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PERFORMANCE OF WASTEWATER TREATMENT WETLANDS IN ESTONIA

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ABSTRACT

In Estonia both natural, semi-natural and constructed wetlands are in use for wastewater treatment. In this thesis, the removal of organic material (BOD_7), total nitrogen and total phosphorus in 8 treatment wetlands is analyzed. The studied wetlands were: a semi-natural wet meadow slope in Koopsi, an FSW channel with macrophytes in Sangla-Rakke, a VSSF sand/plant filter in Põlva, a hybrid wetland system in Kodijärve, an FSW wetland in Põltsamaa, a hybrid system in Kõo, a hybrid system in Paistu and the semi-natural floodplain of the Valgejõgi River. In the semi-natural wet meadow slope in Koopsi, 65% of BOD_7, 67% of N and 80% of P was removed, and outflow values were in all cases below the standard limits. The outlet concentration of the heavily loaded bioditch in Sangla-Rakke varied – the average concentrations of BOD_7, N and P were 22, 5.4 and 1.4 mg l^{-1} respectively. Apart from nitrogen, the VSSF sand/plant filter in Põlva showed satisfactory treatment efficiency: 82%, 36% and 74% respectively for BOD_7, N and P. Similarly, nitrogen removal was insufficient in the hybrid wetland in Kodijärve, where the average outflow values for BOD_7, N and P were 13.4, 46.2 and 3.4 mg^{-1} respectively. The FWS wetland in Põltsamaa did not work well, and outflow values varied greatly, in the case of BOD_7, N and P from 1.8 to 250, from 1.3 to 42 and from 1.6 to 9.7 mg l^{-1} respectively. The hybrid system in Kõo works well in the case of BOD_7 and phosphorus, and purification efficiency for BOD_7, N and P was 87.9%, 65.5% and 72.3% respectively. The hybrid system in Paistu shows low output values of BOD_7 and P: 5.5, 19.2 and 0.4 mg l^{-1} for BOD_7, N and P respectively. The floodplain peatland for tertiary treatment shows low output values of nitrates and P: 0.2–1.8 and 1.5 mg l^{-1} respectively. For domestic wastewater treatment in subsurface flow wetlands, the main problem was the insufficient removal of nitrogen. Nitrogen removal was higher in well aerated hybrid wetland systems. Semi-natural wetlands showed good performance in the treatment of secondary wastewater. The results show that hybrid CW systems consisting of subsurface flow filters can efficiently operate in conditions of very variable hydraulic load and cold winter conditions. Locally produced LWA as a filter material in CWs has shown good hydraulic conductivity and phosphorus sorption capacity. The Paistu CW can be considered one of the best systems in Estonia, with proper design and outstanding purification results.

1. INTRODUCTION

Natural wetlands have been used as convenient wastewater discharge sites for as long as sewage has been collected (Kadlec and Knight, 1996). Natural wetlands are still used for wastewater treatment, but at present the use of constructed wetlands is becoming more popular and effective around the world (Vymazal, 2001). Constructed wetland treatment systems are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils and their associated microbial assemblages to assist in treating wastewater (Vymazal, 2001). They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment (Vymazal *et al.*, 1998). These systems have potential for the treatment of municipal wastewater, as well as from farms, landfills and some industrial areas. Because of their great volume, slow purification processes and heterogeneity, constructed wetland treatment systems are tolerant to changing hydraulic and nutrient loadings. This makes them more suitable than conventional treatment plants for the treatment of wastewater from individual houses, tourist resorts and other objects with variable wastewater flowrates and pollutant loadings. In addition, constructed wetlands have been used for the purification of wastewater from villages and small towns. As wetland treatment is an extensive technology with a great demand for area, the use of constructed wetlands for wastewater treatment is more suitable in sparsely populated areas. Constructed wetlands are able to remove suspended solids, organic matter, nitrogen, phosphorus, trace metals, bacteria and viruses, organic pollutants as well as other substances (chloride, sodium and potassium, sulphur, silicon) from wastewater. Various constructed wetland systems demonstrate great differences in purification efficiency. Constructed wetlands are usually designed and operated for wastewater treatment, but they can also have other functions.

There are about 800 small purification plants in Estonia. Since mostly small purification plants were constructed during the 1970s, they are now in bad shape. According to a study by Eesti Veevärk AS (2002), 40% of existing small purification plants work unsatisfactorily, and the main problem is the inadequate removal of nutrients. Because of that, as well as the high cost of new conventional purification plants, constructed wetlands are gaining popularity in Estonia (Kuusik, 1995). There are almost 30 wetland treatment systems in Estonia (Tooming, 2005), among which there are different examples of this technology. Despite the knowledge obtained from studies of existing constructed wetland in Estonia, as well as from other countries with cold climates, there is still a hesitant position concerning the use of constructed wetland treatment technology in Estonia (Tooming, 2005). For example, in a study for the determination of the best available technology for small purification plants, constructed wetlands have been considered usable only for the treatment of wastewater from individual houses, especially during the warm period (Eesti Veevärk, 2002). Therefore it is important to gather and analyze data from various existing treatment wetlands over a longer period and develop suitable technologies for different conditions.

Objectives

The main objectives of this PhD dissertation are: 1) to analyze the performance of 8 existing Estonian treatment wetlands, and 2) to compare different types of constructed wetlands regarding their capacity for the removal of organic matter, nitrogen and phosphorus, 3) to highlight the most important positive and negative aspects of treatment wetlands in Estonian conditions.

2. OVERVIEW OF CONSTRUCTED WETLANDS FOR WASTEWATER TREATMENT

Constructed wetlands can be divided into different groups. The basic classification is based on the type of macrophytic growth, and further classification is based on the water flow regime (Vymazal, 2001) (Fig. 1). Different types of constructed wetlands can be combined with each other or with conventional treatment plants in order to take advantage of the best features of each wetland type.

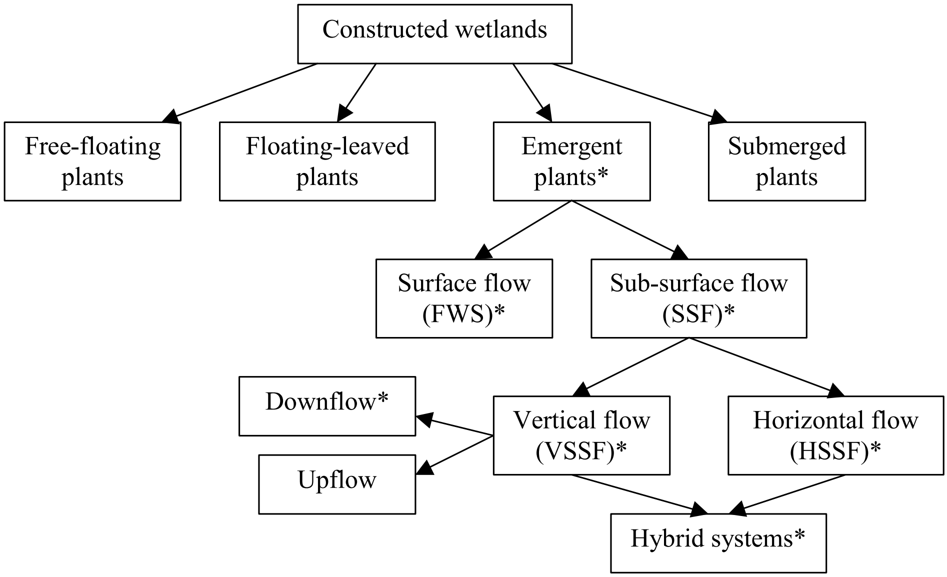

Figure 1. Classification of constructed wetlands for wastewater treatment (Vymazal, 2001). * – types of constructed wetlands analyzed in current dissertation.

2.1. Constructed wetlands with free-floating plants

Free-floating plants have most of their photosynthetic parts above the surface of the water and their root systems below it. Typical plant species that have been used in large-scale applications are water hyacinth (*Eichhornia crassipes*) and duckweed species (*Lemna, Spirodela*, and *Wolffiella*) (Kadlec and Knight, 1996). Free-floating plants can be used for raw sewage as well as for primary or secondary treated effluents (Gumbricht, 1993).

The use in temperate climates of constructed wetlands with water hyacinth, one of the most productive plants in the world, is limited, because hyacinth needs high temperatures for growth (Vymazal *et al.*, 1998). The major disadvantages of duckweeds compared to waster hyacinth are their shallow root systems and sensitivity to wind, but their major advantage is their lower sensitivity to colder climates (U.S. EPA, 1998). Nevertheless, still treatment wetlands with duckweed in temperate climates can be used as seasonal (summer) wastewater treatment plants, since in winter they only work as anaerobic or facultative lagoons (Bonomo *et al.,* 1997).

2.2. Constructed wetlands with floating-leaved macrophytes

Floating-leaved macrophytes include plant species that are rooted in the substrate, and their leaves float on the water surface. *Nymphaea* spp., *Nuphar lutea* and *Nelumbo nucifera* are typical representatives of this group. So far only a few systems have used this type of vegetation, and the use of constructed wetlands with floating-leaved species for wastewater treatment is considered questionable (Vymazal, 2001).

2.3. Constructed wetlands with submerged plants

The photosynthetic tissue of submerged aquatic plants is entirely submerged. According to Gumbricht (1993), *Cladophora* spp, *Enteromorpha* spp, *Potamogeton* spp, *Ceratophyllum* spp, *Myriophyllum* spp, *Elodea canadensis* and *E. nuttalli*, *Ulva lactuca* and *Egeria densa* have been studied for wastewater treatment, but the use of submerged macrophytes for wastewater treatment is still in the experimental stage (Vymazal *et al.,* 1998). The development of ephiphytic communities on the leaves of vascular plants may reduce photosynthesis in submersed macrophytes. Because of the shading of submersed macrophytes by algae and their sensitivity to anaerobic conditions, they have found their widest use as a tertiary treatment step, polishing the effluent or eutrophied natural waters (U.S. EPA, 1988; Gumbricht, 1993). Summing up different removal functions, the potential removal rate for submerged pond systems in temperate zones lies somewhere between 0,5–2 g N m^{-2} d^{-1} and 0,1–0,3 g P m^{-2} d^{-1} (Gumbricht, 1993).

2.4. Constructed wetlands with emergent macrophytes

Constructed wetlands for wastewater treatment with emergent macrophytes can be constructed with many different designs. In general these can be categorized into two major groups according to their flow pattern: free water surface systems (FWS wetlands) and systems with sub-surface flows (SSF wetlands); sub-surface flow wetlands can be further categorized into horizontal subsurface flow systems (HSSF or HF wetlands) and vertical sub-surface flow systems (VSSF wetlands) (Vymazal, 2001). Combinations of wetlands consisting of different wetland types are classified as hybrid systems (Vymazal *et al.,* 1998).

2.4.1. Free water surface systems

A typical free water surface constructed wetland is a sequence of sealed shallow basins containing 20–30 cm of rooted soil, with a water depth of 20–40 cm, and dense emergent vegetation covering a significant part of the surface (Vymazal, 2001). Free water constructed wetland design variables include total area, the number, size, depth and shape of wetland cells, hydraulic retention time, vegetation types and coverage, inlet and outlet type and location, and internal flow parameters (U.S. EPA, 2000).

In free water surface wetlands, inflow water containing particulate and dissolving pollutants slows and spreads through a large area of shallow water and emergent vegetation. Settleable organics are rapidly removed in FWS wetlands by quiescent conditions, deposition and filtration (Kadlec and Knight, 1996). Attached and suspended microbial growth is responsible for soluble BOD (Vymazal, 2001). FSW wetlands typically have aerated zones and anoxic or anaerobic zones in deeper parts of ponds or in sediments. Major oxygen sources in FSW are surface aeration and photosynthesis carried out by phytoplankton, periphyton, and submerged plants (U.S. EPA, 2001). In FSW nitrogen removal may be achieved by plant uptake/harvesting, nitrification/ denitrification, volatilization and ion exchange, but it is most effectively removed by nitrification/denitrification (Vymazal, 2001; U.S. EPA, 2001). According to Vymazal et al. (1998), FSW systems provide sustainable removal of phosphorus, but at relatively slow rates. Phosphorus removal in FSW systems occurs from adsorption, absorption, complexation and precipitation. However, precipitation with Al, Fe and Ca ions, as the major process in P removal, is limited by little contact between water column and the soil (Vymazal *et al.,* 1998). Significant amounts of nutrients may be stored in sediments.

Based on the data from the literature, Vymazal (2001) has summarized the following design criteria and recommendations for FSW: pre-treatment – to at least the primary level; organic loading – <80 kg BOD_5 ha^{-1} d^{-1}; hydraulic loading – 0.7–5.0 cm d^{-1}; detention time: 5–15 days; aspect ratio (L:W) – 2:1 to

10:1; water depth – 0.4 m; bottom slope – 0.5%; soils – 20–30 cm to support the growth of emergent macrophytes, no special requirements for high hydraulic conductivity (local soil is used in many cases); vegetation – most commonly used species: in North America – *Scirpus spp*., *Typha spp*.; in Europe – *Phragmites australis*; harvest frequency – 3 to 5 years.

2.4.2. Horizontal subsurface flow systems

A horizontal subsurface flow constructed wetland is a constructed wetland consisting of a trench or bed underlain with an impermeable layer of clay or synthetic liner. The bed contains porous media that will support the growth of emergent vegetation, and wastewater flows slowly under the surface of the bed, more or less horizontally through the rhizosphere of the wetland plants. The most commonly used macrophytes are *P. australis* and *Typha latifolia*. The wastewater is treated by filtration, sorption and precipitation processes in the soil, and by microbiological degradation.

Organic compounds in the HSSF are degraded aerobically as well as anaerobically by bacteria attached to plants' underground organs and media surface. The oxygen required for aerobic degradation is supplied directly from the atmosphere by the diffusion or oxygen leakage from macrophyte roots and rhizomes, although the oxygenation of the rhizosphere in HSSF constructed wetlands is insufficient (Vymazal, 2001). Nitrogen is removed in HSSF constructed wetlands by nitrification/denitrification, volatilization, adsorption and plant uptake, although the major removal mechanism is nitrification/ denitrification (Kadlec and Knight, 1996; Vymazal *et al.,* 1998). As oxygenation of the rhizosphere in HSSF wetland systems is insufficient, incomplete nitrification is the major cause of limited nitrogen removal (Brix and Schierup, 1989; Vymazal, 2001). Phosphorus is primarily removed by adsorption and precipitation reactions with soil media (Jenssen *et al.,* 1993, Kadlec and Knight, 1996). However, media used for HSSF wetlands (e.g. pea gravel, crushed stones) do not usually contain great quantities of Fe, Al and Ca, and therefore removal of phosphorus is generally low (Vymazal, 2001). This has led to investigations to find more efficient wetland media, such as the Light Weight Aggregates (LWA) or Light Expanded Clay Aggregates (LECA) (Zhu *et al.*, 1997; Johansson, 1998; Jenssen and Krogstad, 2003, Adam *et al.*, 2005) or shell sands (Søvik and Kløve, 2005). Several investigations have demonstrated that the assimilation of nutrients in plants in constructed wetlands play a minor role, usually less than 10% of nitrogen and less than 5% of phosphorus can be removed in constructed wetlands with harvesting (Geller *et al.*, 1990; Mander *et al.*, 2003; Toet *et al.,* 2005).

According to data from various studies gathered by Vymazal (2001), the removal rate of nitrogen and phosphorus in HSSF wetland systems is 121–3817 g N m^{-2} y^{-1} and 25–389 g P m^{-2} y^{-1} respectively, in the case of nitrogen and phosphorus treatment efficiency was 11.4–76.4% and 4.8–65.0 % respectively.

Based on the data from the literature, Vymazal (2001) has summarized the following design criteria and recommendations for HSSF constructed wetlands: pretreatment: to at least the primary level; organic loading: <150 kg BOD_5 $ha^{-1}d^{-1}$ (usually <80 kg BOD_5 $ha^{-1}d^{-1}$); hydraulic loading: ST: < 5 cm d^{-1}, TT :< 20 cm d^{-1}; specific area: ST: approx. 5 m^2 PE^{-1}, TT: 1 m^2 PE^{-1}; detention time: >5 days; aspect ratio (L:W): 3:1 (could be <1:1); media: washed gravel, crushed stones (3–16 mm); hydraulic conductivity of media 10^{-3}–3.10^{-3} m s^{-1}; media depth: 0.6–0.8 m (average); media porosity: 0.3–0.45; bottom slope: 1.0%; liner: HDPE, LDPE, PVC (thickness 0.5–1.00 mm); vegetation: most frequently used species: in Europe *P. australis*; in North America *Scirpus* spp., *Typha* spp. The most common difficulties experienced by wetland treatment systems have been related to maintaining partially aerated soil conditions (Kadlec and Knight, 1996). Authors have pointed out that when wetland systems are overloaded by oxygen-demanding constituents or are operated with excessive water depth, highly reduced conditions occur in sediments, resulting in plant stress and reduced removal efficiencies for BOD and ammonia nitrogen.

