finley et al., 2009). If such reuse opportunities could be put into practice, a large quantity of fresh water could be saved.

The preceding investigations that have been carried out by other authors have revealed many different possibilities for greywater treatment (March and Gual, 2009; Abu Ghunmi et al., 2010; Mourad et al., 2011). In this PhD dissertation CWs are considered to be one option. CWs, especially subsurface flow filters (VF and HF filters), are well suited to greywater treatment (Jenssen and Vråle, 2003). There are, however, great variations in the loading rates and characteristics of greywater, so further research is required (Li et al., 2009).

1.2. The importance of oxygen supply in CWs

Carbon compounds present in wastewater are degraded in CWs through both anaerobic and aerobic processes, but as the aerobic process is faster, most of the organic carbon is consumed by aerobic processes. As regards nitrogen removal, sequential nitrification/denitrification appears to be the major mechanism, with high respiratory oxygen demand and low oxygen availability in constructed wetlands making nitrification the rate-limiting step (Tanner et al., 1999; Harris and Mæhlum, 2003).

There is substantial evidence that the removal of organic matter and nitrogen in CWs is, in addition to temperature, determined by the availability of dissolved oxygen in the treatment system (Allen et al., 2002; Noorvee et al., 2005; Kadlec and Wallace, 2008). Therefore it is of great importance to develop innovative methods to enhance oxygen supply in the CW matrix and thereby the purification efficiency of the treatment system in order to minimize the space needed for wastewater treatment.

1.3. Methods used to enhance oxygen supply in CWs

The high oxygen demand of wastewater together with the limited oxygen supply of the CW filter often limits the amount of dissolved oxygen available for nitrification processes. Nitrification could also be limited by insufficient contact between wastewater and micro-organisms due to the lower oxygen consumption rate of autotrophic nitrifying bacteria compared to heterotrophic carbon consuming bacteria (Sikora et al., 1995).

1.3.1. Vertical-flow CWs

In a vertical-flow filter, wastewater is pumped onto the filter body at alternating periods, water flows vertically through the filter media, is collected by the drainage system on the bottom of the filter and flows into the next stage. Effective aeration is achieved by generating rapid water flow through the filter media, the phenomenon called passive air-pump. Thus the filter consists of material with different hydraulic conductivity. Usually, the two VF filters are loaded intermittently, which allows the degradation of accumulated suspended organic material in order to prevent clogging of the filter (Green et al., 1997) and also lets the surface dry out for certain periods of time (von Felde and Kunst, 1997).

VF ensures better oxygenation of filter media, which favours aerobic processes and therefore ensures better organic matter and ammonia nitrogen removal than horizontal-flow filter (Green et al., 1997; Cooper et al., 1999; Mæhlum, T. and Stålnacke, 1999; Noorvee et al., 2005; Sun et al., 2003). It has been shown (Brix et al., 2002; Noorvee et al., 2005; Noorvee et al., 2007 b) that BOD and SS can be removed successfully in a VF filter, and sufficient nitrification is achieved even at low temperatures.

A common problem regarding the VF filter is the uneven distribution of water onto the filter surface and the short contact time between wastewater and filter material. In addition, the VF filter does not assure sufficient N_{tot} removal if the anoxic conditions required for denitrification are not evolved.

1.3.2. The re-circulation of treated water

In order to improve the purification efficiency of CW systems, the re-circulation of treated water is often used (Sun et al., 1999; Brix et al., 2002; Green et al., 2002; Sun et al., 2003). Re-circulation is not used in HF filter systems, as the process considerably increases hydraulic loading. It is, however, appropriate in VF filters, as materials of much higher hydraulic conductivity are used in VF filters. Re-circulation assures better oxygenation of wastewater, as water is repeatedly pumped back onto the surface of the filter. Re-circulation also favours purification processes through longer contact time between wastewater and micro-organisms attached to the filter material (Sun et al., 2003).

The positive effect of re-circulation on purification efficiency, especially regarding N_{tot} removal, has been described in several studies (Brix et al., 2002; Green et al., 2002; Sun et al., 2003). It has been shown that the re-circulation of treated water in a vegetated VF filter improves BOD and ammonia nitrogen removal (Sun et al., 2003). Brix et al. (2002) studied the effect of the re-circulation of treated water on denitrification processes occurring in the septic tank and found that a re-circulation rate of 100% (1:1) resulted in 50% denitrification, which was concurrently more stable and effective when re-cirulation was applied. Noorvee (2007) and Noorvee et al. (2007a) recommend that the re-circulation rate should be from 100 to 300 percent of the inflowing wastewater in order to achieve satisfactory results in terms of effective BOD and COD removal and nitrification/denitrification, as well as TSS removal.

1.3.3. Batch-operated CW systems

In a batch operated CW, the filter is rapidly filled to capacity, remains filled for a sufficient period of time and is repeatedly drained and refilled. The advantage of batch-operation over continuous-flow operation in wetland systems is supported by the fact that even at very low drain-fill frequencies, the batch operation of SSF CWs ensures that the microbial population at any given point will be exposed to decreasing organic carbon concentration, which allows the wetland environment to be subjected to temporal redox variation (between aerobic and anoxic conditions), therefore enhancing BOD and N removal (Stein et al., 2003).

1.3.4. CWs with fluctuating water level

In CW systems with fluctuating water levels, the CW cells are filled and drained (water level fluctuation) with the same wastewater at a determined frequency over a certain period of time. When the filter is filled with wastewater, anoxic and anaerobic conditions are developed over a short period. During the draining process, an additional flux of oxygen is sucked into the filter, which favours aerobic treatment processes. Thus it is necessary to perform several short fill-drain cycles in order to enhance nitrification processes (Tanner et al., 1999).

Tanner et al. (1999) studied the effect of water level fluctuation on COD, ammonia nitrogen and N_{tot} removal in CW mesocosms and found that an increase in the frequency of short fill-drain cycles (0–6 cycles per day over 7 days) remarkably improved the purification efficiency of organic matter and reduced forms of nitrogen, and that COD and N_{tot} removal can be enhanced by optimizing the frequency of fill-drain cycles.

1.3.5. Tidal-flow CWs

Several recent studies have shown that the purification efficiency of CWs can be enhanced by applying an innovative operation method called “tidal-flow” (Sun et al., 1999; Sun et al., 2005; Austin et al., 2003; Zhao et al., 2004). During the tidal-flow operation, the wetland matrix is alternately filled with wastewater and drained. When the wetland is filled, air is repelled from the matrix. When the wetland is drained, air is drawn from the atmosphere into the matrix (Sun et al., 2005). Tidal-flow operation has the potential to enhance the removal of BOD through aerobic processes and the removal of ammonia nitrogen through nitrification, as the maximum pollutant-biofilm contact is established and the rate of oxygen transfer is increased during the operation (Sun et al., 1999).

Nitrogen removal through sequential nitrification and denitrification in tidal-flow systems is mainly based on adsorption processes (McBride and Tanner, 2000; Austin et al., 2003). During the process ammonium ions (NH_4^+) present in wastewater adsorb onto a negatively charged biofilm. During the draining process, atmospheric oxygen is drawn down into the filter body, resulting in rapid aeration of the biofilm and nitrification of NH_4^+. Nitrate ions rapidly desorb from the biofilm into the wastewater during the subsequent filling of the filter and are used as an electron acceptor during denitrification (Austin et al., 2003). Thus the essential factor for nitrogen removal in tidal-flow systems is absorption of NH_4^+ ions for the nitrification process (Tanner et al., 1999; McBride and Tanner, 2000), which depends on the characteristics, especially on the cation exchange capacity of the filter material used in the treatment system (Austin, 2006).

Austin et al. (2003) conducted experiments with a vegetated tidal-flow CW system with re-circulation using artificial wastewater ($BOD_5 = 402$ mgL^{-1}; $N_{tot} =$ 38 mg L^{-1}; Q = 1.7 m^3 d^{-1}), and achieved BOD_5 and N_{tot} concentrations below 10 mg L^{-1}, showing that tidal VF CW systems ensure sufficient N_{tot} removal through a simultaneous nitrification/denitrification process. Studies (Austin et al., 2003; Sun et al., 2005) have shown that tidal-flow CW systems require substantially less space than conventional CW systems to obtain the same purification efficiency. In addition, nitrogen removal through the nitrification/ denitrification process in the tidal-flow system is energetically more effective, as atmospheric oxygen is used for the nitrification. The major disadvantage of tidal-flow CW systems is that until now there is no good technical solution to enable their use in cold climate conditions if a hard freeze is possible (Austin and Wallace, 2007).

It appears that each of the method described above has its advantages and disadvantages. Preceding experiments have yielded promising results regarding the methods that use water level fluctuation and concurrent variable redox conditions such as batch-operation, water level fluctuation and tidal-flow operation. The aim of developing new operating methods is to enhance purification efficiency and reduce the space requirements of CW systems. There is, however, still little information available on the performance of batch-operated and tidal-flow CWs, as most of the studies that had been carried out until a few years ago have been conducted in lab conditions using artificial wastewater (Austin et al., 2003; Stein et al., 2003; Sun et al., 2005).

1.4. The selection of filter materials

Constructed wetlands have demonstrated their ability to treat large amounts of wastewater using special filter materials (Jenssen and Vråle, 2003). In this study we analyzed different types of filter materials, such as industrial by-products (hydrated oil shale ash) and man-made products (Filtralite® and Filtralite-P®) in both VF and HF filters. VF filters are suitable for oxygen-demanding processes such as nitrification, while HF filters are especially used for anaerobic processes. The main purification processes in horizontal flow filters are sorption, filtration and sedimentation (Vymazal et al., 1998).

Filtralite and Filtralite-P® are expanded light weight clay aggregates that are specially designed for wastewater treatment. Filtralite-P® is a modified filter material, and it has a high pH, Ca and Mg content (Jenssen and Krogstad, 2003), so it is well-suited to phosphorus removal.

Oil shale is a kerogenous sediment/rock mined in Estonia and it is used in Estonian thermal power plants. It is a highly calcareous solid fuel with a low energetic value (Vohla et al., 2005, 2011), and leaves large amounts of ash (45–48% of dry mass of shale). Recently Vohla et al. (2005) and Kaasik et al. (2008) have shown the great potential of Estonian Ca-rich hydrated ash sediment as a possible alternative filter material for CWs. Hydrated oil shale ash has great phosphorus-binding capacity. This is due to its high pH and high content of Ca-minerals, of which ettringite and portlandite are the most important (Kaasik et al., 2008; Liira et al., 2009).

