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The efficiency and reliability of pollutant removal in a hybrid constructed wetland with giant miscanthus and Jerusalem artichoke in Poland

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ABSTRACT

In this paper, we analysed the pollutant removal efficiency and reliability of a vertical and horizontal flow hybrid constructed wetland (CW) planted with giant miscanthus and Jerusalem artichoke. The wastewater treatment plant, located in south-eastern Poland, treated domestic sewage at an average flow rate of 1.2 $m^3 \cdot d^{-1}$. The tests were carried out during 5-years of operation of the sewage treatment plant (2011–2016). During this period, sewage samples were collected from three stages of wastewater treatment in four seasons (winter – February, spring – May, summer – August, and autumn – November). The following parameters were measured: BOD_5, COD, total suspended solids, total nitrogen, and total phosphorus. The average effectiveness of organic pollutant removal expressed by BOD_5 and COD was 98.8 and 97.6%, respectively, and the removal efficiency for total suspended solids was 93%. The average values of BOD_5, COD, and total suspended solids in wastewater discharged to the receiver were significantly lower than the limit values required in Poland. The efficiency of total nitrogen and total phosphorus removal was 64.1 and 68.1%, respectively, and the average values of these components in the outflow from the treatment plant exceeded the standard levels. A reliability analysis performed using the Weibull probability model showed that the reliability of pollutant removal in the tested CW system was very high for BOD_5 and COD (100%). It was also demonstrated that the tested CW did not provide effective elimination of biogenic elements (nitrogen and phosphorus), as evidenced by the low reliability values – 32 and 28%, respectively. The investigated hybrid CW system with giant miscanthus and Jerusalem artichoke removed organic and biogenic pollutants with a similar efficiency as systems using classic plant species such as reed and willow.

Key words: wastewater treatment, hybrid constructed wetlands, vertical flow, horizontal flow, pollutant removal, efficiency and reliability

1. Introduction

Domestic wastewater treatment plants are an optimal solution for the disposal of small amounts of wastewater in areas of dispersed development, where the construction of a sewage system is economically unjustified (García et al., 2013; Mikosz and Mucha, 2014; Jóźwiakowski et al., 2015). Issues related to the operational reliability of low capacity treatment plants below 5 $m^3 \cdot d^{-1}$ are still rarely brought up due to the lack of precise requirements regarding the application of various technological solutions for home sewage treatment plants and their control during operation. Such a situation is not conducive to the creation and implementation of new, effective technologies. On the contrary, it favours the cheapest solutions, mainly systems with a leach drain, which are used for discharging untreated wastewater into the ground, and therefore, their application for waste water treatment raises serious questions (Jóźwiakowski et al., 2015, Zhang et al., 2015). Moreover, many solutions applied in small sewage treatment plants, including those based on conventional methods, in conditions of high variability of hydraulic load, pollution load and operating conditions do not guarantee high efficiency of removal of pollutants from sewage (Marzec, 2017). With a constant increase in the number of ineffective technological solutions applied, the risk of their negative impact on water quality increases (Bugajski, 2014; Pawełek and Bugajski, 2017).

Therefore, the reliability of small sewage treatment plants should be an important criterion in planning the development of technical infrastructure in rural areas, which will enable the selection of optimal and environmentally safe solutions (Jóźwiakowski et al., 2015; Jucherski et al., 2017). There are more and more suggestions that all treatment plants, regardless of their size and type of receiver, should be placed under the control of competent authorities. At the same time, the popularity of constructed wetland systems, which can be used in various conditions, including protected areas and areas of high landscape value, is increasing due to their high pollutant removal efficiency (Vymazal, 2011; 2013; Jóźwiakowski, 2012; Paruch et al., 2011; Jóźwiakowski et al., 2017; Gajewska et al., 2015).

Constructed wetlands, and in particular hybrid treatment plants consisting of at least two beds with different sewage flows (vertical and horizontal), ensure effective removal of organic matter (BOD_5 and COD) (Vymazal, 2011) and slightly less effective removal of nutrients (Kadlec and Wallace, 2008; Vymazal and Kropfelova, 2008). The removal of contaminants in constructed wetland systems is related to the functioning of the biological membrane formed during the flow of wastewater through the material filling the beds. The plants growing in the wetland support the process of treatment (Vymazal, 2013; Foladori et al., 2012; Vymazal and

Březinová, 2014; Wu et al., 2015). The rhizosphere produces an oxygenated microenvironment, while other layers of the bed provide anaerobic or anoxic conditions. Roots and rhizomes of plants increase the hydraulic permeability of the soil and loosen its structure (Birkedal et al., 1993). Until now, depending on the climatic conditions, different plant species have been used in constructed wetland systems, mainly common reed and willow (Vymazal, 2011; Jóźwiakowski, 2012). These plants are characterized by quite intensive growth, even on a very poor substrate (Gruenewald et al., 2007), hence the possibility of using constructed wetland systems not only for wastewater treatment, but also for biomass production for energy purposes (Cerbin et al., 2012; Posadas et al., 2014; Lu and Zhang, 2013). In this respect, research on the use of other plants, e.g. giant miscanthus or Jerusalem artichoke, in constructed wetland systems may be of interest (Gizińska-Górna et al., 2016). The high energy potential of these plants is a result of high yield and biomass calorific value, which depends on its chemical composition (Bridgwater and Peacocke, 2000; Bellamy et al., 2009; Long et al., 2010). In European conditions, the yield of giant miscanthus in field cultivation ranges from 10 to 30 Mg DM·ha^{-1} (Szulczewski et al., 2018), and Jerusalem artichoke from 9 to 25 Mg DM·ha^{-1} (Baldini et al., 2004; Gunnarsson et al., 2014). The calorific value of dried biomass of giant miscanthus varies from 14 to 17 MJ·kg DM^{-1}, and for Jerusalem artichoke varies from 15 to 19 MJ·kg DM^{-1} (Szulczewski et al., 2018; Gizińska-Górna et al., 2016). The possibilities of their use in wastewater treatment are less recognized, especially in moderate climate conditions. Jerusalem artichoke has not been used in constructed wetland systems yet, while research on the use giant miscanthus has been carried out on a pilot scale and under warm climate conditions. Their results indicate that the efficiency of pollutants removal in the beds planted with giant miscanthus may be similar to those found in the case of classical plant species, including common reed (Toscano et al., 2015; Barbagallo et al., 2014).

The aim of the present study is to analyse the reliability and effectiveness of pollutant removal in a hybrid constructed wetland wastewater treatment plant with giant miscanthus (*Miscanthus giganteus x* Greef et Deu) and Jerusalem artichoke (*Helianthus tuberosus L.*) during five years of its operation.

2. Materials and methods

2.1. Characteristics of the experimental facility

The analysed plant is located in Skorczyce, Poland (51°00′36″N, 22°11′51″E). Its task is to treat domestic sewage from a multi-family building. The plant has been in operation since

2011 and its planned capacity is 2.5 $m^3 \cdot d^{-1}$. In the analyzed system, sewage from the building was drained into a three-chamber preliminary settling tank, where it was pre-treated in physical and biological processes.

The tank is made of concrete, and its active capacity is 8.64 m^3. In the next stage, the sewage flows through a system of two VF-HF type soil and plant beds (biological treatment). A first bed, with vertical sewage flow (VF), has an area of 96 m^2 and a depth of 0.8 m, and the second bed, with horizontal sewage flow (HF), has an area of 80 m^2 and a depth of 1.2 m. The beds have been isolated from the native soil by a PEHD waterproofing geomembrane of 1 mm thickness. The VF bed was filled with a layer of sand (1-2 mm) with a height of about 0.8 m. The filling of the HF bed to the height of 1.0 m consisted of sand (1-2 mm), on which there was laid the humus soil layer with a height of 0.2 m and it was obtained during the construction of the sewage treatment plant (Figures 1, 2). The first bed was planted with giant miscanthus (*Miscanthus x giganteus* Greef et Deu.), the second with Jerusalem artichoke (*Helianthus tuberosus* L.) (Photo 1). Every year, after the winter season, the aboveground plant shoots and part of the tubers (Jerusalem artichoke) are removed from the fields. The recipient of the treated wastewater is the Urzędówka River (Figures 1, 2).

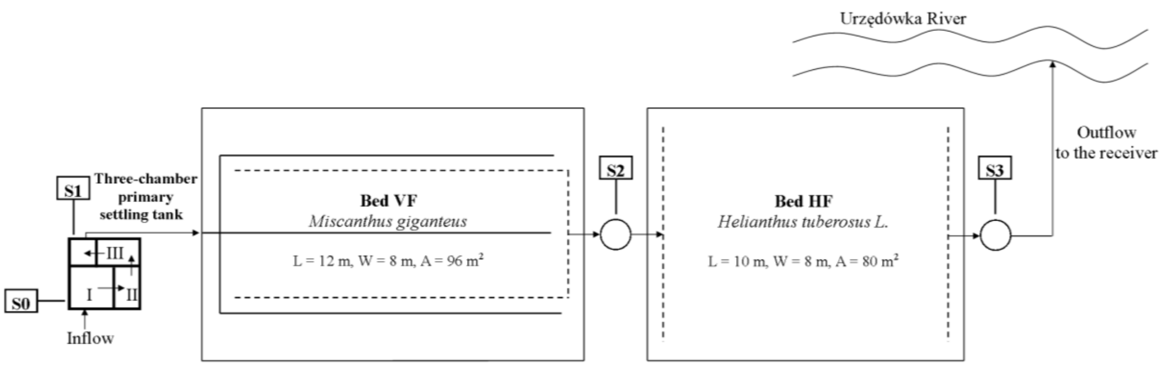


Fig. 1. Technological scheme of the tested VF-HF constructed wetland system (Gizińska-Górna et al., 2012; 2017a)

Notation: S0, S1, S2, S3 – sampling points

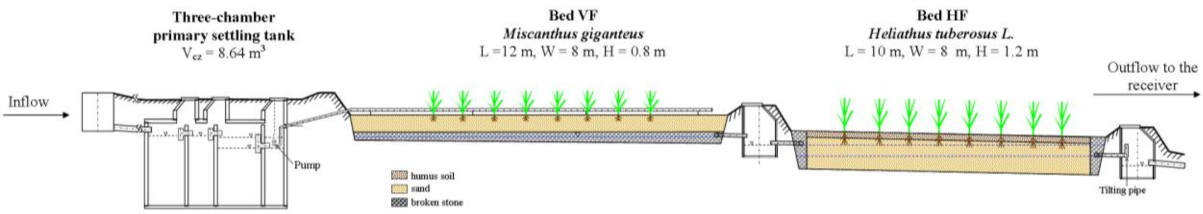


Fig. 2. Longitudinal profile of the tested VF-HF constructed wetland system (Gizińska-Górna et al., 2012)

Photo 1. Hybrid constructed wetland, VF-HF type, with giant miscanthus (on the left) and Jerusalem artichoke (on the right) (Jóźwiakowski, 2016)

During the study period, the amount of wastewater discharged to the treatment plant represented only about half of the design value, as the actual number of inhabitants served by the plant had decreased since its construction. The amount of sewage inflow to the treatment plant was determined on the basis of water meters readings in the building and average water consumption. In addition, the amount of sewage introduced into the VF-HF system was measured by using a flow meter installed on the discharge pipe between the preliminary settling tank and the VF bed. The average inflow of wastewater during the tests was 1.2 $m^3 \cdot d^{-1}$, and the hydraulic load of the first bed was 12.5 $mm \cdot d^{-1}$. Mechanically treated wastewater was pumped into the first bed (VF) twice a day, about 0.6 m^3 each time, and then it flowed gravitationally to the second bed (HF), and finally to the receiver. At the outflow from the HF bed a tilting pipe was installed, which allowed to raise the level of sewage in this field during summer. Theoretical wastewater retention time was determined on the basis of the parameters of the beds (horizontal dimensions, porosity of the material used to fill the bed, the height of the layer filled with sewage) and average daily wastewater inflow (Conley et al., 1991) and for the VF bed it was 4.8 d. Thanks to the use of a tilting pipe behind the HF bed, the wastewater retention time in this bed was about 21.2 d in the vegetation period and 10.6 d in the winter period.

2.2. Analytical methods

The efficiency and reliability of pollutant removal in the analysed treatment plant in south eastern Poland were assessed based on influent and effluent wastewater data collected in the years 2011–2016 (5 years). Sewage samples were taken seasonally: in February, May, August and November, at four points of the plant: S0 – raw sewage from the first chamber of the preliminary settling tank, S1 – mechanically treated wastewater, S2 – wastewater flowing out of the VF bed with giant miscanthus, S3 – wastewater flowing out of the HF bed with Jerusalem artichoke (Figure 1). In total, 20 measurement series were made.

The samples were analysed to determine pH, dissolved oxygen, ammonium nitrogen, nitrate and nitrite nitrogen, total nitrogen, total phosphorus, total suspended solids (TSS), biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD). The concentration of dissolved oxygen and the pH were determined using a WTW Multi 340i meter. Nitrate and nitrite nitrogen were determined with a Slandi LF 300 photometer, and ammonium nitrogen was measured with a PC Spectro spectrophotometer from AQUALYTIC. This latter instrument was also used to determine total nitrogen after oxidation of the samples in a thermoreactor at 100°C. Total phosphorus was determined with WTW's MPM 2010 spectrophotometer after oxidation of the samples at 120°C. BOD_5 was measured by the dilution method using WTW Multi 340i, and COD was estimated by the same method with a WTW MPM 2010 spectrophotometer after oxidation at 148°C. Total suspended solids were determined by filtration through paper filters. Sampling, transport and processing of the samples and their analysis were carried out in accordance with Polish standards (PN-74/C-04620/00; PN-EN 25667-2; PN-EN 1899-1:2002; PN-ISO 15705:2005; PN-EN ISO 6878:2006P; PB-01/PS; PN-EN 872:2007), which are in accordance with APHA (2005).

In addition, the yield and chemical composition of plant biomass from beds were determined. Plant material for biomass research was collected annually (starting from 2013) at the end of winter, February or March. The samples of plants were collected by hand from plots with an area of 1 m^2. In plant samples, there were determined such characteristics as dry matter content by gravimetric method, after drying at 105°C (PN-EN ISO 18134-3:2015-11) and the content of some selected chemical components, including nitrogen and phosphorus (PN-EN 15104:2011; PN-EN ISO 6491:2000).

