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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): a two-chamber vertical subsurface flow (VSSF) filter bed followed by a horizontal subsurface flow (HSSF) filter bed, 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 filter beds 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 ($k = 17.1 \pm 12.4$ m yr^{-1}). The Paistu CW, with its proper design and outstanding purification results, can be considered one of the best systems in Estonia.

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

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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, 1997; Arias et al., 2001; Drizo et al., 2002; Jenssen and Krogstad, 2003; Ádám et al., 2005). Lightweight aggregates (LWA) or light–expanded clay aggregates (LECA) have shown both good water permeability and phosphorus sorption capability (Johansson, 1997; Zhu et al., 1997; 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, 1997). Filtralite P^{TM}, the new generation of Norwegian-produced LWA, is especially developed for P sorption (Ádám et al., 2005). This new LWA is an illite-based clay mineral 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 CWs 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^{TM} 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, located in Sultsi village, Viljandi County, Estonia (58°14.5′N; 25°35.6′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 bed (2 m × 108 m) and a 216 m^2 HSSF filter bed. Both filter beds are filled with LWA (name of the local

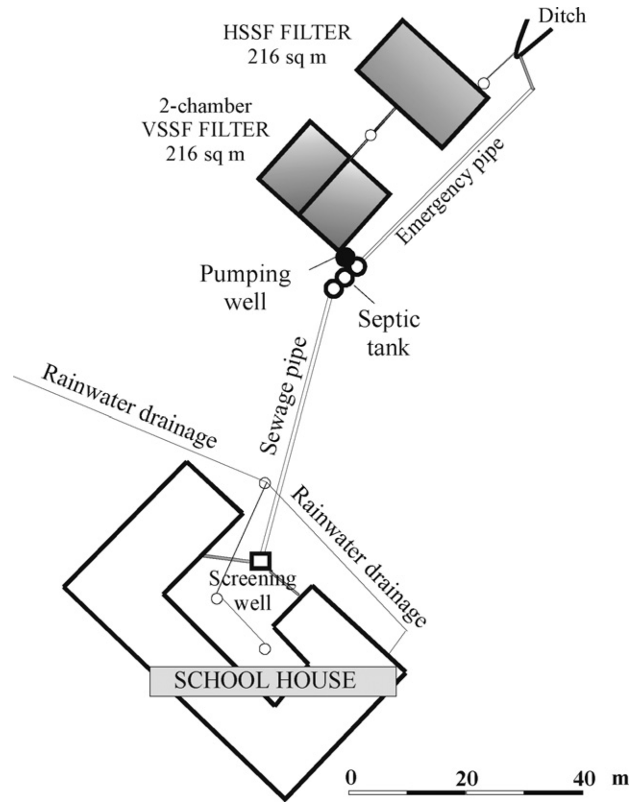

Fig. 1 – Location scheme of the hybrid constructed wetland system in Paistu, Viljandi County, Estonia.

Estonian product: FIBO) of different size. In both VSSF filter beds, a 0.5 m LWA layer (10–20 mm size) above the PVC liner is covered by a 0.3 m layer of finer LWA (2–4 mm), which increases the oxygen transport into the bed. The VSSF filter beds are covered with a 0.20 m topsoil layer and lawn. A water-permeable geomembrane isolates the soil layer from the upper LWA layer. The HSSF filter bed (depth 0.9 m) is filled with 2–4 mm 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).

Before entering the hybrid wetland system, wastewater passes through a two-chamber 30 m^3 septic tank (Fig. 1). The VSSF filter beds are intermittently loaded at 1 h 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 filter 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 filter beds 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 three measurement series (20.02.05, 17.04.05, 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 (%) and mass removal (MR; $\mathrm{g\,m^{-2}\,d^{-1}}$) was calculated according to Kadlec and Knight (1996).

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):

$$\ln\left[\frac{C_0 - C^*}{C_i - C^*}\right] = -\frac{k}{q}, \tag{1}$$

where k is the area-based, first-order rate-constant ($\mathrm{m\,yr^{-1}}$), q the hydraulic loading rate ($\mathrm{m\,yr^{-1}}$), C_0 the effluent concentration ($\mathrm{g\,m^{-3}}$), C_i the influent concentration ($\mathrm{g\,m^{-3}}$) and C^* is the irreducible background wetland concentration ($\mathrm{g\,m^{-3}}$).