1.5. Environmental impact of intermittent loading to CWs

Little is known of the effects of intermittent loading on GHG emissions from CWs. Several studies have shown that in artificial riparian wetlands, intermittent hydrological regimes reduce both CH_4 (Altor and Mitsch 2006; Sha et al., 2011) and N_2O emissions (Hernández and Mitsch, 2006; Song et al., 2010). However, rapid changes in the water table in peatland mesocosms triggered a significant pulse in both CH_4 and N_2O emissions within 1 to 2 days (Dinsmore et al., 2009). Similarly, intermittent aeration in full-scale biological nutrient removal wastewater treatment plants (Foley et al., 2010) and aerobic/anaerobic batch reactors (Hu et al., 2010) caused incomplete nitrification and denitrification and consequently higher N_2O emissions. Several studies have demonstrated a significant increase in N_2O and a decrease in CH_4 emissions from rice paddies with intermittent irrigation (Yue et al., 2005; Zou et al., 2005; Huang et al., 2007). Therefore, in addition to the positive effect of intermittent loading of CWs in the form of oxygen transfer and purification efficiency, the environmental impact through possible changes in GHG emission should also be taken into account.

1.6. Objectives

This PhD dissertation focuses on the methods used to enhance oxygen supply in CWs, such as VF systems, systems with effluent recirculation, systems with fluctuating water level, tidal-flow systems and batch-operated systems. The performance of batch-operated CW and conventional CWs is compared. Also, different aspects of advanced management of hybrid constructed wetlands such as the importance of filter materials and appropriate loading rates and regimes are studied and discussed.

The main objective of this PhD dissertation is to evaluate the potential of several design and operational methods to improve the performance of hybrid constructed wetlands and filter systems.

The sub-objectives for achieving the main goal are:

I. to investigate the anticipated advantages of a batch-operated CW system on conventional CW systems (HF and VF filters) on the basis of a batch-operated CW pilot system. During the test period, the purification and aeration capacity of the batch-operated system are studied, and the effect of different operational regimes on the purification efficiency of the filter system is also investigated.

II. to compare continuous flow hybrid filters and batch-operated filters and test different regimes, in order to determine optimal loading, design parameters, management schemes and operational regimes for LWA based FSs in cold climate conditions for the treatment of wastewater without conventional biological treatment before the FS.

III. to determine the treatment capacity of hydrated oil shale ash (an industrial by-product) and Filtralite® in compact highly-loaded filter systems in order to reduce BOD and COD values and nutrient concentration in household greywater, which includes water from kitchen sinks and dishwashers.

IV. to clarify the effect of intermittent hydrological regime in subsurface flow constructed wetlands on CH_4 and N_2O emissions and soil respiration (CO_2 flux). As pulsing enhances wetland aeration, we hypothesize that the intermittent loading of CWs would decrease methane emissions and enhance soil respiration, which would increase N_2O emission from CWs.

2. METHODS

The following CW systems are examined in this PhD dissertation:

1) the Ilmatsalu pilot-scale batch-operated CW for domestic wastewater treatment
2) the Rebase pilot-scale compact hybrid CW for greywater treatment

2.1. Ilmatsalu batch-operated CW

2.1.1. Experimental design

During summer 2005, a pilot-scale batch-operated filter was established near the existing ASTP in Ilmatsalu for the treatment of municipal wastewater from Ilmatsalu settlement (Karabelnik et al., 2008; publication I).

The system consists of a septic tank (2 m^3), a distribution well, eight identical LWA filter cells operated in batch mode (with a depth of 1.15 m and an area of 1 m^2 each) and an outflow/recirculation well (Fig. 1). As the experimental period of the pilot CW is expected to be only one year, the cells were not planted. Therefore the FS does not meet the strict definition of a wetland, and we used the term "LWA filter system". During the winter, when ambient temperatures were below zero, the filter and the covers of wells were isolated with 50 mm foamed plastic to keep the system from freezing due to its small dimensions.

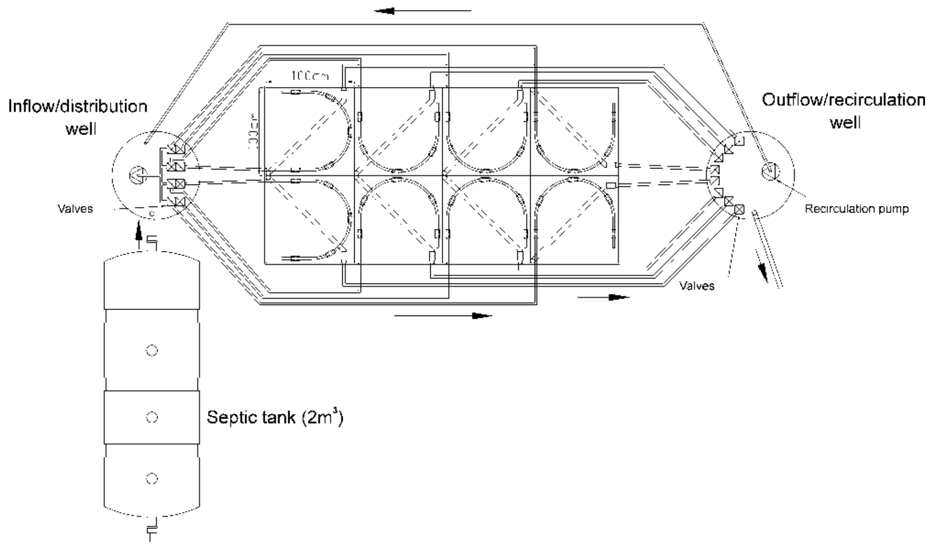

Figure 1. Plan view of Ilmatsalu batch-operated SF with associated septic tank, inflow and outflow well.

The cells are filled with a 1.15 m deep LWA. The LWA used in the Ilmatsalu pilot filter system is produced from local clay mineral in Estonia (trademark name Filtralite S) and does not have the characteristics of Filtralite-P, for instance the high phosphorus sorption capacity reported by Jenssen and Krogstad (2003). It is, however, suitable for use in CWs due to its high hydraulic conductivity, porosity and good insulation properties (Jenssen and Krogstad, 2003). The fraction of 2–4 mm was used in all of the cells. The porosity of the humid LWA measured at site was 0.43 m^3m^{-3}.

2.1.2. Operation

The hydraulic and pollution load of the Ilmatsalu LWA filter is determined by the test regime, the pore volume of the filter material and the water level in the wetland cells. While operating in batch mode, it is possible to re-circulate the treated water. The batch cycle consists of filling time, incubation time (variable), draining time (~0.5–1 h) and recuperation time (up to ~24 h). The inflow and outflow fluxes of the cells are controlled by 25 mm solenoid valves installed in the inflow and outflow wells. As the hydraulic load of the Ilmatsalu LWA filter system was ~0.5 m^3 during the six test periods, the hydraulic retention time (HRT) of the septic tank was 4 days.

Wastewater from the grit channel of the ASTP is first pumped into the septic tank and further flows to the inflow well, from which it is pumped to the cells through solenoid valves. The cells are filled and drained in rotary mode: when the first cell is filled, the next is drained, etc. Pumps and valves are operated by a controller installed in the service building of the ASTP. The time between the fill and drain operation of the same cell is the incubation time, and the time between drain and fill operation of the same cell is the recuperation (rest) time. The recuperation (rest) period allows for the degradation of accumulated suspended organic material in order to prevent clogging of the filter (Green et al., 1997). In addition, intermittent flushing lets the surface dry out for certain periods of time (von Felde and Kunst, 1997). Recirculation of the treated water is achieved by pumping the water from the outflow well back to the inflow well at the same time as filling takes place.

Different operational regimes were tested during the experiments. The variations in loading rates are mainly dictated by varying incubation and recuperation time, loading rate and re-circulation rate. The FS was operated from the beginning of November 2005 till the end of December 2006, and this thesis covers the experimental data about 6 different operational regimes with hydraulic load, incubation and recuperation times, re-circulation rates and water quality parameters in the inflow reported in Table 1.

Table 1. Parameters of different operational regimes (recirculation rate is given as a percent of the daily inflow rate) and average values of water quality parameters in the inflow of the Ilmatsalu FS.

Parameter	Operational regime					
	1	2	3	4	5	6
Duration	**Nov–Dec**	**Jan–Mar**	**Mar–May**	**May–Jul**	**Aug–Oct**	**Oct–Dec**
Water level in SF cell (m)	1.1	0.8	1.1	1.1	1.1	1.1
Incubation time (d)	7	~5.3	~5.3	3.5	2.3	1.8
Recuperation time (h)	~23	~17	~17	~11	~7	~5
Re-circulation rate (%)	0	0	20	100	200	300
Q (m^3 d^{-1})	0.47	0.46	0.53	0.47	0.47	0.47
pH	7.5	7.3	7.3	7.2	7.2	7.3
Temp (^{0}C)	5.4	3.1	7.3	13.4	14.6	8.4
BOD_7 (mg L^{-1})	135	191	168	237	206	100
TSS (mg L^{-1})	33	48	37	66	97	55
COD_{Cr} (mg L^{-1})	224	311	248	385	383	163
N_{tot} (mg L^{-1})	54	44	33	68	82	40
P_{tot} (mg L^{-1})	6.6	6.6	5.8	8.1	10.3	6.6

2.1.3. Sampling and comparison parameters

Water grab samples from the inflow of the cells (outflow of the septic tank) and the outflow of the cells were taken randomly once a week. Water samples were analyzed by an accredited laboratory according to Estonian standards for pH, BOD_7, SS, COD_{Cr}, N_{tot}, NH_4-N, NO_2-N, NO_3-N, P_{tot}. Temperature and dissolved O_2 were measured on site. A total of 8, 9, 7, 10, 9 and 11 samples were taken during the first, second, third, fourth, fifth and sixth operational regime, respectively.

This thesis presents the data and the purification efficiencies of 6 different operational regimes in the pilot FS. For the comparison of purification efficiencies, BOD_7, COD_{Cr}, SS, N_{tot}, and P_{tot} are used as performance indicators. In addition, the oxygen demand (OD) of the wastewater was calculated on the basis of the following equation:

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

Where OD is oxygen demand (gO_2 d^{-1}); BOD_{in} is BOD_7 concentration in the inflow of FS (gO_2 m^{-3}); BOD_{out} is the Estonian effluent standard for BOD_7 in treatment plants <2000 person equivalent (15 gO_2 m^{-3}); NH_4-N_{in} is NH_4-N concentration in the inflow of FS (g m^{-3}); NH_4-N_{out} – since there is no exact effluent standard for treatment plants smaller than 2000 person equivalent in Estonia, the set target is that all of the NH_4-N should be removed (0 g m^{-3}); Q – flow rate (m^{-3} d^{-1}).

