

MAGDALENA GAJEWSKA*, HANNA OBARSKA-PEMPKOWIAK*

EFFICIENCY OF POLLUTANT REMOVAL BY FIVE MULTISTAGE CONSTRUCTED WETLANDS IN A TEMPERATE CLIMATE

In recent years, an increase in interest in hybrid constructed wetland systems (HCWs) has been observed. These systems are composed of two or more filters with different modes of sewage flow. Based on over eight years of monitoring, carried out at five local HCWs located in the Pomerania Region of Northern Poland, the effective removal of organic matter (from 74.9 to 95.5% COD) in the loading range $1.5\text{--}17.0 \text{ g COD}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ was confirmed. Efficiency of total nitrogen (TN) removal varied from 23.4 to 79.2%. The most effective removal of TN ($2.0 \text{ g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) occurred in the system with vertical flow compartments with intermittent loadings.

1. INTRODUCTION

Agricultural regions of Poland are inhabited by approximately 30% of the country's population. Almost all villages use water from local supply systems. Due to the scattered households in the countryside, installation of central sewage systems is technically difficult and economically expensive. Therefore, individual household treatment systems are often used instead. Most Polish villages (ca. 41.5%) use local sewage systems or septic tanks. It is estimated that about 1 km^3 per year of untreated wastewater in these regions is discharged to surface water or to the soil.

Protection of the natural environment in Poland has led to regulations demanding thorough wastewater treatment in rural areas [1, 2]. For this reason, the idea of treating wastewater in constructed wetlands (CW) has gained in popularity [3, 4]. During the last twenty years, some three hundred facilities of this type have been constructed in Poland.

In the temperate climate, constructed wetlands are built mainly as soil filters with vertical or horizontal flow. In the vertical flow constructed wetland (VF CW) the dominating processes are organic matter mineralisation and ammonia nitrification due to

*Gdańsk University of Technology, ul. Narutowicza 11/12, 80-233 Gdańsk, Poland. Corresponding author M. Gajewska, e-mail: mgaj@pg.gda.pl

better oxygen conditions in comparison with the horizontal flow constructed wetland (HF CW) [5–7]. Until recently in Poland and Germany, mainly one stage systems with horizontal flow of sewage have been used. Problems with clogging and unstable efficiency of nitrogen removal caused interest in VF CWs owing to better oxygen transfer characteristics within the beds, enhanced by intermittent loading of sewage [6, 8, 9]. Single stage VF CWs, with the unit area of $4 \text{ m}^2 \cdot \text{pe}^{-1}$, provide effective organic matter removal for loadings up to $40 \text{ g COD} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and the effluent meets very strict Austrian requirements irrespective of season and air temperature (final effluent concentrations below $90 \text{ mg} \cdot \text{dm}^{-3}$ COD, $25 \text{ mg} \cdot \text{dm}^{-3}$ BOD₅) [9]. According to Sardon [10], removal efficiency of BOD₅ as high as 86% is achievable by HF CWs at the BOD loading rate of $21.0 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ while 95% removal is achievable by VF CWs at $22.1 \text{ g BOD} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$. In Canada VF CWs used for landfill leachate treatment provided up to 99% removal of BOD₅ and up to 97% decrease of ammonium nitrogen with the hydraulic loading rate (HLR) of $40 \text{ mm} \cdot \text{d}^{-1}$ and the BOD load rate of $42 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{d}^{-1}$ [11]. It has also been indicated that the maximum allowable loading of organic matter applied to a hydrophyte bed is $25 \text{ g COD} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and that effective nitrification and nitrogen removal in VF CWs take place when HLR does not exceed $300 \text{ mm} \cdot \text{d}^{-1}$ [12, 13]. However, excessive loading of organic matter may cause bed clogging with a resulting decrease in pollutant removal efficiency [14, 15]. Thus, according to Alvarez [16] effective pretreatment of raw wastewater (e.g. anaerobic pretreatment) could minimize the danger of clogging and improve the efficiency of pollutant removal in CWs as well as resulting in a reduction of 30–50% of the necessary wetland area.

In recent years, an increase in interest in hybrid constructed wetland systems has been observed [6–8]. These systems are composed of two or more filters with both VF and HF CWs. HCWs combine the benefits of both types of beds, with claims of better final effluent quality (lower organic matter concentration, complete nitrification and partial denitrification) [6, 11, 16]. In addition, HCWs require a smaller unit area and achieve higher efficiency of pollutant removal in comparison with that of one stage systems.