Based on the published data (Kadlec and Knight, 1996), the C^* values of $1\,\mathrm{mg\,L^{-1}}$ for BOD_7 and $1.5\,\mathrm{mg\,L^{-1}}$ 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 $0.05\,\mathrm{mg\,L^{-1}}$, respectively.

The available data show 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:

$$k_T = k_{20}\theta^{T-20}, \tag{2}$$

where k_T is the reaction rate coefficient at temperature T (°C), k_{20} the reaction rate coefficient at 20 °C, θ the temperature factor and T is temperature (°C).

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 ($\mathrm{cm\,d^{-1}}$) and initial mass loading rates ($\mathrm{g\,m^{-2}\,d^{-1}}$) 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 $7.4\,\mathrm{m^3\,d^{-1}}$ on average, and fluctuating from 0 (in the night and from the end of June until the beginning of September) to $17.7\,\mathrm{m^3\,d^{-1}}$ (Table 1). In conventional wastewater treatment systems, 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 8.3–6.1 °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.

The inflow concentrations of dissolved oxygen are unusually high for the outflow from a septic tank (Table 1). This can be related to possible aeration of wastewater in pumping well during the intermittent loading events.

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 decreased significantly in the outflow from the HSSF filter bed. To compare with the septic tank effluent (inflow to the VSSF), the respective average values of these wastewater indicators in the HSSF filter bed outflow decreased by approximately 18, 6, 6, 3, 20, and 11 times (Tables 2 and 3). A remarkable purification of wastewater was found also in the VSSF filter bed: outflow values were, respectively, 5, 4, 2, 2, 7, and 4 times lower than in the HSSF filter bed outflow, however, only the BOD_7 value decreased significantly. Thus, both the purification efficiency (%) and mass removal ($\mathrm{g\,m^{-2}\,d^{-1}}$) of the entire CW is outstanding (Table 3). 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).

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 (Table 2). This phenomenon can be related to changes in microbial communities in the spring period (April–May; see also Mander et al., 2000).

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 ($\mu s\,cm^{-1}$)		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	nd	nd	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
S.D.	7.3	4.7	367	126	2.7	2.9	3.5	3.9	0.25	0.31

nd: Not determined.

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 (Table 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 filter bed. The HSSF filter bed 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 $10\,mg\,L^{-1}$; Table 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 (Table 2). Slight but not significant increase in organic N (N_{org} = total N—NH_4—N—NO_2—N—NO_3—N; Table 2) 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 (Table 2): 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, 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 stand will probably enhance the denitrification providing more carbon for this process.

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 (Figs. 2 and 3). 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 filter beds in winter (Table 2), 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).

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 BOD_7 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 4). Lower water

Table 2 – Value of BOD_7 and concentration of total suspended solids (TSS), NH_4—N, NO_2—N, NO_3—N, total N, and total P (all in mg L^{-1}) in the inflow to the VSSF (In), outflow from the VSSF (Out1), and outflow from the HSSF part (Out2) of the hybrid CW

