The Removal of Nitrogen Compounds in Constructed Wetlands in Poland

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Abstract

More than 100 constructed wetlands are in operation in Poland. Most of them are one-stage wetland systems with horizontal subsurface flow. Constructed wetlands ensure efficient removal of organic matter (BOD_5, COD_{Cr}) and suspended solids, but efficiency of nitrogen compound removal in many cases is insufficient.

From 1995 to 2001 a study on the removal of contaminants in 11 individual pilot households as well as 4 local community plants equipped with one-stage horizontal flow bed and 4 local community equipped with hybrid reed wetland systems composed of HF-CW and VF-CW filters were carried out. The hybrid constructed wetlands ensure more stable removal rates of nitrogen in comparison with one stage systems. The removal of nitrogen takes place in VF beds and HF beds (denitrification) applied as the second and third stage of primary hybrid treatments. The removal of nitrogen was limited by efficiency of the nitrification process in VF beds in wetland systems.

Keywords: constructed wetlands, nitrogen removal, single household and local systems, hybrid systems, efficiency, HF-CW, VF-CW filters

Introduction

In Poland almost all farms are supplied with water by central water supply systems or from individual wells. However, only 8.2% of the farms are equipped with sewage systems. Central wastewater treatment plants are not an adequate solution due to dispersed development. The main problem is that individual and local systems are not connected to the central WWTPs. The Polish limit values for nitrogen concentration in sewage discharged to surface waters and soil are: $N_{tot} < 30$ mg/l and $N\text{-}NH_4 < 6$ mg/l. The values are obligatory in all instances when the amount of sewage exceeds 5 m^3/day. Sources producing small amounts of wastewater (slightly above 5 m^3/day) found themselves in a relatively bad situation, since frequently it is too expensive to introduce highly efficient sewage treatment methods there.

Water consumption rate in rural areas is substantially smaller than in cities. Most often it is in the range 50-100 l/day as compared to 150 l/day in cities. Therefore, the produced sewage is more concentrated and is more difficult to treat in conventional systems.

In the last decade more than 100 constructed wetland systems were built in Poland. Most of them are one-stage systems with horizontal subsurface flow which are fed with sewage after mechanical treatment. Unfortunately, due to a lack of sufficient knowledge and improper maintenance, the efficiency of contaminant removal, especially of nitrogen compounds, was low. Only within the last seven years have combined horizontal/vertical flow systems been introduced.

The removal efficiencies of nitrogen compounds in several HF-CWs in individual pilot and local systems as well as in hybrid systems are presented in this paper.

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Table 1. Characteristic of individual farms' HF-CWs near Lublin, Ostroleka and Ciechanow.

No. of system	Number of persons [PE]	Characteristic of beds		
		Area	Plants	filter material
3near Lublin, Lublin voyevodship				
1	9	45	willow	medium sand
2	6	50	willow	medium sand
3	7	38	willow	medium sand
4	7+10 in summer season	50	willow	medium sand
near Ostroleka, Mazowsze voyevodship				
5	6	60	willow	natural soil, mainly (85% medium sand)
6	5	35	reed	natural soil, mainly (75% coarse sand)
7	6+15 in summer season	35	reed	natural soil, mainly (75% coarse sand)

near Ciechanow, Mazowsze voyevodship

No. of system	Number of persons [PE]	Characteristics of bed				
		Area [m^2]	Plants	Shape L·W [m]	substrate material	k_{10}^{**} [m/d]
I	6	27.0	willow	"U" (2·10)·1.3	mix (gravel & Pollytag) U^*=3.4	650
II	4	18.0	willow	rectangular 18.0·1.0	mix (gravel & Pollytag) U^*=3.4	650
III	5	22.5	willow	"U" (2·10)·1.1	coarse sand U^*=2.6	100
IV	8	36.0	willow	"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]

Methods

The study was performed on 11 individual farm wetlands: four in Lublin voyevodship, three others near the town of Ostroleka and another four near Ciechanow in Mazowsze voyevodship. The general characteristics of the investigated pilot farmer wastewater treatment plants in villages in Poland are given in Table 1.

