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17 CONSTRUCTED WETLAND SYSTEMS IN POLAND

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ABSTRACT

Efficiency of removal of contaminants in individual and local constructed wetland systems operating in 1995–2000 in Poland was analysed. Individual plants were composed of filter beds of horizontal subsurface flow planted with willow (*Salix viminalis*) or reed *(Phragmites australis*).
The local systems were hybrid constructed wetland systems consisting of horizontal and vertical flow filters. All systems were fed with septic tank effluent.
Removal of organic matter and suspended solids was found to be very efficient. However the removal of nitrogen (especially ammonia nitrogen) in one stage systems was insufficient. It was proved that hybrid systems ensure higher efficiencies of nitrogen removal than horizontal flow systems.

KEYWORDS

Constructed wetlands, wastewater treatment, rural areas, single household and local systems, efficiency.

1. INTRODUCTION

In Poland there is considerable interest in ecological methods of wastewater purification. This situation is caused by insufficient or lack of sewage treatment in villages and small towns (usually only a first stage is in operation) and lack of methods for pollutant removal from surface sources.
The rural areas in Poland, populated with 14.6 million of people (38% of population), are exposed to the inflow of contaminants from household sewage. Farms are supplied with water by central water supply systems or from individual wells. Unfortunately only 8.2% of the farms are equipped with the sewer systems. It is estimated that approximately 25% of sewage produced in Poland is drained directly to the ground and surface water.
Collection and treatment of wastewater in areas with low population density is in many places unsatisfactory. Constructed wetlands have been in use for several years for the treatment of sewage from small communities and from very sparse single households.
Constructed wetland systems in Poland are applied mainly to provide secondary treatment of domestic wastewater after mechanical pretreatment (Kowalik et al. 1995, 1998). Due to

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climate conditions vegetated submerged beds (VSB) are mostly applied. The number of VSB constructed wetlands in operation in Poland is at present ca. 100.
Evaluation of several individual pilot wetland systems for single farms in Lublin and Mazowsze voyevodships was carried out. All systems consist of two stages of sewage treatment: first stage is a digestion tank (three chamber) serving as a mechanical step, and the second is a VSB filter with horizontal flow of sewage covered with willow or reed. Evaluated constructed wetland systems ensured high removal efficiency of organic matter (BOD_5, COD) and suspended solids but efficiency of nitrogen compounds removal varies in wide range and in many cases is insufficient. It was proved that higher efficiency of nitrogen removal is possible in systems with at least two beds with horizontal (HFCW) and vertical (VFCW) flow of sewage – the so called hybrid constructed wetlands (Cooper & de Maeseneer 1996). Improper maintenance of settling tanks and surface run off are blamed for lower efficiency of evaluated systems.
In the period from 1995 to 1999 measurements of removal of contaminants in a hybrid reed systems composed of HFCW and VFCW filters treating sewage from local communities of Sarbsko and Wiklino in Pommerania voyevodship were carried out.
It was found out that sufficient removal of organic matter (70–90%) took place in the HF filters. The removal of nitrogen took place in VF beds and in HF beds (denitrification) applied as the second and the third stage of biological wastewater treatment. The removal of nitrogen was limited by efficiency of nitrification process in VF beds in wetland systems.
The purpose of this paper is the evaluation of efficiency of full scale constructed wetlands for treatment sewage from single households and local communities.