2.4.3. Systems with vertical subsurface flow

Constructed wetlands with vertical subsurface flow are quite similar to HSSF wetlands. The main differences between these systems lie in the feeding systems and in the direction of water flow in the filter media. VSSF wetland systems are intermittently fed with large batches, thus flooding the surface; wastewater gradually percolates down the bed and is collected by a drainage network at the base (Vymazal, 2001). This kind of feeding leads to good oxygen transfer and hence makes aerobic purification processes possible. The pretreatment of inflow is usually needed to avoid clogging of the filter media.

The major treatment processes in a VSSF are the same as in an HSSF. However, VSSF beds are far more aerobic than HSSF beds and are good for both nitrification and BOD removal, (Vymazal, 2001). Cooper (1999) recommends 1 m^2 pe^{-1} for BOD removal only, and 2 m^2 pe^{-1} for BOD removal and nitrification. On the other hand, VSSF beds do not provide much denitrification, and problems with denitrification may be solved using a two-stage plant (Vymazal *et al.,* 1998). The removal of phosphorus is related to the choice of filter media.

According to Vymazal (2001), some VSSF wetlands have been constructed to use the upflow of wastewater (wastewater is brought to the filter bottom and passes the filter in an upwards direction).

2.4.4. Hybrid systems

Various types of wetlands can be combined in order to achieve higher treatment effect. However, hybrid systems most frequently comprise VSSF and HSSF systems arranged in a staged manner to promote nitrogen removal by creating conditions for both nitrification and denitrification (Vymazal, 2001). Apart from that, sub-surface flow wetlands can be combined with free-water surface wetlands.

3. MATERIAL AND METHODS

3.1. Description of selected treatment wetlands

Budgets of organic matter (BOD) and the total nitrogen and total phosphorus of the following systems are analyzed (Table 1; Fig. 1 and 2):

- A combined overflow-subsurface flow root-zone system on a *Phalaris arundinacea*-slope in Koopsi, Tartu County;
- An aquatic macrophyte channel (bioditch) in Sangla-Rakke, Tartu County;
- A vertical flow sand/plant filter in Põlva, Põlva County;
- Originally a two-chamber horizontal subsurface flow sand-plant filter with *T. latifolia, Iris pseudacorus*, and *P. australis*, now a hybrid system with a vertical flow filter, horizontal flow filter and phosphorus removal unit in Kodijärve, Tartu County;
- A cascade of 4 serpentine ponds with *T. latifolia* and *P.australis*, for secondary treatment of wastewater from the town of Põltsamaa, Jõgeva County;
- A hybrid wetland system consists of two vertical flow filters followed by a horizontal subsurface flow filter with *P. australis* in Paistu, Viljandi County;
- A hybrid wetland system consists of a two-bed vertical subsurface flow filter planted with *P. australis*, an HSSF filter planted with *T. latifolia* and *P. australis*, and two free water surface wetland beds planted with *T. latifolia* in Kõo, Viljandi County;
- A floodplain on alluvial and peatland soil of the Valgejõgi River for secondary treatment of wastewater from the town of Tapa in Lääne-Viru County.

Table 1. Design parameters of selected treatment wetlands in Estonia.

Name	Type	Wastewater type	Year of construction	Area (m^2)	Loading (PE[1])
Koopsi	Semi-natural wet meadow slope with *P. arundinacea*	Effluent from sedimentation pond	1989	2400	500
Sangla-Rakke	FSW channel with helophytes (bioditch)	Effluent from sedimentation pond	1989	140	190
Põlva	VSSF sand/plant filter	Effluent from septic tank	1994	90	40
Kodijärve	Hybrid system (VSSF+HSSF)	Effluent from septic tank	1996	350	60
Põltsamaa	FSW (cascade of macrophyte ponds)	Effluent from activated sludge plant	1997	12000	6670
Kõo	Hybrid system (VSSF+HSSF+FSW)	Effluent from septic tank	2001	1200	300
Paistu	Hybrid system (VSSF+HSSF)	Effluent from septic tank	2002	432	64
Tapa	Semi-natural floodplain	Effluent from activated sludge plant	2002	651	10000

[1] – population equivalent, 1 PE = 60 g BOD_7 d^{-1}.

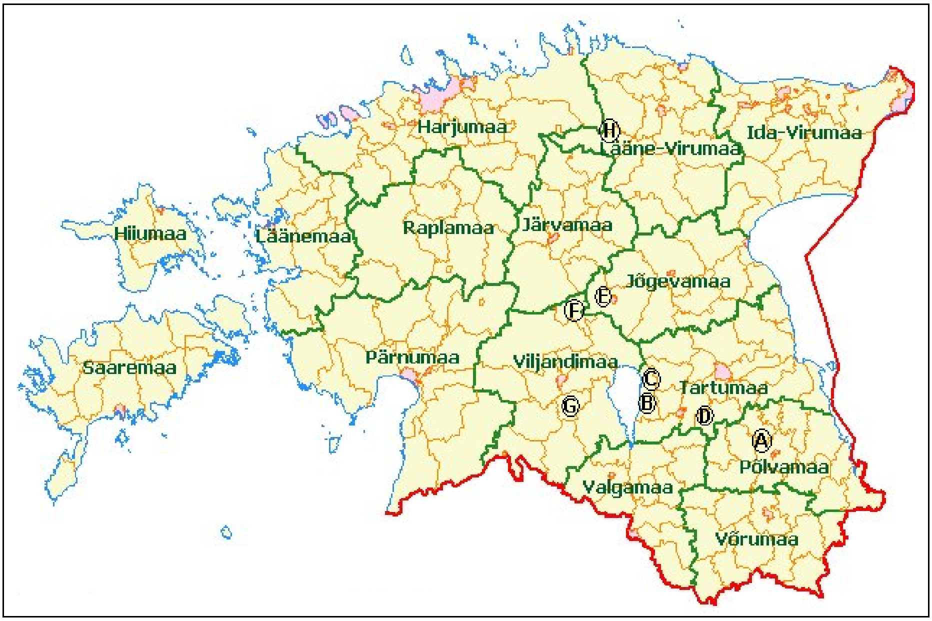

Figure 1: Location of investigated systems in Estonia. A – the sand/plant filter in Põlva, B – the *Phalaris*-slope in Koopsi, C – the bioditch in Sangla-Rakke, D – the hybrid wetland system in Kodijärve, E – the Põltsamaa treatment wetland, F – the hybrid wetland system in Kõo, G – the hybrid wetland system in Paistu, H – seminatural experimental plot on floodplain peatland of Valgejõgi (Map source – Estonian Land Board).

3.2. Sampling and analysis

Water from inlet and outlet of treatment wetland systems in Põlva, Koopsi and Sangla-Rakke was sampled once a month from April 1989 to October 1995. Water samples from the inlet and outlet of the Kodijärve system were taken once a month during the study period from January 1997 to April 2005. Since October 2002, after the establishment of the VSSF at Kodijärve, water samples were also taken from the outlet of the VSSF. The water discharge was measured automatically in the outlet using tipping buckets. In Põltsamaa the water samples were taken from the inlet of the first pond and from the outlets of all ponds, once a month from April 1997 to January 2001, and samples were also taken from April to June 2004 and from February to April 2005. The water discharge was measured from the inlet of the first pond and the outlet of the last pond. In Kõo the water samples were taken 8 times from October 2001 to February 2002 from the inflow of the system and the outflow of the VSSF, HSSF and FWS. In Paistu 18 series of water samples from October 2003 to October 2005 were taken from the inflow and outflow of the VSSF and HSSF.

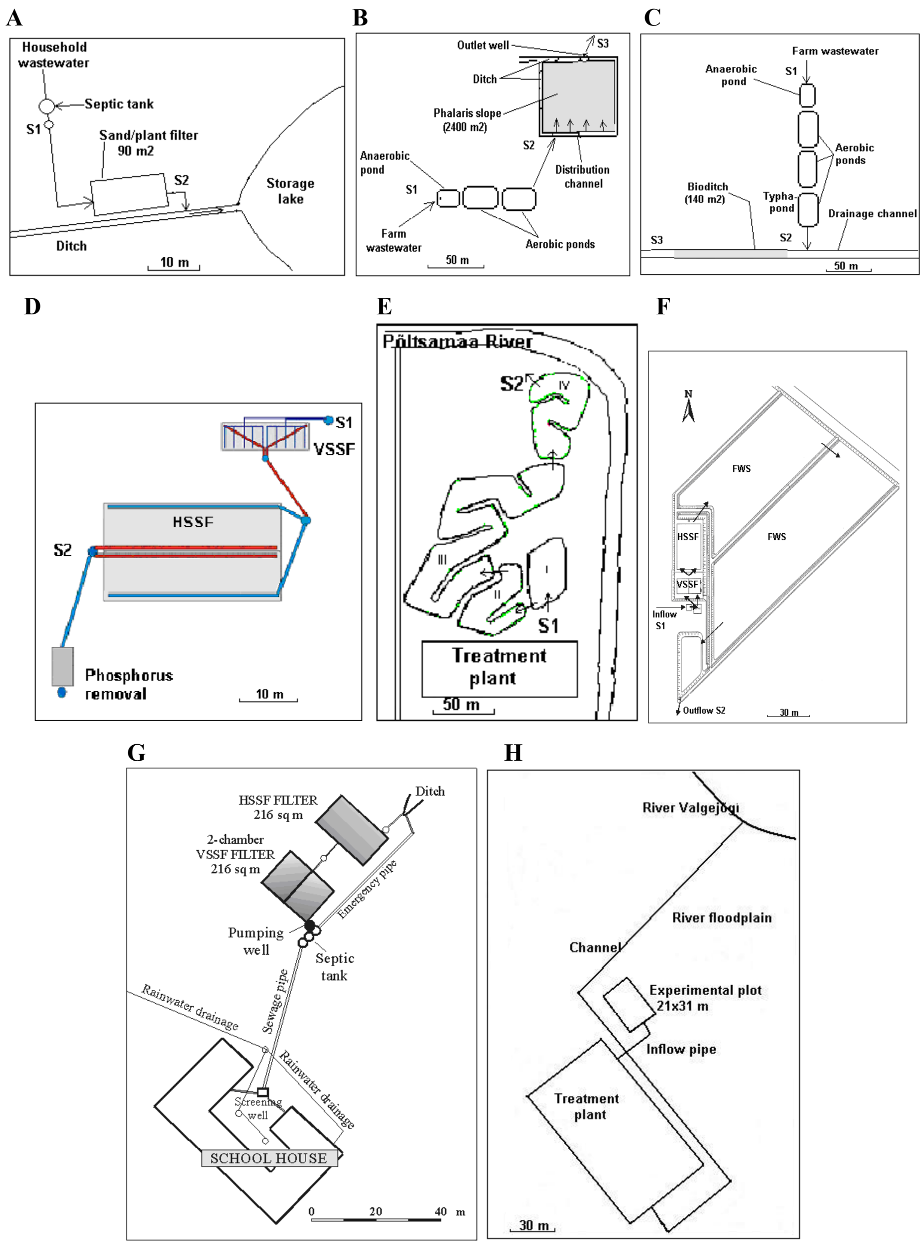

Figure 3: Design schemes of investigated systems. A – the sand/plant filter in Põlva, B – the *Phalaris*-slope in Koopsi, C – the bioditch in Sangla-Rakke, D – the hybrid wetland system in Kodijärve, E – the Põltsamaa treatment wetland, F – the hybrid wetland system in Kõo, G – the hybrid wetland system in Paistu, H – seminatural experimental plot on floodplain peatland of Valgejõgi (Mauring, *et al*, 2001, Publication I; Teiter, 2005; Öövel *et* al., 2005, Publication IV; Vohla *et al.*, 2006; Öövel *et al.*, 200X, Publication V). S1...S3 – sampling points.

In Tapa 5 series of water samples were taken from August to October 2002 from the inflow pipe and piezometers installed in the floodplain.

Water samples were analyzed for BOD_7, SS, NH_4^+-N, NO_2^--N, NO_3^--N, total N, PO_4^{3-}-P and total P (all according to APHA, 1989) in the laboratories of Tartu Environmental Research Ltd. and Tartu Water Ltd.

In Kodijärve, soil samples were taken in September/October from 1997 to 2004 in both basins from a depth of 0–0.1 m, 0.3–0.4 m and 0.6–0.7 m and analyzed for N, P and organic matter (C) content at the Laboratory of Plant Biochemistry at the Estonian Agricultural University.

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

$$PE = (C_{in}–C_{out})/C_{in}*100 \quad (1)$$

where:

- *Cin* – average value of inflow concentration (mg L^{-1});
- *Cout* – average value of outflow concentration (mg L^{-1}).

Mass removal (*MR*; g m^{-2} d^{-1}) is calculated on the basis of the following equation (see Kadlec and Knight, 1996):

$$MR = \{(C_{in} * Q_{in}) – (C_{out}*Q_{Out})\}/A \quad (2)$$

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 concentrations in inflow and outflow (mg L^{-1}).

In the FWS system in Põltsamaa, these calculations are as follows:

$$PE = (C_{I\ in}–C_{IV\ out})/C_{I\ in}*100 \quad (3)$$

where:

- C_I *in* – average value of pond I inflow concentration (mg L^{-1});
- C_{IV} *out* – average value of pond IV outflow concentration (mg L^{-1}).

$$MR = \{(C_{I\ in} * Q_{I\ in}) – (C_{IV}\ out *Q_{IV}\ out)\}/A \quad (4)$$

where:

- *A* – area of CW (m^2);
- $Q_{I\ in}$ and $Q_{IV\ out}$ – average values of water discharge in inflow to pond I and outflow from pond IV (m^3 d^{-1});
- $C_{I\ in}$ and $C_{IV\ out}$ – average concentrations in inflow to pond I and outflow from pond IV (mg L^{-1}).

The removal of BOD_7, total P, and total N in Kodijärve and Paistu was also described using an area-based first-order model (later called the k-C* model) (Kadlec and Knight, 1996; Kadlec, 2000):

$$\ln[(C_o - C^*)/(C_i - C^*)] = -k/q \qquad (5)$$

where:

- k= the area-based, first-order rate constant (m yr^{-1});
- q= the hydraulic loading rate (m yr^{-1});
- C_o= the effluent concentration (g m^{-3});
- C_i= the influent concentration (g m^{-3});
- C*= the irreducible background wetland concentration (g m^{-3}).

Based on published data (Kadlec and Knight, 1996), the C* values of 1 mg l^{-1} for BOD_7 and 1.5 mg l^{-1} for total N were chosen. In the case of Kodijärve, the C* value of 0.9 mg l^{-1} for BOD_7 was chosen, to use a lower value than the lowest outlet concentration. It is known that wetlands have very low natural total P background concentrations (Kadlec and Knight, 1996). The C* value for total P was assumed to be 0.03 mg l^{-1}.

The available data show that the effects of temperature on BOD and phosphorus removal are negligible in subsurface flow wetlands (Mander and Mauring, 1997; Wittgren and Maehlum, 1997; Noorvee *et al.,* 2005b). However, processes such as ammonification, nitrification and denitricication have been proven to be temperature-dependent. Therefore, rates of ammonia and total nitrogen will also be temperature-dependent (Kadlec, 2000). K_T values for nitrogen reduction have to be converted to k_{20} values for purposes of comparison. The relation between k_T and k_{20} is the Arrhenius equation:

$$k_T = k_{20}\theta^{T-20}, \qquad (6)$$

where:

- k_T= the reaction rate coefficient at temperature T (^oC);
- k_{20}= the reaction rate coefficient at temperature 20 ^oC;
- θ= the temperature factor;
- T= temperature (^oC);

An estimate of the temperature factor of ammonia oxidation is θ=1.04 and for total N reduction θ=1.05 (Kadlec and Knight, 1996).

Outlet concentrations are compared with limit values set by the Water Act of Estonia, which are for purification plants with loading between 2000–9999 PE for BOD_7 and P 15 and 1.5 mg l^{-1}. For such a treatment plant, there are no limit values for N, and therefore in the case of N, the recommended limit value of 15 mg l^{-1} is used. In the Water Act of Estonia, there are no outflow limit values for a treatment plant whose loading is less than 2000 PE. For small purification plants, outflow standard limits are set on a case by case basis. In this work, limit values for smaller purification plants for BOD_7, total N and total P are 20, 20 and 1.5 mg l^{-1} respectively.