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" [9]. Systems near Ciechanow were designed and implemented by the Institute of Building, Mechanisation and Electrification of Agriculture in Warsaw in 1997.

The design parameters and dimensions of beds near Ciechanow were as follows:

- 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 [5].
- 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 mix 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 flue dust 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).

Characteristics of local communities' HF-CWs located near Gorzow Wielkopolski systems is presented in Table 2. Average flow of sewage for local HF-CWs near Gorzów varied 26.3-90 m^3/day. These systems were constructed in the beginning of the 1990s without sufficient knowledge of the design.

The studies were carried out at three hybrid constructed wetlands in Darżlubie, Sarbsk and Wiklino near Slupsk in Pomeranian voyvodships, as well as in

Table 2. Characteristics of local communities HF-CWs near Gorzów

WWTPs	Flow [m^3day^{-1}]	Area [m^2]	Depth [m]	Unit area [m^2PE^{-1}]
Wawrów	90.0	3500	0.8	2.7
Gralewo	46.3	3325	0.9	3.0
Małyszyn	26.3	4800	0.4	4.0
Rokitno	45.0	1200	0.4	10.0

Table 3. The characteristics of the constructed wetland hybrid systems

WWTP	Flow [m^3/day]	Configuration	Area [m^2]	Depth,[m]	Unit area,[m^2PE]
Wiklino I- before modernisation	18.7	HF-CW I VF-CW HF-CW II	1050 624 540	0.6 0.4 0.6	7.0 4.0 3.4 total 14.4
Wiklino II- after modernisation	18.6	HF-CW I VF-CW HF- CW II	1050 624 540	0.6 0.4 0.6	7.0 2.0 3.4 total 12.4
Sarbsk *	29.7	HF- CW VF- CW	1610 520	0.6 0.5	8.5 2.6 total 9.1
Darżlubie	56.7	HF-CW I Cascade filter HF-CW II VF-CW HF-CW III	1200 400 500 250 1000 total 3350	0.6 0.6 1.0 0.6	1.6 0.5 0.7 1.3 total 4.1
Sobiechy	7.6	HF-CW VF-CW	448 44 total 492	0.6 1.0	2.1 0.2 total 2.3

*) The sewage outflowing from VF-CW bed was recirculated

Sobiechy in Podlaski voyvodship. The sewage after mechanical treatment was pumped into biological treatment unit consisting of HF-CW and VF-CW beds. In the systems located in Sarbsk and in Sobiechy the sewage outflowing from the VF-CW bed was recirculated. In the Wiklino and Darżlubie systems additional HF-CW bed was constructed. All systems were grown with reed.

The characteristics of the systems and configuration of beds is given in Table 3. The average flow of sewage varied from 7.6 to 56.7 m^3/day.

Samples of sewage were collected once or twice a month during one or two years of operation of the systems.

Four communities' HF-CWs located near Gorzow Wielkopolski were investigated by [10] during seven years of operation. In Wiklino sewage samples were collected from April 1998 to February 2000 (before modernization) and from March to May 2000 (Wiklino II - after modernization). In spring 2000 the modernization of the system supplying sewage into the VF-CW bed was completed only in Wiklino. Due to installation of the pump, periodical inflow of sewage into the single unit of VF-CW bed became possible. Periodical dosage of sewage resulted in better aeration of the bed [6].

Average samples of sewage were collected before and after HW-CWs in local form plants. From the hybrid systems average samples of sewage were taken after subsequent stage of treatment.

Measurements of physical and chemical parameters included: temperature of sewage and air, ammonium nitrogen ($N\text{-}NH_4^+$), nitrate, nitrite and organic nitrogen and alkalinity.