When we replace the standard values (BOD_{out} and NH_4-N_{out}) in Eq. 1 with the real values of effluent concentrations during the experiments, we obtain the total aeration capacity ($gO_2\ d^{-1}$) of the FS, and when we divide this with the area of the FS, we obtain the specific aeration capacity of the FS ($gO_2\ m^{-2}\ d^{-1}$).

2.2. Rebase pilot-scale compact CW

An onsite indoor experiment for the treatment of household greywater was in operation from October 2009 to July 2011 (Karabelnik et al., 201X; Kasak et al., 2011; publication III and IV). The study was carried out using greywater from a single household of five residents. The separated greywater piping system was built in order to collect wastewater from showers, hand basins, the laundry and the kitchen.

2.2.1. The experimental system

The experimental pilot scale hybrid filter system (A, B, C, D; Fig. 2) consists of three shallow (h = 20 cm) parallel VF filters (VF; 0.02 m^3 each) followed by hydraulically saturated horizontal flow filters (HF; 0.06 m^3 each).

The HLR of raw greywater was 32–80 L d^{-1} (100–250 mm d^{-1}), with an additional re-circulation rate of 300%, which was found to be an optimal rate for the improvement of the aeration and overall purification efficiency of CWs (Põldvere et al., 2009; publication II). For re-circulation, a re-circulation well (R, 0.07 m^3; Fig. 2) was used.

The filter materials are different fractions of Filtralite® in the VF of systems A, B and C (2–4 mm round, 4–10 mm crushed and 4–10 mm round respectively), Filtralite-P® in the HF of systems A, B and C in the fraction of 0–4 mm, and alkaline Ca-rich crushed/screened hydrated oil shale ash sediment (d = 5–20 mm) in the VF and HF of system D.

Raw greywater was pre-treated in a settling tank (2 m^3) and then led to the collection well (0.4 m^3) in the test building. The pump in the collection well allocated equal parts of greywater to each system.

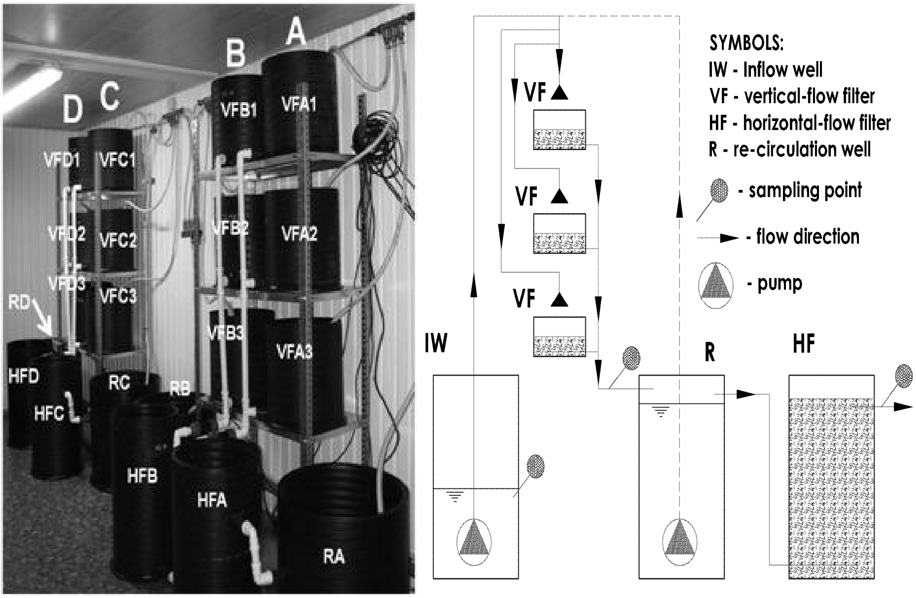

Figure 2. Pilot-scale layout (left): filter systems A, B, C and D consisting of three VF filters (VF; on shelf), followed by horizontal flow filters (HF; on floor) and re-circulation wells (R; on floor). The operational scheme of the filter system is presented on the right.

2.2.2. Operational periods

The experiment was divided into two main periods based on the greywater loading rate applied to the systems. The first period represents results from October 2009 to February 2010. In addition, results from 01.12.2009 – 22.12.2009 deviated from normal due to a technical problem: blackwater and greywater were accidentally mixed because of the high groundwater level in the blackwater infiltration bed. The second period began in February 2010, when system C was switched off due to poor purification efficiency compared to the other Filtralite® systems. Thereafter, the total HLR was raised from 32.5 L d^{-1} to 80 L d^{-1} per parallel system (Table 2). During the second period from August 2010, the household began to use phosphorus-free detergents in order to determine the potential of phosphorus-free chemicals to reduce P loading in greywater. From April 2010 no further samples from system A were taken due to the non-satisfactory performance of the filter material, although the system was still running. Thus the data representing the results of the second period only comprise systems B and D. During the last period the unexpected failure of the test building's heating system caused partial freezing of the filters, which somewhat affected the filters' performance.

Table 2. System layout, flow regime and operational characteristics of the compact filter

Parameter	Unit	Period 1 (Oct. 2009–Feb. 2010)	Period 2 (Feb.2010–June 2011)
Number of parallel systems	–	4	2
Total HLR per system	L d^{-1}	32.5	80
Hydraulic loading per VF filter [a]	mm d^{-1}	426	1048
Hydraulic loading per HF filter	mm d^{-1}	319	786
Hydraulic retention time in HF filter	h	16	6
Number of pumping cycles	cyc d^{-1}	20	40
Length of pumping cycle	sec	15	12
Re-circulation rate	%	300	300
Number of re-circulation cycles	cyc d^{-1}	60	120
Length of re-circulation cycle	sec	15	15

[a] – including re-circulation

The median parameters of raw and pre-treated greywater did not differ significantly during the two test periods (Table 3). The median ratio between BOD: N_{tot}:P_{tot} in pre-treated greywater was 59:2.5:1 and 67: 2.5:1 during periods 1 and 2 respectively.

Table 3. Median parameters (±StDev) of raw and pre-treated greywater during the test periods

Parameter	Unit	Period 1		Period 2	
		Raw greywater	Pre-treated greywater	Raw greywater	Pre-treated greywater
pH	–	6.8 ± 0.2	7.0 ± 0.2	6.8 ± 0.2	7.0 ± 0.1
TSS	mg L^{-1}	155 ± 26	130 ± 14	160 ± 63	140 ± 39
BOD_7	mgO_2 L^{-1}	385 ± 72	300 ± 77	500 ± 175	340 ± 91
COD_{Cr}	mgO_2 L^{-1}	640 ± 135	530 ±87	750 ± 197	540 ± 94
N_{tot}	mgO_2 L^{-1}	13.0 ± 2.6	12.5 ± 3.2	16.5 ± 5.7	13.0 ± 2.4
NH_4-N	mgN L^{-1}	1.9 ± 1.4	2.8 ± 1.9	5.8 ± 4.1	4.4 ± 1.9
NO_3-N	mgN L^{-1}	0.02 ± 0.005	0.02 ± 0.003	0.02 ± 0.003	0.02 ± 0.003
P_{tot}	mgP L^{-1}	6.8 ± 2.7	5.1 ± 1.4	7.5 ± 6.3	5.1 ± 5.8
PO_4-P	mgP L^{-1}	3.9 ± 1.19	3.9 ± 0.79	5.5 ± 5.1	3.7 ± 4.97

2.2.3. Sampling and data analysis

Water samples from a septic tank, a collection well and two sampling points of each parallel system were taken regularly. The raw greywater samples were collected from the primary settling tank. Samples from the test plant were taken from the collection well, the outflow from the VF filters and the outflow from the HF filters, which also make up the system's outflow. Five analyses were carried out on site: pH (also in the laboratory), temperature, oxygen concentration, dissolved oxygen and conductivity, which were all taken using a portable device (WTW Multi 350i). For the remaining parameters, samples were stored in a thermal box before being transported to the laboratory.

In the water samples, BOD_7, COD_{Cr}, N_{tot} NH_4-N, NO_3-N, NO_2-N, P_{tot}, PO_4-P, SO_4^{2-} and pH were determined in a certified laboratory using standard methods (APHA, 2005). A total of 14 and 13 samples were taken during the 1st and 2nd periods respectively.

This thesis presents data and compares the purification efficiencies of different filter material and operational regimes in a pilot-scale hybrid filter system. For the comparison of purification efficiencies and outflow concentrations, BOD_7, $COD_{Cr,}$ TSS, N_{tot}, and P_{tot} are used as performance indicators. The normality of the variables was verified using the Kolmogorov-Smirnov, Lilliefors and Shapiro-Wilk's tests. Since the variables were not always normally distributed, non-parametric Mann-Whitney U-tests and Wilcoxon Matched Pair tests were carried out in order to compare the performance of the filter systems during different operational periods and the performance of parallel filter systems during the same period respectively.

3. RESULTS AND DISCUSSION

3.1. Ilmatsalu batch-operated CW

3.1.1. Purification efficiencies

The purification efficiencies of the Ilmatsalu LWA filter during the six periods are reported in Table 4 and shown in Fig. 3. The pollution parameters of the effluent of the Ilmatsalu LWA filter met the normative values of CODcr and TSS during all of the test periods. The BOD7 normative concentration of 15 mg L^{-1} was achieved during the 5^{th} and the 6^{th} periods when the re-circulation rate of 200% and 300% was applied, respectively. The normative values of N_{tot} and P_{tot} was not achieved – the lowest mean outflow concentration of P_{tot} (2.5 mg L^{-1}) was recorded in the 1^{st} period, whereas the lowest mean outflow concentration of N_{tot} (21 mg L^{-1}) was recorded in the 6^{th} period. The average pH values of the effluent constantly decreased during the test periods, approaching the pH values in the inflow wastewater during the last periods. The highest pH values (pH~9) were recorded during the 1^{st} test period. The above-mentioned phenomenon is closely related to the characteristics of the LWA, and is also described in hybrid CWs in Norway (Harris and Mæhlum, 2003).

The lowest mean purification efficiency of BOD_7 (74%) was recorded during the 2^{nd} period, when the water level in LWA filter cells was lowered to 0.8 m for the cold period, also reducing the active volume of the filter media. There were, however, no significant differences in purification efficiencies during the first three periods, indicating the lack of significance of the 20% re-circulation rate applied in the 3^{rd} period. The reason recirculation rate did not influence BOD_7 removal is probably because the recirculation rate was too low (for technical reasons a higher recirculation rate could not be applied at that time). Usually recirculation rates upwards of 50% are used in order to achieve better aeration of the wetland matrix and/or enhance denitrification (Laber et al., 2003). The latter is also supported by the fact that the purification efficiency of BOD increased significantly and exceeded 95% during the 5^{th} and 6^{th} periods, when the re-circulation rate of 200–300% was applied.