3.3. Statistical analysis

The statistical analysis of the data was performed using the programme Statistica 6.0. The normality of variables was verified using the Kolmogorov-Smirnov, Lilliefors' and Shapiro-Wilk's tests. Apart from water and air temperature, water discharge and conductivity, the parameters' distribution differed from normal, and hence non-parametric tests were performed. We used the Wilcoxon Matched Pairs Test and the Mann-Whitney U-Test to check the significance of differences between the inflow and outflow parameters. We also used Spearman Rank Correlation analysis to analyze the relationship between the water quality indicators. The level of significance of $\alpha = 0.05$ was accepted in all cases.

For data interpolation in the semi-natural peatland plot in Tapa Kriging method is used. Kriging with linear variogram model is found to represent best the measured values. All sampling points were taken into account to interpolate values within the experimental area. Floating boundary conditions (i.e. extrapolation) were allowed in calculation, while data lying outside the sampling area were truncated in the final data representation.

4. RESULTS AND DISCUSSION

4.1. *Phalaris*-slope in Koopsi

The seminatural wet meadow covered with *P. arundinacea* is used for the secondary treatment of dairy farm wastewater (flowrate 130 $m^3\ d^{-1}$). This semi-natural wetland is not insulated below to prevent groundwater pollution, and therefore it was possible to construct it without disturbing the natural plant cover.

Table 2. Inflow and outflow concentrations, purification efficiency and mass removal in the *Phalaris*-slope in Koopsi (average ± standard deviation). For non-normally distributed data average (av), min and max values are given. (Mander and Mauring, 1997).

Parameter	BOD_7	Total N	Total P
Number of analysis (n)	23	23	23
Inflow ($mg\ l^{-1}$)	av 17.0 min 4.0 max 70.0	16.0±5.8	4.1±2.7
Outflow ($mg\ l^{-1}$)	av 4.0 min 1.0 max 18.5	5.0±2.5	0.7±0.4
Efficiency (%)	65±21	67±17	80±12
Mass removal ($g\ m^{-2}\ d^{-1}$)	1.7±0.6	0.7±0.23	0.5±0.11

Because of primary purification in sedimentation ponds, inflow concentrations to the *Phalaris*-slope were quite low, especially in the case of organic matter. Due to the sufficiently low areal loading and long detention time, the *Phalaris*-slope showed a high efficiency of total N and total P removal, and outflow values were significantly lower than effluent limit values. In the case of BOD, purification efficiency was relatively lower, although the average outlet value of BOD_7 was only 4 $mg\ l^{-1}$, which is comparable to the water quality of stream water (Table 2). The low output of N indicates that plant cover creates a pattern of aerobic and anaerobic zones where there are optimal conditions for both nitrification and denitrification. Effective P removal is apparently caused by the high iron content of the soil (Mauring, *et al.*, 2001, Publication I). Nevertheless, part of the effluent is formed by overland flow, both nutrient removal and outlet concentrations have been relatively stabile.

4.2. Bioditch in Sangla-Rakke

In the case of the Sangla-Rakke wetland purification system, this is part of a drainage channel with intensive macrophyte growth, receiving farm wastewater (flowrate 125 m^3 d^{-1}) that is purified in sedimentation ponds. Although purification took place in three aerobic and anaerobic ponds and a pond with *T. latifolia*, influent parameters values were remarkably high. As a result of high input loading, the areal loading of 40 g BOD m^{-2} d^{-1} was considerably higher than suggested for FWS constructed wetlands. Although overloading, removal rates were highest among the studied wetlands (except for BOD_7, which was the second highest) (Table 3). This supports the idea that until reasonable loading there is a significant positive correlation between input load and mass removal (Mander and Mauring, 1994; Mauring *et al.*, 2001, Publication I).

As typical for an FSW, the removal efficiency of organic matter was satisfactory (81%), but due to high input loading the average concentrations in outflow slightly exceeded limit values. There were no big problems with N removal, because of relatively low input concentrations and satisfactory removal efficiency, concentrations in the outflow were well below standard limits. Although free water surface wetlands typically have a comparatively low P purification efficiency, P purification in the bioditch was satisfactory (69%), and concentrations in the outflow were low.

Table 3. Inflow and outflow concentrations, purification efficiency and mass removal in the bioditch in Sangla-Rakke (average ± standard deviation) (Mander and Mauring, 1997).

Parameter	BOD_7	Total N	Total P
Number of analysis (n)	17	18	19
Inflow (mg l^{-1})	136±112	17.8±10.8	5.2±3.6
Outflow (mg l^{-1})	22±18	5.4±4.0	1.4±1.3
Efficiency (%)	81±9	66±12	69±19
Mass removal (g m^{-2} d^{-1})	3.5±2.7	2.7±2.0	1.6±1.2

4.3. Vertical subsurface flow sand/plant filter in Põlva

The vertical subsurface flow sand-plant filter in Põlva was built to treat wastewater from a group of individual houses. The area of the filter is 90 m^2, the upper part of the filter consists of sand and gravel, the lower part is made of soil, and the filter is planted with *P. australis* and *T. latifolia*. Sewage is pumped into the filter in intervals, and the wastewater flowrate was 2 m^3 d^{-1}.

Despite the relatively high variation of BOD_7 values in both the inlet (27–460 mg O_2 l^{-1}) and outlet (7–50 mg O_2 l^{-1}) (Table 4), the average removal efficiency of BOD_7 in the Põlva VSSF was satisfactory (82%). Nevertheless, average outflow concentration was slightly above the standard value. There were problems with N removal in the Põlva VSSF filter, as the average removal efficiency was only 36%, and inlet and outlet concentrations varied between 18–54 and 17–34 mg l^{-1}, respectively. Although VSSF filters are usually aerobic, the low removal of N in Põlva VSSF was caused by insufficient nitrification (Mauring *et al*., 2001, Publication I). The insufficient nitrification could be caused by weak vegetation development during the first two seasons. Iron release from the filter indicates anaerobic conditions in the deeper parts of the filter, which are suitable for denitrification. Occasional surface runoff may also result in less efficient purification.

Table 4. Inflow and outflow concentrations, purification efficiency, and mass removal in the vertical subsurface flow sand/plant filter in Põlva (average ± standard deviation). For non-normally distributed data average (av), min and max values are given. (Mander and Mauring, 1997).

Parameter	BOD_7	Total N	Total P
Number of analysis (n)	27	10	27
Inflow (mg l^{-1})	173±114	40.5±10.6	10.9±4.2
Outflow (mg l^{-1})	av 28 min 6 max 160	24.8±5.9	2.6±2.0
Efficiency (%)	82±12	36±14	74±15
Mass removal (g m^{-2} d^{-1})	2.1±1.7	1.0±1.2	0.4±0.11

During the study period, the average inlet and outlet values of total P were 10.9 (from 6.2 to 22.0) and 2.6 (from 0.4 to 8.8) mg P l^{-1} respectively. P removal was satisfactory, and the average removal efficiency was 74%, which is comparable to other studied subsurface flow wetlands. However, over a longer period there might be a saturation problem. The increasing Fe release from the sand filter indicates the increasing of anaerobic conditions and the reduction of P retention capacity.

4.4. The hybrid wetland system in Kodijärve

The horizontal subsurface flow (HSSF) stage of the Kodijärve hybrid constructed wetland system was constructed in 1996 to treat the wastewater of the hospital with average wastewater flowrate 4.2 m^3d^{-1}. The double bed HSSF filter (312.5 m^2) is filled with coarse iron-rich sand and covered predominantly with *P. australis* and *Scirpus sylvaticus*. In the summer of 2002 the system was improved – between the outflow from the septic tank and the inflow to the wetland, a vertical subsurface flow (VSSF) filter (two intermittently loaded crushed limestone filled beds of a total area of 37.4 m^2) was constructed. Also, an additional 10 m^2 phosphorus sedimentation filter was constructed at the outflow of the HSSF. In this paper, the purification processes of the VSSF and the HSSF are analyzed, observing inflow to the wetland system as outflow from the septic tank and outflow as the average outflow from both HSSF filters. The effect of the establishment of a VSSF and phosphorus sedimentation filter is analyzed in studies by Noorvee *et al.* (2005a) and Vohla *et al.* (2005).

Summary results of average inflow and outflow concentrations, purification efficiency and mass removal of the most important nutrients and organic matter are given in Table 5. Figure 4 shows the variation of the inlet and outlet concentrations.

In the case of Kodijärve, the concentrations of nutrients in the inflow to the wetland system are higher than is usual for domestic wastewater, caused by decreasing water consumption. Because of decreasing water consumption, the wetland system is operating on lower hydraulic loading than that for which it was originally designed. Table 5 indicates that the Kodijärve hybrid wetland system was satisfactorily efficient in terms of BOD_7 and P, which were 89% and 75% respectively. On the other hand, nitrogen purification was less efficient, and the purification efficiency of nitrogen was 52%.

Table 5. Inflow and outflow concentrations, purification efficiency, and mass removal in the hybrid wetland system in Kodijärve (average±standard deviation). For non-normally distributed data average (av), min and max values are given.

Parameter	BOD_7	Total N	Total P
Number of analysis (n)	96	96	102
Inflow (mg l^{-1})	124.9±57.6	96.5±29.6	13.9±4.3
Outflow (mg l^{-1})	av 13.4 min 1.0 max 69.3	46.2±15.8	3.4±1.7
Efficiency (%)	89.0±12.8	52.1±19.0	75.2±18.7
Mass removal (g m^{-2} d^{-1})	1.6±1.5	1.2±1.0	0.18±0.16

The main problem encountered by the treatment plant was with nitrification, caused by anaerobic conditions dominant in deeper parts of HSSF beds (Mander *et al.*, 2001, Publication III). Due to insufficient nitrification, the removal of NH_4-N was unsatisfactory (54%) and most of N in outflow was in form of NH_4-N. On the other hand, because of anaerobic conditions, denitrification was efficient and concentrations of NO_3-N in outflow were relatively low. To improve aeration in the wetland system, in the summer of 2002 a vertical flow wetland was built between the septic tank and the HSSF part, as the first stage

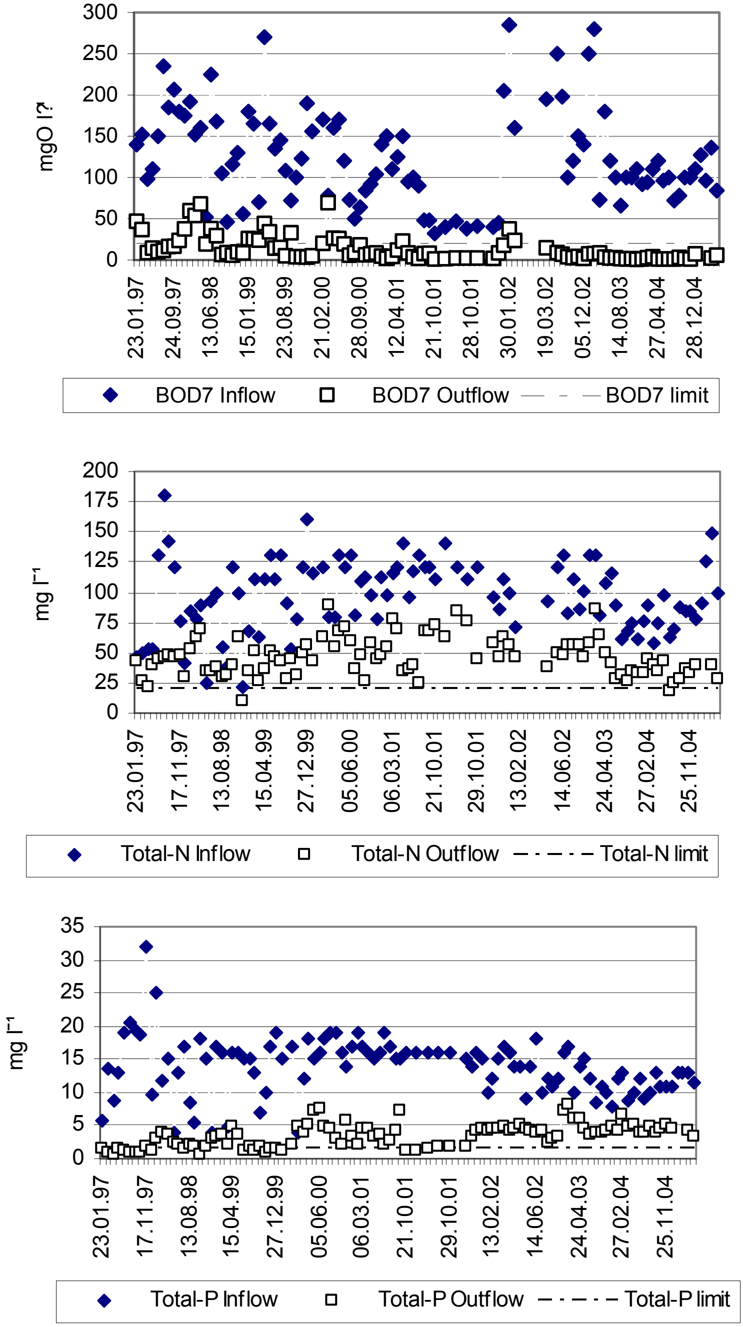

Figure 4. Variation of concentrations of organic material (after BOD_7), N and P in inflow and outflow in the hybrid wetland system in Kodijärve.

of the hybrid wetland system. Due to the VSSF, aeration conditions improved in the wetland system. Hence there has been a significant improvement in the removal of organic material, and the mass removal rate of NH_4-N and total nitrogen improved significantly, although the improvement of purification efficiency was not significant (Noorvee *et al.,* 2005a). In the case of phosphorus, the mass removal rate significantly improved after the establishment of the VSSF, but unfortunately purification efficiency significantly decreased at the same time (Noorvee *et al.,* 2005a). After the establishment of the VSSF, there have been problems with denitrification in the Kodijärve wetland system, reflected by increased average nitrate concentrations in outflow. Efficient denitrification is found to be retarded by improved aeration conditions in the HSSF, as well as by the low amount of organic material (Noorvee *et al.,* 2005a). During the investigation period, the outlet concentrations of phosphorus were slowly increasing, and at the same time the purification efficiency and annual phosphorus retention decreased. At the same time, there is constant Fe outwash from the HSSF, caused by anaerobic conditions in deeper parts of the HSSF, which decreases phosphorus sorption capacity. Thus the phosphorus retention capacity of the filter material in the HSSF wetland is apparently reaching its limit. To improve phosphorus removal, the additional 10 m^2 phosphorus sedimentation filter filled with the sediment from oil shale ash plateau was constructed at the outflow of the HSSF. The sedimentation filter showed satisfactory removal of phosphorus, but unfortunately there appeared saturation problems during relatively short time and filter needs some improvement (Vohla *et al.,* 2005).

Although the average purification efficiency of phosphorus was satisfactory, the average outflow concentrations exceed limit values. Also, the outflow concentrations of nitrogen exceed the recommended level of 20 mg l^{-1}. In the case of organic matter, average outflow concentrations meet the limit value.
The average values of the area-based first-order rate-constant k for the BOD_7, total N and total P of the hybrid CW throughout the whole study period were 15.8; 7.6; and 6.7 m yr^{-1}, respectively. In the case of the Kodijärve CW, the k values are lower than reported in the literature (Kadlec and Knight, 1996; Kadlec, 2000). Lower k values are caused by low hydraulic load, as well as anaerobic conditions in the CW (Noorvee *et al.,* 2005).

The N, P, and carbon contents in the filter material show a variable pattern in both in space and time (Mauring *et al.,* 2001, Publication I). During the period from 1997 to 2003, the concentrations of N, P and C were generally increasing. On the contrary, from 2003 to 2004 some decrement can be observed (Fig. 5).