2. METHODS

Four of the individual farms constructed wetlands were located in the Lublin voyevodship, three other near the town of Ostroleka and another four near Ciechanow in Mazowsze voyevodship. Systems located near Lublin and Ostroleka were constructed under the UNEP WHO and Polish Ministry of Environmental Protection, Natural Resources and Forestry programme „Sanitation of rural areas and proper agricultural practices" (Obarska-Pempkowiak et al. 1997). Systems near Ciechanow were designed and implemented by the Institute of Building, Mechanization and Electrification of Agriculture in Warsaw.
The design parameters and dimensions of beds near Ciechanow were following:

- the area of the bed was based on a surface area per capita loading 4.5 m^2/PE, which means that specific surface loading of a bed was approximately 29 mm/day,
- length of the bed, L=20,0 m, equal at all plants,
- width of the beds was variable, depending on the number of persons; W = 1.0 m, 1.1m 1.3 m and 1.5 m for 4 PE, 5PE, 6 PE and 8 PE, respectively (Eymont, 1995).
- average depth of the bed of individual system was equal to 1.0 m, slope of the bed bottom 1.0‰.

The first seven filter systems (1, 2, 3, 4, 5, 6, 7) were filled with medium grain sand while the next (I, II, IV) were filled with a mixture of gravel (grain size 0.5 – 8 mm) and an artificial aggregate „Pollytag" (grain size 4.0 – 8.0 mm). „Pollytag" aggregate is produced from ash of an average composition: SiO_2 – 58%, Al_2O_3 – 22%, Mg – 1.4%, S – 0.3%. Porosity of granules is about 40%. Using of „Pollytag" aggregates as a filter medium increased retention time, sorption capacity of the beds and ability of bonding toxic substances. One filter bed (III) was filled with coarse sand (grain size 0.1 – 3 mm).

The general characteristics of the investigated pilot farmer wastewater treatment plants in the villages near Ostroleka and Lublin are given in the Table 1 and for Przymorze village near Ciechanow in Table 2.

Table 1. Characteristic of pilot HFCWs near Lublin and Ostroleka.

No. of system	Name of the farmer	Number of persons (PE)	Characteristic of beds		
			area	plants	filter material
Lublin voyevodship					
1	Olejnik	9	45	willow	medium sand
2	Próchniak	6	50	willow	medium sand
3	Chołaj	7	38	willow	medium sand
4	Podstawka	7+10 in summer season	50	willow	medium sand
Mazowsze voyevodship					
5	Kesler	6	60	willow	natural soil, mainly (85% medium sand)
6	Shiffer	5	35	reed	natural soil, mainly (75% coarse sand)
7	Łysakiewicz	6+15 in summer season	35	reed	natural soil, mainly (75% coarse sand)

Table 2. Characteristic of pilot HFCWs in Przymorze village near Ciechanow.

No. of system	Name of farmer	Number of persons [PE]	Characteristics of willow bed			
			area [m^2]	shape L×W [m]	substrate material	k_{10}** [m/d]
I	Antoni Antczak	6	27.0	„U" (2×10)×1.3	mix (gravel & Pollytag) U*=3.4	650
II	Franciszek Kuc	4	18.0	rectangular 18.0× le0	mix (gravel & Pollytag) U*=3.4	650
III	Grzegorz Wikliński	5	22.5	„U" (2×10)×1.1	coarse sand U*=2.6	100
IV	Tadeusz Wikliński	8	36.0	„U" (2×10)×1.5	mix (gravel & Pollytag) U*=3.4	650

*) *$U = d_{60}/d_{10}$ – grain uniformity coefficient*
**) *k_{10} – hydraulic conductivity (from the Hazen formula) [according to Polish Standard]*

The studies were carried out at two hybrid constructed wetlands in Sarbsk and Wiklino near Slupsk (Pommeranian voyvodship). The sewage after mechanical treatment was pumped into biological treatment unit consisting of HF-CW and VF-CW beds. In the system located in Sarbsk the sewage outflowing from the VF-CW bed was recirculated. In the Wiklino system additional HF-CW II bed was constructed.

In spring 2000 the modernisation of the system supplying sewage into the VF-CW bed in Wiklino was completed. Due to installation of the pump periodical inflow of sewage into the single unit of VF-CW bed became possible. Periodical dosing of sewage resulted in better aeration of the bed (Gajewska & Obarska-Pempkowiak, 2001).