Table 4. Hydraulic retention times (HRT), mass loading rates (g m^{-2} d^{-1}), purification efficiencies (PE, %) and mass removal rates (g m^{-2} d^{-1}) of organic matter (by BOD_7), total suspended solids, COD_{Cr}, N_{tot} and P_{tot} at outflow of filter systems (FS).

Period	HRT (day)	Mass loading rate (g m^{-2} d^{-1})					PE at outflow (%)					Mass removal rate (g m^{-2} d^{-1})				
		BOD_7	TSS	COD_{Cr}	N_{tot}	P_{tot}	BOD_7	TSS	COD_{Cr}	N_{tot}	P_{tot}	BOD_7	TSS	COD_{Cr}	N_{tot}	P_{tot}
1	8	8.0	1.9	13.3	3.2	0.4	88	82	70	16	62	7.1	1.6	9.6	0.5	0.2
2	6	11.0	2.0	17.9	2.5	0.4	74	91	61	0	36	8.2	1.7	11.1	0.0	0.1
3	7	9.9	2.3	14.6	1.9	0.3	83	81	69	8	41	8.4	2.0	10.3	0.2	0.1
4	8	14.0	2.4	22.8	4.0	0.5	91	83	83	43	53	12.7	2.1	18.9	1.8	0.3
5	8	12.2	2.5	22.6	4.8	0.6	96	84	90	51	53	11.7	2.2	20.4	2.5	0.3
6	8	5.9	2.5	9.7	2.3	0.4	95	89	85	48	44	5.6	2.3	8.2	1.1	0.2

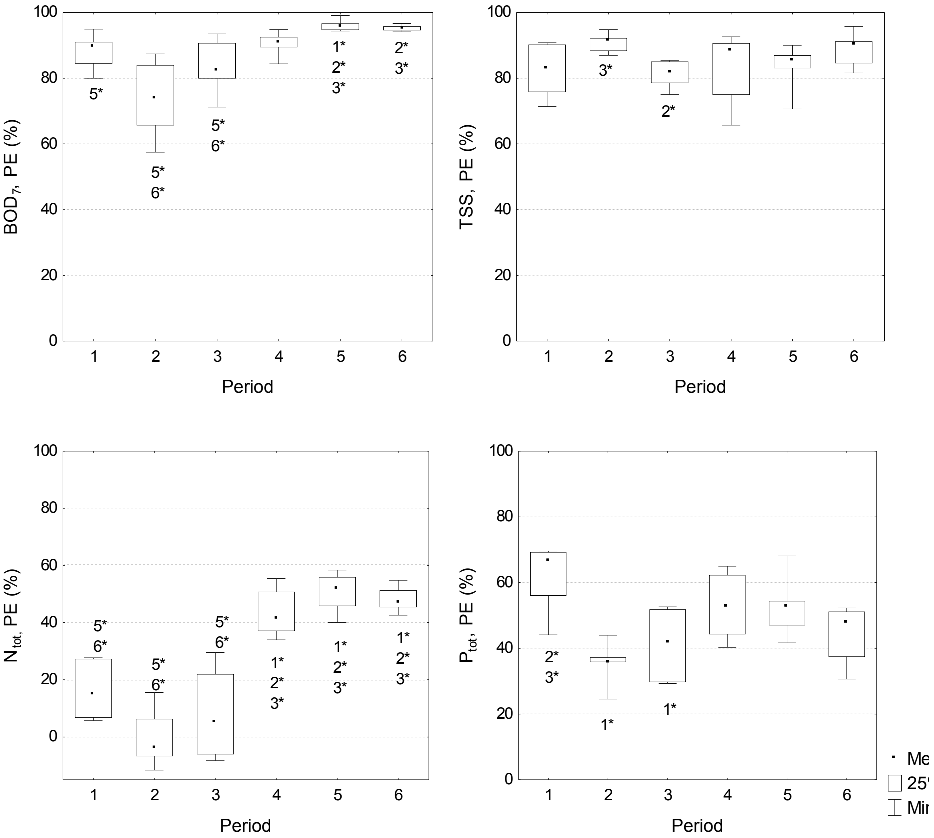

Figure 3. Purification efficiencies (PE, %) of BOD_7, TSS, N_{tot} and P_{tot} in six different operational periods in the Ilmatsalu batch-operated filter system. 1* – significantly differing values ($p<0.05$) between operational periods (period number given).

The batch LWA filter system showed poor or non-existent N_{tot} removal rates during the 1st, 2nd and 3rd treatment periods. During the first three treatment periods, NH_4-N was the major species of N, comprising 80–95% of the N_{tot}, while nitrate nitrogen (NO_3-N) levels were negligible, indicating an unsatisfactory oxygen supply limiting nitrification (von Felde and Kunst, 1997). The reason for the negative value of N_{tot} purification efficiency in the 2nd period is probably the lower N_{tot} loading rate in the 2nd period compared to the 1st period (3.18 g m^{-2} d^{-1} and 2.52 g m^{-2} d^{-1} N respectively). Due to the characteristics of the NH_4-N absorption process, N residence time in the CW could be increased relative to HRT, resulting in long delays in the treatment system's response to changes in N loading (Kadlec et al., 2005). Similarly to BOD purification efficiency, N_{tot} purification efficiency also improved significantly during the last three periods, in which higher re-circulation rates were applied, reaching the highest level of 51% in the 5th period, indicating better oxygen conditions in the wetland matrix. In the 6th period, however, N_{tot} purification efficiency was lower than in the 5^{th} period. The reason for the decreased N_{tot} purification efficiency in the 6^{th} period compared to the 5th period is probably the lack of organic carbon in wastewater. The latter is clearly shown by the higher NO_3-N concentrations (with the mean value reaching 3.9 mg L^{-1} in the 6^{th} period) and lower BOD_7 concentrations (with the mean value falling to 4.6 mg L^{-1} in the 6^{th} period) in the outflow of Ilmatsalu batch-operated LWA filter, indicating that denitrification was the limiting step in the nitrogen removal process.

The mean P removal rate of the Ilmatsalu LWA filter during the six periods was 48%. The P removal rate was slightly higher in the 1^{st} period, reaching 62%. P removal in a constructed wetland is directly dependent on the filter material. The dominant phosphorus removal of the LWA takes place through the precipitation of calcium phosphates, which depends on the pH of the LWA (Jenssen and Krogstad, 2003). Therefore, better P removal in the 1^{st} period may be related to higher outflow pH. While the mean pH value of outflow in the 1^{st} period was 8.9, it decreased significantly during latter periods, to a mean value of 7.5 in the 6^{th} period.

The Spearman Rank Order Correlation analysis shows a significantly positive correlation between the re-circulation rate and purification efficiency of BOD_7, COD_{cr}, N_{tot}, and NH_4-N. However, we also found a significantly positive correlation between the water temperature and purification efficiency of BOD_7, COD_{cr}, N_{tot}, and NH_4-N, which probably indicates the concurrence of increasing re-circulation rates and rising water temperature, as the experimental period lasted only 13 months. The stronger influence of higher re-circulation rates rather than higher water temperature on the purification efficiency of BOD_7 and N_{tot} is displayed by the fact that the mean purification efficiencies of BOD_7 and N_{tot} were not significantly lower in the 6^{th} period than in the 5^{th} period, although the water temperature was significantly lower – 8.5 ºC and 15.6 ºC respectively.

3.1.2. The rate of organic matter removal

In order to compare the performance of batch-operated FS with other systems, the rate of organic matter removal is calculated using the following "Kickuth" equation, which is widely used for constructed wetlands in the secondary and tertiary treatment of municipal sewage (Sun et al., 2005):

$$A_h = \frac{(\ln C_0 - \ln C_e) \times Q}{K_{BOD}}, \qquad \text{(Eq.2)}$$

where Q_d is the average daily flow rate of the sewage ($m^3\ d^{-1}$); C_0 and C_e are values of BOD_7 ($mgO_2\ L^{-1}$) at the inlet and outlet of the FS respectively; A_h is surface area (m^2) and K_{BOD} is the rate constant ($m\ d^{-1}$), when the removal of organic matter is described using first-order kinetics. Although there is no clear evidence that the rate of organic matter removal in constructed wetlands is indeed first-order, especially as concerns the treatment of strong sewage, and many studies have argued that position (Kadlec, 2000), it may still be used as a method for the comparison of different FS (Sun et al., 2005). Table 5 presents the K_{BOD} values for different operational regimes using average data about BOD_7 concentrations.

Table 5. Values of K_{BOD} for different operational regimes

Operational regime	**1**	**2**	**3**	**4**	**5**	**6**
K_{BOD} value	0.13	0.08	0.12	0.14	0.19	0.18

As shown in Table 5, the K_{BOD} values range between 0.08–0.19 $m\ d^{-1}$, which are higher than reported for typical values of 0.07–0.1 $m\ d^{-1}$ for HF filters in the UK (Cooper, 1999). The average value of K_{BOD} during the first three operational regimes was 0.11 $m\ d^{-1}$, but the average value of K_{BOD} during the next three operational regimes was 0.17 $m\ d^{-1}$, indicating the positive effect of re-circulation on the rate of organic matter removal. Nevertheless, K_{BOD} values reported in Table 3 are lower than those reported by Sun et al. (2005) for four-stage tidal-flow FSs without re-circulation (0.28–0.40 $m\ d^{-1}$) and with 100% re-circulation (0.38–0.93 $m\ d^{-1}$).

3.1.3. Aeration capacity

In addition to the rate of organic matter removal, another typical parameter used to estimate the performance of an FS is aeration capacity ($gO_2\ m^{-2}\ d^{-1}$), which shows the amount of oxygen that is introduced into wastewater per unit of area per day. In order to estimate the performance of an FS, it is necessary to compare the aeration capacity with the oxygen demand of the inflow wastewater to the FS ($gO_2\ m^{-2}\ d^{-1}$). Table 6 reports the average values of the oxygen demand of wastewater in the inflow of the FS and aeration capacity during the six operational periods calculated using the equation presented in chapter 2.1.3 (Eq.1).