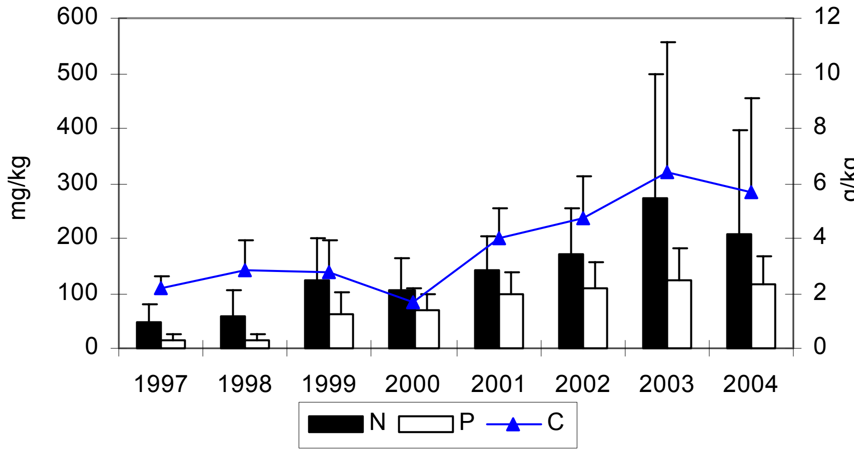

Figure 5. Change in average concentrations of N, P, and C in filter material of Kodijärve HSSF.

4.5. The free water surface treatment wetland system in Põltsamaa

The Põltsamaa free water surface constructed wetland is a cascade of 4 serpentine ponds designed for the secondary treatment of wastewater from the conventional treatment plant in Põltsamaa (about 5000 inhabitants). The total area of the CW reaches 1.2 ha, and the area of shallow ponds (average water depth 0.5 m, first pond 1.0 m) varies from 0.2–0.3 ha. The 2nd and 3rd pond were planted with *T. latifolia* and the 4th pond with *P. australis*. Average inflow flowrate was 700 $m^3 d^{-1}$. This system was constructed in 1997.

Figure 6 shows the variation of the 1st pond inlet and the 4th pond outlet parameters in this system. The average inflow and outflow concentrations, purification efficiency and mass removal of the most important nutrients and organic matter is given in Table 6.

Table 6 indicates that there are great problems with purification processes in the Põltsamaa FSW. The problems are mostly caused by the malfunctioning of the Põltsamaa conventional treatment plant. Because of that, large variations in inflow concentrations and flowrates can be observed. Although the constructed

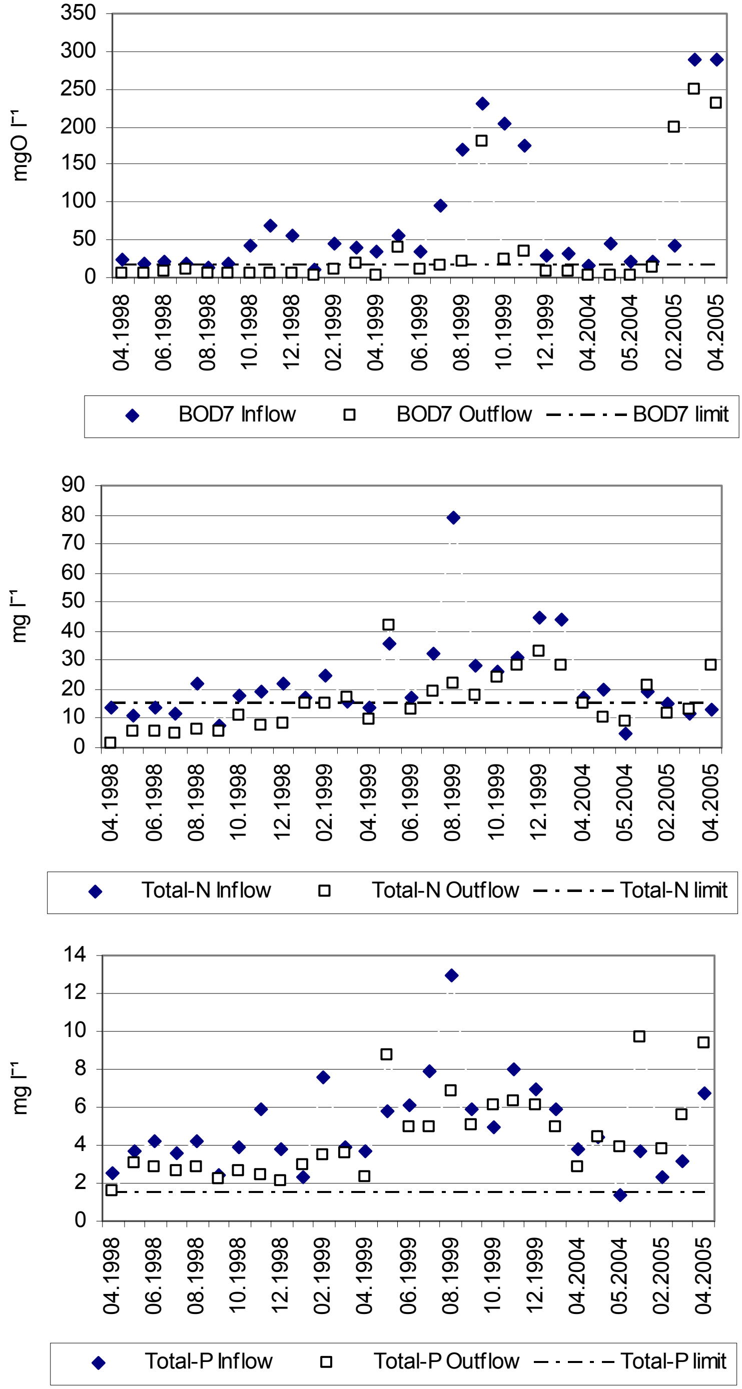

Figure 6. Inlet and outlet concentrations of organic material, N and P in the Põltsamaa free water surface wetland.

Table 6. Inflow and outflow concentrations, purification efficiency and mass removal in the free water surface treatment wetland in Põltsamaa (average±standard deviation). For non-normally distributed data average (av), min and max values are given.

Parameter	BOD_7	Total N	Total P
Number of analysis	29	29	29
Inflow (mg l^{-1})	av 74.5	22.4±14.6	4.9±2.4
	min 11.5		
	max 290.0		
Outflow (mg l^{-1})	av 39.2	15.4±9.7	4.4±2.2
	min 1.8		
	max 250.0		
Efficiency (%)	av 51.9	av 24.3	av –1.4
	min -376.2	min -115.4	min -178.6
	max 92.6	max 90.7	max 59.3
Mass removal (g m^{-2} d^{-1})	av 2.5	av 0.5	av 0.1
	min -4.7	min -1.0	min -0.3
	max 12.9	max 4.9	max 0.5

wetlands are usually able to manage variable conditions, in Põltsamaa the variations in input loading seem to be too great. In the worst case the organic material loading reached 200 kg BOD_5 ha^{-1} d^{-1}, which significantly exceeds the recommended optimum organic loading rate of <80 kg BOD_5 ha^{-1} d^{-1} for FSW (Vymazal, 2001). Also, in some cases there was a hydraulic overloading of the system. Due to the high and extremely variable input load, the BOD_7, total N and total P values in the outlet of the FSW were high and extremely variable: 1.8–250; 1.3–42 and 1.6–9.7 mg l^{-1} respectively. In the case of organic matter and P, the average outflow concentrations exceed limit values. The situation is the worst in the case of P, except for one case; outflow concentrations do not meet limit value and the average purification efficiency was negative. Low purification of P is typical for FSW wetlands. This is mainly caused by little contact between the water column and the soil, which limits precipitation with metals, as the major process in phosphorus removal. Removal of nitrogen was low, although average inflow concentrations were low and average outflow concentrations of nitrogen meet the recommended limit. Low nitrogen removal was in most cases caused by insufficient nitrification because there was no significant ammonia removal in this system. To improve purification in the Põltsamaa FWS wetland, it is important to guarantee the normal performance of the Põltsamaa conventional treatment plant, and it is also necessary to remove sediments from FWS ponds.

4.6. The hybrid wetland system in Kõo

The hybrid treatment wetland system at Kõo consists of a two-bed vertical subsurface flow (VSSF) filter (2×64 m^2, filled with 5–10 mm crushed limestone, planted with *P. australis*), an horizontal sub-surface flow (HSSF) filter (365 m^2, filled with 15–20 mm crushed limestone, planted with *T. latifolia* and *P. australis*), and two free water surface (FWS) wetland beds (3600 and 5500 m^2, planted with *T. latifolia*). The estimated inflow to the system is 40 m^3d^{-1}. The wetland system was constructed in 2000 for the purification of the raw municipal wastewater generated by about 300 population equivalents.

Summary results of average inflow and outflow concentrations, purification efficiency and mass removal of the most important nutrients and organic matter are given in Table 7.

Table 7. Inflow and outflow concentrations, purification efficiency and mass removal in the hybrid wetland system in Kõo (average ± standard deviation). For non-normally distributed data average (av), min and max values are given.

Parameter	BOD_7	Total N	Total P
Number of analysis (n)	8	8	8
Inflow (mg l^{-1})	141±111.6	50.9±31.8	7.04±4.39
Outflow (mg l^{-1})	av 17.4	av 17.9	av 2.03
	min 3.0	min 2.5	min 0.14
	max 90.0	max 65.0	max 8.7
Efficiency (%)	87.9±10.9	65.5±24.4	72.3±24.6

Both inflow as well as outflow concentrations are variable in the Kõo hybrid wetland system. Limited data from the Kõo hybrid wetland system show satisfactory purification efficiency in the case of organic matter and phosphorus, although average effluent concentrations of phosphorus slightly exceed limit value. Nitrogen purification was less efficient, but the quality of outflow is satisfactory. In the case of nitrogen purification, there seems to be some problem with nitrification, reflected by relatively high NH_4-N concentrations in outflow (average NH_4-N outflow concentrations were 12.8 mg l^{-1}). This may be caused by inadequate aeration in VSSF caused by too high organic material loading. One can expect some improvement of purification, caused by the development of vegetation in the wetland system. No long-term conclusions, however, can be drawn on the basis of the limited data from the Kõo hybrid wetland system.

4.7. The hybrid wetland system in Paistu

The hybrid wetland system in Paistu consists of a two-chamber vertical sub-surface flow (VSSF) filter (2×108 m^2) and a 216 m^2 horizontal sub-surface flow (HSSF) filter bed. Both filters are filled with LWA (name of the local Estonian product: FIBO) of different sizes. The HSSF bed is planted with *P. australis*, whereas the VSSF beds are covered by topsoil and lawn. The treatment system was constructed in 2002, and it treats the wastewater of 140 people (120 students and 20 teachers and staff members, which for schoolhouses is calculated as 64 PE; Kuusik, 1995).

The summary results of average inflow and outflow concentrations, purification efficiency and mass removal of the most important nutrients and organic matter is given in the Table 8. Figure 7 shows the temporal variation of the inlet and outlet concentrations.

Table 8. Inflow and outflow concentrations, purification efficiency, and mass removal in the hybrid wetland system in Paistu (average±standard deviation). For non-normally distributed data average (av), min and max values are given.

Parameter	BOD_7	Total N	Total P
Number of analysis (n)	18	18	18
Inflow (mg l^{-1})	91.8±46.9	64.3±30.1	4.4±2.2
Outflow (mg l^{-1})	av 5.5 min 2.1 max 28.0	19.2±6.7	0.4±0.3
Efficiency (%)	90.8±13.1	62.8±21.6	88.6±11.3
Mass removal (g m^{-2} d^{-1})	1.53±1.28	0.48±0.42	0.06±0.04

Typically for schoolhouses, water discharge showed significant changes on both the diurnal and annual levels, being 7.4 m^3d^{-1} on average, and fluctuating from 0 (in night and in summer) to 17.7 m^3d^{-1}. In conventional wastewater plants, such a change in hydraulic loading normally causes the collapse of purification processes (Wittgren and Maehlum, 1997). Nevertheless, in the Paistu hybrid CW system, no significant problems have been detected. Both the BOD_7 value and the concentrations of N and P increased significantly in the outflow from the HSSF, the respective average values were 5.5; 19.2, and 0.4 mg l^{-1}. A remarkable purification also occurred in the VSSF filter bed, although the purification of BOD was most significant. Average outflow concentrations met limit values for organic material, total-N and total-P.

In terms of purification efficiency and mass removal, the wetland system demonstrates outstanding results. The relatively high standard deviation values of mass removal are caused by changing hydraulic loading. Comparison of

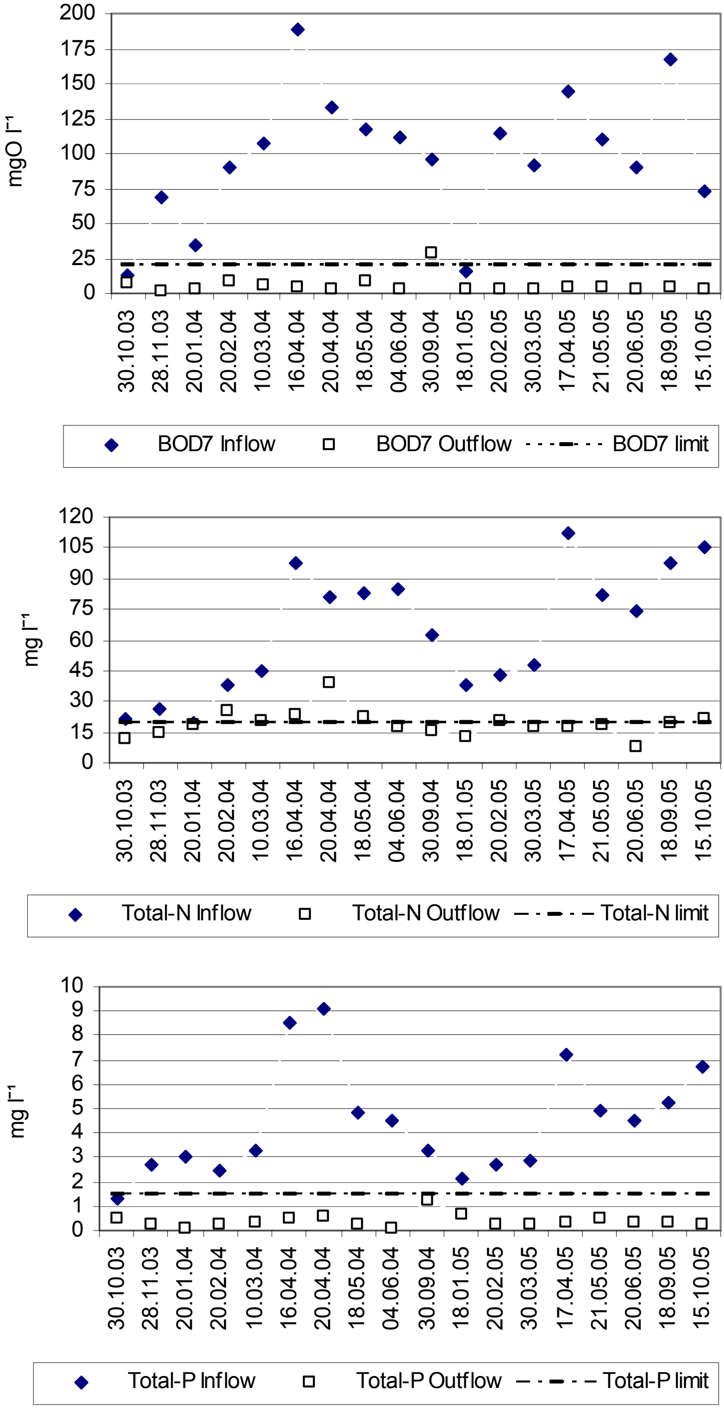

Figure 7. Variation of concentrations of organic material, N and P in inflow and outflow of the hybrid wetland system in Paistu.

removal efficiency and mass removal in warm and cold periods showed that there were no significant differences between these parameters in cold and warm periods for the entire CW. On the other hand, nitrate concentrations in the outflow of both VSSF and HSSF were significantly higher in winter, which points to lower denitrification efficiency during the cold period (Öövel *et al.*, 200X, Publication V).

The average and standard deviation values of the area-based first-order rate-constant k for BOD_7, total N and total P of the entire hybrid CW throughout the whole study period were 20.1±13.4; 18.2±13.3, and 17.1±12.4 m yr^{-1} respectively. These values fit into the range of those described in other studies (Kadlec and Knight, 1996; Kadlec, 2000), whereas for total P, the k value from Paistu was among the highest reported. There was no significant difference in the k values of most of the indicators between the warm and cold periods, except for total N, which was higher during the warm period in the HSSF filter. The hydraulic load was significantly correlated with the k values of all studied parameters. Also, the mass loading and mass removal rates were significantly correlated.

Although the Paistu hybrid constructed wetland system shows outstanding results in term of purification of BOD_7 and total P, in the case of nitrogen there is room for improvement. In the Paistu system, nitrification seems to be satisfactory, although denitrification efficiency varies remarkably. This could be caused by the slower growth of denitrifiers. The development of the root zone will probably enhance denitrification. Another way to enhance denitrification is to prolong retention time by increasing the water table in the HSSF filter (Öövel *et al.*, 200X, Publication V).