However, the influence of the sewage application and discharge regimes on removal efficiency of pollutants in HCWs remains unrecognized. Also there is lack of knowledge regarding the efficacy of systems in the post-vegetative period (November to March), especially when the temperature falls below $4 \text{ }^\circ\text{C}$.

In order to explore these issues, an evaluation was carried out of hydrophyte bed performance during the period of 1998–2006. The investigations were conducted at facilities with various bed configurations and sewage flow modes.

The aim of this paper is the evaluation of seasonal and long-term performance of five HCWs, as well as assessment of the relationship between pollutant removal efficiency and bed configuration. The effects of influent loading rates of and VF bed configuration on the removal efficiency were also analyzed.

2. METHODS

The studies were carried out at five local Hybrid Constructed Wetlands, treating primary settled domestic wastewater in Darżlubie, Wieszyno, Wiklino, Sarbsk and Schodno in the Pommerania Region of Poland. Final discharge of treated effluent was to the Baltic Sea. All facilities were planted with reed. The characteristics of the HCW systems studied are shown in Table 1.

Table 1

Characteristics of the hybrid constructed wetland systems

Plant	Q [m ³ ·d ⁻¹]	Configuration	Area [m ²]	Depth [m]	Hydraulic load [mm·d ⁻¹]	Unit surface area [m ² ·pe ⁻¹]
Sarbsk	29.7	HF	1610	0.6	18.5	8.5
		VF	520	0.5	38.6	2.6
			Σ2130		13.9	Σ9.1
Wiklino	18.6	HF I	1050	0.6	17.7	7.0
		VF	624	0.4	46.9	2.0
		HF II	540	0.6	34.4	3.4
			Σ2214		8.4	Σ12.4
Wieszyno	24.5	HF I	600	0.6	40.8	3.0
		VF	300	0.6	81.7	1.5
		HF II	600	0.6	40.8	3.0
			Σ1500		16.3	Σ7.5
Schodno	2.2 (winter)	HF I	416	0.6	5.3–21.4	27.8–6.4
		VF I	307	0.45–0.6	7.2–28.9	20.5–4.7
	8.9 (summer)	HF II	432	0.6	5.1–20.6	28.8–6.6
		VF II	180	0.45–0.6	12.2–9.4	12.0–2.8
		Willow plantat.	Σ1300		1.7–6.8	Σ20–6.7*
Darżlubie	56.7	HF I	1200	0.6	47.3	2.0
		Cascade bed	400	0.6	141.2	0.67
		HF II	500	1.0	113.4	0.8
		VF	250	0.6	226.8	0.4
		HF III	1000		56.7 16.9	1.7
			Σ3350			Σ5.6

*In the summertime the wastewater treated is used for irrigation of a willow plantation with the surface area of approximately 400 m².

In all the HCWs studied, the first biological stage of treatment was horizontal flow (HF) CW. The analysed systems differ from one another in the order and number of subsequent stages (Table 2). In Sarbsk, sewage is introduced without resting to two VF beds working in parallel. At Wiklino two VF CWs work alternately with fortnightly resting.

In Wieszyño, two VF beds work in series and are loaded without resting. In Schodno, ca. 65% of the sewage is pumped intermittently to one of four VF beds. The remaining sewage is pumped directly to the HF II bed.

Table 2

Operating conditions of vertical flow constructed wetlands (VF CWs)

Plant	Configuration	Operation condition of VF beds
Wiklino	$\boxed{\text{VF CW}}$ $\boxed{\text{VF CW}}$	alternately, intermittent
Wieszyño	$\boxed{\text{VF CW}}$ \Rightarrow $\boxed{\text{VF CW}}$	in series, continuous
Sarbsk	$\boxed{\text{VF CW}}$ $\boxed{\text{VF CW}}$	parallel, continuous recirculation into HF
Darżlubie	$\boxed{\text{VF CW}}$ VF CW	parallel, continuously
Schodno	$\boxed{\text{VF CW I}}$ $\boxed{\text{VF CW I}}$ $\boxed{\text{VF CW J}}$ $\boxed{\text{VF CW J}}$ $\boxed{\text{VF CW II}}$ $\boxed{\text{VF CW II}}$	VF I – 4 compartments alternately, intermittent VF II – 2 compartments alternately, intermittent

Wastewater treated in HF II bed is pumped into two beds of VF II that alternate with an intermittent loading regime. In summer, treated wastewater is directed for irrigation to the willow plantation (*Salix viminalis*) and in winter it is finally discharged directly from the HCW to soil by the means of a drainage system.