2.3. Statistical analysis

On the basis of the obtained results, characteristic values of pollution parameters in sewage from the three different treatment stages were determined, including average, minimum and maximum values, medians, standard deviations, and coefficients of variation. Additionally, the relative frequency of occurrence of the characteristic concentration levels of the tested parameters in the sewage flowing into the treatment plant was determined. The classes for each pollution parameter have been chosen to obtain a frequency distribution that would be as detailed as possible without affecting the clarity of the structure of the statistical collection.

On the basis of the average values of the pollution parameters in the incoming (C_{in}) and outgoing (C_{out}) wastewater, the average pollutant removal efficiency was calculated according to equation 1:

$$\eta = 100\left(1 - \frac{C_{out}}{C_{in}}\right) [\%] \tag{1}$$

Additionally, the effectiveness of the tested hybrid system was analysed on the basis of mass removal rates (*MRR*) of the main pollutants contained in wastewater. MRR values were determined from equation 2 (Gajewska and Obarska-Pempkowiak, 2011):

$$MRR = \frac{C_{in}Q_{in} - C_{out}Q_{out}}{A} \ [g \cdot m^{-2} \cdot d^{-1}] \tag{2}$$

where: A – surface area of the constructed wetland system [m^2], Q_{in} and Q_{out} – average inflow and outflow of wastewater [$m^3 \cdot d^{-1}$], C_{in} and C_{out} – average concentrations of pollutants in the wastewater flowing into and out of the system [$g \cdot m^{-3}$].

The calculated indicators are theoretical, because they are based on the assumption that the outflow of sewage from particular elements of the treatment plant is equal to the inflow.

The technological reliability of the wastewater treatment plant in Skorczyce was assessed for the basic pollution parameters (BOD_5, COD, total suspended solids, total nitrogen, and total phosphorus) using elements of Weibull's reliability theory. The Weibull distribution is an overall probability distribution used in reliability testing and assessment of the risk of exceeding the limit values for pollutant concentrations in treated wastewater (Bugajski, 2014; Jucherski et al., 2017; Jóźwiakowski et al., 2017; Bugajski et al., 2012; Jóźwiakowski et al., 2018). The Weibull distribution is characterised by the following probability density function:

$$f(x) = \frac{c}{b} \cdot \frac{x-\theta}{b}^{(c-1)} \cdot e^{-\left(\frac{x-\theta}{b}\right)^{c}} \tag{3}$$

where: x – a variable describing the concentration of a pollution parameter in the treated effluent, b – scale parameter, c – shape parameter, θ – position parameter.

Assuming: $\theta < x$, $b > 0$, $c > 0$.

The reliability analysis was based on the estimation of Weibull distribution parameters using the method of highest reliability. The null hypothesis that the analyzed variable could be described by the Weibull distribution was verified with the Hollander-Proschan test at the significance level of 0.05% (Bugajski et al., 2012). The values of basic pollution parameters in treated wastewater discharged to the receiver were analysed. Reliability was determined from the distribution figures, taking into account the normative values of the parameters specified in the Regulation of the Minister of the Environment (2014) for wastewater discharged from treatment plants of less than 2000 p.e.: BOD_5 – 40 $mgO_2 \cdot dm^{-3}$, COD –

150 $mgO_2 \cdot dm^{-3}$, total suspended solids – 50 $mg \cdot dm^{-3}$, total nitrogen – 30 $mg \cdot dm^{-3}$, and total phosphorus – 5 $mg \cdot dm^{-3}$. In the case of nitrogen and total phosphorus, the values defined for wastewater discharged into lakes and their tributaries and directly into artificial water reservoirs situated in flowing waters were adopted as standard values (Regulation of the Minister of the Environment, 2014). The analysis was carried out using Statistica 13 software.

3. Results and discussion

3.1. Pollutant concentrations in treated wastewater

The efficiency and reliability of pollution removal in the tested treatment plant in south-eastern Poland were determined on the basis of results of tests of mechanically treated sewage (S1) flowing into the VF-HF constructed wetland system and sewage treated in beds with vertical (S2) and horizontal (S3) flow. Characteristic values of the pollution parameters are presented in Table 1.

In addition, the quality of raw sewage flowing from the building to the primary settling tank (S0) was taken into account, but it was not the subject of the main analysis.

Pollutant concentrations in sewage flowing into the treatment plant

The average values of pollution indicators in raw sewage outflowing from the building to the preliminary settling tank were respectively: 704 $mgO_2 \cdot dm^{-3}$ for BOD_5, 1486 $mgO_2 \cdot dm^{-3}$ for COD, 710 $mg \cdot dm^{-3}$ for total suspended solids, 172 $mg \cdot dm^{-3}$ for total nitrogen and 23.5 $mg \cdot dm^{-3}$ for total phosphorus (Table 1). These values were clearly higher than those reported in typical domestic wastewater (Heidrich et al., 2008; Bugajski and Bergel, 2008). This may have resulted from the fact that the majority of the building's inhabitants were unemployed people in a difficult financial situation. Due to the low standard of water and wastewater facilities and the need for economical water management, its unit consumption in the building was at a low level, which could result in an increase in the concentration of pollutants in the sewage. In the preliminary settling tank, mainly solid fractions were removed. As a result of physical processes, TSS content decreased by nearly 60%. At the same time, there was observed a decrease in the concentration of organic pollutants, expressed as BOD_5 (by 23%) and COD (by 12%) as well as total nitrogen (by 9%) and total phosphorus (by 11%). Nevertheless, the concentration of pollutants in the sewage outflowing from the settling tank to the system of VF-HF beds was high. The average values of these parameters at this stage of treatment were: 537 $mgO_2 \cdot dm^{-3}$ for BOD_5, 1309 $mgO_2 \cdot dm^{-3}$ for COD, 297 $mg \cdot dm^{-3}$ for total suspended solids, 157 $mg \cdot dm^{-3}$ for total nitrogen, and 21.0 $mg \cdot dm^{-3}$ for total phosphorus

(Table 1). The pH value ranged from 6.67 to 7.94, and the concentration of dissolved oxygen was in the range of 0.09 to 2.60, with the average concentration of 0.50 mg·dm^{-3}. The average contents of ammonium nitrogen, nitrate nitrogen, and nitrite nitrogen in mechanically treated wastewater were 136 mg·dm^{-3}, 2.87 mg·dm^{-3}, and 0.23 mg·dm^{-3}, respectively. The recorded values were significantly higher than those reported in the literature for mechanically treated wastewater from single-family buildings (Jucherski et al., 2017; Jóźwiakowski et al., 2017; Jóźwiakowski et al., 2018; Bugajski and Bergel, 2008). This was associated with low water consumption, leading to the formation of highly concentrated wastewater.

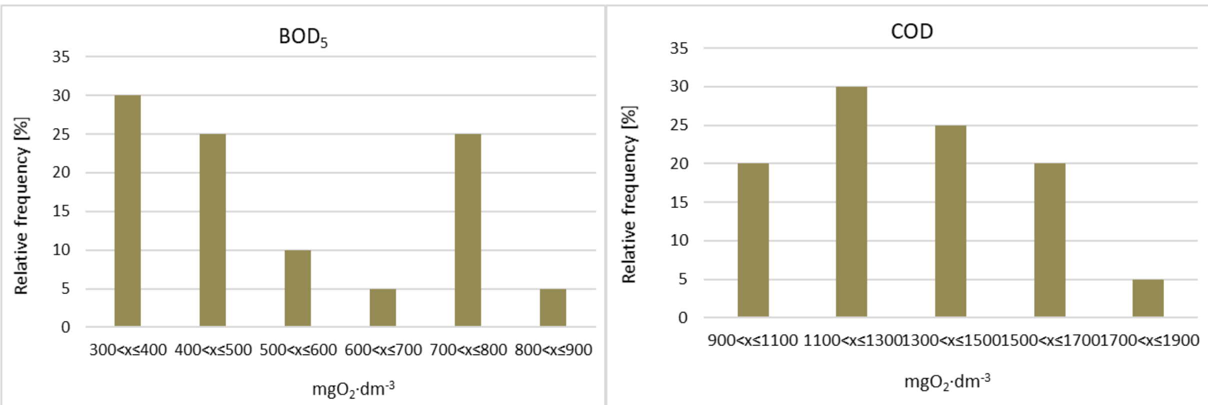
Table 1. Basic statistics for the indicator values in the treated wastewater (n = 20)

Parameters		Statistic					
		Average	Median	Min	Max	SD	Cv
Dissolved oxygen [mgO_2·dm^{-3}]	S0	**0.35**	0.22	0.08	1.19	0.31	89.51
	S1	**0.50**	0.37	0.09	2.60	0.55	109.11
	S2	**2.92**	3.03	0.37	5.17	1.34	45.89
	S3	**5.58**	5.55	1.27	11.42	2.69	48.24
pH	S0	**7.26**	7.29	6.50	7.89	0,44	6.04
	S1	**7.17**	7.13	6.67	7.94	0.29	4.06
	S2	**7.10**	7.08	6.68	7.55	0.24	3.37
	S3	**7.47**	7.42	6.93	8.70	0.49	6.51
BOD_5 [mgO_2·dm^{-3}]	S0	**704.0**	690.5	376.0	1262.0	202.9	28.82
	S1	**537.0**	471.0	310.0	862.0	172.4	32.10
	S2	**18.2**	16.3	1.8	58.0	15.1	82.60
	S3	**6.6**	3.1	0.1	36.9	9.1	137.40
COD [mgO_2·dm^{-3}]	S0	**1486.9**	1485.0	990.0	1920.0	249.8	16.80
	S1	**1309.0**	1295.0	910.0	1740.0	237.4	18.08
	S2	**68.4**	52.0	11.0	170.0	43.4	63.52
	S3	**31.8**	29.0	8.0	81.0	20.3	63.83
TSS [mg·dm^{-3}]	S0	**710.9**	523.2	136.0	2052.0	520.4	73.20
	S1	**297.0**	235.0	60.0	1390.0	284.7	95.67
	S2	**39.0**	28.5	1.9	114.0	31.1	79.77
	S3	**18.0**	10.2	1.8	65.1	20.2	112.45
Total nitrogen [mg·dm^{-3}]	S0	**172.3**	171.0	114.0	238.0	32.2	18.70
	S1	**157.0**	150.5	120.0	216.0	22.7	14.45
	S2	**82.4**	83.0	34.0	134.0	25.1	30.42
	S3	**56.4**	39.0	10.0	150.0	43.7	77.46
Ammonium nitrogen [mg·dm^{-3}]	S0	**147.2**	139.5	47.0	230.0	42.7	29.02
	S1	**136.0**	134.5	43.0	204.0	31.3	23.06
	S2	**21.3**	18.2	1.6	65.2	18.7	87.77
	S3	**12.9**	3.8	0.1	47.1	16.4	127.44
Nitrate nitrogen [mg·dm^{-3}]	S0	**2.11**	0.99	0.03	17.11	3.64	172.89
	S1	**2.87**	0.86	0.28	29.67	6.47	225.24
	S2	**24.48**	24.96	2.71	57.70	16.07	65.65
	S3	**20.25**	13.48	0.86	58.20	19.89	98.22

Nitrite nitrogen [mg·dm^{-3}]	S0	**0.28**	0.270	0.08	0.471	0.15	55.07
	S1	**0.23**	0.19	0.08	0.43	0.13	56.71
	S2	**1.03**	0.73	0.06	4.04	1.02	98.99
	S3	**0.50**	0.13	0.03	3.62	1.00	198.99
Total phosphorus [mg·dm^{-3}]	S0	**23.5**	23.1	15.3	30.2	4.6	19.69
	S1	**21.0**	21.1	17.2	23.9	1.9	8.89
	S2	**12.0**	11.6	8.5	21.0	3.0	24.83
	S3	**6.7**	6.8	1.3	11.0	2.6	39.47

Notation: S0 – raw wastewater ;S1 - inflow to bed VF; S2 - outflow from bed VF; S3 - outflow from bed HF; SD - standard deviation; Cv - coefficient of variation, n - number of samples

Figure 3 shows nomograms of the frequency of occurrence of pollution parameter concentrations, grouped in different ranges. BOD_5 in the wastewater flowing into the hybrid VF-HF system did not fall below 300 $mgO_2 \cdot dm^{-3}$ across measurements. The most common values were in the range of 300–400 $mgO_2 \cdot dm^{-3}$ (30% of cases), 400–500 and 700–800 $mgO_2 \cdot dm^{-3}$ (25% each), and 500–600 $mgO_2 \cdot dm^{-3}$ (10%). The COD values were very high and showed little volatility. In 30% of cases, the parameter was within the range of 1100–1300 $mgO_2 \cdot dm^{-3}$, in 25% – 1300–1500 $mgO_2 \cdot dm^{-3}$, and in 20% – 900–1100 and 1500–1700 $mgO_2 \cdot dm^{-3}$ (Figure 3). Differentiation of COD values in mechanically treated sewage could be the result of variability in the composition of raw sewage and also the operation of the settling tank. Lower COD values were recorded during the tank's working phase, when the sedimentation process played a major role. A similar effect could occur after each removing of scum and some part of sludge from the tank, which was one of the operating works. In other periods, sludge fermentation could have caused sludge flotation, decreased the sedimentation effect and increased the concentration of pollutants in sewage flowing out from the settling tank.