4.8. Tertiary treatment on floodplain peatland

The 300 m wide floodplain of the Valgejõgi River has been used for 25 years as a sink of concentrated municipal wastewater with a maximal discharge of 60,000 to 80,000 m^3d^{-1} (Mander et al., 1997). In 1997, a new conventional wastewater treatment plant was constructed. Therefore the loading of nutrients to the Valgejõgi River decreased significantly, and the quality of the Valgejõgi River improved significantly (Öövel et al, 2005, Publication IV). However, in the case of nutrients, the Tapa purification plant does not work efficiently. Therefore the outlet concentrations of Tapa purification plant are still too high in the case of total P, total N and nitrate to meet legal standards. Organic material removal is high. Thus there is both a need and an opportunity for tertiary treatment of wastewater on the river's floodplain.

For the experimental plot, we chose a 21x31 m quadrate on the floodplain that was covered by willow bushes and sedge-dominated fen patches. Because of the absence of precipitation during the study period, the groundwater level in the peatland remained deeper than piezometers. Therefore, the water sampled in the tubes was 100% the filtrate of the sewage plant effluent. Inflow to the experimental plot, as part of outflow from the conventional treatment plant, is estimated at 60 m^3d^{-1}. In the case of nutrients, remarkable purification occurred on the floodplain peatland. Nitrate, as the majority of total N concentration, decreased significantly, from 34 to 1.5 mg l^{-1}, and thus purification efficiency was between 50–85%. As NH_4-N concentrations in the treatment plant effluent were low, concentrations increased slightly along the distance from the inflow pipe. Total P concentrations decreased significantly in the experimental plot, varying from 12–13 in inflow to 0.2–1.8 mg l^{-1} in outflow, and purification efficiency was 68–75%. As the content of organic matter in treatment plant effluent was low, concentrations increased slightly in the distal part of the sampling plot. Due to variations in vegetation and microrelief, aeration conditions in the peat were variable (average redox potential in piezometers was from 68 to 235 mV). Despite the low groundwater level, the peat was slightly anaerobic, offering optimal conditions for denitrification. During periods of higher groundwater level, the peat will be less aerated, which might retard phosphorus removal in deeper parts of the peatland. To provide effective removal of phosphorus and nitrate, it is important to avoid the bypass flow of effluent, which may cause a significantly lower removal of nutrients (Heikkinen *et al*., 2003). The durability of good removal capacity is a question for further study.

5. CONCLUSIONS

As different pollutants act differently in wastewater and in wetlands, it is possible to apply different types of constructed wetlands to achieve the best result. In selecting the type of treatment wetland, it is always important to consider the characteristics of the wastewater, as well as the hydraulic regime.

The 8 studied wastewater treatment constructed wetlands can be divided into two groups: subsurface flow constructed wetlands treating effluent from a septic tank, and free surface water or seminatural wetlands for secondary treatment.

In the case of subsurface flow constructed wetlands, the average outflow concentrations for BOD_7, total nitrogen and total phosphorus were 16 (from 6 to 28); 27 (from 18 to 46) and 2 (from 0.4 to 3) mg l^{-1} respectively, and treatment efficiency 87 (from 82 to 91), 54 (from 36 to 66) and 77 (from 72 to 87)% respectively. The average mass removal rates for BOD_7, nitrogen and phosphorus were 2.3 (from 1.5 to 4.1), 0.9 (from 0.5 to 1.2) and 0.2 (from 0.06 to 0.4) g m^{-2} d^{-1} respectively. This indicates that removal of organic matter and total phosphorus in all of the studied subsurface flow wetland systems was satisfactory. Although not in all cases, the average outflow parameters met standard values. In the case of organic matter, the situation was worst in the VSSF in Põlva and in Kodijärve hybrid wetland system until the construction of the VSSF. In Kodijärve wetland system, it was caused by poor aeration conditions, as is typical for horizontal subsurface flow wetlands. After the establishment of the aerating VSSF filter, outflow values of organic matter are remarkably low. In the case of the Põlva VSSF filter, insufficient aeration was caused by poor vegetation development during the first years. Phosphorus removal is typically good in subsurface flow wetlands, but the longevity of this process must be monitored. In the Kodijärve hybrid wetland system HSSF, for example, the phosphorus removal capacity appears to reach its limit. So far good results have been accomplished with LWA in the Paistu hybrid wetland system; because of higher porosity, it should be able to maintain its removal capacity longer than sand. The most problematic compound in subsurface flow wetlands is nitrogen. As expected, higher nitrogen removal occurred in hybrid wetland systems in Kõo and Paistu, with well-aerated VSSF filters followed by less aerated HSSF filters. In both of these wetland systems, the average nitrogen outflow concentrations were below limit values. Both Põlva and Kodijärve had problems with nitrification, which is caused by insufficient aeration. After establishment of the VSSF filter in Kodijärve, there are good conditions for nitrification, but the limiting step is denitrification.

The seminatural constructed wetlands in Koopsi, Sangla-Rakke and the floodplain peatland of Valgejõgi demonstrated good performance in the case of all of the studied parameters. In Koopsi, Sangla-Rakke and the Valgejõgi floodplain, the average outflow values were below standard limits, except for organic matter content in Sangla-Rakke. In the case of Sangla-Rakke, the average purification efficiency of BOD_7 was as high as 91%; higher outflow concentrations were caused by the overloading of the wetland system. Despite the overloading, removal rates were remarkably high compared with other studied wetlands. Results indicate that in seminatural wetlands, there is great variation of conditions that support removal processes of various contaminants.

The free water surface wetland system in Põltsamaa is the worst example among the studied treatment wetland systems. Because of technical problems at the Põltsamaa conventional treatment plant, there were extremely high variations in inflow loading, and in some cases the system was highly overloaded. Because of that, removal processes were inhibited, and at the end of the study period the wetland system became a source of organic material and nutrients.

Investigations of 8 different treatment wetlands indicate that in the case of proper design and construction and good maintenance, constructed wetlands should be considered an alternative to other wastewater treatment methods. Constructed wetlands can be used especially for individual houses, farms and tourist resorts where there is variable input loading that makes it difficult to use conventional purification methods. In the case of domestic wastewater treatment, the best results are obtained by hybrid wetland systems, where it is possible to create aerobic as well as anaerobic conditions for both nitrification and denitrification, which is difficult to achieve in a one-stage treatment wetland. Seminatural wetlands are effective in the treatment of secondary wastewater. Their good performance is mainly caused by great variations in aerating conditions. It can be concluded that treatment wetlands with greater variations in environmental conditions are able to offer better treatment of wastewater.

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SUMMARY IN ESTONIAN

Heitveepuhastus-märgalade efektiivsus Eestis

Märgalasid on heitvee puhastamiseks kasutatud juba pikka aega, ehkki varasemal ajal olid märgalad kasutusel pigem kellelegi mittevajaliku kohana, kuhu oli mugav heitvett juhtida. Viimasel ajal on leidnud üha enam rakendust heitvee puhastamine selleks spetsiaalselt konstrueeritud märgalades. Konstrueeritud reoveepuhastus-märgalade eeliseks looduslike märgalade ees on paremad võimalused kombineerimaks erinevaid pinnase, veerežiimi ja taimestiku omadusi saavutamaks puhastusprotsesside võimalikult efektiivne toimumine. Tehismärgalade kõrval on siiski oma koht heitvee puhastuses ka looduslikel ja poollooduslikel märgaladel. Lähtuvalt märgalataimestikust saab tehismärgalasid jagada erinevatesse tüüpidesse: märgalad veepinnal ujuvate taimedega, märgalad veesiseste taimedega, märgalad ujulehtedega taimedega ning helofüütidega märgalad. Viimased jagunevad omakorda sõltuvalt vee voolamise tingimustest gruppidesse.

Reoainete eraldamine heitveest toimub erinevate bioloogiliste, keemiliste ja füüsikaliste protsesside tulemusel, erinevaid puhastusprotsesse pidurdavad või soodustavad erinevad keskkonnategurid. Seega on erineva konstruktsiooniga puhastusmärgalad erineva puhastusvõimega. Teisalt võib puhastusvõime varieeruda suurel määral ka sarnase konstruktsiooniga märgalade hulgas. Seega oligi käesoleva uurimistöö eesmärkideks analüüsida 8 erineva Eesti puhastusmärgala toimimist ning võrrelda erinevaid märgalatüüpe orgaanilise aine, lämmastiku ning fosfori puhastuse võime osas.

Töös käsitletakse järgmisi puhastusmärgalasid: kombineeritud pindmise ja pinnasisese vooluga *Phalaris arundinacea* nõlv Koopsis; märgalataimestikuga kraav Sangla-Rakkes; vertikaalvooluline taimestik-pinnasfilter Põlvas; algselt horisontaalvooluline taimestik-pinnasfilter, nüüdseks hübriidne märgalasüsteem Kodijärvel; avaveeline märgalasüsteem Põltsamaal; hübriidsed märgalasüsteemid Kõos ja Paistul ning Tapa linna heitvee järelpuhastuseks kasutatav jõelamm. Uuritud märgalad näitavad võrdlemisi erinevaid tulemusi. Ehkki *Phalaris*-süsteemi puhastusvõime ei olnud orgaanilise aine ja lämmastiku osas just kuigi kõrge (BHT_7, üld-N ja üld-P osas vastavalt 65%, 67% ja 80%), olid väljavoolu kontsentratsioonid alati väga madalad. Ajutiste suurte sisendkoormuste tõttu oli taimestikuga kraavi väljundparameetrid väga varieeruvad: BHT_5 5-100; üld-N 6-16 ja üld-P 1-4 mg l^{-1}. Orgaanilise aine ja üld-P osas oli Põlva vertikaalvoolulise süsteemi efektiivsus märkimisväärne (keskmiselt BHT_7 – 82% ja üld-P – 74%), kuid lämmastikueraldus oli problemaatiline (keskmiselt 36%). Sarnaseid tulemusi näitas ka Kodijärve märgalasüsteem, mille BHT_7, üld-N ja üld-P keskmised puhastusefektiivsused olid vastavalt 89%, 52% ja 75%, keskmistes väljavoolukontsentratsioonides võib rahule jääda eelkõige madala orgaanilise aine sisaldusega. Avaveeline Põltsamaa märgalasüsteem ei töötanud ootustele vastavalt, selle peamiseks põhjuseks tuleb pidada tehnilisi probleeme linna puhastusseadmes. Probleemide tõttu olid väljavoolukontsentratsioonid äärmiselt varieeruvad: BHT_7 – 1,8-250; üld-N – 1,3-42 ja üld-P 1,6-9,7 mg l^{-1}. Kõo hübriidsüsteemis toimus BHT_7 ja üld-P puhastusprotsessid efektiivselt (vastavalt 88% ja 72%), mõnevõrra madalam oli üld-N puhastus (efektiivsus 65%). Paistu hübriidsüsteemi keskmised väljundparameetrid orgaanilise aine ja fosfori osas olid märkimisväärsed – BHT_7 – 5,5 ja üld-P – 0,4 mg l^{-1}, kuid ka üld-N keskmine kontsentratsioon jäi allapoole soovituslikku piirväärtust (19 mg l^{-1}). Pool-looduslikul lammialal toimus märgatav järelpuhastus, üld-P ja nitraadi kontsentratsioonid olid 0,2–1,8 ja 1,5 mg l^{-1}.

Lähtudes nii märgalasüsteemide konstruktsioonist kui puhastatava vee päritolust, saab uuritud märgalasüsteemid jagada kahte gruppi: eelkõige pinnasisese vooluga märgalad, mis puhastavad mehhaanilise eelpuhastuse läbinud olmereovett ning pool-looduslikud ja avaveelised märgalad, mida kasutatakse järelpuhastuseks. Esimese grupi puhul on tüüpiliseks jooneks kõrge orgaanilise aine ning natuke madalam, kuid siiski märkimisväärne fosfori puhastusefektiivsus. Efektiivsemates märgalasüsteemides jäid keskmised orgaanilise aine ja üld-P kontsentratsioonid allapoole reostuse piirväärtusi. Samas tuleb juhtida tähelepanu fosfori kõrge puhastusvõime võimalikule lühiealisusele (näiteks oli Kodijärve horisontaalfiltri liiva fosfori sidumisvõime ammendumas). Enim erinevusi esines üld-N puhastuses. Nagu oli ka oodata, näitasid paremaid tulemusi hübriidsed märgalad, milles on järjestikuliselt ühendatud enam aereeritud vertikaalvoolulised filtrid ja valdavalt anaeroobsed horisontaalvoolulised filtrid, mis võimaldavad järjestikku toimida nitrifikatsioonil ning denitrifikatsioonil. Selle tulemusena olid ka keskmised väljavoolu kontsentratsioonid madalamad kui soovituslikud lämmastiku-sisalduse piirväärtused. Uuringud näitavad, et pool-looduslikud märgalad on efektiivsed eelnevalt puhastatud heitvee järelpuhastamiseks, kõigi kolme uuritud pool-loodusliku märgala puhul olid keskmised väljavoolu kontsentratsioonid reostuse piirväärtustes väiksemad (va. orgaanilise aine sisaldus Sangla-Rakke süsteemis, mis oli põhjustatud süsteemi ülekoormamisest). Kahjuks on andmed Põltsamaa avaveelise märgala kohta vastukäivad, kuid siiski saab tuua välja mõningad avaveelistele märgaladele iseloomulikke jooni – heitvee ning pinnase vähese kokkupuute tõttu on üld-P puhastus madal, ebapiisava taimestiku arengu korral prevaleerivad anaeroobsed tingimused, mistõttu võib probleeme esineda ka üld-N puhastusega.

Saadud tulemused näitavad, et heitveepuhastus-märgalad on täiesti arvestatavaks alternatiivseks võimaluseks heitvee puhastamisel. Oluline heitveepuhastus-märgalade eelis konventsionaalsete tehnoloogiate ees ilmneb muutliku voolurežiimi ja koormuste puhul, näiteks üksikmajapidamiste, talude või turismiasustuste heitvee puhastamisel. Üldistades võib väita, et mida suurem on tingimuste heterogeensus märgalasüsteemis, seda efektiivemaks võivad kujuneda selle puhastusprotsessid.

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PUBLICATIONS

SCHOOLHOUSE WASTEWATER PURIFICATION IN A LWA-FILLED HYBRID CONSTRUCTED WETLAND IN ESTONIA

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ABSTRACT

This paper analyses the purification efficiency and mass removal of organic material, suspended solids, nitrogen and phosphorus in a hybrid constructed wetland (CW) system treating wastewater from a basic school in Paistu, Estonia. The CW consists of two subsurface flow filter beds using Lightweight Aggregates (LWA), and a two-chamber vertical subsurface flow filter (VSSF) followed by a horizontal subsurface flow filter (HSSF), with a total area of 432 m^2. This CW was constructed in summer 2002 by the Centre for Ecological Engineering in Tartu (CEET). Eighteen series of water samples (from 30.10.2003 to 15.10.2005) were undertaken. The analyses show the outstanding purification effect of the system: for BOD_7 the average purification efficiency is 91%; for total suspended solids (TSS) – 78%, for total P – 89%, for total N – 63%, and for NH_4-N – 77%. The average outlet values for the above-listed parameters were 5.5, 7.0, 0.4, 19.2 and 9.1 mg L^{-1} respectively. According to our results, the purification parameters meet the standards set by the Water Act of Estonia for wastewater treatment plants of 2000–9999 PE: 15, 25, and 1.5 mg L^{-1} for BOD_7, TSS and total P respectively. The results show that hybrid CW systems consisting of subsurface flow filters can work efficiently in conditions of changing hydraulic loading and relatively cold climate. We did not find significant differences between the removal efficiency, mass removal, and values of the first-order rate-constant k for most water quality indicators during the warm (May-October) and cold (November-April) periods. Locally produced LWA as a filter material in CWs has shown good hydraulic conductivity and phosphorus sorption capacity (k = 17.1±12.4 m yr^{-1}). The Paistu CW, with its proper design and outstanding purification results, can be considered one of the best systems in Estonia.