Removal efficiency in all systems was calculated as a quotient of contaminant concentration difference in influent (C_0) and effluent (C) after subsequent steps of constructed wetland and concentration (C), $\eta=(C_0\text{-}C)/C_0$.

Results and Discussion

One Stage Constructed Wetlands

Total nitrogen loading in investigated farm systems located near Lublin (no 1, 2, 3, 4) and Ostroleka (no 5, 6, 7) was between 8.9 and 19.8 kg/ha day. However, in the systems located near Ciechanow (no I, II, III, IV) was higher and was between 8.7 and 33.4 kg/ha day.

Sewage generated on farms no 1, 2, 3 and 5 were similar to municipal sewage. Average water consumption in these farms was equal to 55 l/PE. The other farmholds produced sewage typical of agricultural activities and average water consumption was 120 l/PE [11].

The efficiency of removal of total nitrogen and ammonia nitrogen was between 20.0-98.0% and 8.0-99.0%, respectively, for pilot farms plants. Comparisons of ammonia nitrogen and total nitrogen concentrations with the permissible concentration in the effluent are presented in Fig. 1.

Systems 2 and 3, grown with willow, fulfilled all criteria regarding required outflow quality. In plants 4 and 7, the permissible values of N_{tot} and $N\text{-}NH_4^+$ were slightly exceeded. The effluent of plant no. 6, grown with reed, concentrations of all analyzed parameters exceeded permissible values.

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

Plants 5, 6 and 7 filled with the subsoil, achieved lower efficiency of nitrogen compounds removal than the plants filled with sorted material, which turned out to have better hydraulic conditions for sewage treatment (plants nos. 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, and of total operating volume of 9.6 m^3, divided into three equal chambers.

Since the volumes of the septic tanks are equal and the number of inhabitants is different in all of the plants, the retention times are also different and changing from 6.1 to 9.8 days. Pre-treated 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.

Analysis showed that at system I, purification of sewage was 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.

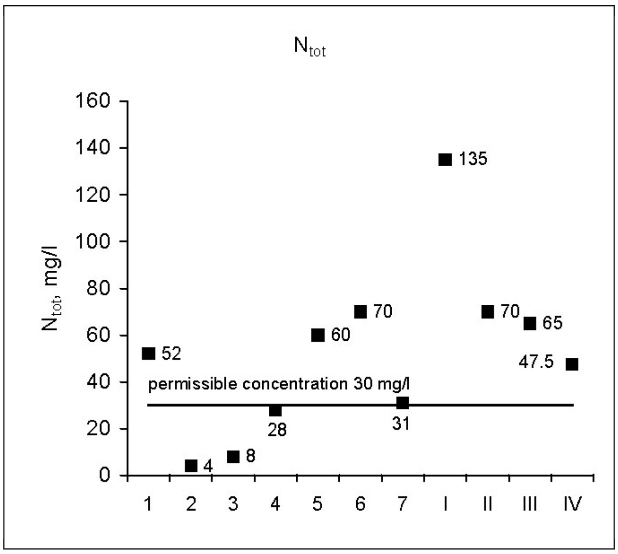
In the system II purification efficiency is rather low, too. In this case the reason is that the shape of the bed is a long rectangle (18 m × 1 m) and at lower air temperatures the wastewater cooling was quicker than in the case of the "U" shaped beds.

In systems II, III and IV, despite the high rates of N_{tot} (from 31.0% to 84.2%), the concentrations of N_{tot} in the effluent were high due to high concentrations of $N\text{-}NH_4^+$ (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 the use of the coarse-grained filling material and a lack of conditions for nitrification in the beds of saturated subsurface horizontal flow. In the wastewater inflowing and outflowing from the willow beds no oxidized forms of nitrogen were found, indicating that ammonification is the dominant process in the beds.

The relationship between both total nitrogen and ammonia nitrogen removal and loading rates for household (farms) are presented in Figs. 2a and 2b.