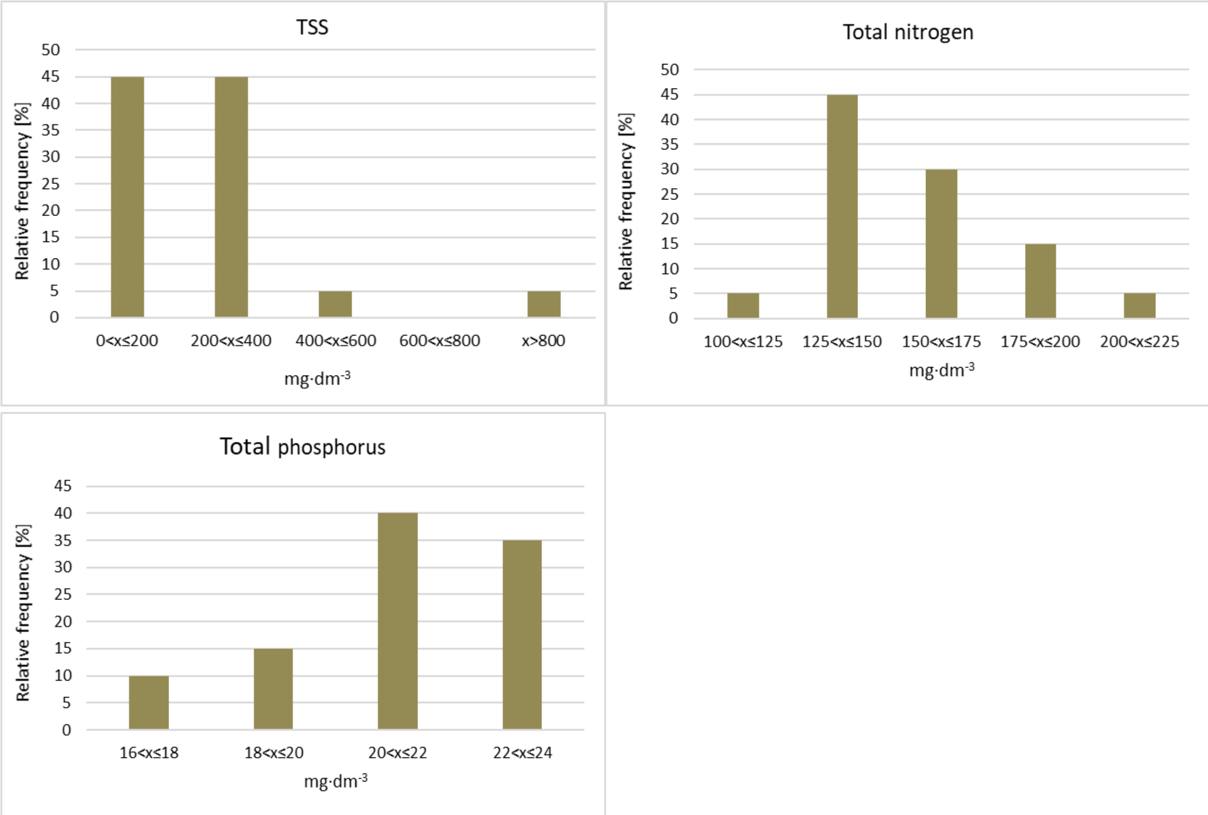


Fig. 3. Frequency histogram of influent parameter values
(BOD_5, COD, TSS, total nitrogen, total phosphorus)

As a rule, total suspended solids did not exceed 400 mg·dm^{-3} (90%). However, this cannot be considered a satisfactory result, given that it concerns wastewater treated mechanically in a three-chamber pre-settling tank. All recorded concentrations of total nitrogen were above 100 mg·dm^{-3}, of which 50% were between 125 and 150 mg·dm^{-3}. Total phosphorus concentrations exceeded 16 mg·dm^{-3} and showed a slight variability. 75% of the results were in the range of 20–24 mg·dm^{-3}; the remaining values (25% of cases) were grouped in the range of 16–20 mg·dm^{-3} (Figure 3).

In addition to the concentrations of pollutants in the treated wastewater, the ratios between the various individual parameters also have a significant impact on the clean-up process. The most important ratios are: COD/BOD_5, BOD_5/TN, and BOD_5/TP. It was found that the wastewater flowing into the tested VF-HF hybrid system was characterized by unfavourable COD/BOD_5 (2.4) and BOD_5/TN (3.0) ratios; the BOD_5/TP ratio was 25.6 (Table 2).

Table 2. Relationships between average values of selected indicators of pollution

Relationship	Recommended value (Heidrich et al., 2008)	Test value
COD/BOD_5	≤2.2	2.4
BOD_5/TN	≥4.0	3.4

BOD_5/TP	≥25	25.6

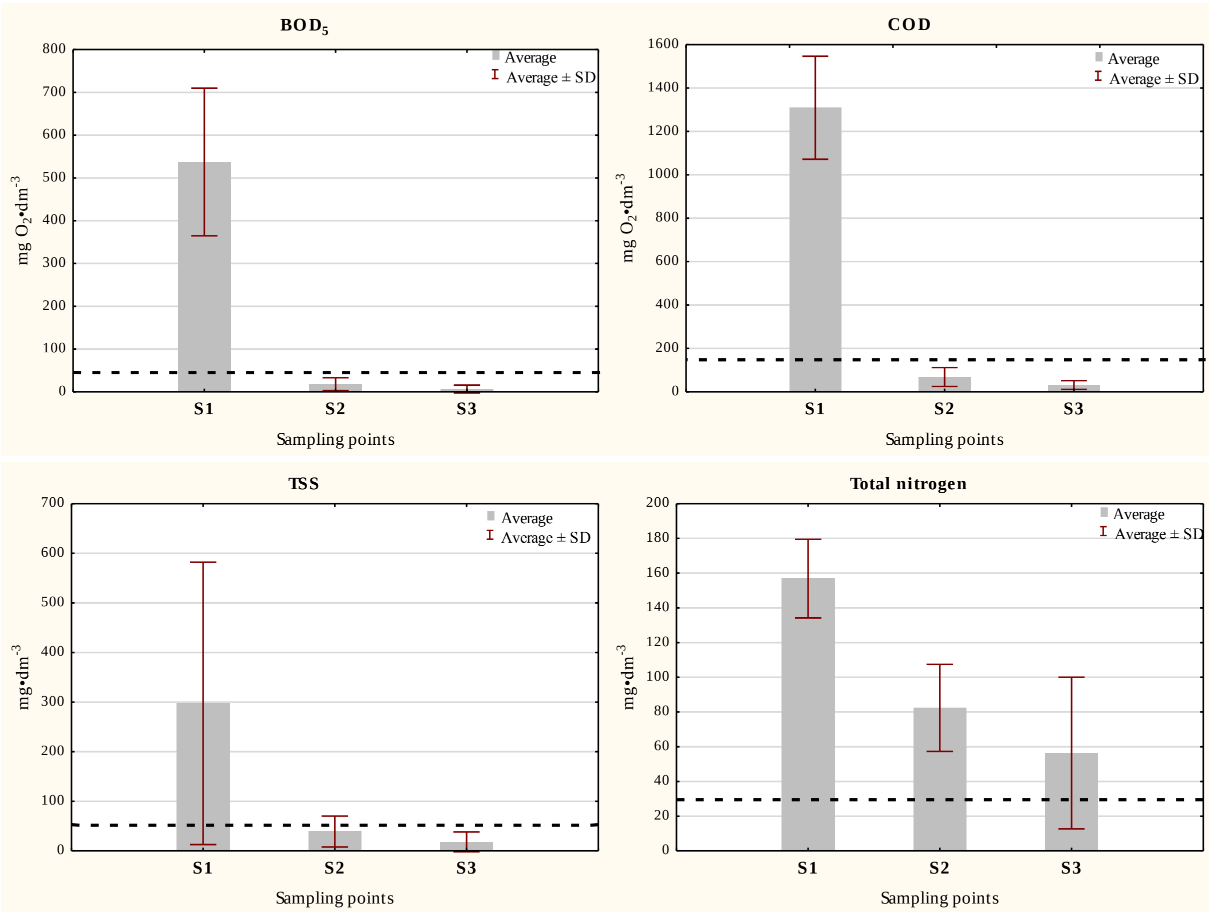
Pollutant concentrations in the effluent from the VF bed

After treatment of the wastewater in the VF bed , the average BOD_5 and COD values were 18 $mgO_2 \cdot dm^{-3}$ and 68.4 $mgO_2 \cdot dm^{-3}$, respectively. The average concentration of total suspended solids was 39.0 $mg \cdot dm^{-3}$, total phosphorus 12.0 $mg \cdot dm^{-3}$, total nitrogen 82.4 $mg \cdot dm^{-3}$. The average values of BOD_5, COD, and total suspended solids in wastewater treated in the VF bed met the requirements specified in the Regulation of the Minister of Environment (2014) for wastewater discharged to waters or to the ground from treatment plants above 2000 p.e. (Figure 4). These results indicate that the VF bed provided favourable conditions for the oxidation of organic pollutants and nitrification. The average oxygen content in the wastewater flowing out from the first bed increased to about 3 $mg \cdot dm^{-3}$ compared to the mechanically treated wastewater, while the average concentration of ammonia nitrogen slightly exceeded 20 $mg \cdot dm^{-3}$. The total nitrogen balance in the VF bed indicates the existence of processes leading to the permanent removal of this component from the wastewater, including, mainly, the process of denitrification and uptake by vegetation. Despite this, the content of total nitrogen at the outflow from the VF bed remained high, on average 82.4 $mg \cdot dm^{-3}$, with values well above 100 $mg \cdot dm^{-3}$. High concentration of total nitrogen suggests that a significant part of ammonia nitrogen after transformation to the nitrate form did not undergo any further transformation. Therefore, the average concentration of nitrate nitrogen in the wastewater discharged from the VF bed was 24.5 $mg \cdot dm^{-3}$ (Table 1). The wastewater discharged from the first bed also contained high concentrations of total phosphorus (an average of 11.0 $mg \cdot dm^{-3}$). For both biogenic parameters, the average values were more than twice as high as the level stipulated by the law as acceptable for treatment plants up to 2000 p.e. discharging sewage into standing waters (Regulation of the Minister of the Environment, 2014).

Pollutant concentrations in the effluent from the HF bed

An HF bed in a hybrid system is designed to optimise total nitrogen and organic compounds removal in anaerobic and oxidised conditions (Vymazal, 2007; Saeed and Sun, 2012). The average concentrations of BOD_5, COD, and total suspended solids in wastewater discharged from the HF bed into the receiver were 6.6 $mg \cdot dm^{-3}$, 31.8 $mg \cdot dm^{-3}$, and 18.0 $mg \cdot dm^{-3}$, respectively (Table 1). The respective median values were 3.1, 29.0, and 10.2 $mg \cdot dm^{-3}$. These values were significantly lower than the limit values stipulated in the

Regulation of the Minister of the Environment (2014). The average concentrations of total nitrogen and total phosphorus in treated wastewater (56.4 mg·dm^{-3} and 6.7 mg·dm^{-3}, respectively) did not meet the above requirements (Figure 4). The average value of total nitrogen in treated wastewater was most strongly affected by the results collected during the initial period of operation of the plant (about 18 months), when the vegetation was not yet fully developed. The analysis of basic statistics highlights two tendencies: clear discrepancies between the extreme values, and high coefficients of variation for the individual pollution parameters of wastewater outflowing from the VF-HF system. Because the concentrations of contaminants in the effluent were low, the results may have been much more strongly influenced by environmental factors, precipitation and temperature, or random changes in operating conditions compared with the results for S1 and S2.



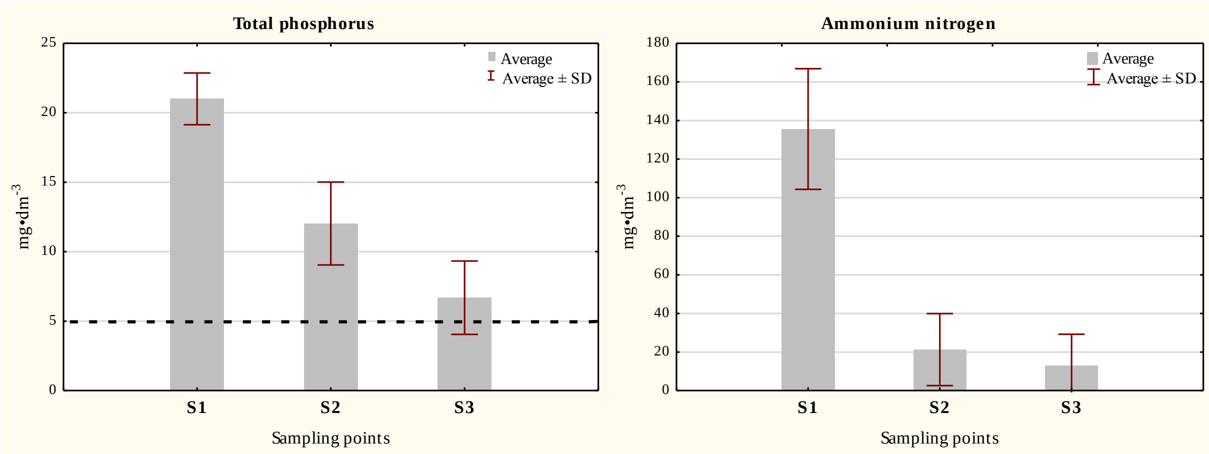


Fig. 4. Dynamics of reduction of pollutant concentrations in the successive stages of treatment

Notation: dashed black line – Polish legal requirements for wastewater discharged into water and soil from treatment plants below 2000 p.e.

(Regulation of the Minister of the Environment, 2014)

3.2. Pollutant removal efficiency

The results indicate that the investigated CW had a high efficiency of removal of organic pollutants and total suspended solids, and a lower efficiency of elimination of biogenic compounds (total nitrogen and total phosphorus). The differences between the various stages of treatment were clear-cut. The largest proportion of the investigated pollutants were eliminated in the VF bed. This bed provided favourable conditions for the biodegradation of organic pollutants and moderately good conditions for the removal of biogenic pollutants. Several factors may have been of significance here, including the way the bed was fed with sewage and the associated availability of oxygen, the hydraulic and pollution loads on the bed, the vegetation, and air and wastewater temperature. The low hydraulic load of the VF bed (an average of 12.5 $mm \cdot d^{-1}$) ensured optimal time of contact of sewage with the microorganisms forming the biological membrane on the filling material (Saeed and Sun, 2012). In addition, cyclic feeding of wastewater to the bed and alternating dry and wet periods, may have, in accordance with generally accepted opinions, increased the diffusion of atmospheric oxygen and improved the conditions for the oxidation of organic pollutants and the course of the nitrification process (Jia et al., 2010; Gervin and Brix, 2001).

The average efficiency of the entire VF-HF system in removing organic pollutants from wastewater in the 5-year research period was 98.8% for BOD_5 and 97.6% for COD (Figure 5). The effects of BOD_5 and COD removal were similar to or higher than those recorded by other authors in hybrid constructed wetland systems operating under similar climatic conditions

(Krzanowski et al., 2005; Gajewska and Obarska-Pempkowiak, 2009; Vymazal and Kröpfelová, 2009).