Key words: BOD, hybrid constructed wetland, *k*-*C** model, LWA, mass removal, nitrogen, phosphorus, treatment efficiency

1. INTRODUCTION

Constructed wetlands (CW) have shown their ability to remove large amounts of organic material, nitrogen and phosphorus from wastewater of various origins (Kadlec and Knight, 1996; Vymazal et al., 1998). Among CWs, subsurface flow filter beds are considered suitable for use in cold climate regions (Mander and Mauring, 1997; Wittgren and Maehlum, 1997; Mander et al., 2000). Horizontal subsurface flow (HSSF) filter beds can usually reliably remove BOD and total suspended solids (TSS), but they do not transfer oxygen at a sufficient rate to achieve full nitrification (Cooper et al., 1999). It has generally been agreed that the main removal mechanisms for nitrogen in CWs are ammonification and nitrification/denitrification (Kadlec and Knight, 1996; Vymazal et al., 1998). The conditions in HSSF CWs are usually anoxic or anaerobic, so that the major obstacle to the higher removal of nitrogen is the low rate of nitrification (Cooper et al., 1999). Combined HSSF and vertical subsurface flow (VSSF) wetlands balance out each other's weaknesses, and it is possible to design a system that successfully removes BOD, total N, total P and TSS (Cooper et al., 1999). These combined systems are also called hybrid CWs (Cooper, 1999), and the VSSF filter bed is most typically used as a pre-treatment system providing a sufficient amount of oxygen for both the mineralization of organic material and nitrification (Cooper et al., 1999; Harris and Maehlum, 2003; Noorvee et al., 2005a). For phosphorus removal, however, the filter media's quality (grain size distribution, pH, specific surface area, and the content of Al, Fe and/or Ca ions) is particularly important (Johansson, 1998; Arias et al., 2001; Drizo et al., 2002; Jenssen and Krogstad, 2003; Ádám et al., 2005). Light Weight Aggregates (LWA) or Light Expanded Clay Aggregates (LECA) have shown both good water permeability and phosphorus sorption capability (Zhu et al., 1997; Johansson, 1998; Harris and Maehlum, 2003; Jenssen and Krogstad, 2003). These filter substrates must be available in large quantities at low cost, but with long-lasting phosphorus sorption capacity (Johansson, 1998). Filtralite P™, the new generation of Norwegian-produced LWA, is especially developed for P sorption (Ádám et al., 2005). This new LWA is an illite-based material with high pH and high Ca and Mg content (Jenssen and Krogstad, 2003). After saturation, this material can be used as an alternative fertilizer in agriculture. Kvarnström et al (2004) demonstrated that all inorganic P that was accumulated in LWA was easily soluble, mobile, and available to plants. In Estonia, the most common filter material in HSSF and hybrid filter beds is local sand. However, there is extensive evidence that local sands can only efficiently remove P for 5–6 years, after which they become saturated (Vohla et al., 2005). Therefore, new effective filter materials are of crucial importance for the successful functioning of CWs (see Korkusuz et al., 2005; Søvik and Kløve, 2005).

The main objectives of this paper are: (1) to determine the purification efficiency and mass removal of organic material, suspended solids, nitrogen, and phosphorus in an LWA-filled hybrid CW system treating wastewater from a basic school in Paistu, Estonia, (2) to analyse the influence of the cold period on purification processes in the Paistu CW. This is the first CW based on the LWA produced on the basis of local clay materials in Estonia. Thus the comparison of this material with widely used Filtralite P and other LWA materials is one of the aims of this study.

2. MATERIAL AND METHODS

2.1. Description of the Constructed Wetland

The hybrid CW for treating wastewater from Paistu Basic School, Viljandi County, Estonia (GPS-determined coordinates: inflow 58° 14,493 N; 25° 35,553 E; outflow 58° 14,519 N; 25° 35,584 E; Fig. 1), was designed and constructed in 2002 by the Centre of Ecological Engineering in Tartu (CEET). It treats the wastewater of 140 people (120 students + 20 teachers and staff members, which for schoolhouses is calculated as 64 population equivalents, PE; Kuusik, 1995), and consists of a two-chamber VSSF filter (2×108 m^2) and a 216 m^2 HSSF filter bed. Both filters are filled with LWA (name of the local Estonian product: FIBO) of different size. In both VSSF beds, a 0.5m LWA layer (10–20mm size) above the PVC liner is covered by a 0.3m layer of finer LWA (2–4mm), which increases the oxygen transport into the bed. The VSSF beds are covered with a 0.20m topsoil layer and lawn. A water-permeable geomembrane isolates the soil layer from the upper LWA layer. The HSSF bed (depth 0.9 m) is filled with 2–4mm LWA and is covered with reed (*Phragmites australis*). The calculated area requirement is 6.8 m^2 PE^{-1}, which is higher than that recommended for similar systems in literature (4–5 m^2 PE^{-1}; Kadlec and Knight, 1996).

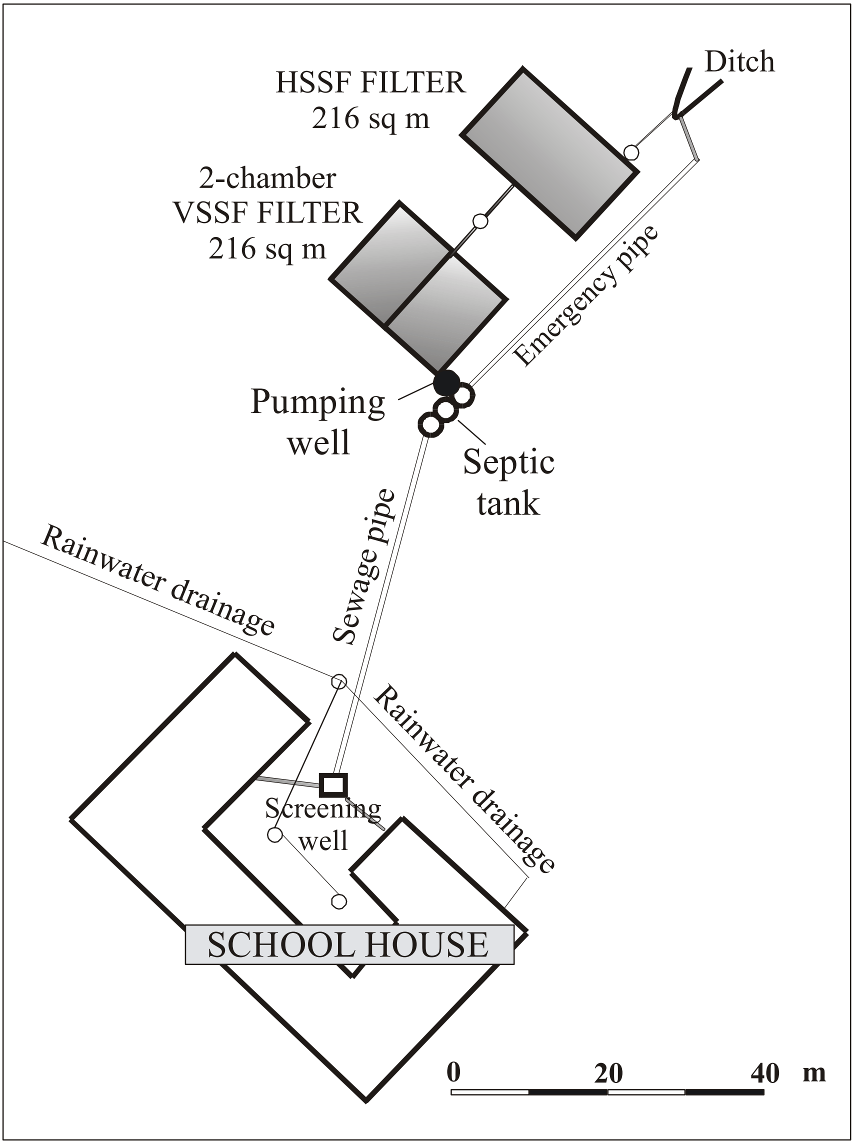


Figure 1. Location scheme of the hybrid constructed wetland system in Paistu, Viljandi County, Estonia.

Before entering the hybrid wetland system, wastewater passes through a two-chamber 30 m^3 septic tank (Fig. 1). The VSSF filter is intermittently loaded at 1 hr pumping intervals. In summer, only one of two beds is (intermittently) in operation, whereas in winter, both beds are used.

2.2 Water Sampling and Analysis

Eighteen series of water samples (from 30.10.2003 to 15.10.2005) were taken. On site, the pH, water temperature, conductivity, and dissolved O_2 in the inflow and outflows from the VSSF and HSSF beds were measured using Evikon portable equipment (Evikon MultiLine F/SET-3, Multiline F/SET-3 and OXI 330/SET). In the laboratory of Tartu Water Ltd., water samples from the inflow and outflows from both VSSF and HSSF filters were analysed for BOD_7, TSS, NH_4^+–N, NO_2^-–N, NO_3^-–N, total N, PO_4^{3-}–P and total P (all according to APHA, 1989). For technical reasons, NO_2–N and NO_3–N, values are missing in 3 measurement series (20.02, 17.04, and 20.06.05).

During each sampling event, water discharge was measured volumetrically. In order to obtain daily average discharge values, a limnigraph installed in the pumping well was used. Air temperature and precipitation data originated from the Viljandi station of the Estonian Meteorological and Hydrological Institute (EMHI).

2.3. Calculations and Statistical Analysis of Data

The purification efficiency (*PE*; %) for water quality indicators was calculated using the following equation (see Kadlec and Knight, 1996):

$$PE = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \,, \qquad (1)$$

where:
- *Cin* – average value of inflow concentration (mg L^{-1});
- *Cout* – average value of outflow concentration (mg L^{-1}).

Mass removal (*MR*; g m^{-2} d^{-1}) is calculated on the basis of the following equation (see Kadlec and Knight, 1996):

$$MR = \frac{(C_{in} \times Q_{in}) - (C_{out} \times Q_{out})}{A} \,, \qquad (2)$$

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 concentrations in inflow and outflow (mg L^{-1}).

The removal of BOD_7, total P, NH_4–N, and total N in Paistu was also described using an area-based first-order model (later called the *k-C** model) (Kadlec and Knight, 1996; Kadlec, 2000):

$$\ln\left[\frac{(C_o - C^*)}{C_i - C^*}\right] = -\frac{k}{q}, \qquad (3)$$

where:

- k = the area-based, first-order rate constant (m yr^{-1});
- q = the hydraulic loading rate (m yr^{-1});
- C_o = the effluent concentration (g m^{-3});
- C_i = the influent concentration (g m^{-3});
- C^* = the irreducible background wetland concentration (g m^{-3}).

Based on the published data (Kadlec and Knight, 1996), the C^* values of 1 mg L^{-1} for BOD_7 and 1.5 mg L^{-1} for total N were chosen. It is known that wetlands have very low natural total P and NH_4-N background concentrations (Kadlec and Knight, 1996). The C^* values for these parameters are assumed to be 0.03 and 0.05 mg L^{-1}, respectively.

The available data shows that temperature effects on BOD and phosphorus removal are negligible in SSF wetlands (Mander and Mauring, 1997; Wittgren and Maehlum, 1997; Noorvee et al., 2005b). However, processes like ammonification, nitrification and denitrification have all been proved to be temperature-dependent. Therefore, rates of ammonium and total nitrogen reduction will also be temperature-dependent (Kadlec, 2000). k_T values for nitrogen reduction have to be converted to k_{20} values for purposes of comparison. The relation between k_T and k_{20} is the Arrhenius equation:

$$k_T = k_{20}\,\theta^{\,T-20}, \qquad (4)$$

where:

- k_T = the reaction rate coefficient at temperature T (ºC);
- k_{20} = the reaction rate coefficient at 20 ºC;
- θ = the temperature factor;
- T = temperature (ºC).

An estimate of the temperature factor of ammonium oxidation is $\theta = 1.04$ and for total N reduction $\theta = 1.05$ (Kadlec and Knight, 1996).

After calculating k values for all three parameters, the dependence of k on hydraulic loadings (cm d^{-1}) and initial mass loading rates (g m^{-2} d^{-1}) was investigated.

The statistical analysis of the data was performed using the programme Statistica 6.0. The normality of variables was verified using the Kolmogorov-Smirnov, Lilliefors' and Shapiro-Wilk's tests. Apart from water and air temperature, water discharge and conductivity, the parameters' distribution differed from normal, and hence non-parametric tests were performed. We used the Wilcoxon Matched Pairs Test and the Mann-Whitney U-Test to check the significance of differences between the inflow and outflow parameters. We also used Spearman Rank Correlation analysis to analyse the relationship between the water quality indicators. The level of significance of $\alpha = 0.05$ was accepted in all cases.

3. RESULTS AND DISCUSSION

3.1. Physical-chemical parameters of wastewater

Typically for schoolhouses, water discharge showed significant changes on both the diurnal and annual scales, being 7.4 $m^3\ d^{-1}$ on average, and fluctuating from 0 (in the night and from the end of June until the beginning of September) to 17.7 $m^3\ d^{-1}$ (Table 1). In conventional wastewater treatment systems in Nordic areas, such a dramatic change in hydraulic loading normally causes the collapse of purification processes (Wittgren and Maehlum, 1997). Nevertheless, in the Paistu hybrid CW, we did not detect any significant problems due to changes in water discharge rate.

The wastewater temperature in the system decreased from an average of 8.3 to 6.1 °C, being ≥1.9 °C even in the case of negative outside air temperatures. The daily mean air temperature fluctuated from –7.7 to 15.2 °C (Table 1).

The conductivity and pH values of wastewater decreased during purification in the CW, whereas the concentration of dissolved O_2 increased slightly (Table 1). In all of these cases, the average changes were not significant.

3.2. BOD_7, total suspended solids, nitrogen and phosphorus

Both the BOD_7 value and the concentration of TSS, NH_4-N, total N, PO_4-P, and total P increased significantly in the outflow from the HSSF filter bed. In the septic tank effluent (inflow to the VSSF), the respective average±standard deviation values were 98.1±46.9, 44.7±34.4, 55.8±30.3, 64.3±30.1, 3.2±2.5, and 4.4±2.2 mg L^{-1}, whereas in the HSSF bed outflow, we measured the following values: 5.5±5.9, 7.0±3.8, 9.1±6.0, 19.2±6.7, 0.16±0.16, and 0.4±0.3 mg L^{-1}. A remarkable purification of wastewater was found also in the VSSF filter bed (outflow values were: 18.8±10.2, 11.8±5.0, 22.9±15.7, 36.1±18.7, 0.46±0.55, and 1.2±0.9 mg L^{-1}, respectively), however, only the BOD_7 value decreased significantly. In terms of purification efficiency (%; 90.8±13.1, 78.1±17.5, 77.3±13.1, 62.8±21.6, 92.9 and 88.6±11.3 for BOD_7, SS, NH_4-N, total N, PO_4-P, and total P, respectively) and mass removal (g m^{-2} d^{-1}; 1.53±1.28, 0.67±0.84, 0.53±0.44, 0.48±0.42, and 0.06±0.04, respectively), the entire CW demonstrates outstanding efficiency (Table 2). The relatively high standard deviation values of mass removal are caused by changing hydraulic loading. Our results are comparable with the results of the mesocosm and small-scale pilot studies from Scandinavia (Harris and Maehlum, 2003; Ádám, et al., 2005).

Table 1. Daily mean air temperature, wastewater discharge and selected water quality indicators in the inflow and outflow of the hybrid treatment wetland in Paistu, Estonia.

Date	Air temperature (t°) °C	Discharge (Q) m^3 d^{-1}	Conductivity µs cm^{-1}		Water temperature (t°) °C		Dissolved O_2 mg L^{-1}		pH	
			Inflow	Outflow	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
30.10.2003	0.4	4.1	768	1216	9.8	6.8	6.2	8.8	7.44	7.61
28.11.2003	5.2	9.1	913	873	9.2	6.5	5.5	8.8	7.55	7.62
20.01.2004	–6.0	12.4	761	843	5.5	4.5	5.5	6.5	7.75	7.71
20.02.2004	–7.7	17.7	920	790	5.6	4.4	4.5	4.9	7.20	7.16
10.03.2004	–0.4	5.9	1021	825	5.8	4.1	12.6	13.1	7.16	6.78
16.04.2004	8.6	0.6	1775	730	5.1	4.0	12.8	13.1	7.24	6.98
20.04.2004	13.4	2.2	1723	856	7.9	4.9	0.0	1.1	7.82	7.44
18.05.2004	9.4	9.9	n.d.	n.d.	8.6	5.7	11.7	12.6	7.04	7.52
04.06.2004	14.2	3.5	1534	834	13.2	9.5	4.4	7.2	7.12	7.65
30.09.2004	8.5	2.0	870	1017	12.1	11.5	0.3	0.0	7.70	7.45
18.01.2005	–0.6	5.0	724	672	5.0	2.0	5.0	2.0	7.40	7.75
20.02.2005	–8.7	12.5	1050	895	4.8	1.9	4.4	5.5	7.25	7.82
30.03.2005	2.2	7.5	1087	912	6.5	4.1	7.2	8.5	7.09	7.77
17.04.2005	7.8	4.9	1753	920	7.7	4.8	5.2	5.9	7.32	7.46
21.05.2005	10.2	10.2	1245	980	8.9	5.9	9.2	10.0	7.09	7.54
20.06.2005	15.2	2.7	1438	920	11.5	9.3	4.7	9.7	7.24	7.12
18.09.2005	8.5	12.4	895	1012	12.3	11.8	5.6	10.2	7.65	6.98
15.10.2005	5.4	9.7	870	1015	9.6	7.2	6.5	9.5	7.34	7.52
Average	**4.8**	**7.4**	**1138**	**900**	**8.3**	**6.1**	**6.2**	**7.6**	**7.36**	**7.44**
StDev	**7.3**	**4.7**	**367**	**126**	**2.7**	**2.9**	**3.5**	**3.9**	**0.25**	**0.31**

n.d. – not determined

Table 2. Performance of the Paistu hybrid constructed wetland system (30.10.2003 – 15.10.2005; average±standard deviation values). a, b – significantly differing values ($p < 0.05$) with inflow values to the VSSF according to the Wilcoxon Matched Pairs Test. Both efficiency and mass removal are calculated for the whole CW.