Date	BOD_7			TSS			NH_4–N			NO_2–N			NO_3—N			Total N			Total P		
	In	Out1	Out2	In	Out1	Out2	In	Out1	Out2	In	Out1	Out2	In	Out1	Out2	In	Out1	Out2	In	Out1	Out2
30.10.2003	12.3	12.3	6.6	25.0	25.0	6.0	18.5	18.0	9.2	0.005	0.017	0.001	0.4	0.6	0.3	21.0	21.0	11.5	1.30	1.30	0.49
28.11.2003	68.0	16.0	2.1	36.0	7.0	6.0	21.5	11.0	10.0	0.007	2.3	0.007	0.7	3.7	0.6	26.5	21.0	14.2	2.70	0.09	0.21
20.01.2004	34.0	2.5	3.0	14.0	4.0	4.0	7.2	1.4	2.2	0.009	0.416	0.266	0.8	3	4.9	19.8	15.0	19.0	3.00	0.66	0.09
20.02.2004	90.0	12.0	8.6	21.0	5.0	4.0	25.5	7.1	5.1	0.048	0.305	0.524	0.7	3.7	4.3	37.8	23.0	25.5	2.50	0.49	0.22
10.03.2004	107.0	12.0	6.0	33.0	5.5	4.5	36.8	10.4	4.5	0.01	0.37	0.075	0.8	2.1	1.9	44.8	21.0	20.8	3.30	1.03	0.33
16.04.2004	189.0	16.0	3.6	58.0	6.0	5.0	90.0	26.0	3.8	0.011	0.673	0.159	0.6	15.5	11	97.8	58.0	23.8	8.50	2.50	0.53
20.04.2004	133.0	28.0	2.8	18.8	12.0	2.3	70.0	27.0	22.5	0.024	0.345	0.133	0.7	9.5	7.5	81.0	42.0	39.1	9.10	2.40	0.56
18.05.2004	117.0	30.0	8.0	155.0	15.0	4.0	72.7	74.0	19.1	0.022	0.214	0.224	0.7	4.2	1.4	82.5	80.0	22.2	4.80	3.80	0.28
4.06.2004	112.0	7.5	3.2	74.0	6.0	5.2	77.5	27.0	17.0	0.01	0.542	0.174	0.5	13	2.5	85.0	78.0	18.0	4.50	0.27	0.10
30.09.2004	96.0	42.0	28.0	20.0	9.5	16.0	31.6	14.0	9.8	0.025	0.556	0.125	0.6	8.6	2.4	62.4	24.0	15.7	3.30	1.60	1.20
18.01.2005	16.0	7.0	3.0	18.0	13.5	8.0	30.0	15.0	4.0	0.026	0.687	0.168	0.7	4.7	6.9	37.9	20.5	12.2	2.10	1.15	0.67
20.02.2005	115.0	15.5	3.5	24.0	11.0	4.5	40.5	17.0	4.8	nd	nd	nd	nd	nd	nd	42.5	28.0	20.5	2.70	0.95	0.21
30.03.2005	92.0	14.0	3.0	22.0	12.5	7.2	44.9	21.0	11.5	0.015	0.338	0.269	0.6	2.7	4.8	47.8	33.0	17.2	2.90	0.89	0.23
17.04.2005	145.0	27.0	3.6	55.0	17.0	12.0	98.0	24.0	7.2	nd	nd	nd	nd	nd	nd	112.0	36.0	18.0	7.20	1.12	0.35
21.05.2005	110.0	18.0	4.0	69.0	19.0	11.0	77.5	31.0	9.5	0.019	0.67	0.334	0.7	3.6	6.5	81.5	42.0	19.0	4.90	0.98	0.52
20.06.2005	90.0	21.0	3.0	45.0	12.0	7.5	72.0	28.0	4.5	nd	nd	nd	nd	nd	nd	74.0	32.0	7.5	4.50	1.10	0.33
18.09.2005	167.0	35.0	4.0	78.0	22.0	14.0	91.0	22.0	9.0	0.025	0.587	0.122	0.6	6.2	3.1	98.0	29.0	19.5	5.25	1.15	0.32
15.10.2005	73.0	22.0	3.5	38.0	10.0	5.2	99.5	39.0	10.0	0.01	0.72	0.145	0.4	2.5	4.7	105.0	47.0	21.0	6.70	0.78	0.25

Estonian standards for wastewater effluents—BOD_7: 25 mg O_2 L^{-1}; TSS: 20 mg L^{-1}; total P: 1.5 mg L^{-1}. Recommended limit for NH_4—N: 10 mg L^{-1}; nd: not determined.

Table 3 – Performance of the Paistu hybrid constructed wetland system (30.10.2003–15.10.2005; average ± standard deviation values)

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

[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.

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 4). 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 5). 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.

Similar 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 bed (Fig. 4). The value of k was significantly higher only for total N in the HSSF filter bed during