The largest part of the pollution load was eliminated in the first stage of treatment in the VF bed. Although the amount of sewage flowing into the treatment plant constituted about 50% of the designed value, the load of organic pollutants in the first bed, was quite high and amounted to 6.7 $g \cdot m^{-2} \cdot d^{-1}$ (BOD_5) and 16.4 $g \cdot m^{-2} \cdot d^{-1}$ (COD), respectively. Moreover, the wastewater flowing into the VF bed was characterised by an unfavourable BOD_5/COD ratio (2.4), which testified to the lower susceptibility of the tested wastewater to biological decomposition. Despite this, nearly 97% of BOD_5 and 95% COD were removed from the VF bed, which is a very good result. The system under investigation was rather insensitive to the high concentrations of organic compounds and their degradability. Caselles-Osorio and Garcia (2006) observed a similar relationship in their studies. Research carried out under similar climatic conditions has shown that the removal efficiency of VF reservoirs with regard to BOD_5 is in the range of 86–98% (Obarska-Pempkowiak et al., 2010; Gajewska et al., 2011; Vymazal, 2010). On the other hand, the efficiency of COD reduction in VF beds, according to various authors, may vary from 79 to 94% (Obarska-Pempkowiak, 2009; Sharma et al., 2010; Masi and Martinuzzi, 2007).

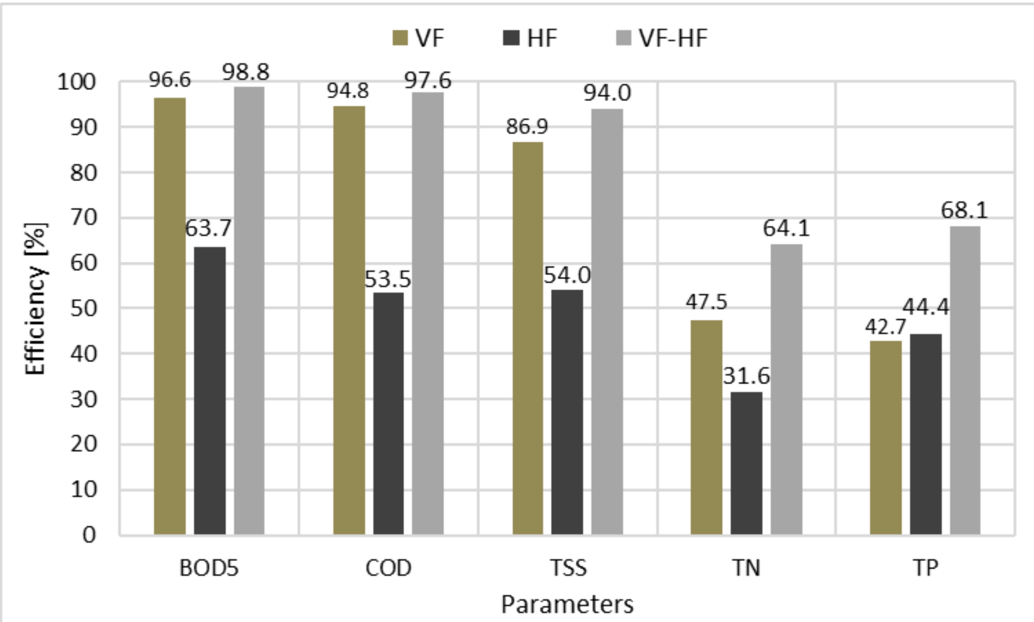


Fig. 5. Average pollutant removal efficiency of the investigated system

In the HF bed, the elimination of organic pollutants (BOD_5 and COD) was 63.7% and 53.5%, respectively. Research carried out by Obarska-Pempkowiak et al. (2010) indicates that HF type systems can provide a higher degree of COD reduction, but at higher contaminant loads.

The average efficiency of removal of total suspended solids in the analysed system was 94%. The VF bed removed nearly 87% of total suspended solids, while the HF bed removed 54% of the solids. The efficiency of the tested system in removing total suspended solids was higher than demonstrated by other authors. For comparison, a HF-VF system investigated by Masi and Martinuzzi (2007) had a total suspended solids removal efficiency of 84% a result that was identical to that obtained by Krzanowski et al. (2005). Hybrid systems analysed by Gajewska and Obarska-Pempkowiak (2009) reached an average total suspended solids removal efficiency of 89%.

The average total nitrogen removal efficiency for the analysed hybrid system was 64.1%, with 47.5% of nitrogen removed in the VF bed and 31.6% in the HF bed. According to Gajewska and Obarska-Pempkowiak (2011), the efficiency of total nitrogen removal in hybrid constructed wetland systems may range from 23 to 80%, depending on the configuration and operating conditions of the beds. In the light of these reports, the effectiveness of the facility tested in this present study was moderately high, but not high enough to obtain stable results at the outflow that would meet the requirements set out in the Polish regulations (Regulation of the Minister of the Environment, 2014). The incomplete removal of nitrogen may have been caused by a lack of appropriate conditions for effective denitrification in the HF bed, especially the deficit of organic compounds and the unfavourable BOD_5/TN ratio inhibiting the denitrification process, or thermal conditions (Vymazal, 2010). The analysis of meteorological conditions in the area of the conducted research (meteorological station in Radawiec near Lublin) showed that the significance of this last factor could have been smaller. Against the background of some long-term data, there can be observed a tendency of increasing the average air temperature (Figure 6). Throughout the entire research period (2011-2016) average annual temperatures were higher than the long-term average (1970-2000) by 0.7–2.0°C. In the six-month period covering the growing season (from April to September) the average differences ranged from 1.0 to 1.8°C, in the remaining period (from October to March) - from 0.4 to 2.5°C (IMWM 2011-2016; CSO, 2017). On this basis, it can be concluded that, apart from periods that are considered to be unfavorable in a moderate climate (December-February) temperature should not be a limiting factor for microbial removal processes.

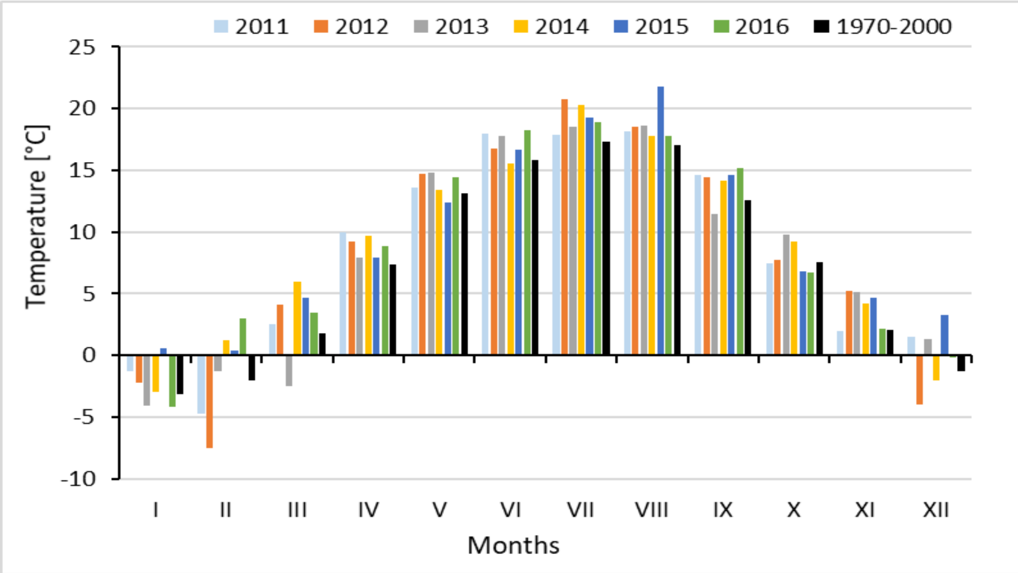


Fig. 6. The average monthly temperatures for Radawiec near Lublin in the years 2011-2016 (IMWM, 2011-2016; CSO, 2017)

The efficiency of total phosphorus removal for the whole VF-HF system was 68.1%. The two beds had similar average phosphorus removal rates, in the range of 42–45%. To compare, the average total phosphorus removal efficiencies for hybrid CW systems studied by other authors range from 70 to 89% (Krzanowski et al., 2005; Sharma et al., 2010). In our study, the highest phosphorus removal rates were found in the initial period of the plant's operation, which confirms the observation that the kind of filling of beds plays an important role in the process of total phosphorus elimination. A useful tool to compare the efficiency of pollutant removal in different facilities or in different units of the same system is the mass removal rate (MRR), which provides a measure of the amount of a component removed per unit area of a constructed wetland systems. Table 3 presents theoretical indicators of main pollutants mass removal (according to formula 2) in each bed and in the whole VF-HF system of the sewage treatment plant in south-eastern Poland. The indicators were determined on the basis of the assumption that the average annual sewage outflow from individual purification stages is equal to the inflow. In fact, these quantities may vary more or less, which is primarily due to evapotranspiration and precipitation (Chazarenc et al., 2003; 2010). The evapotranspiration efficiency in CW is subject to great fluctuations, depending on seasonal conditions, it can range from 0 to 50 $mm{\cdot}d^{-1}$ (Chazarenc et al. 2010). According to Herbst and Kappen (1999) in natural bog systems with common reed in northern Germany, in the full vegetation period, it may exceed 10 $mm{\cdot}d^{-1}$, but in other periods (from November to April) it approaches zero. These researchers also found that under certain conditions (cloudy and rainy weather) the efficiency of evapotranspiration during the year may be similar or even lower than the total precipitation. Also Chazarenc et al. (2003) in the research conducted on the HF field of the multi-stage constructed wetland confirmed the possibility of maintaining balance of beds evapotranspiration by precipitation. In the case of the analyzed sewage treatment plant, factors limiting the efficiency of evapotranspiration could be the proximity of high plants at the south-western side, which cause periodic shading of beds and reduce air movement. Moreover, the research of Toscano et al. (2015) indicate that the efficiency of evapotranspiration on the beds planted with giant miscanthus, even under warm climate conditions, is clearly lower than on the beds with common reed.

Despite the lower than planned hydraulic load, the pollution load in the investigated system was comparable to those found in other constructed wetlands tested in Poland (Gajewska and Obarska-Pempkowiak, 2011). The MRR mass removal ratios of organic pollutants were relatively high, similar to those recorded in two- and three-stage constructed wetland systems, described by Gajewska and Obarska-Pempkowiak (2011).

Similarly, in the case of total nitrogen, the MRR value did not differ significantly from the values determined for other plants (Gajewska and Obarska-Pempkowiak, 2011; Brix et al., 2003).

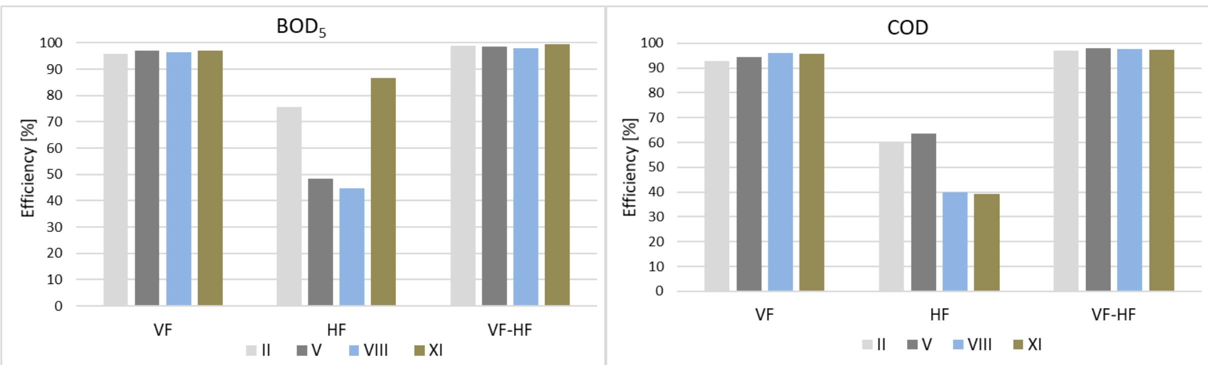
The VF bed played a decisive role in the removal of organic pollutants. The mass removal rates determined for this field were many times higher than in the case of the HF bed (Table 3).

Table 3. Mass removal rates of BOD_5, COD, total nitrogen (TN) and total phosphorus (TP)

Parameters		VF	HF	VF-HF
BOD_5	Load [$g \cdot m^{-2} \cdot d^{-1}$]	6.71	0.27	3.66
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	6.49	0.17	3.62
COD	Load [$g \cdot m^{-2} \cdot d^{-1}$]	16.36	1.02	8.93
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	15.51	0.54	8.70
TN	Load [$g \cdot m^{-2} \cdot d^{-1}$]	1.96	1.23	1.07
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	0.93	0.39	0.68
TP	Load [$g \cdot m^{-2} \cdot d^{-1}$]	0.26	0.18	0.14
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	0.11	0.08	0.10

The investigated wastewater treatment plant in south-eastern Poland, with giant miscanthus and Jerusalem artichoke, provided efficiency in the area of organic and biogenic compounds removal similar to other systems using classic plant species that function under similar operating conditions. In such systems, plants perform an auxiliary role, creating favorable conditions for the activity of microorganisms and the course of biochemical processes in the bed (Langergraber, 2005; Wu et al., 2013 a, b). This is confirmed by the research carried out on the treatment plant in Skorczyce, including the lack of seasonal variability of treatment effects, mainly organic pollutants. In the case of the VF bed and the entire VF-HF system, the average removal effects were constant during the whole year (Figure 7). Higher variability was found on the HF field, however, it is difficult to relate this to seasonal conditions, because the average efficiency of BOD_5 decreasing was the highest in autumn and winter. Most researchers point to the reverse regularity (Zhao et al., 2011; Saeed and Sun, 2012), although some studies did not show differences between the removal of these compounds in the summer and winter (Bulc, 2006). The lack of a clear influence of seasonal conditions on microbial removal processes can be associated with the dominance of physical processes. In addition, Plamondon et al. (2006) suggested that the factor that balances the dependence of kinetics on biological reactions on temperature in a cooler climate can be favorable oxygen conditions.

The average efficiency of nitrogen and phosphorus removal from wastewater was slightly higher in August and November. However, the share of plants in the uptake of pollutants from sewage, expressed as nitrogen and phosphorus content in biomass was relatively small. The yield of giant miscanthus on the VF field in the first year of operation was at a low level – 0.42 kg DM·m^{-2} (Gizińska-Górna et al., 2017b). In the following years, it fluctuated within the limits of 3.55–4.43 kg DM·m^{-2} and was clearly higher than the yields recorded in field crops of this plant (Szulczewski et al., 2018). The average nitrogen content in aboveground parts of giant miscanthus was 5.8 g·kg DM^{-1}, which means that with the highest yield (2016), approximately 2.5 kg of nitrogen were accumulated in the biomass. At the content of phosphorus – 0.26 g·kg DM^{-1} its mass accumulated in aboveground parts of giant miscanthus amounted to a maximum level of 0.11 kg.