Table 6. Average values of the oxygen demand of wastewater and aeration capacity of FS during the six operational periods

Operational regime	**1**	**2**	**3**	**4**	**5**	**6**
Oxygen demand ($gO_2\ m^{-2}\ d^{-1}$)	19.1	19.4	19	28.2	29.2	13.1
Aeration capacity ($gO_2\ m^{-2}\ d^{-1}$)	8.5	8	10.7	20.1	21.1	10.3

According to the results reported in Table 6, the highest aeration capacity of 21.1 $gO_2\ m^{-2}\ d^{-1}$ was achieved during the 5th operational period, when the re-circulation rate of 200% was applied. Also, the increase in re-circulation rates during the last three operational periods improved the average aeration capacity of the FS about twofold compared to the average aeration capacity during the first three operational periods. In the case of VF filters, the average aeration capacity is considered to be 30 $gO_2\ m^{-2}\ d^{-1}$ (Cooper, 1999; Vymazal et al., 1998), and could reach up to 50–90 $gO_2\ m^{-2}\ d^{-1}$ without re-circulation (Cooper et al., 1999). Sun et al. (2003) found that the aeration capacity of the VF filter increased from 29.7 $gO_2\ m^{-2}\ d^{-1}$ to 57.1 $gO_2\ m^{-2}\ d^{-1}$ when re-circulation was applied. Furthermore, Sun et al. (2005) reports an aeration capacity of up to 473 $gO_2\ m^{-2}\ d^{-1}$ in the tidal-flow system. Therefore the aeration capacity of the Ilmatsalu batch-operated FS is comparable to a VF filter when re-circulation of effluent is applied, but is substantially lower than the aeration capacity of a VF filter with re-circulation or tidal-flow systems. In comparing the aeration capacities of different systems, however, the oxygen demand of inflow wastewater has also been taken into consideration, as the aeration capacity of the systems depends on the oxygen demand of wastewater. The latter also explains the slightly lower aeration capacity during the 6th operational period compared to the 5th period, regardless of the application of the higher re-circulation rate.

3.1.4. General discussion

The higher re-circulation rate of the wastewater significantly improves the aeration and overall purification efficiency of the batch-operated FS. In Ilmatsalu pilot filter systems, we observed a significant positive correlation between the re-circulation rate and purification efficiency of BOD_7, COD_{cr}, N_{tot} and NH_4-N. We also found a significantly positive correlation between the water temperature and purification efficiency of BOD_7, COD_{cr}, N_{tot} and NH_4-N. However, the positive effect of water temperature on purification efficiency could partly be explained by the fact that the application of higher re-circulation rates was in part concurrent with the rise in water temperatures during the test period.

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 to 200 percent of the inflowing wastewater in order to achieve satisfactory results in terms of effective BOD_7 and COD_{cr} removal and nitrification (Põldvere et al., 2009; publication II). In the Ilmatsalu batch-operated LWA filter the purification efficiency of BOD_7 depends mostly on the enhancement of the recirculation rate, as the HLRs of different periods were nearly equal.

If one applies higher re-circulation rates, the hydraulic constraints of the filter material must also be taken into consideration. Typical hydraulic loading for VF is 40–500 mm d^{-1} (Kadlec et al., 2000) or 100–400 mm d^{-1} (Paing et al., 2006). Average recommended hydraulic loading for HF CW varies from 20 to

100 mm d^{-1} (Kadlec et al., 2000). During the study period, the HLRs regarding the re-circulation rates of tested filter systems reached 84 and 236 mm d^{-1} in the case of continuous-flow and batch-operated systems respectively. However, no negative side-effects such as clogging were observed when the higher recirculation rates were applied. Also, higher re-circulation rates did not significantly affect the phosphorus removal rate. Inorganic chemical reactions, such as phosphorus adsorption and precipitation, are normally rapid processes that are not greatly affected by the increasing of wastewater-media contact time (Noorvee, 2007 and Noorvee et al., 2007a). Therefore, employing effluent re-circulation may have little impact on P_{tot} removal (Sun et al., 2003). Noorvee (2007), however, has concluded that a very high re-circulation rate (up to 600%), when the filter material acts as a phosphorus precipitating substrate, has a negative effect on TSS and P_{tot} removal (studied in the Rämsi LWA FS, in Estonia).

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 the wastewater into the septic tank, where more organic matter is available for denitrification. Since the change in the re-circulating origin in the case of the Nõo hybrid filter system (interim + outflow well or only 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 the additional improvement of purification performance, and back-pumping only from the outflow well is more adequate (Noorvee, 2007).

Unfortunately the LWA (Filtralite S, M, L) used as filter material rapidly lost its phosphorus adsorption and sedimentation properties. In LWAs, especially in Filtralite P, 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 favours the precipitation of phosphates (Jenssen and Krogstad, 2003). Although we did not register great changes in pH in our systems, it is 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 (Brix and Arias, 2005).

3.2. Rebase pilot-scale compact CW

3.2.1. A comparison of different filter materials

The filter systems and filter materials are compared on the basis of the results of the first period during which all of the systems were sampled (see Fig. 4).

The median reduction of the COD value was 83–88% for Filtralite® systems and 80% for the oil shale ash system, while the BOD_7 value was on average reduced by 87–95% and 85% respectively. Regarding organic matter removal, all of the Filtralite® systems performed significantly better than the oil shale ash system, reaching mean COD outflow values of 58–88 mgO_2 L^{-1} for

Filtralite® and 105 $mgO_2\ L^{-1}$ for oil shale ash systems. The respective values for BOD_7 were 20–43 $mgO_2\ L^{-1}$ and 38 $mgO_2\ L^{-1}$.

Among the Filtralite® systems, system B (VF with 4–10mm crushed Filtralite®) performed significantly better than other Filtralite® systems (A and C) regarding organic matter and TSS removal. There were, however, no significant differences between Filtralite® systems A and C.

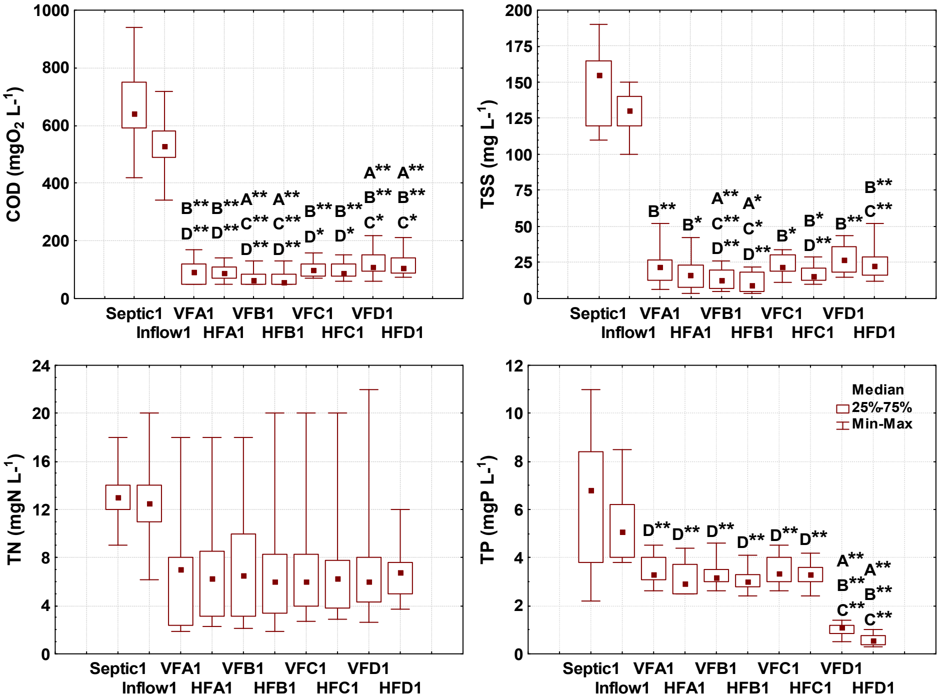

Figure 4. Outflow values of COD_{Cr} and concentrations of TSS, N_{tot} and P_{tot} of four parallel filter systems during period 1. The letters A, B, C and D indicate the symbol of a parallel system. The VF and HF show the outflow value or concentration of the VF filter and parallel filter system respectively. Letters with an asterisk (*) above the bars indicates differences between respective values or outflow concentrations of parallel filter systems: * – at p level <0.05 and ** – at p level <0.01. Inflow and outflow parameters differed significantly (p<0.01) in all cases.

The removal efficiency of N_{tot} was moderate, and the median efficiency of Filtralite® systems and the oil shale ash system were 47–55% and 46% respectively. Nevertheless, a median outflow concentration of 6.0–6.8 $mgN\ L^{-1}$ was achieved. Still, there were no significant differences in N_{tot} removal between different Filtralite® systems and between Filtralite® and oil shale ash systems.

The results of P_{tot} removal showed that the mean reduction of P_{tot} in the ash filter system was 89%, achieving a median effluent concentration of 0.55 mg L^{-1} compared to the respective 40–44% and 2.9–3.3 mgP L^{-1} for Filtralite® systems. Whereas the same filter material (Filtralite-P®) was used in the HFs of all of the Filtralite® systems, no significant differences were observed between the different Filtralite® systems.

Surprisingly, the results show that most of the organic matter, TSS and even N_{tot} and P_{tot}, was removed in the VF filters, while the HF filters showed minor or sometimes even negative removal efficiencies. The mean overall contribution of the reduction of the COD value of the HF filters was 1.3%, while the HF of system B had no effect whatsoever on COD reduction performance.

3.2.2. The effect of loading rate on performance

During period 2, when two filter systems, B (Filtralite®-based) and D (oil shale ash-based), were tested under ~2.5 times higher loading rates, the systems performed similarly to period 1 (see Fig.5). The median COD removal of system B remained at 88%, while the respective number for system D decreased from 80% to 76%. The removal of BOD_7 in both systems was only slightly better during period 1: for system B 95% and 92% respectively, and for system D 85% and 78% respectively. Regarding organic matter, TSS and N_{tot} removal, however, there were no significant differences between the two periods.

Nevertheless, the TSS removal of the VF filters decreased significantly. The mean removal of TSS in the VF of system B was 90% in period 1 compared to 86% in period 2, and the respective outflow values were 13 mg L^{-1} and 19 mg L^{-1}. The respective values for system D were 80% and 66%, and 27 mg L^{-1} and 54 mg L^{-1}. While the results show that most of the organic matter, TSS and even N_{tot} and P_{tot} was removed in the VF filters during the lower loading rate conditions, in the higher loading rate conditions the contribution of HF in the overall performance of filter systems increased. The mean overall contribution of the reduction of the COD value of the HF filters of system B and D was 3.7% compared to the 1.4% during period 2. The respective numbers for the reduction of TSS concentration were 2.4% compared to 7.5%.