The average efficiencies in the loading ranges from 5 to 18 kg/ha day (ammonia) and from 9 to 35 kg/ha day (total nitrogen), and efficiency removal was about 50%. The efficiency of the removal was calculated as a ratio



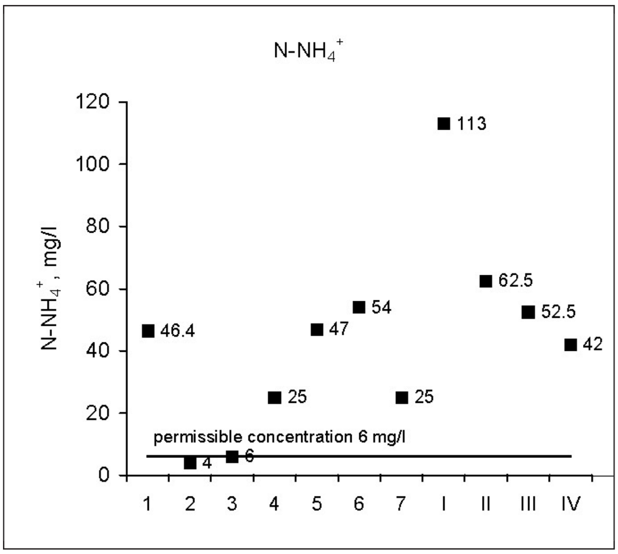


Fig. 1. Average concentration of ammonia nitrogen and total nitrogen in effluent in individual HF-CWs.

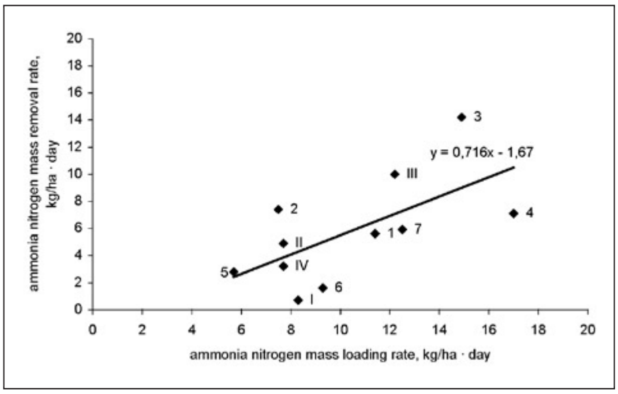


Fig. 2a. Ammonia nitrogen mass loading and removal rates in HF-CW household system.

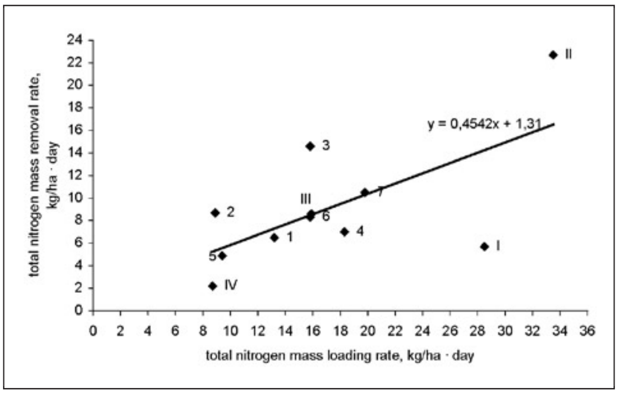


Fig. 2b. Total nitrogen mass loading and removal rates in HF-CW household system.

of the difference of the average loads of nitrogen forms in influent and effluent to the average load of respective nitrogen in influent. Substantial scatter of individual farm efficiency can be noticed -most likely caused by insufficient care of the facilites.

Similar comparisons were made for four local communities' HF-CWs. Comparisons of ammonia nitrogen and total nitrogen concentrations with the permissible concentration in the effluent of these systems in Fig. 3 is presented. Only two systems (with the lowest mass loading of nitrogen) fulfilled the Polish outlet criteria for N_{tot} [12]. However, no system met the requirements for ammonia nitrogen.