Combined spot samples were taken monthly at each stage of the HCWs from 1998 to 2006 (Table 3) and analysed for pH, total suspended solids (TSS), organic matter (BOD₅, COD), total nitrogen, ammonium nitrogen, nitrate, nitrite, total phosphorus. Analyses were carried out according to the methods of Polish Standards and recommendations given in the Environment Ministry Decree [1]. Hydraulic load rates to each first stage were also recorded, based on the pump hour run meters.

Removal efficiency η was calculated as a quotient of pollutant load difference between the influent (L_{inf}) and effluent (L_{out}) after each treatment stage:

$$\eta = \frac{L_{\text{inf}} - L_{\text{out}}}{L_{\text{inf}}}$$

The mass removal rate (MRR) was calculated based of the following equation:

$$\text{MRR} = \frac{C_{\text{inf}} Q_{\text{inf}} - C_{\text{out}} Q_{\text{out}}}{A}$$

where: A is the surface area of CW [m^2], Q_{inf} and Q_{out} – average values of wastewater discharged in inflow and outflow [$\text{m}^3 \cdot \text{d}^{-1}$], C_{inf} and C_{out} – average concentrations of contaminant in inflow and outflow [$\text{mg} \cdot \text{dm}^{-3}$].

3. RESULTS AND DISCUSSION

3.1. WASTEWATER QUALITY AND POLLUTANT REMOVAL EFFICIENCY

Average pollutant concentrations in the influent and effluent of the HCWs studied are shown in Tables 3 and 4.

Table 3

Average concentrations for each parameter in the raw influent

Parameter	Schodno $n^x = 18$	Darżlubie $n^x = 21$	Wiklino $n^x = 88$	Wieszyno $n^x = 18$	Sarbsk $n^x = 38$
TSS, $\text{mg} \cdot \text{dm}^{-3}$	156.6 ± 51.2	359.5 ± 87.9	539.3 ± 127.2	1269.5 ± 167.6	819.9 ± 208
COD, $\text{mg O}_2 \cdot \text{dm}^{-3}$	880.0 ± 189.2	837.5 ± 156.3	466.3 ± 92.7	1021.9 ± 251.2	687.6 ± 162.9
BOD ₅ , $\text{mg O}_2 \cdot \text{dm}^{-3}$	448.5 ± 123.2	401.5 ± 51.3	265.2 ± 51.7	657.3 ± 118.5	420.0 ± 87.2
TN, $\text{mg} \cdot \text{dm}^{-3}$	96.1 ± 36.7	176.3 ± 35.6	104.1 ± 10.2	114.0 ± 22.1	73.8 ± 21.9
N-NH ₄ ⁻ , $\text{mg} \cdot \text{dm}^{-3}$	78.0 ± 28.5	82.6 ± 23.4	87.3 ± 9.0	84.8 ± 15.3	47.1 ± 13.7
N-NO ₃ ⁻ , $\text{mg} \cdot \text{dm}^{-3}$	0.1	1.3 ± 0.3	0.8 ± 0.2	1.0 ± 0.4	0.9 ± 0.1
N _{org} , $\text{mg} \cdot \text{dm}^{-3}$	16.6 ± 3.9	90.8 ± 26.8	16.2 ± 5.3	27.9 ± 8.9	25.9 ± 7.3
TP, $\text{mg} \cdot \text{dm}^{-3}$	14.6 ± 3.9	15.3 ± 0.8	15.2 ± 0.7	20.1 ± 1.2	11.9 ± 0.9

n^x – number of samples.