The characteristic of subsequent beds in Wiklino and Sarbsk is given in Table 3.

Table 3. The characteristics of constructed wetland systems in Wiklino and Sarbsk.

WWTP	Flow [$m^3 d^{-1}$]	Configuration	Area [m^2]	Depth [m]	Hydraulic load [$mm d^{-1}$]	Unit area [$m^2 PE^{-1}$]
Wiklino I – before modernisation	18.7	HF VF HF	1050 624 540	0.6 0.4 0.6	17.9 24.1 27.5	7.0 4.0 3.4 total 14.4
Wiklino II – after modernisation	18.6	HF VF HF	1050 624 540	0.6 0.4 0.6	17.7 46.9 25.7	7.0 2.0 3.4 total 12.4
Sarbsk	29.7	HF VF	1610 520	0.6 0.5	18.5 38.6	8.5 2.6 total 9.1

Averaged samples of influent (sewage after mechanical stage before the constructed wetland), effluent (sewage after the constructed wetland) and after subsequent stages of biological treatment were collected once or twice a month in investigated systems.
The measurement period in pilot systems located near Lublin and Ostroleka was divided into two periods:

- the first period of measurement lasted for 18 months (summer 1995–96), from start up till reaching full operation capacity of a plant),
- the second period lasted for 11 months (in 1997, both vegetation and non-vegetation season was covered.

During the first period the systems reached their full efficiency: growth of reed and willow took place and the rhizosphere typical of swamp ecosystem developed. In this paper only the data obtained in the second period was analysed.
In case of pilot systems near Ciechanow, averaged samples were collected once a month in 1998.
In the wetland system in Wiklino the samples were collected from April 1998 till May 2000 (Wiklino I – from April 1998 till February 2000 before modernisation of the system and from March to May 2000 – after introducing of periodical inflow of sewage).
In Sarbsk samples were collected from April 1998 to October 1998. Later on collection of samples was stopped due to improper operation of the plant. Measurments of physical and chemical parameters included: temperature of sewage and air, total suspended soilds, BOD_5, COD_{Cr}, ammonium nitrogen ($N–NH_4^+$), nitrate, nitrite and organic nitrogen, total phosphorus.
Analyses in systems located near Lublin and Ostroleka were performed by the Laboratory of Voyevodship Inspection of Environmental Protection. Other analyses were performed at Technical University of Gdansk.
Removal efficiency was calculated as a quotient of contaminants concentration difference in influent (C_0) and effluent (C) after subsequent steps of constructed wetland and concentration (C), $\eta = (C_0 - C)/C_0$.

3. RESULTS AND DISCUSSION

The BOD_5 loading in pilot individual plants near Lublin and Ostroleka in 1997 ranged between 1.21 and 5.76 g O_2 m^{-2} d^{-1}. The loading of COD ranged from 2.79 to 9.06 g O_2 m^{-2} d^{-1} with the exemption of the plant no. 7, where it was equal to 18.06 g O_2 m^{-2} d^{-1}. The loading of organic nitrogen was higher in the Ostroleka region and varied from 0.31 to 0.72 g m^{-2} d^{-1}, while in the Lublin region it ranged between 0.09 and 0.17 g m^{-2} d^{-1}. Total phosphorus loading in investigated plants was between 0.09 and 0.47 g m^{-2} d^{-1}.

Sewage generated in the farms no. 1, 2, 3 and 5 were similar to municipal sewage. Average water consumption in these farmholds was equal to 55 l per PE. The remaining farmholds produced sewage typical for agricultural activities and average water consumption was 120 l per person (Sikorski 1997).Lower concentration of organic matter in sewage effluent from septic tank in plant no. 5 was caused by improper construction of outflow of this tank and led to decomposition of sewage before the wetland system.

Evaluation of the operating efficiency of the individual pilot plants is based on averaged values of typical contaminants in effluent in the function of their loadings. Appropriate comparisons with the permissible concentrations of analysed contaminants in effluent are shown in Fig. 1.