Loading of total nitrogen and ammonia nitrogen varied in range 2.3-36.9 kg/ha day and 1.6-30.3 kg/ha day respectively. The efficiency of removal N_{tot} was between 56.5-75.6% and for $N\text{-}NH_4^+$ was 56.1 and 63.0%. The relationship between the mass loading of N_{tot} in these systems and the mass of N_{tot} removed is illustrated in Figs. 4a and 4b.

The efficiencies seem to be remarkably stable judging from a small scatter of experimental points. The facilities are well taken care and this may explain the stable performance of the systems.

Hybrid Wetland Systems

Concentration of total nitrogen in the influent and efficiency of the removal after subsequent stages of treatment in investigation hybrid systems is presented in Table 4.

A general decrease in the loading rate of nitrogen resulted in a higher efficiency of nitrogen removal. In Darżlubie and Sobiechy the operation of VF-CWs was insufficient. For this reason the concentration of total nitrogen in the effluent exceded the permissible value.

Removal of ammonia nitrogen was satisfactory only in Wiklino II (after modernization) (Fig. 5). The relationship between the mass loading of N_{tot} and the mass of N_{tot} removed is given in Fig. 6. The removal rates of total ni-

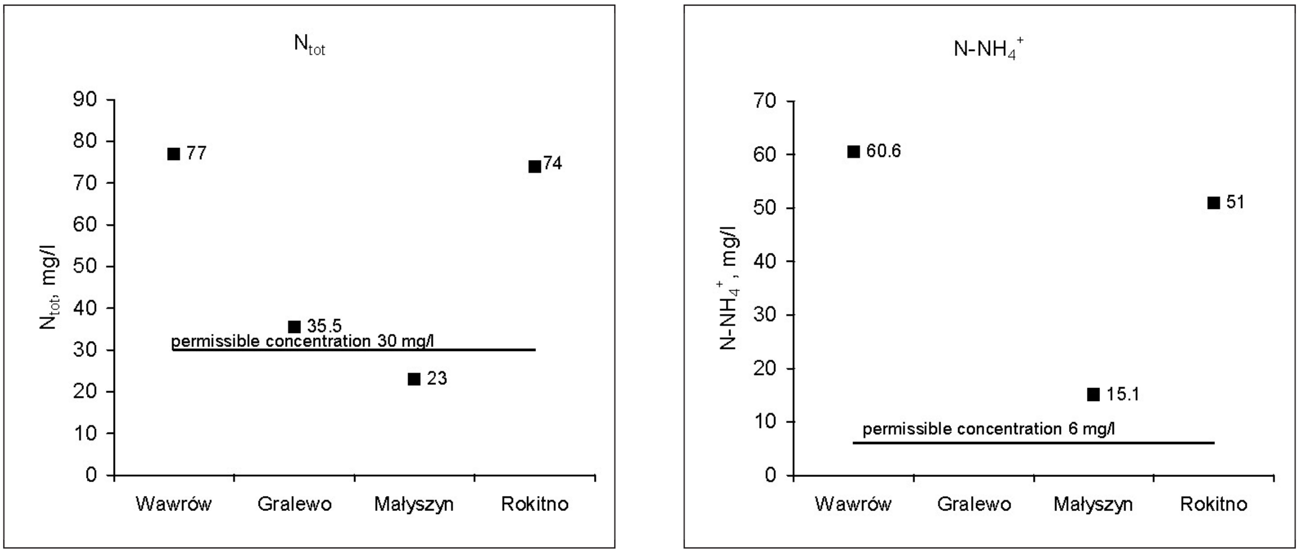


Fig. 3. Average concentration of ammonia nitrogen and total nitrogen in the effluent in local HF-CWs near Gorzów, Poland.

Table 4. Concentration of total nitrogen in influent and efficiency of the removal after sequential stages of treatment in hybrid systems.