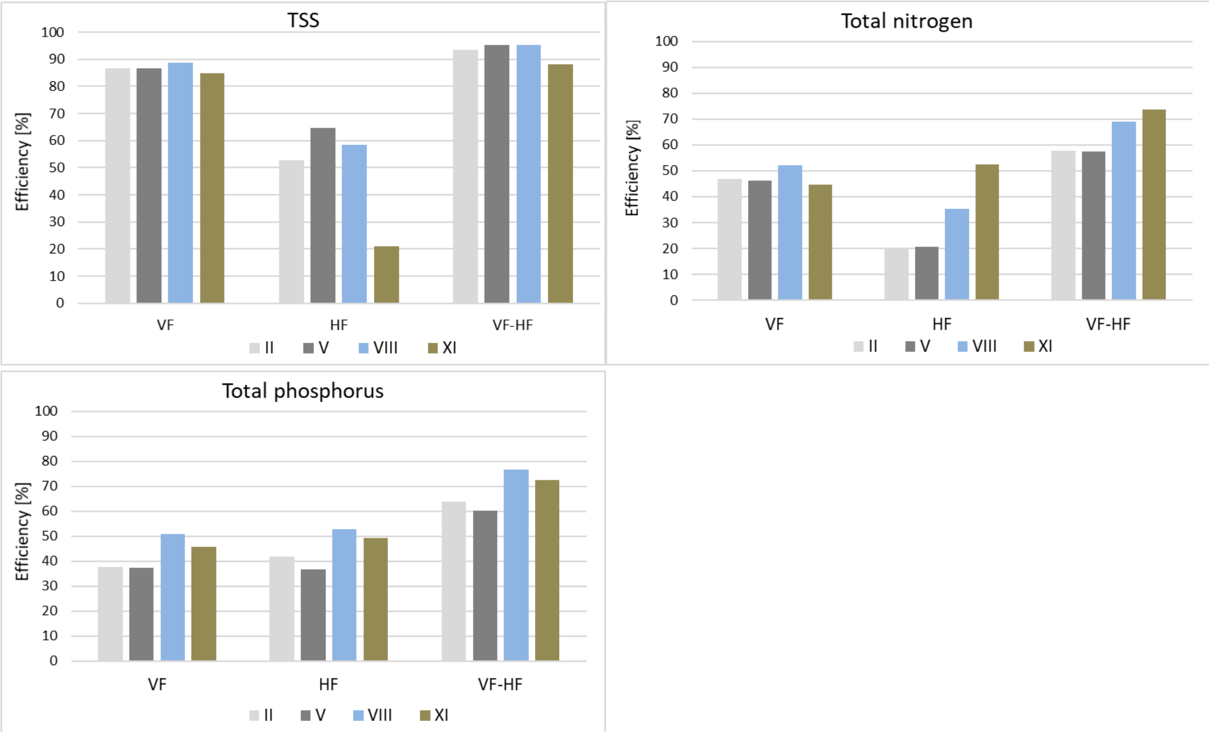


Fig. 7. Average removal efficiency of pollutants in different months of the research. Notation: II – February; V – May; VIII – August; XI – November

The yield of Jerusalem artichoke on the HF bed ranged from 0.83 kg DM·m^{-2} in 2013 to 1.43 kg DM·m^{-2} in 2015. The average nitrogen content in aboveground parts of plants was 3.4 g·kg DM^{-1}, and phosphorus – 0.34 g·kg DM^{-1}. In 2015, the nitrogen and phosphorus masses contained in the aboveground biomass were respectively 0.47 kg and 0.047 kg.

In the years which were most favorable in terms of yield of giant miscanthus and Jerusalem artichoke (2015 and 2016), the share of nitrogen accumulated in the biomass of both plants in relation to the mass of nitrogen removed in these years in the VF-HF system ranged from 5% to 6.3%. For phosphorus, it was about 2.6%. Baring in mind the fact that the plant activity associated with biomass production is limited to the growing season (in south-eastern Poland it usually lasts from April to September), it can be concluded that real contribution of the plants to nutrient removal by uptake was higher and exceeded 10% in the case of nitrogen and 5% in the case of phosphorus.

In this case, it can be concluded that the physiochemical processes, such as oxidation or adsorption by the substrate elements, could have a big influence on nitrogen removal (Bulc, 2006; Saeed and Sun, 2012). Physicochemical processes, especially substrate sorption, could also be very important in the elimination of phosphorus from wastewater (Jóźwiakowski et al., 2018; Xu et al., 2006).

3.3. Pollutant removal reliability

The reliability of the tested wastewater treatment plant, defined as its ability to dispose of the expected amount of wastewater to the extent required by the wastewater receiver, was determined using the Weibull method. The method allows a more in-depth analysis of qualitative data than is possible with average values, through the prism of legal requirements for sewage discharged to the environment. The first step was to estimate the parameters of distribution and verify the null hypothesis that empirical data could be described by Weibull's distribution. The data sets were the values of the basic pollution parameters (BOD_5, COD, TSS, total nitrogen, total phosphorus) in the wastewater discharged from the VF-HF constructed wetland system to the receiver.

The null hypothesis was confirmed. The results of the Hollander-Proschan goodness-of-fit test along with the estimated parameters, are presented in Table 4.

Table 4. Parameters of the Weibull distribution and results of the Hollander-Proschan goodness-of-fit test

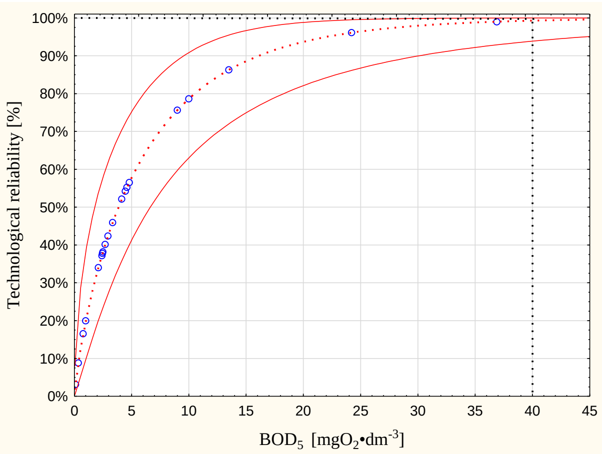
Parameter	Parameters of Weibull distribution			Hollander-Proschan goodness-of-fit test	
	θ	c	b	stat	p
BOD_5	0.0000	0.8410	5.9731	0.1732	0.8625
COD	5.4646	1.7097	35.8400	0.1496	0.8810
TSS	1.6182	0.9676	17.6798	0.3140	0.7535
Total Nitrogen	9.0606	1.3572	61.8000	0.1807	0.8565
Total Phosphorus	-0.2000	2.8367	7.4737	-0.3043	0.7608

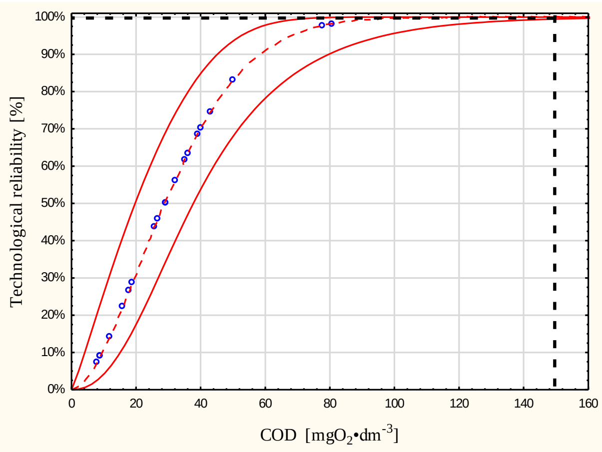
Symbols: stat – value of the test statistic, p – significance level of the test; when $p \leq 0.05$ the distribution of data is not a Weibull distribution

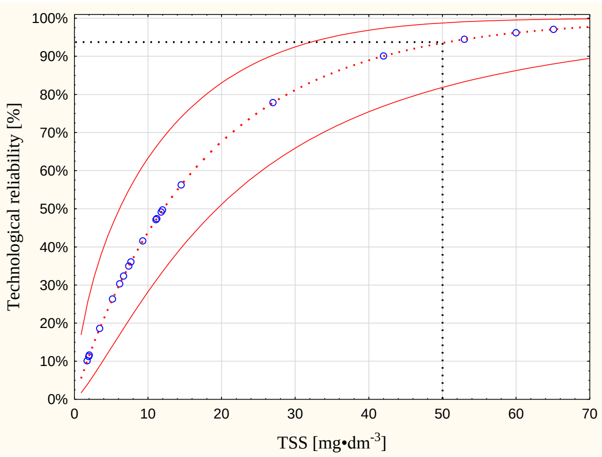
The goodness-of-fit of the obtained distributions was high at 75–88%, at a significance level $\alpha = 0.05$. The technological reliability of the treatment plant was determined on the basis of the distribution functions, taking into account the limit values for the parameters, as specified in the Regulation of the Minister of Environment for WWTPs of less than 2000 p.e. (Regulation of the Minister of the Environment, 2014) (Figure 8).

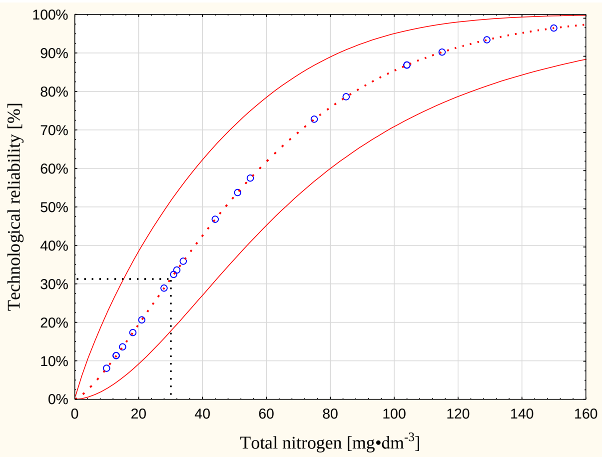
The organic pollutant removal reliability expressed by BOD_5 and COD was 100% (Figure 8). This means that the plant operated without any problems throughout the testing period, and the values of the tested parameters in the treated wastewater did not exceed the acceptable levels stipulated in the Polish law (40 and 150 $mgO_2 \cdot dm^{-3}$, respectively). This leads to the conclusion that, with an operator risk of α = 0.05, the plant should successfully pass inspection with regard to the parameters concerned throughout the year.

The reliability of removal of total suspended solids from sewage in the tested system was 93%. On this basis, it can be concluded that the plant operated smoothly on average 339 days a year. The period of failure-free operation is equivalent to the period when the concentration of total suspension particles in the wastewater discharged to the receiver was below the required limit (50 mg·dm^{-3}).









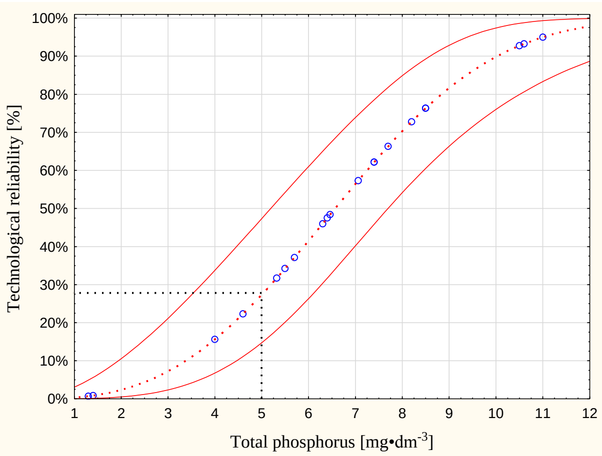


Fig. 86. Weibull cumulative distribution functions and the technological reliabilities determined for each pollution parameter

Notation: dashed red line – reliability function, continuous red line – confidence intervals, dashed black line – probability of reaching the effluent parameter limit

According to the guidelines proposed by Andraka and Dzienis (2003), the minimum reliability level for treatment plants below 2000 p.e. should be 97.27%, which means that these plants, even when operating poorly for 9 days a year, still have a 95% chance of successfully going through inspection procedures. Given these guidelines, it can be assumed that the limit concentrations of total suspended solids in the CW investigated in this present study can be exceeded without affecting the plant's operation on 17 days a year.

The reliability of removal of nutrients was significantly lower than in the case of organic pollutants. The probability that the total nitrogen concentration in treated effluents would reach the limit value (30 mg·dm^{-3}) established for effluents discharged from a treatment plant of less than 2000 p.e. to standing waters was 32%. This means that the total nitrogen concentration in treated wastewater exceeded the limit value, and the plant operated incorrectly on 249 days a year.

An even lower level of reliability was found for total phosphorus removal. The probability that the concentration of this parameter in treated wastewater would reach a value below 5 mg·dm^{-3} was 28%. This means that the plant operated correctly for only 102 days a year, and excessive concentrations of total phosphorus in treated wastewater were recorded on 254 days a year.

The reliability levels obtained indicate that the hybrid constructed wetland with giant miscanthus and Jerusalem artichoke performed very well in terms of organic pollutant removal. The facility guaranteed stable low BOD_5 and COD results for the treated wastewater, which meant it was highly likely to be positively evaluated in the case of an inspection. These conclusions are consistent with the reports of other authors, which indicate that hybrid systems are very reliable with respect to BOD_5 and COD reduction (Jucherski et al., 2017; Jóźwiakowski, 2012). At the same time, the reliability of the tested VF-HF system was higher than that of single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et al., 2017) or other small sewage treatment plants using other technological solutions. For comparison, the organic pollutant removal reliabilities (expressed as BOD_5 and COD) of plants operating on the basis of conventional treatment methods (activated sludge, biological bed, hybrid reactor), were 60–88% and 89–92%, respectively, and in extreme cases as low as 30% (Marzec, 2017; Bugajski et al., 2012; Wałęga et al., 2008).