Table 4

Average concentrations for each parameter in the effluent from HCWs

Parameter	Schodno $n^x = 18$	Darżlubie $n^x = 21$	Wiklino $n^x = 88$	Wieszyno $n^x = 18$	Sarbsk $n^x = 38$
TSS, $\text{mg} \cdot \text{dm}^{-3}$	48.6 ± 20.1	92.0 ± 27.3	36.3 ± 17.2	106.4 ± 31.7	45.6 ± 49.9
COD, $\text{mg O}_2 \cdot \text{dm}^{-3}$	178.1 ± 38.1	210.5 ± 67.8	31.5 ± 8.9	175.9 ± 99.3	44.2 ± 15.9
BOD ₅ , $\text{mg O}_2 \cdot \text{dm}^{-3}$	96.6 ± 20.1	72.0 ± 21.4	10.9 ± 4.1	85.9 ± 53.6	19.0 ± 1.7
TN, $\text{mg} \cdot \text{dm}^{-3}$	37.2 ± 9.9	56.5 ± 16.9	21.7 ± 5.5	87.3 ± 14.8	27.6 ± 8.5
N-NH ₄ ⁻ , $\text{mg} \cdot \text{dm}^{-3}$	30.6 ± 8.7	30.3 ± 11.5	6.0 ± 4.3	67.1 ± 14.2	16.8 ± 11.2
N-NO ₃ ⁻ , $\text{mg} \cdot \text{dm}^{-3}$	0.3	5.9 ± 2.8	9.6 ± 6.7	0.6 ± 0.3	5.03 ± 9.38
N _{org} , $\text{mg} \cdot \text{dm}^{-3}$	7.2 ± 1.3	22.5 ± 5.6	4.3 ± 1.7	19.53 ± 12.91	5.8 ± 2.3
TP, $\text{mg} \cdot \text{dm}^{-3}$	3.5 ± 0.9	6.9 ± 2.1	7.2 ± 1.6	14.6 ± 3.9	8.9 ± 3.1

n^x – number of samples.

Influent wastewater quality varied considerably between the HCWs, that at Wieszyño receiving the highest concentrations, high concentrations of TSS, BOD₅ and COD at the beginning of the biological stage of treatment indicating improper septic tank operation. On the other hand, considerable variation in influent quality was observed at Schodno, with high values of standard deviation observed (reaching 30%). Very high concentrations of organic matter in the influent to Darżlubie and Schodno HCWs suggested that, together with domestic wastewater, manure liquid from a farm and sewage from a food company were entering the system.

According to current Polish Standards [1], sewage discharged from less than 2000 pe and above 50 pe has to fulfil the following criteria: BOD₅ ≤ 40 mg·dm⁻³, COD ≤ 150 mg·dm⁻³, and SS ≤ 50 mg·dm⁻³. Discharges to nutrient sensitive areas must meet additional criteria: TN ≤ 30 mg·dm⁻³, TP ≤ 5 mg·dm⁻³. The effluent from the systems at Wiklino and Sarbsk fulfilled Polish Standards [1]. All other facilities, in spite of considerable pollutant removal efficacy, did not provide proper effluent quality.

The relative ability of the HCWs to remove organic matter (expressed as COD) was:

$$\text{Wiklino} > \text{Sarbsk} > \text{Wieszyño} > \text{Schodno} > \text{Darżlubie} \\ 95.5\% > 93.6\% > 84.7\% > 79.8\% > 74.9\%$$

The relative average TN removal of the systems was:

$$\text{Wiklino} > \text{Darżlubie} > \text{Sarbsk} > \text{Schodno} > \text{Wieszyño} \\ 79.2\% > 67.9\% > 62.6\% > 61.3\% > 23.4\%$$

The highest efficiency of nitrogen removal was observed in the Wiklino HCW in which the VF beds were operated alternately and wastewater was introduced intermittently. Likewise at the Schodno facility, high efficiency of TN removal was observed despite very high concentrations in the inflow. These observations confirm that the HCWs are successful at nitrogen removal.

Table 5

Mean values of loads and mass removal rates (MRR) of pollutants in HCWs [g·m⁻²·d⁻¹]

Plant	COD		BOD ₅		TN	
	Load	MRR	Load	MRR	Load	MRR
Schodno	6.1	4.8	3.1	2.4	0.7	0.4
Darżlubie	14.2	10.6	6.8	5.6	3.0	2.0
Wieszyño	16.7	13.8	10.7	9.3	1.9	0.4
Wiklino	3.9	3.7	2.2	2.1	0.9	0.7
Sarbsk	9.6	9.0	5.9	5.6	1.0	0.65

As well as nitrogen removal, intermittent loading of VF beds operating alternately with resting periods (Wiklino) was especially effective at enhanced organic matter removal. In Table 5, the mean organic matter (COD and BOD₅) and nitrogen inlet loads are compared with the mass removal rate (MRR).