Object	In flow [mg/l]	HF-CW I [%]	VF- CW [%]	HF-CW II [%]	Total effect [%]
Wiklino I before modernisation	95.6 ± 11.8	35.8	38.9	47.5	79.4
Wiklino II after modernisation	88.8 ± 6.1	21.6	58.6	55.6	85.6
Sarbsk	74.3 ± 13.0	38.4	52.0	-	81.5
Darżlubie	134.0 ± 10.0	9.7	27.9	39.4	63.6
Sobiechy	72.9 ± 16	-	-	-	53.8

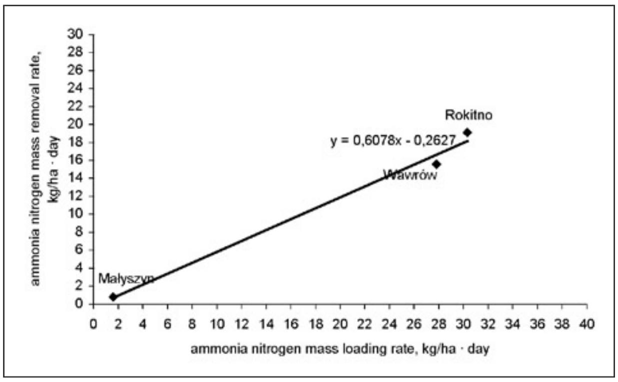


Fig. 4a. Ammonia nitrogen mass loading and removal rates in local HF-CWs near Gorzów, Poland.

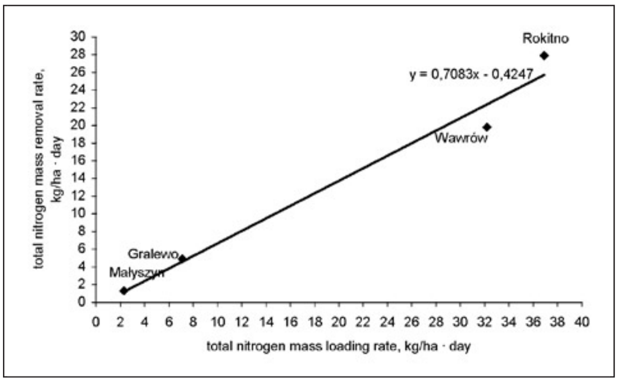


Fig. 4b. Total nitrogen mass loading and removal rates in local HF-CWs near Gorzów, Poland.

trogen were more stabilized and larger in comparison with those at one-stage systems and varied from 4.2 to14.6 kg/ha day. The average removal rate was 7.8 kg/ha day. The values are very similar to those given by [1] (3.0-7.0 kg/ha day). The system in Darżlubie was efficient but very huge mass loadings made it impossible to get a satisfactory removal of nitrogen. It was caused by overloading of the system by liquid manure from individual farms.

On the basis of the determined average annual loads of analyzed nitrogen compounds in Wiklino I, it is possible to estimate the rate of transformation or removal of nitrogen from the area of hybrid constructed wetland.

The ability of nitrogen removal and transformation was estimated as a quotient of the difference between the incoming and the outflowing load of different of nitrogen species and the bed area.