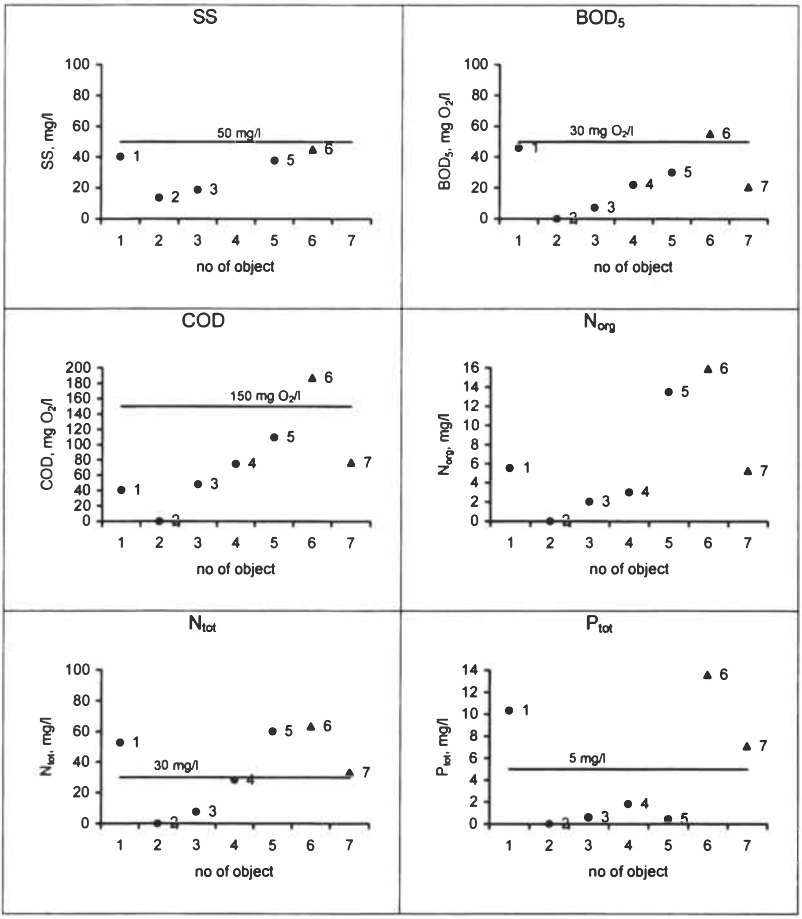

Fig. 1. Average concentrations of characteristic of contaminants in effluent in analysed constructed wetlands: with willow (●) and reed (▲) near Ostrołęka and near Lublin.

Plants no. 2 and 3 inhabited by willow fulfilled all criteria regarding required outflow quality. Plants no. 4 and 7 slightly exceeded the permissible values of N_{tot} and $N–NH_4^+$. Plant no. 6 inhabited by reed exceeded permissible values of all analysed parameters.

Improper operation of septic tanks and lack of good link between the subsequent units were the most frequent reasons of recontamination of sewage and lower efficiency of sewage treatment in case of constructed wetlands no. 1, 6, 7 and partly no. 4 and 5. Another reason for poor operation of the plant no.6 was that it was partly silted-up.

Results indicated that all monitored constructed wetlands inhabited by willow (*Salix viminalis*) achieved higher efficiency of phosphorus removal (over 80%) compared to the plant inhabited with reed (*Phragmites australis*). These results suggest that rhizosphere of willow may create conditions for phosphorus washing out, which does not take place in case of the rhizosphere of reed.

Plants no. 5, 6 and 7 filled with the subsoil achieved lower efficiency of contamination removal than the plants filled with sorted material which turned out to have better hydraulic conditions for sewage treatment (plants no. 2 and 3).