Parameter	Inflow to the VSSF mg L^{-1}	Inflow to the HSSF mg L^{-1}	Outflow from the HSSF mg L^{-1}	Efficiency %	Mass removal g m^{-2} d^{-1}
BOD_7	98.1±46.9	18.8±10.2 [a]	5.5±5.9 [b]	90.8±13.1	1.53±1.28
Suspended solids	44.7±34.4	11.8±5.0	5.8±3.5 [b]	78.1±17.5	0.67±0.84
NH_4-N	55.8±30.3	22.9±15.7	9.1±6.0 [b]	77.3±13.1	0.53±0.44
Total N	64.3±30.1	36.1±18.7	19.2±6.7 [b]	62.8±21.6	0.48±0.42
PO_4-P	3.2±2.5	0.46±0.55	0.16±0.16	92.9±7.0	0.04±0.04
Total P	4.4±2.2	1.2±0.9	0.4±0.3 [b]	88.6±11.3	0.06±0.04

We found a remarkable temporal variation of water quality indicators in the inflow to the CW. At the same time, the outflow concentrations showed some decrease in spring, however, these changes were not significant (Fig. 2). This phenomenon can be related to changes in microbial communities in the spring period (April–May; see also Mander et al., 2000; Nurk et al, in press). In most cases, all of the water quality indicators showed outflow concentrations below the standards set by the Water Act of Estonia or below the recommended values (Fig. 2).

The VSSF guarantees an efficient mineralization of organic matter and a satisfactory nitrification value. Also, the adsorption and sedimentation of phosphorus already takes place in the VSSF bed. The HSSF filter improves all of the parameters, and is supposed to denitrify the nitrate.

Although the entire CW demonstrates satisfactory performance regarding the NH_4-N concentration, most of values being below the recommended level of 10 mg L^{-1}; Fig. 2), in terms of total N removal, it needs some improvement. For instance, nitrate nitrogen concentration stays relatively high in the outflow from the HSSF (Fig. 3). Slight but not significant increase in organic N (Norg = total N – NH_4-N – NO_2-N – NO_3-N; Fig. 3) concentration may be related to the release of organic material from the biofilm-filled concaves in the LWA material. The dynamics of NO_2-N concentration clearly demonstrates the benefits of two-stage hybrid CWs (Fig. 4): significant increase in NO_2-N concentration after the VSSF filter beds indicates that the vertical flow filter works well for the first stage of the nitrification process, whereas a significant decrease of nitrite nitrogen level in the outflow of the HSSF filter bed shows that the horizontal flow filter works well for the second stage of nitrification (see also Cooper 1999; Cooper et al., 1999). Nevertheless, efficiency of denitrification, which transforms NO_3-N into N_2 and N_2O, varies remarkably,

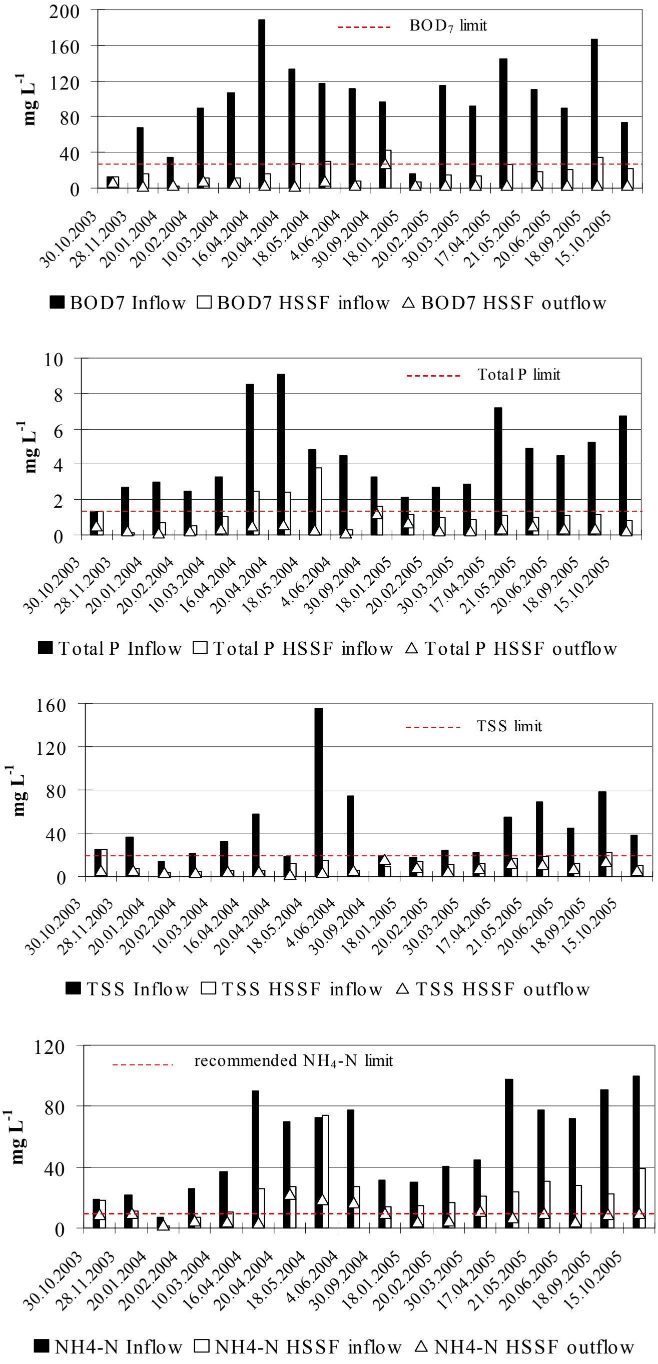


Figure 2. Removal of organic material (BOD_7 value), total suspended solids (TSS), total P, and NH_4-N in the Paistu hybrid constructed wetland system.

causing temporary high NO_3-N values in the HSSF outflow. It is recommended that the water table in the HSSF filter bed be increased in order to allow a longer retention time in the system and to enhance the denitrification process. Apparently the denitrifiers need more time to grow and stabilize. Likewise, the development of reed rootzone will probably enhance the denitrification.

Comparison of removal efficiency (%) and mass removal (g m^{-2} d^{-1}) of total N, NH_4-N, TSS, organic material (based on BOD_7 value), total P, and PO_4-P in warm (May-October) and cold (November-April) periods showed that, although there was a slight decrease in median values of most performance indicators in winter, there were no significant differences between these parameters in cold and warm periods for the CW as a whole (Fig. 5 and 6). The median values of BOD_7 and PO_4-P even showed a slight but non-significant increase in winter.

On the other hand, we found significantly higher nitrate concentrations in the outflow of both VSSF and HSSF filters in winter (Fig. 3), which points again to lower denitrification efficiency during the cold period. These results coincide very well with the results from similar investigations of subsurface flow filter systems in cold climate areas (Harris and Maehlum, 2003).

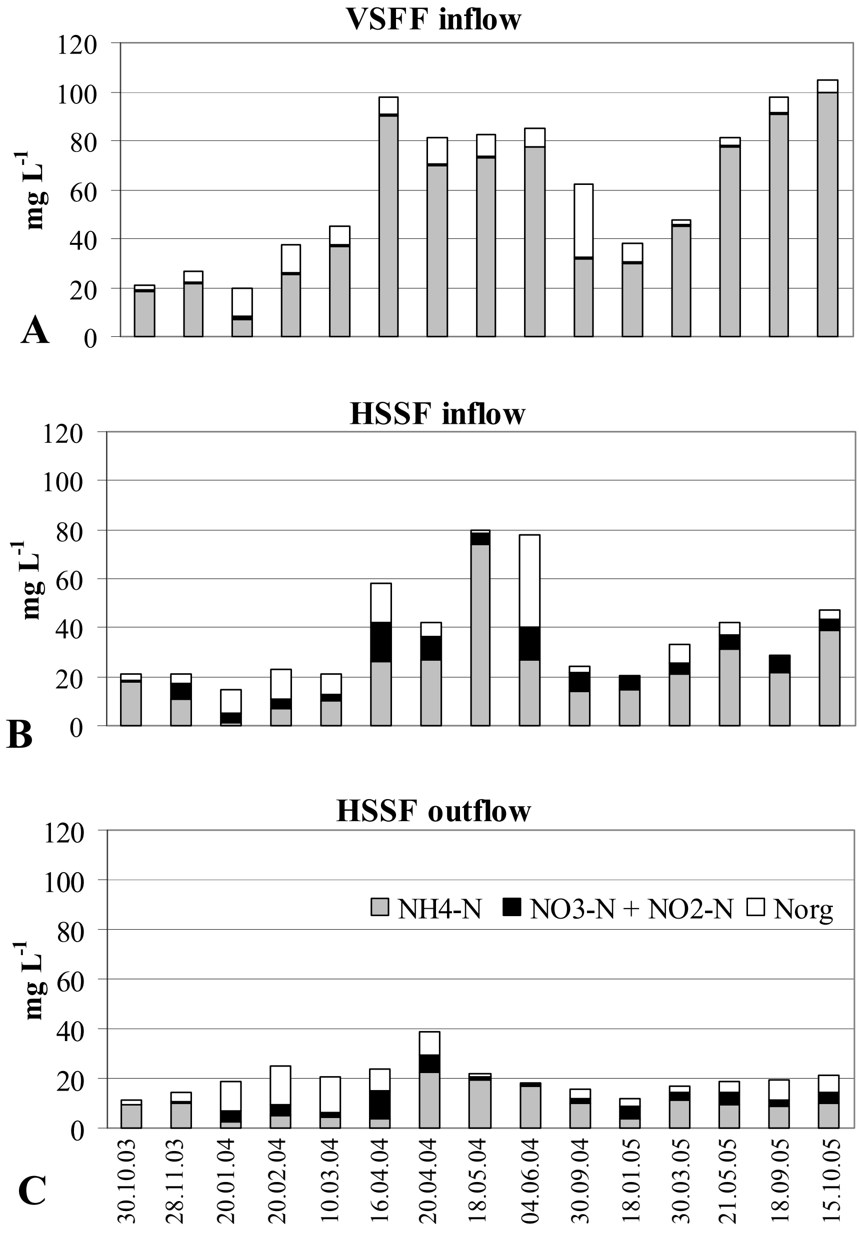


Figure 3. Concentration of NH_4-N, sum of NO_2-N and NO_3-N, and Norg (= total N - NH_4-N – NO_2-N – NO_3-N) in the inflow to the VSSF, inflow to the HSSF, and outflow from the HSSF parts of the hybrid CW.

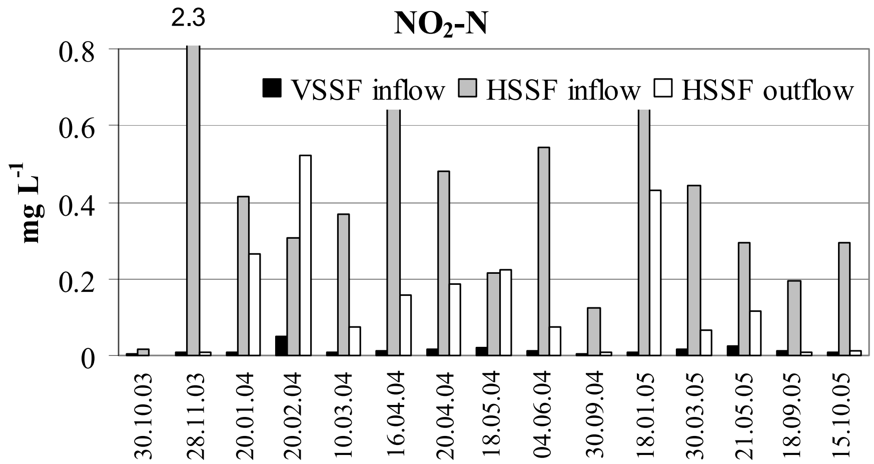


Figure 4. NO_2-N concentration in the inflow to the VSSF, inflow to the HSSF, and outflow from the HSSF parts of the hybrid CW.

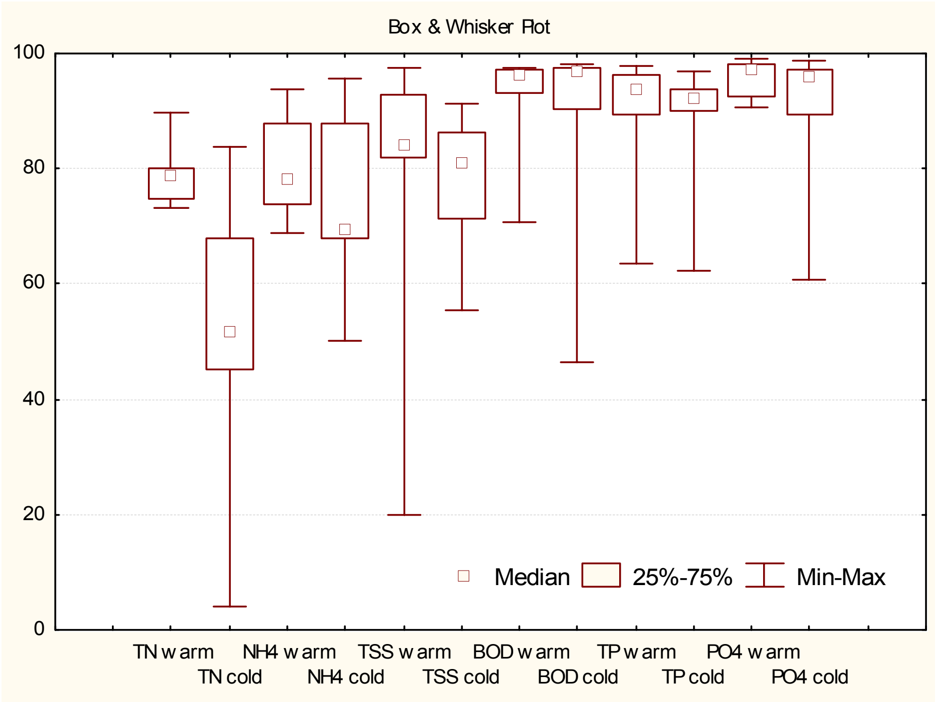
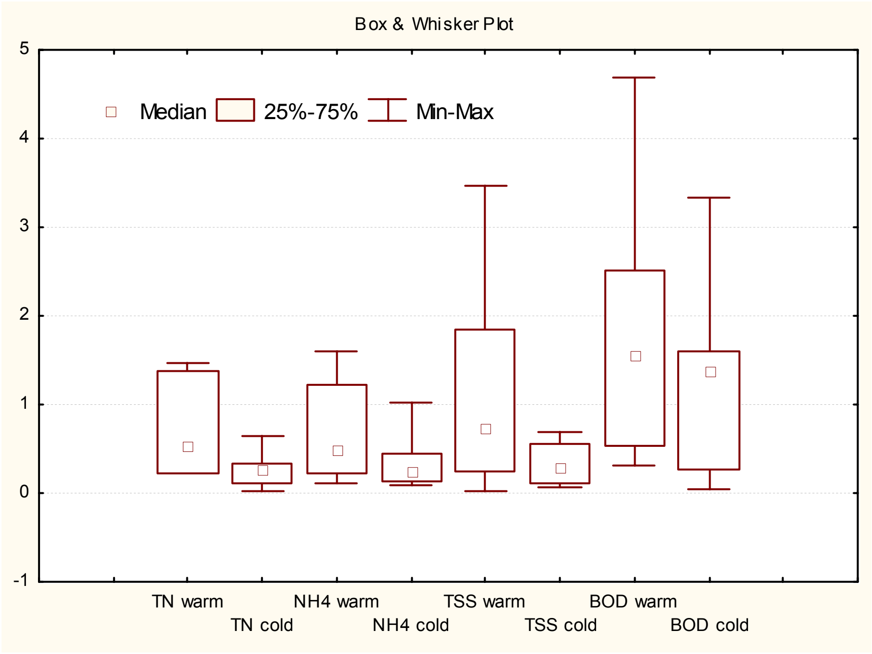


Figure 5. Comparison of removal efficiency (%) of total N, NH_4-N, total suspended solids (TSS), organic material (BOD_7 value), total P, and PO_4-P in warm (May-October) and cold (November-April) periods calculated for the whole CW.