A wide range of loadings was applied in Schodno HCW, receiving almost one tenth the load rate of Wieszyno. However, the maximum allowable loadings given in the literature (COD = 40 g·m⁻²·d⁻¹ and TN = 20 g·m⁻²·d⁻¹) [9, 10] were not exceeded. Studies in Spain [17] on HF beds with BOD load ranging from 0.8 to 23.0 g·m⁻²·d⁻¹ and on VF beds from 12.8 to 29.8 g·m⁻²·d⁻¹ showed 80.0% and 95.0% BOD₅ removal, respectively. In the Polish HCWs organic matter loading ranged from 0.8 (Schodno) to 10.7 g·m⁻²·d⁻¹ (Wieszyno), while the removal efficiency ranged from 78.5% (Schodno) to 95.9% (Wiklino).

Based on analysis of the obtained results, it could be concluded that the Schodno HCW, in spite of receiving the lowest loading rates, did not provide the highest pollutant removal efficiency. In contrast, high organic matter loading in Wieszyno resulted in poor nitrogen removal efficiency despite satisfactory organic matter removal. The highest MRR of TN was obtained in the Darżlubie HCW in spite of quite high values of organic matter loading (Table 5). The MRR was almost three times higher than the value of 0.7 g·N·m⁻²·d given for systems in Denmark [7]. The obtained results suggest that the MRR of pollutants from 1 m² changed in proportion to the loading value.

At the same time, organic matter in the HCWs was removed highly effectively over a wide loading range, irrespective of the HCW configuration. However, the MRR of TN related more closely to the HCW configuration than to the applied nitrogen loading.

3.2. SEASONAL CHANGES OF POLLUTANT REMOVAL

Seasonal changes in the quality of wastewater influent and effluent are presented in Fig. 1. The analysed systems were categorised into two groups, based on influent TSS, BOD₅, COD concentrations: 1) Wieszyno, Sarbsk and Wiklino – treatment of wastewater from multistage family houses – low concentrations of pollutants applied during the growing season (Figs. 1a, 2a); 2) Darżlubie and Schodno – higher concentrations of applied pollutants during the growing season (Figs. 1b, 2b). Regardless of season, performance of group 1 HCW was better than that of group 2, the effluent BOD and TN of which exceeded Polish permissible values in the vegetative season [1].

Comparison of seasonal average removal efficiencies for Wiklino and Darżlubie is presented in Fig 3.

Whilst BOD removal efficiency was not seasonally dependent, TN removal was ca. 10% higher in the growing season at both facilities. Other differences were rela-

tively small and may have been caused either by flow irregularity and/or fluctuations of inlet pollutant concentrations.

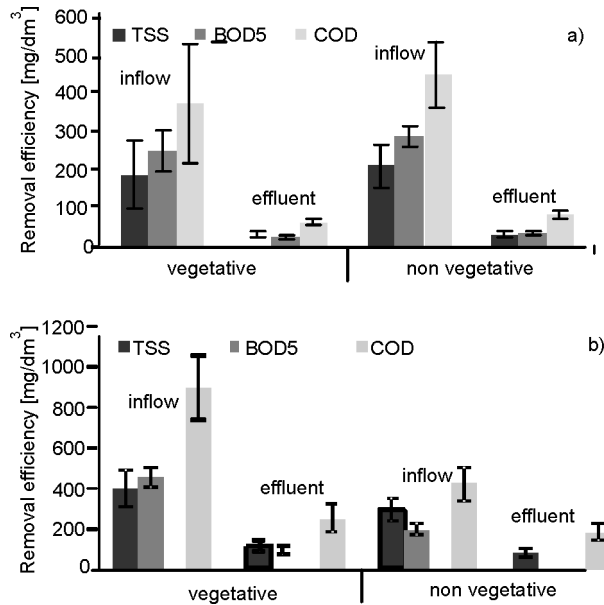


Fig. 1. Organic matter and total suspended solid concentrations in vegetative and post vegetative season in a) Wiklino, b) Darzlubie