In the systems located near Ciechanow there were no problems with operation of septic tanks. In all of the plants there were septic tanks of the same construction.. The tanks were circular, concrete, of the total functional volume of 9.6 m^2, divided into three equal chambers.

Since the volumes of the septic tanks are equal and number of inhabitants is different in all of the plants, the detention times are also different and changing from 6.1 to 9.8 days. Pretreated wastewater (i.e. septic tank effluent) is pumped to the willow bed by a submerged pump located in the third chamber of the septic tank. In spite of high concentrations of contaminants in the inflowing sewage, the septic tanks worked properly.

The beds were fed with wastewater periodically, usually 2 times per day. The volume of each dose was equal to 0.5 m^3 and the discharge time was only 5 minutes, thus momentary loading was rather high.

Average annual concentrations of BOD_5 and N_{tot} for inflowing and outflowing sewage are shown in Fig. 2.

Average concentrations of the contaminants at the sewage outflowing from the willow beds and the admissible values according to Polish regulations are shown in Fig.3.

The analysis showed that at the system I (the Antczak farm) purification of sewage was very poor. It was probably caused by the fact that there was no tight connection of vertical barrier in the bed which resulted in shortening of the detention time.

In the system II (the Kuc farm) purification efficiency is rather low too. In this case the reason is that the shape of the bed is a long rectangle (18 m × 1 m) and at lower air temperatures cooling of wastewater was quicker than in the case of the „U" shaped beds.

The systems II, III and IV efficiently removed suspended soilds and P_{tot}. Despite of high rates of BOD_5 removal (from 68.7% to 79.5%) and N_{tot} (from 31.0% to 84.2%), the concentrations of N_{tot} in the effluent were high due to high concentrations of $N–NH_4^+$ (47.8 to 57.5 mg/l).

The results indicated that in the investigated willow beds sorption of NH_4^+ did not take place. This was due to using the coarse-grained filling material and lack of conditions for nitrification in beds of saturated subsurface horizontal flow. In the wastewater inflowing and outflowing from the willow beds no oxidised forms of nitrogen were found, indicating that ammonification is the dominant process in the beds.

Transformations of nitrogen taking place during sewage treatment are strongly associated with decay of inflowing organic matter and red-ox potential of the soil which is dependent on oxygen supply. Thus investigation of quantity of organic matter and nitrogen and oxygen balance in sewage in analysed hybrid constructed wetlands were conducted. Achieved results proved high removal efficiency of organic matter and suspended solids in investigated

systems. The highest removal efficiencies were observed in Wiklino II – after modernisation and for BOD_5 and COD they were equal to 92.5% and 89.4% respectively.
Average concentrations of nitrogen compounds after subsequent steps of treatment in analysed systems are given in Table 4.