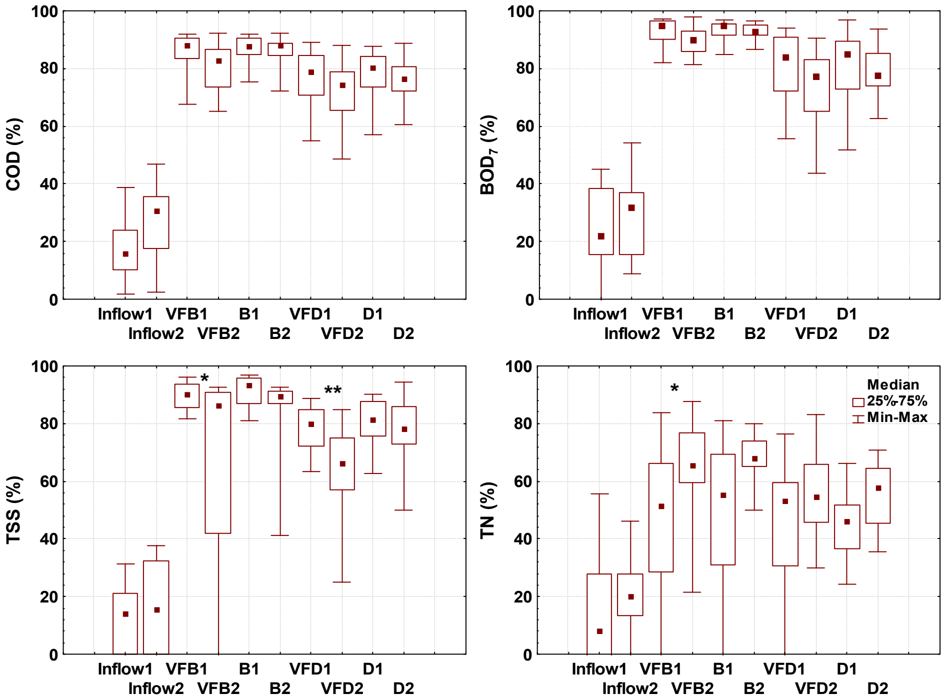

Figure 5. Purification efficiencies of COD, BOD_7, TSS and N_{tot} of the B and D systems during two periods at different loading rates. The number indicates the period. The letters B and D indicate the symbol of a parallel system. The VF indicates the outflow value or concentration of the VF filter. B and D indicate the overall purification efficiency of the filter system. Asterisks indicate significant differences between the respective values of concentrations in periods 1 and 2: * – at p level <0.05 and ** – at p level <0.01.

3.2.3. Dynamics of pollutant removal

The dynamics of pollutant removal are presented for systems B and D, which were both sampled throughout the entire experiment (see Fig.6 and Fig. 7).

It can be seen from Fig. 4 that N_{tot} removal during period 1 was affected by the failure of the system, which led to the temporary inflow of diluted blackwater into the experimental system and significantly raised the mean N_{tot} outflow concentrations of both filter systems. The effect of the failure on the performance of the systems in other outflow parameters appears to be irrelevant.

Regarding the oil shale ash, the results indicate that under cold water temperature (median 8ºC) and high pH (median outflow value for the period was 9.2) conditions, the filter system needs a longer starting period to develop a microbial community for biological processes. It appears that it takes around 50–70 days from the beginning of the experiment to establish a microbial community and obtain stable outflow pH values for systems B and D.

Although there were no significant differences between the two periods regarding organic matter, TSS and N_{tot} removal, the dynamics of pollutant removal indicate that due to the higher HLR in period 2, the greywater-typical fluctuations of pollutant content in inflow (Eriksson et al.. 2009) are more distinctly reflected in the outflow values and concentrations. The highest peak in the outflow values and the concentrations of all pollutants was caused by the unexpected failure of the heating system of the test building during the last period, which caused partial freezing of the filters. Nevertheless, it can be observed that in some cases the fluctuations in inflow concentrations together with a high HLR can lead to washout of finer particles, which was the case of the higher mean TSS concentrations in the outflow of the VFB filter during period 2.

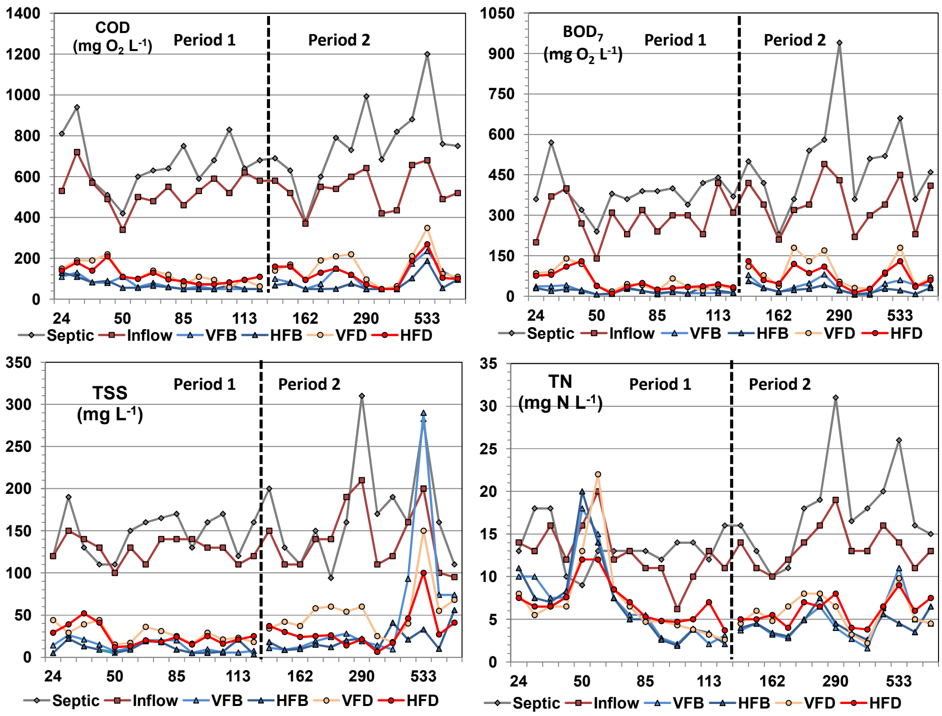

Figure 6. Dynamics of COD, BOD7, TSS and TN removal in filter systems B (4–10 mm crushed Filtralite®) and D (hydrated oil shale ash). VF – vertical flow filter outflow, HF – horizontal flow filter outflow. The dashed vertical line represents the end of the first period. The X axis shows the time (in days) from the beginning of the experiment.

Regarding P_{tot} removal, the Filtralite® and oil shale ash system showed distinctively different dynamics (see Fig.7). During period 2, when the HLR and P_{tot} concentration increased considerably, the outflow concentration of the Filtralte® system increased significantly (up to 9.1 mg L^{-1}), although the outflow concentration of the oil shale ash system was still fairly stable (up to 2.1 mg L^{-1}).

Since the household began to use phosphorus-free detergents, the P_{tot} concentration in the raw and pretreated greywater fell to mean values of 2.6 and 1.5 mg L^{-1} respectively during the period 2. Concurrently, the mean outflow concentration of the Filtralite® system fell to 1.2 mg L^{-1}, while the mean outflow concentration for the oil shale ash system showed only a slight decrease and fell to 1.6 mg L^{-1}.

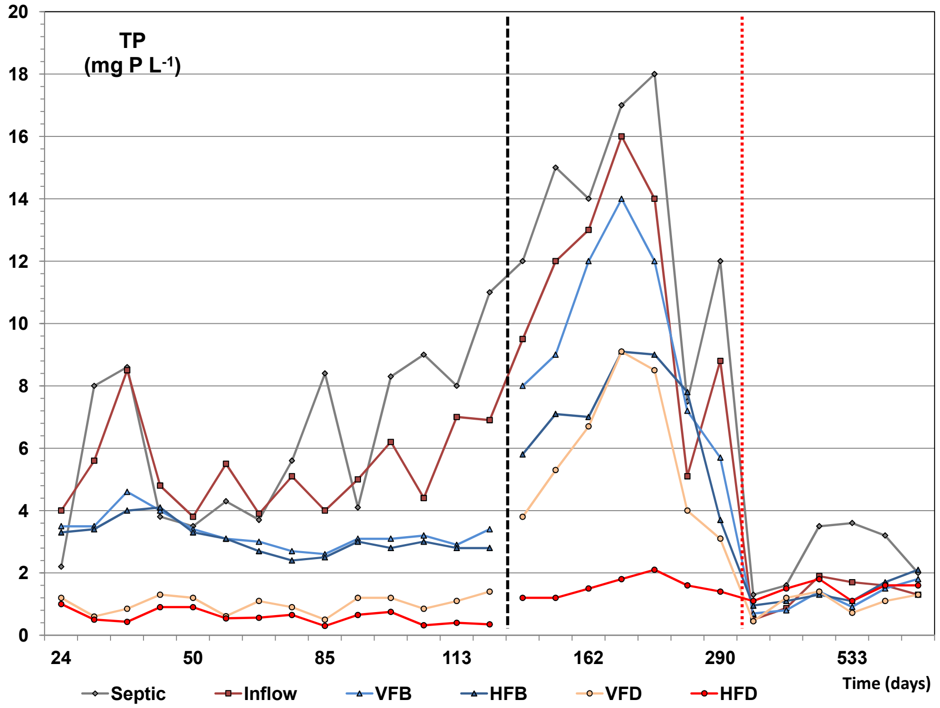

Figure 7. Dynamics of total phosphorus (TP) removal in filter systems B (4–10 mm crushed Filtralite®) and D (hydrated oil shale ash). VF – vertical flow filter outflow, HF – horizontal flow filter outflow. The dashed vertical line represents the end of the first period, and the dotted vertical line indicates the beginning of the use of phosphorus-free chemicals.

3.2.4. General discussion

The composition of raw greywater in our study corresponds to the typical values for mixed greywater (Li et al., 2009), and according to the suggested BOD_5:COD ratio (~0.5) shows good biodegradability. In addition, the raw greywater had a nearly balanced COD:N:P ratio, as suggested by Metcalf and Eddy (1991).

We achieved the good results regarding the removal of BOD, COD and TSS in highly-loaded filter systems treating mixed greywater. The mean BOD_7 removal of Filtralite® systems was up to 92% at an organic loading rate of 90.7 gO_2 m^{-2} d^{-1} and a HLR of 1048 mm m^{-2} d^{-1}. There are, however, only a few studies of similar filter systems that have been conducted with greywater under high hydraulic and pollutant loading rates. In using such filter systems, it is common for either high HLRs to be applied using low-strength greywater (Kadewa et al., 2010) or for lower HLRs to be applied using medium-strength greywater (Paulo et al., 2009). There are, however, several studies conducted in Norway analyzing the potential and different applications of Filtralite® as a filter medium for constructed wetlands and filter systems under various hydraulic and pollutant loading rates (Rasmussen et al., 1996; Heistad et al., 2001; Jenssen et al., 2005).