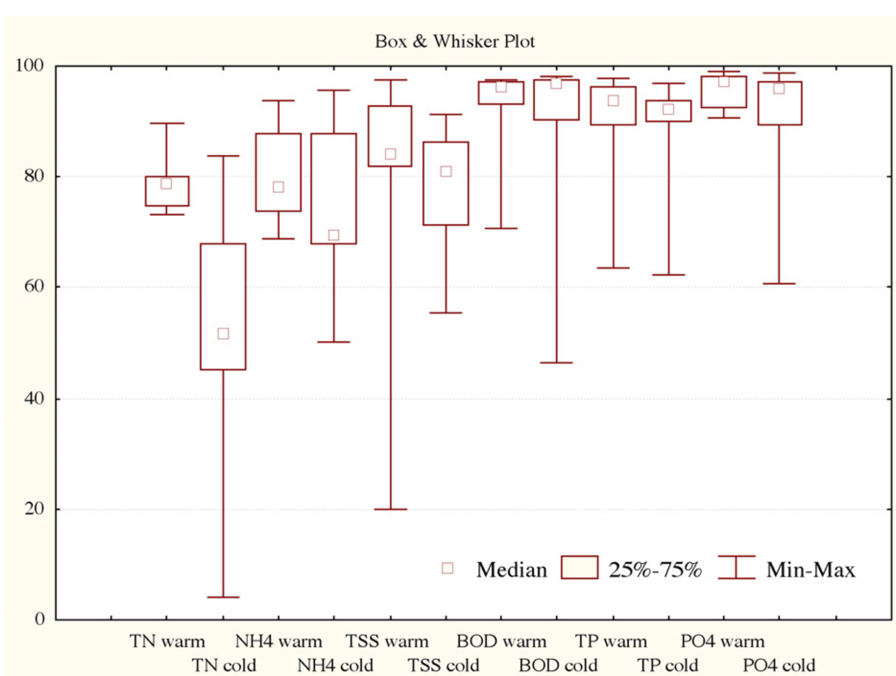

Fig. 2 – Comparison of removal efficiency (%) of total N, NH_4—N, total suspended solids (TSS), organic material (BOD_7 value), total P, and PO_4—P in warm (May–October) and cold (November–April) periods calculated for the whole CW.

Table 4 – 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

	BOD_7 (I)	Total P (I)	PO_4—P (I)	SS (I)	Total N (I)	NH_4—N (I)	Q (I)	Cond (I)	Water t° (I)	O_2 (I)	pH (I)	Air t°	BOD_7 (O)	Total P (O)	PO_4—P (O)	TSS (O)	Total N (O)	NH_4—N (O)	Q (O)	Cond (O)	Water t° (O)	O_2 (O)	pH (O)
BOD_7 (I)	1.00																						
Total P (I)	**0.74**	1.00																					
PO_4—P (I)	**0.62**	**0.85**	1.00																				
TSS (I)	**0.55**	**0.50**	**0.57**	1.00																			
Total 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															
Water t° (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°	**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										
Total 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								
TSS (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							
Total 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			
Water t° (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

Q: water discharge; Cond: conductivity; TSS: total suspended solids. Bold values are statistically significant ($p < 0.05$).