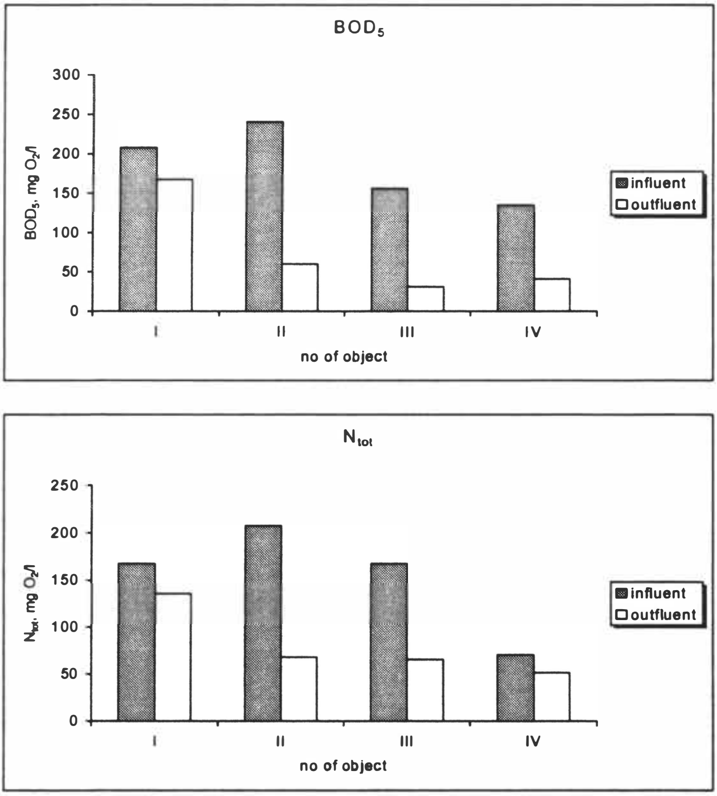

Fig. 2. Average concentration of characteristic of contaminants in sewage in constructed wetlands near Ciechanów.

In both plants in inflowing sewage nitrogen was present mainly in two forms: organic nitrogen and ammonia nitrogen. Organic nitrogen represented 1/3 of the total inflowing nitrogen and its concentrations varied from 11.2 to 35.3 mg/l.
Before modernisation of constructed wetland in Wiklino, the concentration of the total nitrogen in the treated sewage decreased by 79.4% while after modernisation the removal efficiency became higher and the concentration decreased by 85.6% (Table5).
In both measurment periods (before and after modernisation) the concentrations of total nitrogen in the effluent from the system in Wiklino did not fulfill the requirements (above 6.0 mg/l).
After introducing of periodical dosing of sewage into the VF-CW bed in Wiklino, efficiency of ammonia nitrogen removal increased from 82.3 to 91.2% (Table 5). Average concentration

of ammonium nitrogen in the effluent after modernisation of the system decreased below 6.0 mg/l (Table 4).