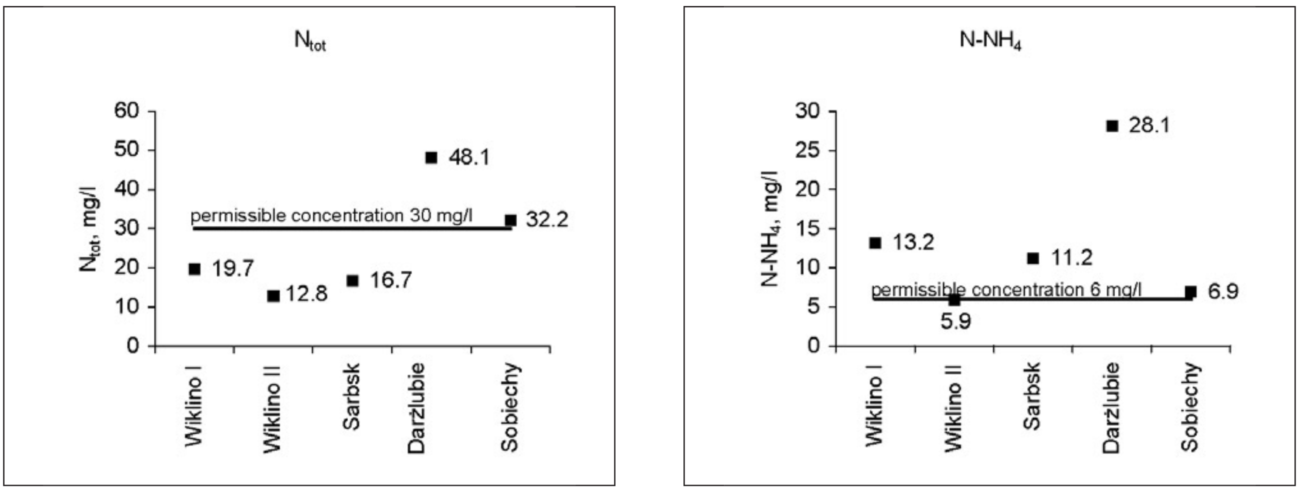


Fig. 5. Average concentration of ammonia nitrogen and total nitrogen in effluent in hybrid system.

Table 5. The rate of amonification, nitrification and denitrification processes in subsequent stages of treatment in Wiklino-constructed wetland, in gN/m^2 day.

Processes	Stage of treatment			
	HF-CW I	VF-CW	HF-CW II	Average
Amonification	0.15	0.15	0.13	0.15
Nitrification	0.68	0.53	0.35	0.56
Denitrification	0.67	0.59	0.51	0.59

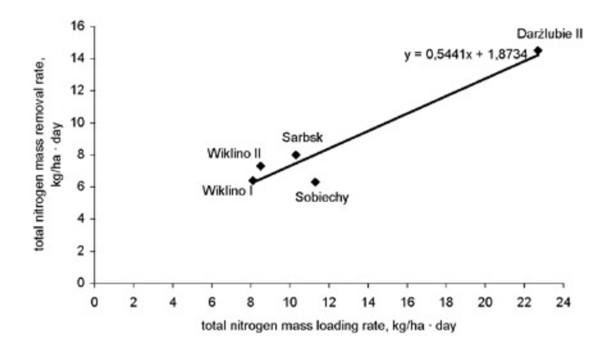


Fig. 6. Total nitrogen mass loading and removal rates in studied hybrid systems.

It was calculated that the average rate of nitrification, in the conditions of the constructed wetland at Wiklino, was equal to 0.56 g/m^2 day and denitrification rate was equal to 0.59 g/m^2 day. The rate of denitrification was probably higher (more intensive) because part of the nitrate was transformed into free nitrogen due to denitrification. The process of amonification was the slowest one and its average rate was equal to 0.15 g/m^2 day. It was also proved that amonification of organic nitrogen took place mainly in the mechanical treatment in the conditions of the Wiklino-constructed wetland (Table 5) [6].

Similar evaluation was carried out for Darżlubie. It was proven that denitrification rate was equal 0.98 gN/m^2 day [9].

Conclusions

Analysis of the results of the monitoring and operation conditions in the plants investigated lead to the following conclusions.

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. Improper operation and maintenance of septic tanks as well as surface runoff (plants: 1, 5, 6) and improper shape are the reasons for too low efficiency of individual pilot systems (plant II).
3. The majority of investigated pilot and local communities' HF-CW did not provide effective removal of ammonia nitrogen due to the lack of conditions for nitrification and sorption.
4. The hybrid constructed wetlands ensure a more stable removal rate of nitrogen in comparison with that at one-stage systems. The average removal rate was 7.8 kg N_{tot}/ha day.

Acknowledgements

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