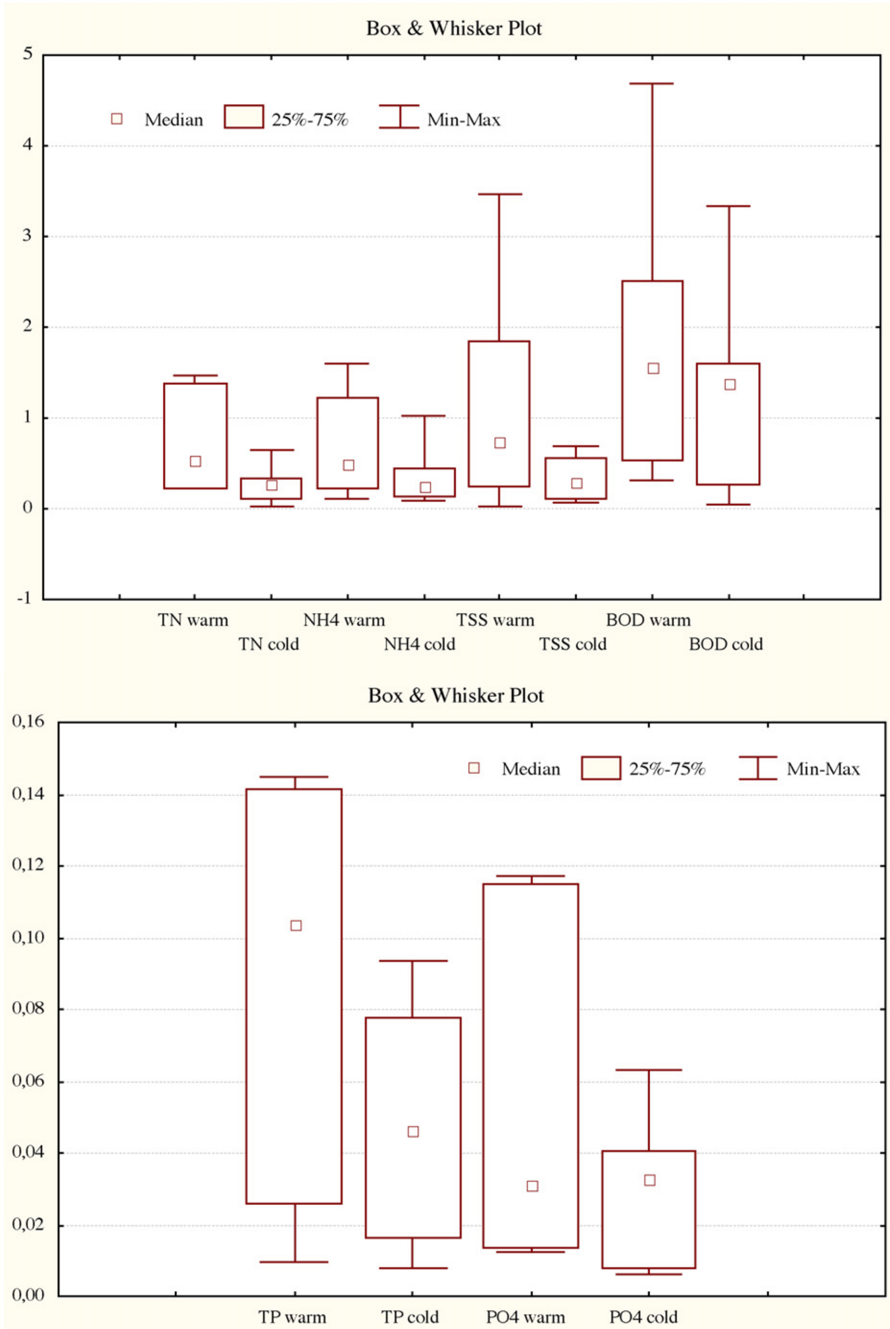

Fig. 3 – Comparison of mass removal ($g\,m^{-2}\,d^{-1}$) of total N, NH_4—N, total suspended solids (TSS), organic material (BOD_7 value) (upper part), and total P and PO_4—P (lower part) in warm (May–October) and cold (November–April) periods calculated for the whole CW.

the warm period. This supports the principal idea that nitrogen removal processes are more temperature-dependent than other purification processes (Kadlec, 2000).

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 6). 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 6; see also Mander et al., 1997). The high R^2 values allow us to assume that the k–C^* model describes the

Table 5 – 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

	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. (2005b)	5.8	3.6*	2.9*	4.9

*—k_{20} values.

Table 6 – 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

	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

Significant values: (bold) $p < 0.05$, (bold with asterisk) $p < 0.001$.

purification efficiency adequately and it can be used for the evaluation of the performance of CWs such as the one studied in this paper.

The system is quite lightly loaded with phosphorus, so the outflow concentrations are low; however, the removed load could be actually much lower as compared to other systems which provide higher outflow concentrations but also higher removal rate (see Vymazal, 2001). This supports our finding that the LWA-filled hybrid CW systems can be very effective even in cold climate conditions.

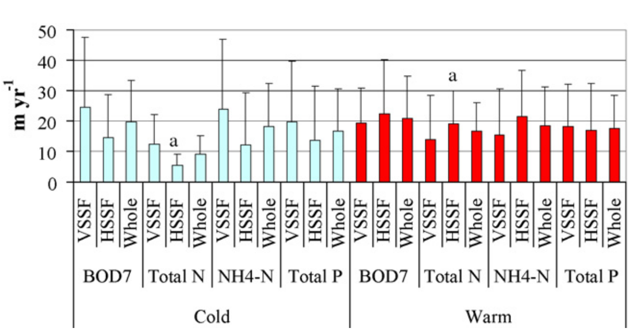

Fig. 4 – Average values of the area-based first-order rate-constant k (m yr^{-1}) for different parts of the Paistu hybrid CW during the cold (November–April) and warm (May–October) periods. For total N and NH_4–N k_{20} values are given. [a]Significantly differing values ($p < 0.05$). Bars indicate standard deviation values.

4. Conclusions

The hybrid CW studied demonstrated an excellent waste water 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 filter beds 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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