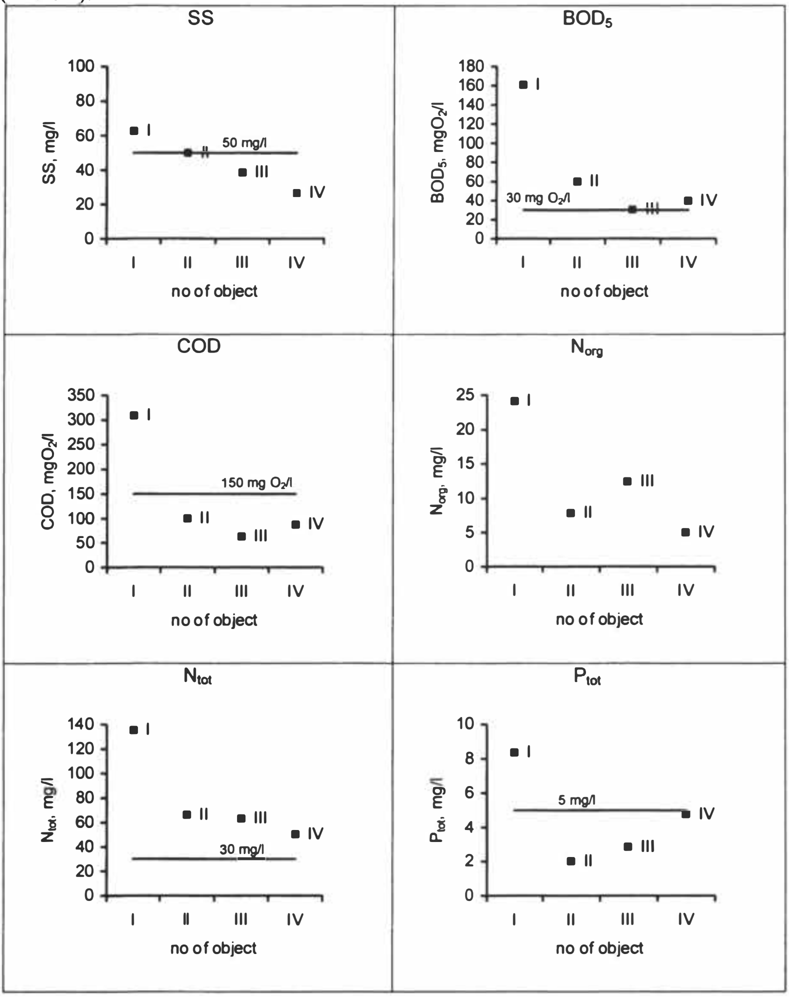

Fig. 3. Average concentration of characteristic of contaminants in effluent in analysed constructed wetlands near Cichanów, Poland.

Similar high efficiency of ammonia nitrogen removal, equal to 73.4% was observed in the constructed wetland in Sarbsk. The main form of nitrogen in effluent was ammonium, and its concentration was twice as high as the permissible value (Table 4).

Table 4. Average concentration of organic matter and nitrogen compounds with standard deviation after subsequent stages of treatment in Wiklino (I and II–before and after modernisation) and Sarbsk.

Parameters	Unit	*Wiklino – I stage*			
		Sampling points			
		Inflow	After HF-CW I	After VF-CW	Outflow (after HF-CW II)
		Average ± δ	Average ± δ	Average ± δ	Average ± δ
BOD_5	mg O_2/l	256,1 ± 22,3	130,1 ± 15,4	72,2 ± 8,0	27,2 ± 4,9
COD_{Cr}	mg O_2/l	394,2 ± 47,7	245,3 ± 38,0	141,5 ± 21,0	67,4 ± 12,5
N_{og}	mg/l	95.6 ± 11.8	61.4 ± 8.3	37.5 ± 5.8	19.7 ± 5.6
$N\text{–}NH_4^+$	mg/l	74.6 ± 8.3	45.4 ± 6.4	24.7 ± 4.4	13.2 ± 4.0
$N\text{–}NO_3^-$	mg/l	0.2	0.38	3.4	0.9
$N\text{–}NO_2^-$	mg/l	0.08	0.13	0.16	0.01
N_{org}	mg/l	20.7± 6.3	15.6 ± 3.6	9.3 ± 3.5	5.5 ± 2.2
pH	–	7.0 ± 0.1	7.2 ± 0.1	7.1 ±0.1	7.2 ±0.2
T_s	°C	14.8	12.8	12.3	11.9
T_{air}	°C	12.0	12.0	12.0	12.0
Parameters	Unit	*Wiklino – II stage*			
		Sampling points			
		Inflow	After HF-CW I	After VF-CW	outflow (After HF-CW II)
		Average ± δ	Average ± δ	Average ± δ	Average ± δ
BOD_5	mg O_2/l	273,0 ± 22,4	140,2 ± 9,4	48,5 ± 12,4	20,4 ± 6,8
COD_{Cr}	mg O_2/l	437,3 ± 37,2	300,1 ± 9,2	113,8 ± 5,8	46,4 ± 12,5
N_{og}	mg/l	88.8 ± 6.1	69.6 ± 2.3	28.8 ± 1.8	12.8 ± 0.5
$N\text{–}NH_4^+$	mg/l	67.1 ± 5.9	51.2 ± 6.5	15.9 ± 2.9	5.9 ± 1.2
$N\text{–}NO_3^-$	mg/l	0.3 ± 0.05	0.33 ± 0.06	5.1 ± 2.6	2.2 ± 1.0
$N\text{–}NO_2^-$	mg/l	0.02± 0.005	0.03	0.04	0.01
N_{org}	mg/l	21.5± 1.1	18.0 ± 0.9	9.0 ± 0.2	4.7 ± 0.3
pH	–	7.3 ± 0.06	7.2 ± 0.06	7.2 ±0.06	7.1 ± 0.06
T_s	°C	15.0	13.7	13.7	13.0
T_{air}	°C	13.7	13.7	13.7	13.7
Parameters	Unit	*Sarbsk*			
		Sampling points			
		Inflow	Inflow into HF-CW	After HF-CW	outflow (After VF-CW)
		Average ± δ	Average ± δ	Average ± δ	Average ± δ
BOD_5	mg O_2/l	316,4 ± 118,2	306,0 ± 113,8	87,2 ± 19,8	42,0 ± 12,4
COD_{Cr}	mg O_2/l	446,0 ± 152,2	426,0 ± 119,4	142,3 ± 36,9	82,3 ± 24,9
N_{og}	mg/l	74.3 ± 13.0	56.5 ± 11.9	34.8 ± 9.1	16.7 ± 0.5
$N\text{–}NH_4^+$	mg/l	42.1 ± 12.0	30.9 ± 9.8	17.8 ± 6.4	11.2 ± 1.2
$N\text{–}NO_3^-$	mg/l	0.2 ± 0.05	0.3 ± 0.1	0.3 ± 0.1	1.2 ± 0.5
$N\text{–}NO_2^-$	mg/l	0.2 ± 0.05	0.06± 0.02	0.06± 0.02	0.1
N_{org}	mg/l	21.5± 1.1	25.3 ± 9.1	16.9 ± 7.9	3.9 ± 0.3
pH	–	7.2 ± 0.1	7.3 ± 0.1	7.2 ±0.1	7.2 ± 0.1
T_s	°C	16.5	15.6	15.8	13.6
T_{air}	°C	16.8	18.3	18.3	18.1