The reliabilities of removal of nutrient contaminants (nitrogen and phosphorus) for the tested facility were 32 and 28%, respectively, which indicates that treated wastewater was highly likely to contain excessive nitrogen and total phosphorus concentrations. Therefore, the performance of the system was not satisfactory in this respect. Tests carried out in other facilities show that similar or higher levels of nutrient removal reliability are reached in single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et al., 2018). Jucherski et al. (2017) reported that the reliabilities of nitrogen and phosphorus removal in the hybrid constructed wetland they studied were significantly higher at 76.8% for total nitrogen and 95.2% for total phosphorus. It should be noted, however, that the normative values for nitrogen and total phosphorus used in reliability assessment refer only to specific cases when treated wastewater is discharged to lakes and their tributaries and directly to artificial water reservoirs situated in flowing waters (Regulation of the Minister of the Environment, 2014). Moreover, according to the Polish law, there is no obligation to control the operation of domestic sewage treatment plants or to perform quality tests of sewage discharged to the environment. In this light, the assessment of nutrient removal reliability of domestic treatment plants is a theoretical issue, which does not mean that it should not become a common part of wastewater management practice in the future. In combination with an analysis of the effectiveness of wastewater treatment, the assessment of the pollutant removal reliability of wastewater treatment plants allows to determine what technological solutions should be promoted when building sewage systems in rural areas to support water protection against pollution and eutrophication. The use of highly efficient and reliable wastewater treatment systems can reduce the use of the cheapest solutions, which instead of protecting the environment pose a potential threat to it. According to the emerging suggestions, it also seems necessary to create administrative and legal instruments in Poland which would enable control of all sewage treatment plants, regardless of their size and type of receiver (Jóźwiakowski et al., 2015; Marzec, 2017; Jóźwiakowski et al., 2018).

4. Conclusions

In the five-year research period, the hydraulic load of the analysed VF-HF system with giant miscanthus and Jerusalem artichoke in south-eastern Poland was about 50% of the design value; however, the load of contaminants did not differ significantly from that found in similar constructed wetlands.

The average effectiveness of organic pollutant removal expressed as BOD_5 and COD was 98.8 and 97.6%, respectively; the corresponding value for total suspended solids was 93%. Under the conditions typical for moderate climate, the hybrid VF-HF system provided high and stable effects of organic pollutants removal throughout the whole year. In the VF bed, the concentration of organic pollutants (BOD_5 and COD) in the inflowing sewage was removed on average by over 94%.

Technological reliability of the constructed wetland wastewater treatment plant with giant miscanthus and Jerusalem artichoke concerning BOD_5 and COD amounted to 100%. Under given operating conditions, the facility ensures failure-free operation and the fulfillment of Polish legal requirements throughout the whole year. The reliability of removal of total suspended solids was 93%.

The efficiencies of total nitrogen and total phosphorus removal were 64.1 %. and 68.1%, respectively, and the average values of these components in the outflow from the treatment plant exceeded the standard levels. The lower efficiency of total nitrogen removal was probably caused by unfavourable denitrification conditions in the HF bed, including the deficit of organic compounds.

The CW had low total nitrogen and total phosphorus removal reliabilities (32% and 28%, respectively.

Giant miscanthus and Jerusalem artichoke showed favorable features when it comes to their use in constructed wetlands, also under moderate climate conditions. They were characterized by high resistance to unfavorable environmental conditions, and even at low hydraulic load, high yield potential. Despite the high yield, their share in the uptake of biogenic pollutants from wastewater was relatively small.

Giant miscanthus is characterized by a clearly higher biomass production than Jerusalem artichoke, has a well-developed root system, and the operation of miscanthus beds is simpler. Jerusalem artichoke generates large amounts of tubers, which allow the plant to compact the entire surface of the bed, and after some time their accumulation can affect the balance of pollutants in the bed. To avoid this, there is often a need to remove them during the operation of the facility.

The investigated hybrid constructed wetland system with giant miscanthus and Jerusalem artichoke had organic and biogenic pollutant removal efficiencies that were similar to those obtained in systems using classic plant species such as reed and willow. Giant miscanthus and Jerusalem artichoke can be successfully used to support wastewater treatment processes in constructed wetland systems, and, owing to their high biomass production potential, they can also be exploited as energy yielding materials.

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The efficiency and reliability of pollutant removal in a hybrid constructed wetland with giant miscanthus and Jerusalem artichoke in Poland

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ABSTRACT

In this paper, we analysed the pollutant removal efficiency and reliability of a vertical and horizontal flow hybrid constructed wetland (CW) planted with giant miscanthus and Jerusalem artichoke. The wastewater treatment plant, located in south-eastern Poland, treated domestic sewage at an average flow rate of 1.2 $m^3 \cdot d^{-1}$. The tests were carried out during 5-years of operation of the sewage treatment plant (2011–2016). During this period, sewage samples were collected from three stages of wastewater treatment in four seasons (winter – February, spring – May, summer – August, and autumn – November). The following parameters were measured: BOD_5, COD, total suspended solids, total nitrogen, and total phosphorus. The average effectiveness of organic pollutant removal expressed by BOD_5 and COD was 98.8 and 97.6%, respectively, and the removal efficiency for total suspended solids was 93%. The average values of BOD_5, COD, and total suspended solids in wastewater discharged to the receiver were significantly lower than the limit values required in Poland. The efficiency of total nitrogen and total phosphorus removal was 64.1 and 68.1%, respectively, and the average values of these components in the outflow from the treatment plant exceeded the standard levels. A reliability analysis performed using the Weibull probability model showed that the reliability of pollutant removal in the tested CW system was very high for BOD_5 and COD (100%). It was also demonstrated that the tested CW did not provide effective elimination of biogenic elements (nitrogen and phosphorus), as evidenced by the low reliability values – 32 and 28%, respectively. The investigated hybrid CW system with giant miscanthus and Jerusalem artichoke removed organic and biogenic pollutants with a similar efficiency as systems using classic plant species such as reed and willow.

Key words: wastewater treatment, hybrid constructed wetlands, vertical flow, horizontal flow, pollutant removal, efficiency and reliability

1. Introduction

Domestic wastewater treatment plants are an optimal solution for the disposal of small amounts of wastewater in areas of dispersed development, where the construction of a sewage system is economically unjustified (García et al., 2013; Mikosz and Mucha, 2014; Jóźwiakowski et al., 2015). Issues related to the operational reliability of low capacity treatment plants below 5 $m^3 \cdot d^{-1}$ are still rarely brought up due to the lack of precise requirements regarding the application of various technological solutions for home sewage treatment plants and their control during operation. Such a situation is not conducive to the creation and implementation of new, effective technologies. On the contrary, it favours the cheapest solutions, mainly systems with a leach drain, which are used for discharging untreated wastewater into the ground, and therefore, their application for waste water treatment raises serious questions (Jóźwiakowski et al., 2015, Zhang et al., 2015). Moreover, many solutions applied in small sewage treatment plants, including those based on conventional methods, in conditions of high variability of hydraulic load, pollution load and operating conditions do not guarantee high efficiency of removal of pollutants from sewage (Marzec, 2017). With a constant increase in the number of ineffective technological solutions applied, the risk of their negative impact on water quality increases (Bugajski, 2014; Pawełek and Bugajski, 2017).

Therefore, the reliability of small sewage treatment plants should be an important criterion in planning the development of technical infrastructure in rural areas, which will enable the selection of optimal and environmentally safe solutions (Jóźwiakowski et al., 2015; Jucherski et al., 2017). There are more and more suggestions that all treatment plants, regardless of their size and type of receiver, should be placed under the control of competent authorities. At the same time, the popularity of constructed wetland systems, which can be used in various conditions, including protected areas and areas of high landscape value, is increasing due to their high pollutant removal efficiency (Vymazal, 2011; 2013; Jóźwiakowski, 2012; Paruch et al., 2011; Jóźwiakowski et al., 2017; Gajewska et al., 2015).

Constructed wetlands, and in particular hybrid treatment plants consisting of at least two beds with different sewage flows (vertical and horizontal), ensure effective removal of organic matter (BOD_5 and COD) (Vymazal, 2011) and slightly less effective removal of nutrients (Kadlec and Wallace, 2008; Vymazal and Kropfelova, 2008). The removal of contaminants in constructed wetland systems is related to the functioning of the biological membrane formed during the flow of wastewater through the material filling the beds. The plants growing in the wetland support the process of treatment (Vymazal, 2013; Foladori et al., 2012; Vymazal and

Březinová, 2014; Wu et al., 2015). The rhizosphere produces an oxygenated microenvironment, while other layers of the bed provide anaerobic or anoxic conditions. Roots and rhizomes of plants increase the hydraulic permeability of the soil and loosen its structure (Birkedal et al., 1993). Until now, depending on the climatic conditions, different plant species have been used in constructed wetland systems, mainly common reed and willow (Vymazal, 2011; Jóźwiakowski, 2012). These plants are characterized by quite intensive growth, even on a very poor substrate (Gruenewald et al., 2007), hence the possibility of using constructed wetland systems not only for wastewater treatment, but also for biomass production for energy purposes (Cerbin et al., 2012; Posadas et al., 2014; Lu and Zhang, 2013). In this respect, research on the use of other plants, e.g. giant miscanthus or Jerusalem artichoke, in constructed wetland systems may be of interest (Gizińska-Górna et al., 2016). The high energy potential of these plants is a result of high yield and biomass calorific value, which depends on its chemical composition (Bridgwater and Peacocke, 2000; Bellamy et al., 2009; Long et al., 2010). In European conditions, the yield of giant miscanthus in field cultivation ranges from 10 to 30 Mg $DM \cdot ha^{-1}$ (Szulczewski et al., 2018), and Jerusalem artichoke from 9 to 25 Mg $DM \cdot ha^{-1}$ (Baldini et al., 2004; Gunnarsson et al., 2014). The calorific value of dried biomass of giant miscanthus varies from 14 to 17 $MJ \cdot kg\ DM^{-1}$, and for Jerusalem artichoke varies from 15 to 19 $MJ \cdot kg\ DM^{-1}$ (Szulczewski et al., 2018; Gizińska-Górna et al., 2016). The possibilities of their use in wastewater treatment are less recognized, especially in moderate climate conditions. Jerusalem artichoke has not been used in constructed wetland systems yet, while research on the use giant miscanthus has been carried out on a pilot scale and under warm climate conditions. Their results indicate that the efficiency of pollutants removal in the beds planted with giant miscanthus may be similar to those found in the case of classical plant species, including common reed (Toscano et al., 2015; Barbagallo et al., 2014).

The aim of the present study is to analyse the reliability and effectiveness of pollutant removal in a hybrid constructed wetland wastewater treatment plant with giant miscanthus (*Miscanthus giganteus x* Greef et Deu) and Jerusalem artichoke (*Helianthus tuberosus L.*) during five years of its operation.

2. Materials and methods

2.1. Characteristics of the experimental facility

The analysed plant is located in Skorczyce, Poland (51°00′36″N, 22°11′51″E). Its task is to treat domestic sewage from a multi-family building. The plant has been in operation since

2011 and its planned capacity is 2.5 $m^3 \cdot d^{-1}$. In the analyzed system, sewage from the building was drained into a three-chamber preliminary settling tank, where it was pre-treated in physical and biological processes.

The tank is made of concrete, and its active capacity is 8.64 m^3. In the next stage, the sewage flows through a system of two VF-HF type soil and plant beds (biological treatment). A first bed, with vertical sewage flow (VF), has an area of 96 m^2 and a depth of 0.8 m, and the second bed, with horizontal sewage flow (HF), has an area of 80 m^2 and a depth of 1.2 m. The beds have been isolated from the native soil by a PEHD waterproofing geomembrane of 1 mm thickness. The VF bed was filled with a layer of sand (1-2 mm) with a height of about 0.8 m. The filling of the HF bed to the height of 1.0 m consisted of sand (1-2 mm), on which there was laid the humus soil layer with a height of 0.2 m and it was obtained during the construction of the sewage treatment plant (Figures 1, 2). The first bed was planted with giant miscanthus (*Miscanthus x giganteus* Greef et Deu.), the second with Jerusalem artichoke (*Helianthus tuberosus* L.) (Photo 1). Every year, after the winter season, the aboveground plant shoots and part of the tubers (Jerusalem artichoke) are removed from the fields. The recipient of the treated wastewater is the Urzędówka River (Figures 1, 2).

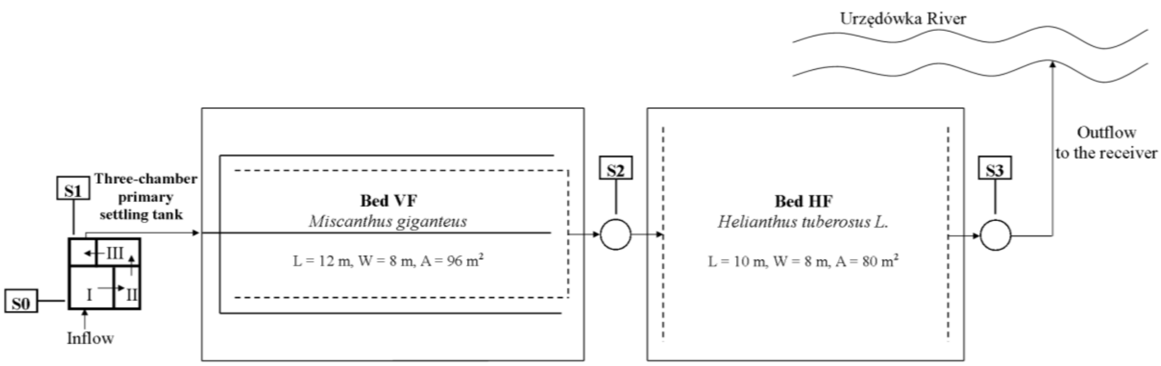


Fig. 1. Technological scheme of the tested VF-HF constructed wetland system (Gizińska-Górna et al., 2012; 2017a)

Notation: S0, S1, S2, S3 – sampling points

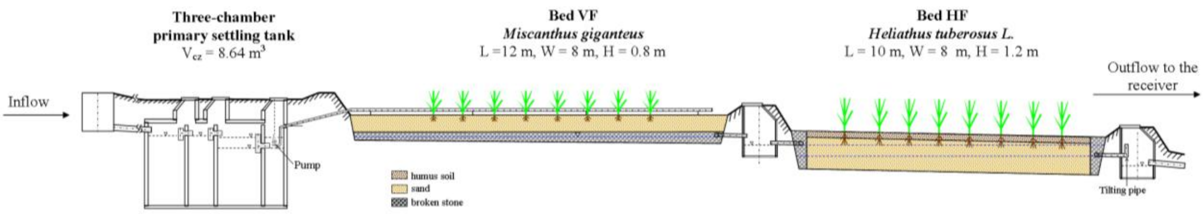


Fig. 2. Longitudinal profile of the tested VF-HF constructed wetland system (Gizińska-Górna et al., 2012)

Photo 1. Hybrid constructed wetland, VF-HF type, with giant miscanthus (on the left) and Jerusalem artichoke (on the right) (Jóźwiakowski, 2016)

During the study period, the amount of wastewater discharged to the treatment plant represented only about half of the design value, as the actual number of inhabitants served by the plant had decreased since its construction. The amount of sewage inflow to the treatment plant was determined on the basis of water meters readings in the building and average water consumption. In addition, the amount of sewage introduced into the VF-HF system was measured by using a flow meter installed on the discharge pipe between the preliminary settling tank and the VF bed. The average inflow of wastewater during the tests was 1.2 $m^3 \cdot d^{-1}$, and the hydraulic load of the first bed was 12.5 $mm \cdot d^{-1}$. Mechanically treated wastewater was pumped into the first bed (VF) twice a day, about 0.6 m^3 each time, and then it flowed gravitationally to the second bed (HF), and finally to the receiver. At the outflow from the HF bed a tilting pipe was installed, which allowed to raise the level of sewage in this field during summer. Theoretical wastewater retention time was determined on the basis of the parameters of the beds (horizontal dimensions, porosity of the material used to fill the bed, the height of the layer filled with sewage) and average daily wastewater inflow (Conley et al., 1991) and for the VF bed it was 4.8 d. Thanks to the use of a tilting pipe behind the HF bed, the wastewater retention time in this bed was about 21.2 d in the vegetation period and 10.6 d in the winter period.