In applying high loading rates, the design considerations of the filter system play a very important role in achieving optimal performance (filter depth, dosing rates and frequency, grain size of filter media, distribution system). The fact that even shallow filters can show excellent BOD removal has been demonstrated in this study and has previously been reported by several authors (Rasmussen et al., 1996; Kadewa et al., 2010). Rasmussen et al. (1996) studied the effect of filter depth on the removal of BOD and bacteria in Filtralite® filters and concluded that BOD removal was independent of filter depth for filters with heights of between 20 and 60 cm, but bacteria removal was lower for the shallow filter depth. If we consider that in our study the 60 cm thick layer was divided into three 20-cm layers of parallel VF filters, the hydraulic and pollutant loading is three times higher than the comparable 60-cm-high filter that is common for VF filters.

Another design issue is the distribution and dosing system, which has to allow the even distribution of water onto the filter surface and to apply individual loading rates and dosing frequencies in order to improve the systems' performance in conditions of high hydraulic loading. This even distribution maximizes the retention time at a given loading rate and assures that the entire volume of the filter is used efficiently for purification processes. In our experiment we used the same spray nozzles as those reported by Heistad et al. (2001), but the pumps ensured the head at nozzles between 3 to 5 m, compared to the 10 to 20 m suggested by Heistad et al. (2001). The higher pressure produces finer water droplets, thereby enhancing oxygenation and ensuring more even distribution, which would probably result in the better utilization of filter material and improved performance of the filter system in BOD, COD and

TSS removal. Therefore the performance of the filter system would likely have been even better when using pumps with a higher pressure head at the nozzles.

Regarding organic matter and TSS removal, all Filtralite® systems performed significantly better than the oil shale ash system. This is most likely due to the finer particle size of the Filtralite® filters, which ensures better removal efficiencies as a result of its larger specific area (Rasmussen et al, 1996). This also explains the better performance of VF filters using 4–10 mm crushed Filtralite® than the systems that used a Filtralite fraction with 4–10 mm round particles. However, unlike the data reported by Jenssen and Vrale (2003) when applying higher HLRs, the finer material tends to clog, as was observed in the VF filters filled with Filtralite® 2–4 mm during period 2. The other explanation for clogging is the additional hydraulic loading from re-circulation together with high organic loading, which caused the rapid growth of biofilm on the surface of the filter material.

The results show that most of the organic matter, TSS and even N_{tot} and P_{tot} was removed in the VF filters. Regarding organic matter removal, this is concurrent with the study reported by Heistad et al. (2006), where a BOD removal of 96% was achieved in a single-pass aerobic pre-treatment filter and indicates that in cases where there is no need for P_{tot} removal or in areas where phosphorus-free detergents are used, the filter system can be designed on the basis of VF filter(s) alone. The application of phosphorus-free chemicals in households can reduce P_{tot} concentration below 1 mg P L^{-1} in septic tank effluent (Jenssen and Vrale, 2003). Microbial contamination should, however, be taken into consideration in such cases.

The excellent P_{tot} removal of the oil shale ash filter was in close accordance to previous studies (Liira et al., 2009; Kõiv et al., 2010). Unlike Liira et al (2009), however, who reported a decrease from 91% to 49% in P_{tot} removal over a five-month period at a loading of 1.66 gP m^{-2} d^{-1} and a residence time of 18 h, in our experiment the P_{tot} removal efficiency remained high (87%), although the loading of P_{tot} at the beginning of period 2 (before the use of phosphorus-free detergents) was ~5 times higher, 0.57 gP m^{-2} d^{-1} and 2.93 gP m^{-2} d^{-1} respectively, at a residence time of 6 h in the HF filter. Nevertheless, the outflow values of P_{tot} increased during period 2, and the P_{tot} removal efficiency of the VF filters dropped from a median value of 81% in period 1 to a median value of 39% at the beginning of period 2, indicating the negative effect of high hydraulic loading over a short retention time.

Contrarily, the fairly poor performance of Filtralite-P® in P_{tot} removal was not expected on the basis of the results reported by Jenssen et al (2005) and Heistad et al. (2006) for the Filtralite-P® systems tested in Norway. One possible explanation for this is the low pH value of the outflow of Filtralite-P® systems. In our experiment the intial pH values of the outflow of the HF filters of Filtralite® systems was around 9.0, dropping to and stabilizing at around 8–8.5 within two months from the beginning of the experiment. Adam et al. (2007) reported that the effluent pH of the column experiment was initially above 10.5, dropping to between 9–9.5 over 303 days, while an overall P removal rate of 91% was measured for the Filtralite-P® treating the secondary wastewater. Whereas the removal of P in Filtralite-P® filters is based on the sorption process that is induced when pH is higher than 8 (Adam et al. 2007), the effect of pH on P removal is likely. One reason for the low pH may be the buffering effect of the $CaCO_3$ system in the influent greywater which prevented pH from rising above 9.

The high loading rates applied to the filter systems allow these to be used in places where space is limited, in areas that are far from central sewage systems or where there is a lack of potable water. Moreover, the occasional sampling of the filter systems for microbial contamination during the first months of operation showed that the effluent quality of all of the filter systems was far below the normative values for the quality of EU bathing water. Thus the effluent can be reused for toilet flushing or irrigation. Based on this study, the preferred filter material for the VF filter could be crushed Filtralite® with a fraction of 4–10 mm, while for the HF filter the suggested material would be hydrated oil shale ash sediment. Nevertheless, the improvements of the filter system regarding pumping pressure and distribution system should also be considered before designing a prototype.

3.3. The environmental impact of intermittent loading to CWs

Considering the positive effect of intermittent loading on CWs` purification efficiency, there are still very few studies that have been conducted on the possible environmental impact of pulsing hydrology, such as on GHG emissions (Mitsch et al. 2005). Measurements of GHG emissions in three types of CWs located in the southern part of Estonia provided a perspective of the aspects of how intermittent loading might influence the fluxes of GHG in CWs with different hydrological regimes (Mander et al., 2011; publication V). The results indicate that intermittent loading to CWs significantly enhanced N_2O fluxes from the inflow parts of the HF and the VF filter of the studied CW systems. However, the fluctuating water table/intermittent loading did not influence the CO_2 and CH_4 fluxes. Nevertheless, the results obtained from the study were in part contradictory to previous studies. Thus, further research is needed to determine the relationships between different operational regimes and the environmental impacts of GHG emissions.

4. CONCLUSIONS

There are several operational methods used to enhance oxygen supply in CWs, such as vertical-flow systems, systems with effluent recirculation, systems with fluctuating water level, tidal-flow systems and batch-operated systems.

In the batch-operated pilot scale LWA filter for the treatment of municipal wastewater, the mean purification efficiencies of BOD_7, N_{tot} and P_{tot} during the test period were 88%, 28% and 48% respectively. The highest purification efficiencies of 96% and 51% for BOD_7 and N_{tot} removal, respectively, were achieved when a re-circulation rate of 200% was applied at the same HLR. Nitrification was the rate-limiting step in nitrogen removal, when 0–20% of re-circulation was applied, indicating poor oxygen conditions in the LWA filter matrix. When the re-circulation rate was increased to 300%, the rate-limiting step in the nitrogen removal process became denitrification, inhibited by the low organic carbon concentration.

The main factors affecting the performance of the batch-operated and continuous flow hybrid FSs as concerns BOD_7 and N_{tot} removal are water temperature and recirculation rate, at which the effect of recirculation and thus retention time was more noticeable. We observed a significant positive correlation between the re-circulation rate and purification efficiency of BOD_7, COD_{cr}, N_{tot} and NH_4-N in FSs treating municipal wastewater. There was no clear influence of other influencing factors such as water temperature, hydraulic and mass loading rate on purification efficiency during the test period, as the filter systems were tested in field conditions using real wastewater. Thus the mass loading rate of filter systems was determined on the basis of the characteristics of wastewater and applied HLR. The re-circulation of wastewater 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 and also makes it possible to avoid over-dimensioning CWs, leading to the establishment of more cost-effective CW systems. The recommended re-circulation rate from 100 to 300 percent of the inflowing wastewater appears to be adequate to improve the performance of FS in terms of effective BOD and COD removal and nitrification/denitrification, as well as TSS and P_{tot} removal.

During the study, the comparison between batch-operated and conventional CWs was made, and the possible advantages of batch-operated CWs were analyzed on the basis of the organic matter removal rate calculated by the "Kickuth" equation and the aeration capacity of the FS. The highest organic matter removal rate of KBHT=0.19 m d^{-1} is approximately two times higher than the removal rate of a typical horizontal-flow CW (that our experimental system most closely matched in terms of flow path) reported in the literature. However, the highest aeration capacity of 21.1 gO_2 m^{-2} d^{-1} is somewhat lower than the average aeration capacity of vertical-flow CWs, and substantially lower than the aeration capacity of a VF filter with re-circulation or tidal-flow systems. We believe that the performance indicators should be interpreted regarding the low inflow concentrations of wastewater, and as shorter hydraulic retention times could be applied in future studies, the performance indicators of batch-operated FS are expected to improve substantially.

Further and more complex research should focus on the investigation of batch-operated LWA filters in terms of applying shorter incubation times and higher organic carbon loading.

The highly-loaded compact filter systems for greywater treatment demonstrated good performance in COD, BOD, TSS and P_{tot} removal. The results provide encouragement for the application of similar full-scale systems in places where space for the establishment of CWs is limited, in areas that are far from central sewage systems and/or where there is a lack of potable water. The system's effluent can be reused for toilet flushing or irrigation. In hybrid filters, the preferred filter material for the VF filter could be crushed Filtralite® with a fraction of 4–10 mm, while for the HF filter the suggested material would be hydrated oil shale ash sediment. The improvements of the filter system regarding pumping pressure and distribution system should, however, also be considered before designing a prototype.

Measurements of GHG emissions in three types of CWs in Estonia indicate that intermittent loading to CWs significantly enhanced N_2O fluxes, but did not influence CO_2 and CH_4 fluxes. Nevertheless, further research is needed to determine the relationships between different operational regimes and the environmental impacts of GHG emissions.