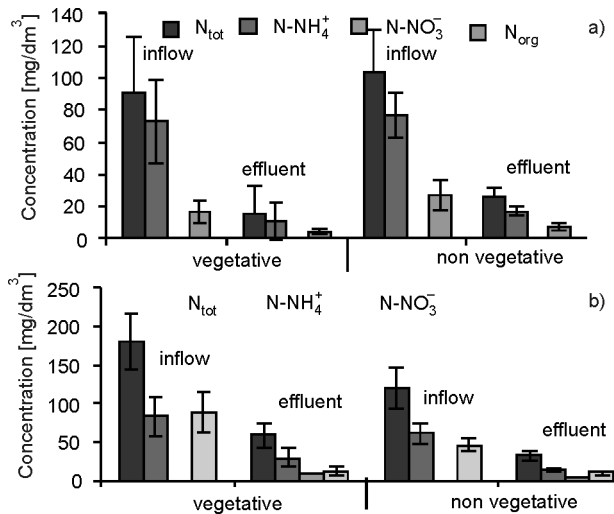


Fig. 2. Concentrations of nitrogen compounds in vegetative and post vegetative season in a) Wiklino, b) Darzlubie

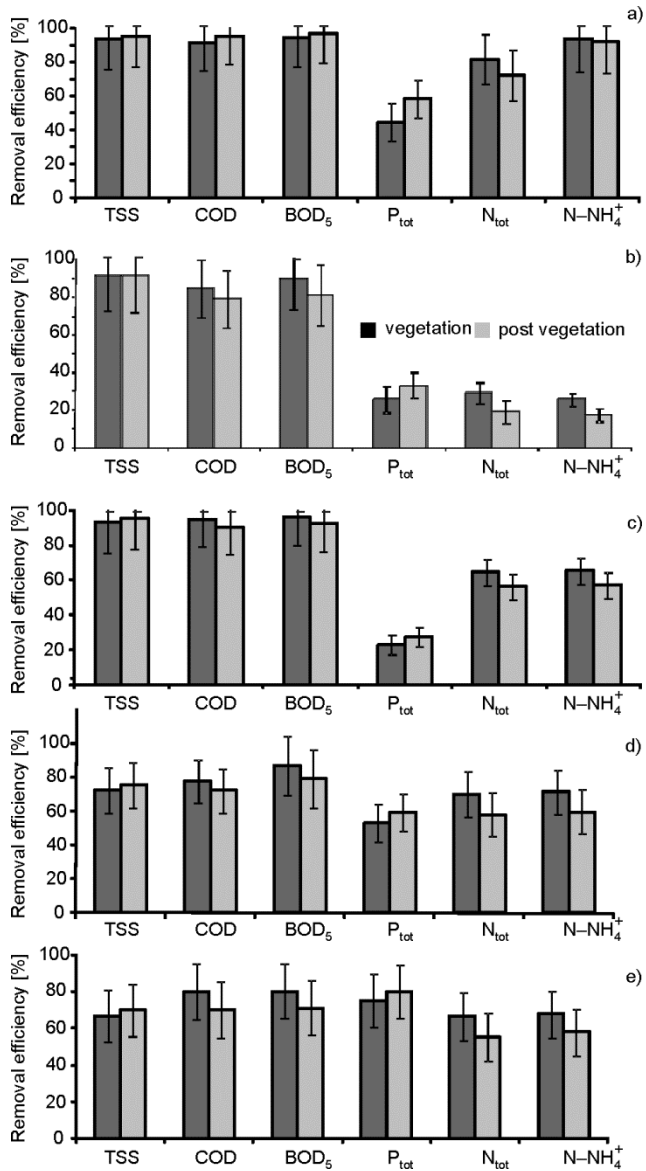


Fig. 3. Removal efficiency of pollutants in vegetative and post vegetative seasons: a) Wiklino, b) Wieszyno, c) Sarbsk, d) Darzłubie, e) Schodno

4. CONCLUSIONS

Hybrid constructed wetlands ensure stable and effective removal of organic matter in the load range $1.5\text{--}17.0 \text{ g COD}\cdot\text{m}^{-2}\cdot\text{d}$, irrespective of the bed configuration used.

Mass removal rates of total nitrogen range from 0.4 to 2.0 g TN·m⁻²·d⁻¹ depending on the configuration of VF CWs used and the sewage input regime.

Organic matter and total phosphorus removal efficiency was not season dependent, in contrast to the removal efficiency of nitrogen compounds.

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