2.2. Analytical methods

The efficiency and reliability of pollutant removal in the analysed treatment plant in south eastern Poland were assessed based on influent and effluent wastewater data collected in the years 2011–2016 (5 years). Sewage samples were taken seasonally: in February, May, August and November, at four points of the plant: S0 – raw sewage from the first chamber of the preliminary settling tank, S1 – mechanically treated wastewater, S2 – wastewater flowing out of the VF bed with giant miscanthus, S3 – wastewater flowing out of the HF bed with Jerusalem artichoke (Figure 1). In total, 20 measurement series were made.

The samples were analysed to determine pH, dissolved oxygen, ammonium nitrogen, nitrate and nitrite nitrogen, total nitrogen, total phosphorus, total suspended solids (TSS), biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD). The concentration of dissolved oxygen and the pH were determined using a WTW Multi 340i meter. Nitrate and nitrite nitrogen were determined with a Slandi LF 300 photometer, and ammonium nitrogen was measured with a PC Spectro spectrophotometer from AQUALYTIC. This latter instrument was also used to determine total nitrogen after oxidation of the samples in a thermoreactor at 100°C. Total phosphorus was determined with WTW's MPM 2010 spectrophotometer after oxidation of the samples at 120°C. BOD_5 was measured by the dilution method using WTW Multi 340i, and COD was estimated by the same method with a WTW MPM 2010 spectrophotometer after oxidation at 148°C. Total suspended solids were determined by filtration through paper filters. Sampling, transport and processing of the samples and their analysis were carried out in accordance with Polish standards (PN-74/C-04620/00; PN-EN 25667-2; PN-EN 1899-1:2002; PN-ISO 15705:2005; PN-EN ISO 6878:2006P; PB-01/PS; PN-EN 872:2007), which are in accordance with APHA (2005).

In addition, the yield and chemical composition of plant biomass from beds were determined. Plant material for biomass research was collected annually (starting from 2013) at the end of winter, February or March. The samples of plants were collected by hand from plots with an area of 1 m^2. In plant samples, there were determined such characteristics as dry matter content by gravimetric method, after drying at 105°C (PN-EN ISO 18134-3:2015-11) and the content of some selected chemical components, including nitrogen and phosphorus (PN-EN 15104:2011; PN-EN ISO 6491:2000).

2.3. Statistical analysis

On the basis of the obtained results, characteristic values of pollution parameters in sewage from the three different treatment stages were determined, including average, minimum and maximum values, medians, standard deviations, and coefficients of variation. Additionally, the relative frequency of occurrence of the characteristic concentration levels of the tested parameters in the sewage flowing into the treatment plant was determined. The classes for each pollution parameter have been chosen to obtain a frequency distribution that would be as detailed as possible without affecting the clarity of the structure of the statistical collection.

On the basis of the average values of the pollution parameters in the incoming (C_{in}) and outgoing (C_{out}) wastewater, the average pollutant removal efficiency was calculated according to equation 1:

$$\eta = 100\left(1 - \frac{C_{out}}{C_{in}}\right) [\%] \quad (1)$$

Additionally, the effectiveness of the tested hybrid system was analysed on the basis of mass removal rates (*MRR*) of the main pollutants contained in wastewater. MRR values were determined from equation 2 (Gajewska and Obarska-Pempkowiak, 2011):

$$MRR = \frac{C_{in}Q_{in} - C_{out}Q_{out}}{A} \ [g \cdot m^{-2} \cdot d^{-1}] \quad (2)$$

where: A – surface area of the constructed wetland system [m^2], Q_{in} and Q_{out} – average inflow and outflow of wastewater [$m^3 \cdot d^{-1}$], C_{in} and C_{out} – average concentrations of pollutants in the wastewater flowing into and out of the system [$g \cdot m^{-3}$].

The calculated indicators are theoretical, because they are based on the assumption that the outflow of sewage from particular elements of the treatment plant is equal to the inflow.

The technological reliability of the wastewater treatment plant in Skorczyce was assessed for the basic pollution parameters (BOD_5, COD, total suspended solids, total nitrogen, and total phosphorus) using elements of Weibull's reliability theory. The Weibull distribution is an overall probability distribution used in reliability testing and assessment of the risk of exceeding the limit values for pollutant concentrations in treated wastewater (Bugajski, 2014; Jucherski et al., 2017; Jóźwiakowski et al., 2017; Bugajski et al., 2012; Jóźwiakowski et al., 2018). The Weibull distribution is characterised by the following probability density function:

$$f(x) = \frac{c}{b} \cdot \frac{x-\theta}{b}^{(c-1)} \cdot e^{-\left(\frac{x-\theta}{b}\right)^{c}} \quad (3)$$

where: x – a variable describing the concentration of a pollution parameter in the treated effluent, b – scale parameter, c – shape parameter, θ – position parameter.

Assuming: $\theta < x$, $b > 0$, $c > 0$.

The reliability analysis was based on the estimation of Weibull distribution parameters using the method of highest reliability. The null hypothesis that the analyzed variable could be described by the Weibull distribution was verified with the Hollander-Proschan test at the significance level of 0.05% (Bugajski et al., 2012). The values of basic pollution parameters in treated wastewater discharged to the receiver were analysed. Reliability was determined from the distribution figures, taking into account the normative values of the parameters specified in the Regulation of the Minister of the Environment (2014) for wastewater discharged from treatment plants of less than 2000 p.e.: BOD_5 – 40 $mgO_2 \cdot dm^{-3}$, COD –

150 $mgO_2 \cdot dm^{-3}$, total suspended solids – 50 $mg \cdot dm^{-3}$, total nitrogen – 30 $mg \cdot dm^{-3}$, and total phosphorus – 5 $mg \cdot dm^{-3}$. In the case of nitrogen and total phosphorus, the values defined for wastewater discharged into lakes and their tributaries and directly into artificial water reservoirs situated in flowing waters were adopted as standard values (Regulation of the Minister of the Environment, 2014). The analysis was carried out using Statistica 13 software.

3. Results and discussion

3.1. Pollutant concentrations in treated wastewater

The efficiency and reliability of pollution removal in the tested treatment plant in south-eastern Poland were determined on the basis of results of tests of mechanically treated sewage (S1) flowing into the VF-HF constructed wetland system and sewage treated in beds with vertical (S2) and horizontal (S3) flow. Characteristic values of the pollution parameters are presented in Table 1.

In addition, the quality of raw sewage flowing from the building to the primary settling tank (S0) was taken into account, but it was not the subject of the main analysis.

Pollutant concentrations in sewage flowing into the treatment plant

The average values of pollution indicators in raw sewage outflowing from the building to the preliminary settling tank were respectively: 704 $mgO_2 \cdot dm^{-3}$ for BOD_5, 1486 $mgO_2 \cdot dm^{-3}$ for COD, 710 $mg \cdot dm^{-3}$ for total suspended solids, 172 $mg \cdot dm^{-3}$ for total nitrogen and 23.5 $mg \cdot dm^{-3}$ for total phosphorus (Table 1). These values were clearly higher than those reported in typical domestic wastewater (Heidrich et al., 2008; Bugajski and Bergel, 2008). This may have resulted from the fact that the majority of the building's inhabitants were unemployed people in a difficult financial situation. Due to the low standard of water and wastewater facilities and the need for economical water management, its unit consumption in the building was at a low level, which could result in an increase in the concentration of pollutants in the sewage. In the preliminary settling tank, mainly solid fractions were removed. As a result of physical processes, TSS content decreased by nearly 60%. At the same time, there was observed a decrease in the concentration of organic pollutants, expressed as BOD_5 (by 23%) and COD (by 12%) as well as total nitrogen (by 9%) and total phosphorus (by 11%). Nevertheless, the concentration of pollutants in the sewage outflowing from the settling tank to the system of VF-HF beds was high. The average values of these parameters at this stage of treatment were: 537 $mgO_2 \cdot dm^{-3}$ for BOD_5, 1309 $mgO_2 \cdot dm^{-3}$ for COD, 297 $mg \cdot dm^{-3}$ for total suspended solids, 157 $mg \cdot dm^{-3}$ for total nitrogen, and 21.0 $mg \cdot dm^{-3}$ for total phosphorus

(Table 1). The pH value ranged from 6.67 to 7.94, and the concentration of dissolved oxygen was in the range of 0.09 to 2.60, with the average concentration of 0.50 mg·dm^{-3}. The average contents of ammonium nitrogen, nitrate nitrogen, and nitrite nitrogen in mechanically treated wastewater were 136 mg·dm^{-3}, 2.87 mg·dm^{-3}, and 0.23 mg·dm^{-3}, respectively. The recorded values were significantly higher than those reported in the literature for mechanically treated wastewater from single-family buildings (Jucherski et al., 2017; Jóźwiakowski et al., 2017; Jóźwiakowski et al., 2018; Bugajski and Bergel, 2008). This was associated with low water consumption, leading to the formation of highly concentrated wastewater.

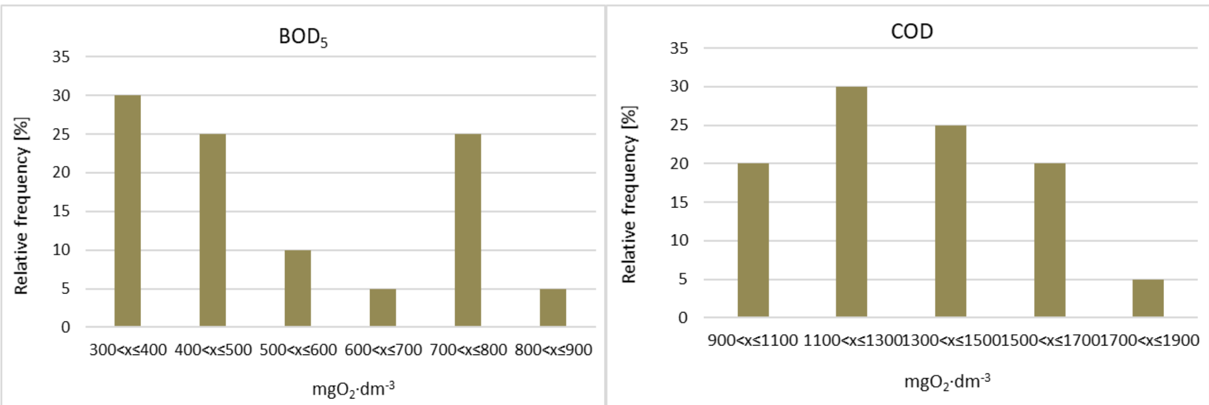
Table 1. Basic statistics for the indicator values in the treated wastewater (n = 20)

Parameters		Statistic					
		Average	Median	Min	Max	SD	Cv
Dissolved oxygen [mgO_2·dm^{-3}]	S0	**0.35**	0.22	0.08	1.19	0.31	89.51
	S1	**0.50**	0.37	0.09	2.60	0.55	109.11
	S2	**2.92**	3.03	0.37	5.17	1.34	45.89
	S3	**5.58**	5.55	1.27	11.42	2.69	48.24
pH	S0	**7.26**	7.29	6.50	7.89	0,44	6.04
	S1	**7.17**	7.13	6.67	7.94	0.29	4.06
	S2	**7.10**	7.08	6.68	7.55	0.24	3.37
	S3	**7.47**	7.42	6.93	8.70	0.49	6.51
BOD_5 [mgO_2·dm^{-3}]	S0	**704.0**	690.5	376.0	1262.0	202.9	28.82
	S1	**537.0**	471.0	310.0	862.0	172.4	32.10
	S2	**18.2**	16.3	1.8	58.0	15.1	82.60
	S3	**6.6**	3.1	0.1	36.9	9.1	137.40
COD [mgO_2·dm^{-3}]	S0	**1486.9**	1485.0	990.0	1920.0	249.8	16.80
	S1	**1309.0**	1295.0	910.0	1740.0	237.4	18.08
	S2	**68.4**	52.0	11.0	170.0	43.4	63.52
	S3	**31.8**	29.0	8.0	81.0	20.3	63.83
TSS [mg·dm^{-3}]	S0	**710.9**	523.2	136.0	2052.0	520.4	73.20
	S1	**297.0**	235.0	60.0	1390.0	284.7	95.67
	S2	**39.0**	28.5	1.9	114.0	31.1	79.77
	S3	**18.0**	10.2	1.8	65.1	20.2	112.45
Total nitrogen [mg·dm^{-3}]	S0	**172.3**	171.0	114.0	238.0	32.2	18.70
	S1	**157.0**	150.5	120.0	216.0	22.7	14.45
	S2	**82.4**	83.0	34.0	134.0	25.1	30.42
	S3	**56.4**	39.0	10.0	150.0	43.7	77.46
Ammonium nitrogen [mg·dm^{-3}]	S0	**147.2**	139.5	47.0	230.0	42.7	29.02
	S1	**136.0**	134.5	43.0	204.0	31.3	23.06
	S2	**21.3**	18.2	1.6	65.2	18.7	87.77
	S3	**12.9**	3.8	0.1	47.1	16.4	127.44
Nitrate nitrogen [mg·dm^{-3}]	S0	**2.11**	0.99	0.03	17.11	3.64	172.89
	S1	**2.87**	0.86	0.28	29.67	6.47	225.24
	S2	**24.48**	24.96	2.71	57.70	16.07	65.65
	S3	**20.25**	13.48	0.86	58.20	19.89	98.22