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6. SUMMARY IN ESTONIAN

Täiustatud meetodid kombineeritud tehismärgalade rakendamisel: keskkonnamõjud ja puhastusefektiivsus

Viimase paari aastakümne jooksul on tehismärgalade tehnoloogia märkimisväärselt arenenud ning tehismärgalade kasutamine reovee puhastamisel on üle maailma levinud reoveepuhastuse ökoloogilise alternatiivina konventsionaalsete reoveepuhastuse tehnoloogiate kõrval. Lisaks laialt levinud praktikale olmereovee puhastamisel, on viimase künmendi jooksul põhjalikumalt uuritud tehismärgalade kasutamist ka hallvee puhastamiseks.

Tehismärgalade orgaanilise aine ja lämmastikuärastuse efektiivsus sõltub olulisel määral lahustunud hapniku kättesaadavusest puhastussüsteemis. Seega, minimeerimaks reovee puhastamiseks vajalikku pindala reostusühiku kohta, on oluline leida ja arendada meetodeid, mis parandavad tehismärgala hapnikuvarustust ning seeläbi ka reovee puhastamise efektiivsust. Hapnikuvarustuse parandamiseks on kasutatud mitmeid meetodeid nagu vertikaalvooluliste pinnasfiltrite kasutamine, heitvee tagasipumpamise rakendamine, muutuva veetasemega süsteemide ning annus- ja loodete-tüüpi süsteemide kasutamine. Lisaks tehismärgala läbiva reovee voolamise erisustele on oluliseks filtersüsteemi puhastusefektiivsust määravaks teguriks filtermaterjali ja selle terasuuruse valik. Filtermaterjal peab tagama ühest küljest optimaalse hüdraulilise juhtivuse, teisest küljest olema piisavalt suure eripinnaga, et tagada vajalike puhastusprotsesside, sh orgaanilise aine ning lämmastiku ärastuse ning fosfori sidumise, efektiivne toimimine. Samuti on kõrgelt koormatud filtersüsteemide puhul määravad mitmed tehnilised aspektid nagu filterkeha sügavus, jaotussüsteem, (reo)vee doseerimise sagedus ja kogus.

Käesolevas doktoritöös keskendutakse tehismärgalade hapnikuvarustuse parandamiseks kasutatavate meetodite uurimisele. Doktoritöö peamiseks eesmärgiks on hinnata mitmete tehniliste ja opereerimislike võtete rakendatavust parandamaks kombineeritud tehismärgalade ja pinnasfiltersüsteemide puhastusefektiivsust. Muuhulgas uuritakse annus-tüüpi pinnasfiltersüsteemi efektiivsust võrreldes läbivooluliste süsteemidega. Samuti uuritakse erinevate kombineeritud tehismärgala pinnasfiltrite puhul puhastusefektiivsuse määravate tegurite nagu sobiva filtermaterjali, selle terasuuruse, hüdraulilise koormuse ja režiimi valiku tähtsust.

Doktoritöö raames rajati kaks katselist pinnasfiltersüsteemi, millest esimene puhastas olmereovett ning teine majapidamise hallvett. Mõlemal juhul kasutati puhastusefektiivsuse tõstmiseks heitvee tagasipumpamist. Uurimustöö esimese osana rajati omereovee puhastamiseks eksperimentaalne kergkruusal põhinev annus-tüüpi pinnasfiltersüsteemi pilootkatse, peamise eesmärgiga hinnata annus-tüüpi pinnasfiltersüsteemi tõhusust reoainete puhastusefektiivsust iseloomustavate kriteeriumide põhjal. Katsete käigus uuriti lisaks erinevate katseliste režiimide mõju pinnasfiltri puhastusefektiivsusele. Uurimustöö teise osana rajati majapidamise hallvee puhastamiseks neli eksperimentaalset kergkruusal ja põlevkivituha settel põhinevat kompaktset mitmekihilise vertikaalfiltriga kombineeritud pinnasfiltersüsteemi pilootkatse seadet, uurimaks kompaktse pinnasfiltersüsteemi orgaanilise aine ning toitainete (lämmastik, fosfor) ärastamise efektiivsust. Katsed teostati kahel erineval hüdraulilisel koormusel ligemale kahe-aastase perioodi jooksul.

Annus-tüüpi pinnasfiltersüsteemi puhul saavutati kõrgeimad puhastusefektiivsused 96% ja 51% vastavalt BHT ja üldlämmastiku osas 200% tagasipumpamise määra rakendamisel ning hüdraulilise viibeaja ~2 päeva juures. Kõrgeim saavutatud orgaanilise aine ärastamise määr oli ~2 korda kõrgem kui horisontaalvooluliste pinnasfiltrite puhul keskmiselt, samas oli annus-tüüpi pinnasfiltri kõrgeim aeratsioonivõime näitaja siiski mõnevõrra madalam kui vertikaalvoolulistel pinnasfiltrite puhul keskmiselt ning oluliselt madalam, kui loode-tüüpi pinnasfiltrite puhul. Kuna pinnasfiltri aeratsioonivõime sõltub lisaks muudele teguritele ka siseneva reovee hapnikutarbest, mis teostatud katsete puhul oli väga madal, siis võib eeldada, et kõrgema hapnikutarbega reovee puhul ja/või väiksema hüdraulilise viibeaja tingimustes on võimalik saavutada ka oluliselt kõrgemad aeratsioonivõime näitajad.

Hallvee puhastamiseks rajatud kompaktsete mitmekihiliste vertikaalfiltritega pinnasfiltersüsteemide puhul saavutati väga head tulemused kõrge reostuskoormuse tingimustes, puhastusefektiivsus BHT järgi keskmiselt kuni 95%, üldlämmastiku järgi kuni 55% ja üldfosfori järgi kuni 89%. Seejuures kujunes orgaanilise aine ning üldfosfori ärastamisel välja selge erinevus filtermaterjalide vahel: kergkruusal põhinevates süsteemides saavutati parem puhastusefektiivsus orgaanilise aine osas, põlevkivituha puhul aga ülfosfori sidumise osas. Filtersüsteemide koormuse suurendamine ~2,5 korda ei mõjutanud oluliselt orgaanilise aine, heljumi ja üldlämmastiku puhastusefektiivsust.

Hallvee puhastamisel saadud tulemused julgustavad sarnaste täismõõduliste kompaktsete süsteemide rakendamist kohtades, kus puudub ühiskanalisatsioon ning kus pinnasfiltri rajamiseks kasutatav ruumiline resurss on piiratud. Puhastatud hallvett on võimalik taaskasutada näiteks vesiklosetis ja kastmisveena kohtades, kus joogivee kogus on limiteeritud. Kombineeritud pinnasfiltrites võiks vertikaalvoolulise filtri materjalina eelistatult kasutada kergkruusa fraktsiooni 4–10 mm, samas horisontaasvoolulises filtris oleks soovitav kasutada põlevkivituha setet. Enne prototüübi väljatöötamist tuleks siiski kindlasti tähelepanu pöörata jaotus- ja pumpamissüsteemi koostoime optimeerimisele.

Lisaks vahelduva voolurežiimi positiivsele mõjule tehismärgalade hapnikuvarustusele ja puhastusefektiivsusele tuleb arvestada ka kasvuhoonegaaside emissioonist tulenevat võimalikku laiemat mõju keskkonnale. Kasvuhoonegaaside mõõtmise tulemused kolmel Eestis asuval reovee puhastamiseks kasutataval tehismärgala pinnasfiltersüsteemil viitavad asjaolule, et vahelduv koormus ja pidev veerežiimi muutumine suurendab oluliselt N_2O emissiooni, samas CO_2 ja CH_4 emissiooni veerežiim ei mõjuta. Siiski on kaugeleulatuvate järelduste tegemiseks vajalik täiendav uurimistöö erinevate tehismärgalades kasutatavate voolurežiimide ja kasvuhoonegaaside emissiooni vaheliste seoste kohta.

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PUBLICATIONS

CURRICULUM VITAE

Kristjan Karabelnik

Date and place of birth: 08.06.1981
Citizenship: Estonia
Marital status: common-law marriage
Address: Narva mnt 84–25, Tartu
Phone: +372 503 9010
E-mail: kristjan.karabelnik@ut.ee; kristjan@alkranel.ee

Education

1999	Tartu Hugo Treffner Grammar School
2003	University of Tartu, Faculty of Biology and Geography, Institute of Geography. Environmental technology. *BSc.*
2007	University of Tartu, Faculty of Physics and Chemistry. Environmental technology, *MSc*. ("*Purification efficiency and oxygen supply of a batch-operated constructed wetland treating municipal wastewater"*).

Working experience (career)

June 2004–...	Alkranel Ltd, project manager
August 2008–...	Environmental Investment Centre, contractual expert
April 2009 – June 2011	University of Tartu, Department of Geography, expert in project "*SANBOX – development of compact wastewater treatment system based on source-separation"*
October 2005 – October 2007	University of Tartu, Institute of Technology, expert in project "*Hybrid constructed wetland systems for wastewater treatment*"

List of publications

Karabelnik, K., Kõiv, M., Kasak, K., Jenssen, P. D., Mander, Ü. 201X. High-strength greywater treatment in compact hybrid filter systems with alternative substrates. Ecological Engineering (In Press).

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ELULOOKIRJELDUS

Kristjan Karabelnik

Sünniaeg ja -koht: 08.06.1981 Tartu
Kodakondsus: eesti
Perekonnaseis: vabaabielus
Aadress: Narva mnt 84–25, Tartu
Telefon: +372 503 9010
E-post: kristjan.karabelnik@ut.ee; kristjan@alkranel.ee
Praegune töökoht, amet: OÜ Alkranel, projektijuht

Haridus

1999	Tartu Hugo Treffneri Gümnaasium
2003	Tartu Ülikool, Bioloogia-geograafia teaduskond. Keskkonnatehnoloogia. *BSc.*
2007	Tartu Ülikool, Füüsika-keemia teaduskond. Keskkonnatehnoloogia. MSc. („Puhastusefektiivsus ja hapnikuvarustus olmereovee puhastamisel annus-märgalafiltris")

Töökogemus

Juuni 2004–...	OÜ Alkranel, veemajanduse spetsialist, projektijuht
August 2008–...	SA Keskkonnainvesteeringute Keskus, lepinguline ekspert
Aprill 2009 – Juuni 2011	Tartu Ülikool, Geograafia osakond, ekspert projekti „SANBOX – kohtsepareerimisel põhineva kompaktse reoveekäitlussüsteemi väljatöötamine" läbiviimisel
Oktoober 2005 – Oktoober 2007	Tartu Ülikool, Geograafia osakond, ekspert projekti „Kombineeritud tehismärgala-süsteemid reovee puhastamiseks" läbiviimisel

Publikatsioonide loetelu

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