Table 5. Efficiency of organic matter and nitrogen compounds removal in subsequent stages of treatment in Wiklino and Sarbsk, %.

Parameter	*Wiklino I*			
	HF-CW I	VF-CW	HF-CW II	Total
BOD_5	49.4	44.5	62.3	89.4
COD_{Cr}	37.7	42.3	52.4	82.9
N_{tot}	35.8	38.9	47.5	79.4
$N\text{–}NH_4^+$	39.1	45.6	46.6	82.3
N_{org}	24.6	40.4	40.8	73.4
	Wiklino II			
	HF-CW I	VF-CW	HF-CW II	Total
BOD_5	48.6	65.4	57.9	92.5
COD_{Cr}	31.4	62.1	57.7	89.4
N_{tot}	2le6	58.6	55.6	85.6
$N\text{–}NH_4^+$	23.7	68.9	62.9	91.2
N_{org}	16.2	50.0	47.8	78.1
	Sarbsk			
	HF-CW	VF-CW	Total	
BOD_5	7le5	5le8	86.3	
COD_{Cr}	66.7	42.2	80.7	
N_{tot}	53.2	52.0	77.5	
$N\text{–}NH_4^+$	57.7	37.1	73.4	
N_{org}	21.4	78.9	81.9	

4. CONCLUSIONS

Taking into consideration conditions in the investigated plants it was concluded that:

1. Technological units for wastewater treatment consisting of septic tank and vegetated subsurface bed (willow or reed) could be recommended for treatment of sewage in rural areas.
2. The review of the one year operation data from pilot beds provides evidence that after a quite short implementation period (1–2 years) the removal of organic matter and phosphorus compounds is possible.
3. The majority of investigated pilot systems did not provide effective removal of ammonia nitrogen due to the lack of conditions for nitrification and sorption.
4. Improper operation and maintenance of septic tanks as well as surface runoff are the reasons of too low efficiency of individual pilot systems.
5. The hybrid constructed wetlands in villages: Wiklino and Sarbsk show very high efficiency of removal of total nitrogen which equals to: 85.6 and 77.5% respectivelye
6. Average concentration of ammonia nitrogen in Wiklino before modernisation and in Sarbsk did not fulfil Polish requirements. Introducing periodical irrigation of VF-CW beds in Wiklino caused decreasing of ammonia nitrogen concentration below permissible value.

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