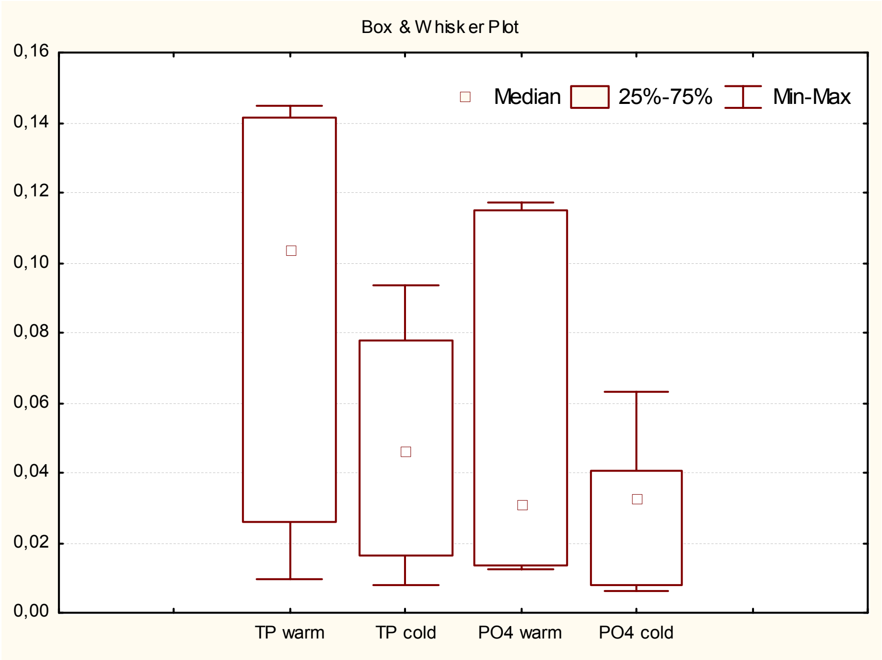


Figure 6. Comparison of mass removal (g m^{-2} d^{-1}) of total N, NH_4-N, total suspended solids (TSS), organic material (BOD_7 value) (upper part), and total P and PO_4-P (lower part) in warm (May-October) and cold (November-April) periods calculated for the whole CW.

Table 3. Spearman Rank Correlation values between air temperature and water quality parameters in the inflow (I) and outflow (O) of the hybrid treatment wetland in Paistu, Estonia. Q – water discharge; Cond – conductivity; SS – suspended solids. Bold values are statistically significant ($p < 0.05$).

	BOD$_7$ (I)	Tot. P (I)	PO$_4$-P (I)	SS (I)	Tot. N (I)	NH$_4$-N (I)	Q (I)	Cond (I)	Wat. t^o(I)	O$_2$ (I)	pH (I)	Air t^o	BOD$_7$ (O)	Tot. P (O)	PO$_4$-P (O)	SS (O)	Tot. N (O)	NH$_4$-N (O)	Q (O)	Cond (O)	Wat. t^o(O)	O$_2$ (O)	pH (O)
BOD$_7$ (I)	1.00																						
Tot. P (I)	**0.74**	1.00																					
PO$_4$-P (I)	**0.62**	**0.85**	1.00																				
SS (I)	**0.55**	**0.50**	**0.57**	1.00																			
Tot. N (I)	**0.72**	**0.86**	**0.78**	**0.69**	1.00																		
NH$_4$-N (I)	**0.69**	**0.82**	**0.76**	**0.72**	**0.98**	1.00																	
Q (I)	–0.14	**–0.50**	**–0.51**	0.01	–0.24	–0.14	1.00																
Cond (I)	**0.75**	**0.64**	**0.64**	**0.49**	**0.57**	**0.58**	–0.38	1.00															
Wat. t^o(I)	0.01	–0.03	0.31	0.47	0.34	0.28	–0.26	0.00	1.00														
O$_2$ (I)	0.07	0.27	0.02	0.44	0.17	0.23	0.13	–0.01	–0.15	1.00													
pH (I)	–0.20	0.42	0.13	**–0.51**	–0.23	–0.30	–0.16	–0.45	0.09	–0.46	1.00												
Air t^o	**0.49**	**0.69**	**0.64**	**0.59**	**0.64**	**0.59**	**–0.55**	**0.58**	**0.63**	–0.02	–0.16	1.00											
BOD$_7$ (O)	0.19	–0.03	–0.15	0.26	0.13	0.07	0.13	–0.12	0.14	0.23	–0.27	–0.08	1.00										
Tot. P(O)	0.18	0.27	0.41	–0.09	0.22	0.14	**–0.60**	0.07	0.01	0.02	0.19	0.29	0.27	1.00									
PO$_4$-P (O)	0.22	0.42	**0.62**	0.20	0.21	0.23	**–0.47**	0.39	0.17	0.18	0.30	0.38	–0.12	**0.47**	1.00								
SS (O)	–0.02	0.01	0.28	0.22	0.27	0.25	–0.21	–0.11	0.44	–0.01	0.09	0.21	0.11	0.38	0.20	1.00							
Tot. N (O)	**0.54**	**0.49**	0.21	0.10	0.31	0.31	0.27	0.30	–0.34	0.15	–0.13	–0.02	0.23	–0.06	–0.08	**–0.66**	1.00						
NH$_4$-N (O)	0.16	0.24	0.22	0.25	0.30	0.24	–0.10	0.18	**0.54**	–0.14	–0.12	0.45	–0.03	–0.06	–0.11	–0.04	0.11	1.00					
Q (O)	–0.14	–0.31	**–0.51**	0.01	–0.24	–0.14	**1.00**	–0.38	–0.26	0.13	–0.16	**–0.55**	0.13	**–0.60**	**–0.47**	–0.21	0.27	–0.10	1.00				
Cond (O)	–0.06	0.11	0.21	0.24	0.24	0.22	–0.01	–0.18	**0.63**	0.03	0.21	0.24	0.30	0.13	0.32	**0.55**	–0.32	0.40	–0.01	1.00			
Wat. t^o(O)	–0.01	0.25	0.28	0.40	0.32	0.25	–0.18	–0.10	**0.97**	–0.18	0.22	**0.59**	0.16	0.00	0.16	0.42	–0.29	0.45	–0.18	**0.65**	1.00		
O$_2$ (O)	0.24	0.31	0.16	**0.71**	0.32	0.39	0.06	0.19	0.15	**0.85**	–0.46	0.28	0.18	–0.08	0.31	–0.01	0.14	–0.10	0.06	0.09	0.10	1.00	
pH (O)	–0.43	**–0.52**	–0.43	–0.31	0.40	–0.33	0.27	–0.30	–0.23	–0.19	–0.03	–0.36	–0.41	–0.39	–0.38	–0.01	–0.38	0.15	0.27	0.00	–0.26	–0.41	1.00

3.3. Correlation between environmental parameters and water quality indicators

We found only a few significant Spearman Rank Correlation values between the variables studied. As expected, the BOD7 value and concentration of suspended solids, total P, PO_4-P, total N, and NH_4-N were significantly correlated in the inflow of the CW (Spearman R values varied from 0.50 to –0.98). Likewise, higher BOD_7, suspended solids, total P, PO_4-P, total N, and NH_4-N values caused higher conductivity in the inflow (Spearman R values from 0.49 and 0.75; Table 3). Lower water discharge caused a significant increase in PO_4-P and total P concentrations in both the inflow and outflow of the CW (Spearman R values varied from –0.47 to –0.60). On the other hand, the significant positive correlation between air temperature and BOD_7, total P, PO_4-P, suspended solids, total N, NH_4-N, and conductivity values in the inflow (Spearman R varied from 0.49 to 0.69) is due to the fact that at higher air temperature the water inflow was lower (Spearman R = –0.55; Table 3). Seemingly, this is caused by significantly lower water consumption in summertime. Water temperature of inflow water was significantly correlated with air temperature (0.63), and ammonia nitrogen and conductivity values in the outflow (0.54 and 0.63, respectively), whereas the outflow water temperature was strongly influenced by inflow water temperature (0.97). Water quality parameters of the HSSF outflow showed less significant correlations than in the inflow. Presumably, further studies using the neural network analyses will help achieve a better understanding of the relationships between water quality parameters (see Zimnoch et al., 2003).

3.4 Application of the *k*-*C** model

The average and standard deviation values of the area-based first-order rate-constant *k* for BOD_7, total N, NH_4-N, and total P of the entire hybrid CW throughout the whole study period were 20.1±13.4, 11.9±8.2, 18.2±13.3, and 17.1±12.4 m yr^{-1}, respectively (Table 4). These values fit in the range of those described in other studies, whereas for total P, the *k* value from Paistu was among the highest reported.

Table 4. Average and standard deviation values of the area-based first-order rate-constant *k* (m yr^{-1}) for BOD, total N, NH_4-N and total P of the entire Paistu hybrid CW throughout the whole study period compared with literature data on *k*. * – k_{20} values.

	BOD	Total N	NH_4-N	Total P
***k* values in Paistu CW**	20.1±13.4	11.9±8.2*	18.2±13.3*	17.1±12.4
Literature data				
Kadlec and Knight, 1996	31–365	0.78–50.1	1.7–37.3	3.4–23.7
Kadlec, 2000	12–52	–	–	29.4
Noorvee et al., 2005	5.8	3.6*	2.9*	4.9

Similarly to removal efficiency and mass removal, we did not find significant differences in *k* values for most of the indicators between the warm and cold periods, neither in the VSSF nor in the HSSF filter (Fig. 7).The value of *k* was significantly higher only for total N in the HSSF filter during the warm period. This supports the principal idea that nitrogen removal processes are more temperature-dependent than other purification processes (Kadlec, 2000).

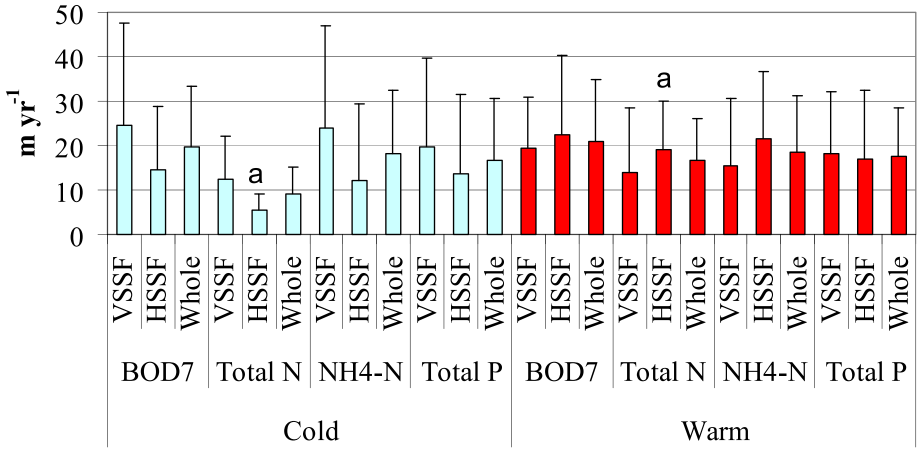


Figure 7. Average values of the area-based first-order rate-constant *k* (m yr^{-1}) for different parts of the Paistu hybrid CW during the cold (November-April) and warm (May-October) periods. For total N and NH_4-N k_{20} values are given. a – significantly differing values ($p < 0.05$). Bars indicate standard deviation values.

There are only positive values of Spearman Rank Correlation (R^2) between the hydraulic load (m^3 yr^{-1}), mass loading rates (g m^{-2} d^{-1}), the mass removal rates (g m^{-2} d^{-1}), and the area-based first-order rate-constants *k* (m yr^{-1}) for organic material (BOD_7), total N, NH_4-N, and total P: among 78 possible R^2 values, 49 were at the significance level $p < 0.05$, whereas 19 were at the level $p < 0.001$ (Table 5). The hydraulic load was significantly correlated with all *k* values, whereas for BOD_7, NH_4-N, and total P, the correlation was strongly ($p < 0.001$) significant. The mass loading rates of all mentioned parameters were significantly correlated with each other. The same is valid for all the mass removal rates and *k* values, with the *k* values showing strongly significant cross correlation. The mass loading and mass removal rates were significantly correlated; in the case of BOD_7 and total P, the R^2 value was 1.00 and 0.99, respectively (Table 5; see also Mander et al., 1997).

The high R^2 values allow us to assume that the *k*-*C** model describes the purification efficiency adequately and it can be used for the evaluation of the performance of CWs such as the one studied in this paper.

Table 5. Spearman Rank Correlation (R^2) between the hydraulic load (HL; $m^3\ yr^{-1}$), mass loading rates (ML; $g\ m^{-2}\ d^{-1}$), the area-based first-order rate-constants k ($m\ yr^{-1}$), and mass removal rates (MR; $g\ m^{-2}\ d^{-1}$) of organic material (BOD), total N (TN), ammonia N (NH_4), and total P (TP) in the Paistu hybrid CW. Significant values: bold – $p < 0.05$, bold with asterisk – $p < 0.001$.

	BOD ML	**BOD *k***	**BOD MR**	**TN ML**	**TN *k***	**TN MR**	**NH_4 ML**	**NH_4 *k***	**NH_4 MR**	**TP ML**	**TP *k***	**TP MR**	**HL**
BOD ML	1.00												
BOD *k*	0.41	1.00											
BOD MR	**1.00***	0.44	1.00										
TN ML	**0.91***	0.47	**0.91***	1.00									
TN *k*	0.46	**0.66**	**0.48**	**0.60**	1.00								
TN MR	**0.56**	0.24	**0.55**	**0.70**	**0.53**	1.00							
NH_4 ML	**0.89***	0.38	**0.89***	**0.97***	**0.64**	**0.72***	1.00						
NH_4 *k*	0.47	**0.86***	0.47	**0.59**	**0.68**	0.35	**0.48**	1.00					
NH_4 MR	**0.58**	0.22	**0.56**	**0.69**	0.37	**0.96***	**0.67**	0.34	1.00				
TP ML	**0.88***	**0.47**	**0.89***	**0.92***	0.44	**0.50**	**0.86***	**0.52**	**0.56**	1.00			
TP *k*	0.43	**0.93***	0.45	0.46	**0.53**	0.08	0.34	**0.85***	0.09	**0.52**	1.00		
TP MR	**0.87***	0.42	**0.87***	**0.91***	0.40	**0.49**	**0.85***	**0.49**	**0.55**	**0.99***	**0.48**	1.00	
HL	**0.50**	**0.92***	**0.52**	**0.53**	**0.61**	0.19	0.42	**0.92***	0.17	**0.53**	**0.92***	**0.48**	1.00

4. CONCLUSIONS

The hybrid CW studied demonstrated an excellent wastewater purification capacity concerning both BOD_7, suspended solids and total P concentration in the outflow from the HSSF filter bed: 5.5±5.9, 5.8±3.5, and 0.4±0.3 mg L^{-1}, respectively. These parameters meet the standards set by the Water Act of Estonia for wastewater treatment plants of 2000–9999 PE. Likewise, the NH_4-N and total N were purified effectively (outflow concentrations 9.1±6.0 and 19.2±6.7 mg L^{-1}; recommended standards 10 and 20 mg L^{-1} respectively).

The results show that hybrid CW systems consisting of subsurface flow filters can efficiently operate in conditions of very variable hydraulic load and cold winter conditions. Locally produced LWA as a filter material in CWs has shown good hydraulic conductivity and phosphorus sorption capacity. The Paistu CW can be considered one of the best systems in Estonia, with proper design and outstanding purification results.

In terms of improving total N removal, it is recommended that the water table in the HSSF filter bed be raised in order to allow a longer retention time in the system.

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