Nitrite nitrogen [mg·dm^{-3}]	S0	**0.28**	0.270	0.08	0.471	0.15	55.07
	S1	**0.23**	0.19	0.08	0.43	0.13	56.71
	S2	**1.03**	0.73	0.06	4.04	1.02	98.99
	S3	**0.50**	0.13	0.03	3.62	1.00	198.99
Total phosphorus [mg·dm^{-3}]	S0	**23.5**	23.1	15.3	30.2	4.6	19.69
	S1	**21.0**	21.1	17.2	23.9	1.9	8.89
	S2	**12.0**	11.6	8.5	21.0	3.0	24.83
	S3	**6.7**	6.8	1.3	11.0	2.6	39.47

Notation: S0 – raw wastewater ;S1 - inflow to bed VF; S2 - outflow from bed VF; S3 - outflow from bed HF; SD - standard deviation; Cv - coefficient of variation, n - number of samples

Figure 3 shows nomograms of the frequency of occurrence of pollution parameter concentrations, grouped in different ranges. BOD_5 in the wastewater flowing into the hybrid VF-HF system did not fall below 300 $mgO_2·dm^{-3}$ across measurements. The most common values were in the range of 300–400 $mgO_2·dm^{-3}$ (30% of cases), 400–500 and 700–800 $mgO_2·dm^{-3}$ (25% each), and 500–600 $mgO_2·dm^{-3}$ (10%). The COD values were very high and showed little volatility. In 30% of cases, the parameter was within the range of 1100–1300 $mgO_2·dm^{-3}$, in 25% – 1300–1500 $mgO_2·dm^{-3}$, and in 20% – 900–1100 and 1500–1700 $mgO_2·dm^{-3}$ (Figure 3). Differentiation of COD values in mechanically treated sewage could be the result of variability in the composition of raw sewage and also the operation of the settling tank. Lower COD values were recorded during the tank's working phase, when the sedimentation process played a major role. A similar effect could occur after each removing of scum and some part of sludge from the tank, which was one of the operating works. In other periods, sludge fermentation could have caused sludge flotation, decreased the sedimentation effect and increased the concentration of pollutants in sewage flowing out from the settling tank.



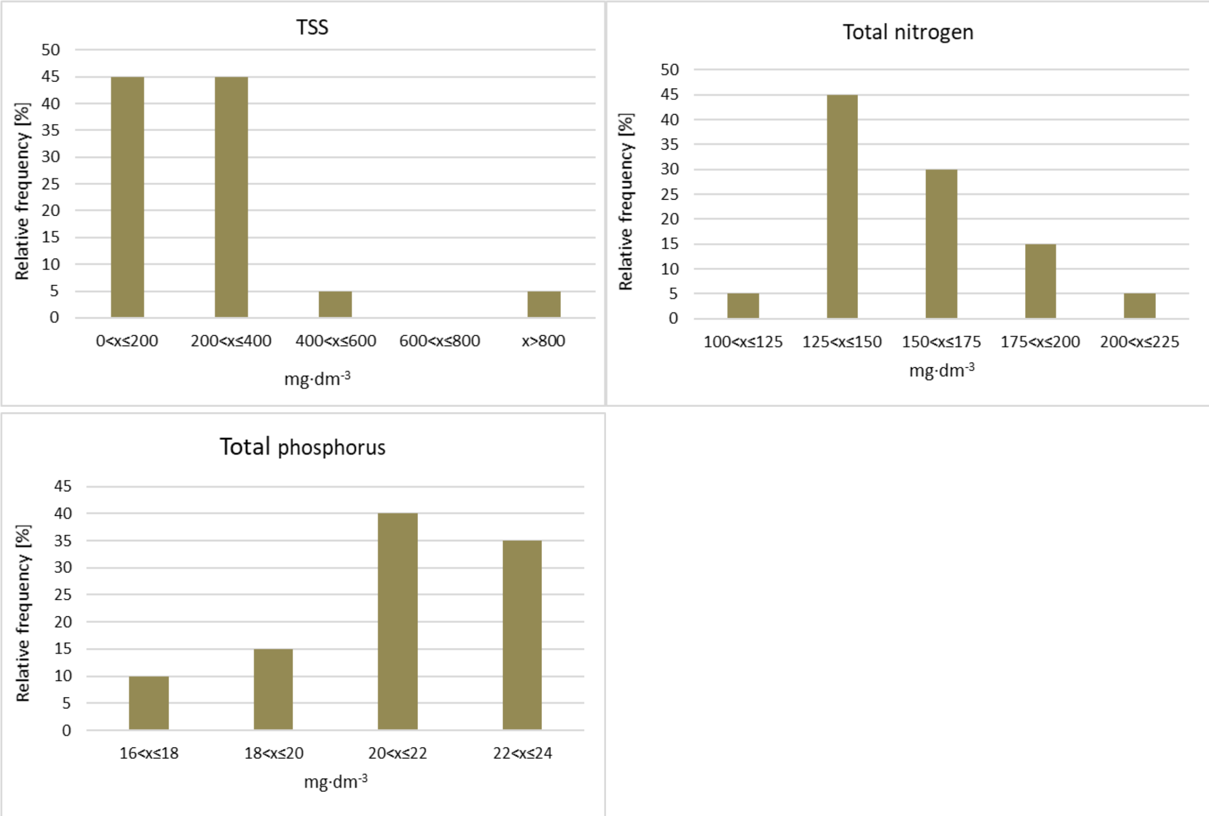


Fig. 3. Frequency histogram of influent parameter values
(BOD_5, COD, TSS, total nitrogen, total phosphorus)

As a rule, total suspended solids did not exceed 400 mg·dm^{-3} (90%). However, this cannot be considered a satisfactory result, given that it concerns wastewater treated mechanically in a three-chamber pre-settling tank. All recorded concentrations of total nitrogen were above 100 mg·dm^{-3}, of which 50% were between 125 and 150 mg·dm^{-3}. Total phosphorus concentrations exceeded 16 mg·dm^{-3} and showed a slight variability. 75% of the results were in the range of 20–24 mg·dm^{-3}; the remaining values (25% of cases) were grouped in the range of 16–20 mg·dm^{-3} (Figure 3).

In addition to the concentrations of pollutants in the treated wastewater, the ratios between the various individual parameters also have a significant impact on the clean-up process. The most important ratios are: COD/BOD_5, BOD_5/TN, and BOD_5/TP. It was found that the wastewater flowing into the tested VF-HF hybrid system was characterized by unfavourable COD/BOD_5 (2.4) and BOD_5/TN (3.0) ratios; the BOD_5/TP ratio was 25.6 (Table 2).

Table 2. Relationships between average values of selected indicators of pollution

Relationship	Recommended value (Heidrich et al., 2008)	Test value
COD/BOD_5	≤2.2	2.4
BOD_5/TN	≥4.0	3.4

BOD_5/TP	≥25	25.6

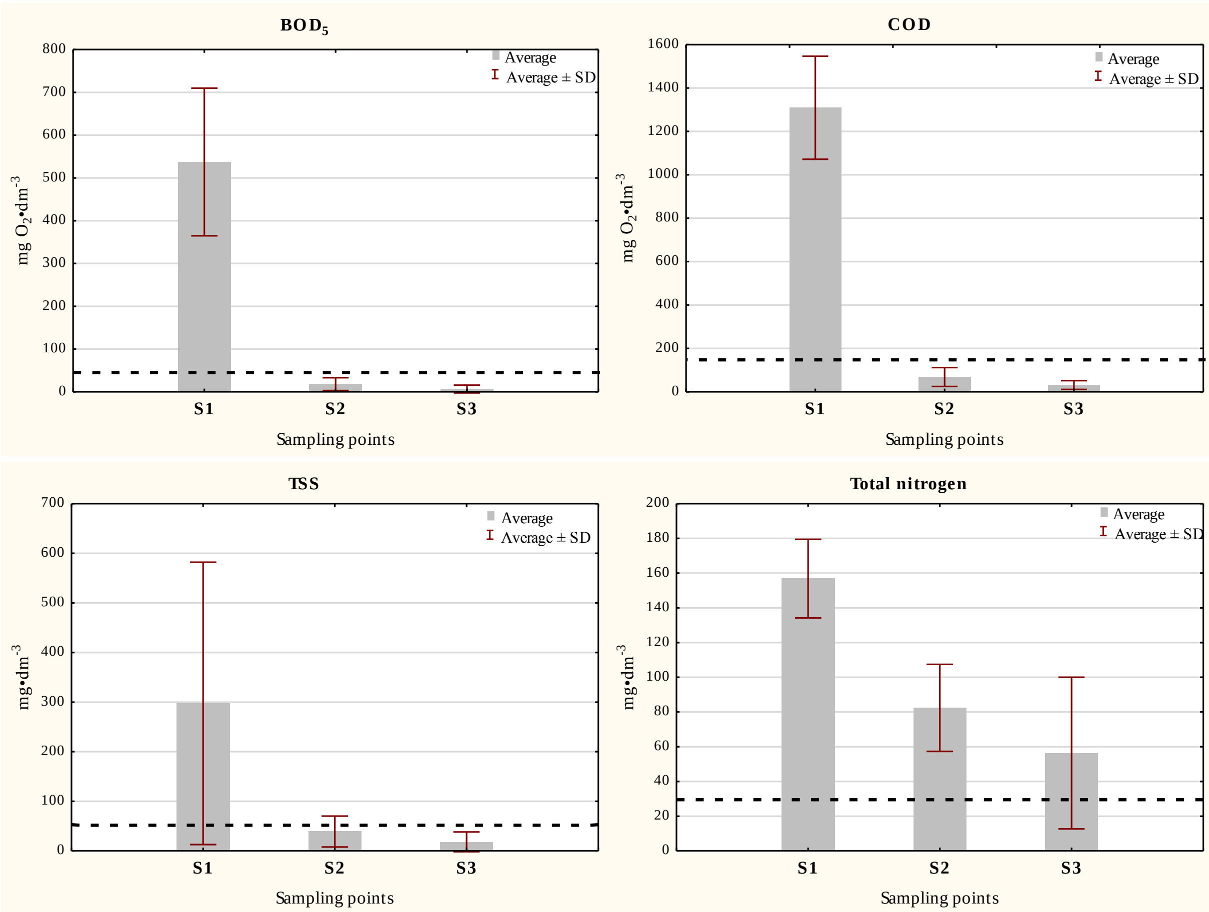
Pollutant concentrations in the effluent from the VF bed

After treatment of the wastewater in the VF bed , the average BOD_5 and COD values were 18 $mgO_2·dm^{-3}$ and 68.4 $mgO_2·dm^{-3}$, respectively. The average concentration of total suspended solids was 39.0 $mg·dm^{-3}$, total phosphorus 12.0 $mg·dm^{-3}$, total nitrogen 82.4 $mg·dm^{-3}$. The average values of BOD_5, COD, and total suspended solids in wastewater treated in the VF bed met the requirements specified in the Regulation of the Minister of Environment (2014) for wastewater discharged to waters or to the ground from treatment plants above 2000 p.e. (Figure 4). These results indicate that the VF bed provided favourable conditions for the oxidation of organic pollutants and nitrification. The average oxygen content in the wastewater flowing out from the first bed increased to about 3 $mg·dm^{-3}$ compared to the mechanically treated wastewater, while the average concentration of ammonia nitrogen slightly exceeded 20 $mg·dm^{-3}$. The total nitrogen balance in the VF bed indicates the existence of processes leading to the permanent removal of this component from the wastewater, including, mainly, the process of denitrification and uptake by vegetation. Despite this, the content of total nitrogen at the outflow from the VF bed remained high, on average 82.4 $mg·dm^{-3}$, with values well above 100 $mg·dm^{-3}$. High concentration of total nitrogen suggests that a significant part of ammonia nitrogen after transformation to the nitrate form did not undergo any further transformation. Therefore, the average concentration of nitrate nitrogen in the wastewater discharged from the VF bed was 24.5 $mg·dm^{-3}$ (Table 1). The wastewater discharged from the first bed also contained high concentrations of total phosphorus (an average of 11.0 $mg·dm^{-3}$). For both biogenic parameters, the average values were more than twice as high as the level stipulated by the law as acceptable for treatment plants up to 2000 p.e. discharging sewage into standing waters (Regulation of the Minister of the Environment, 2014).

Pollutant concentrations in the effluent from the HF bed

An HF bed in a hybrid system is designed to optimise total nitrogen and organic compounds removal in anaerobic and oxidised conditions (Vymazal, 2007; Saeed and Sun, 2012). The average concentrations of BOD_5, COD, and total suspended solids in wastewater discharged from the HF bed into the receiver were 6.6 $mg·dm^{-3}$, 31.8 $mg·dm^{-3}$, and 18.0 $mg·dm^{-3}$, respectively (Table 1). The respective median values were 3.1, 29.0, and 10.2 $mg·dm^{-3}$. These values were significantly lower than the limit values stipulated in the

Regulation of the Minister of the Environment (2014). The average concentrations of total nitrogen and total phosphorus in treated wastewater (56.4 mg·dm^{-3} and 6.7 mg·dm^{-3}, respectively) did not meet the above requirements (Figure 4). The average value of total nitrogen in treated wastewater was most strongly affected by the results collected during the initial period of operation of the plant (about 18 months), when the vegetation was not yet fully developed. The analysis of basic statistics highlights two tendencies: clear discrepancies between the extreme values, and high coefficients of variation for the individual pollution parameters of wastewater outflowing from the VF-HF system. Because the concentrations of contaminants in the effluent were low, the results may have been much more strongly influenced by environmental factors, precipitation and temperature, or random changes in operating conditions compared with the results for S1 and S2.



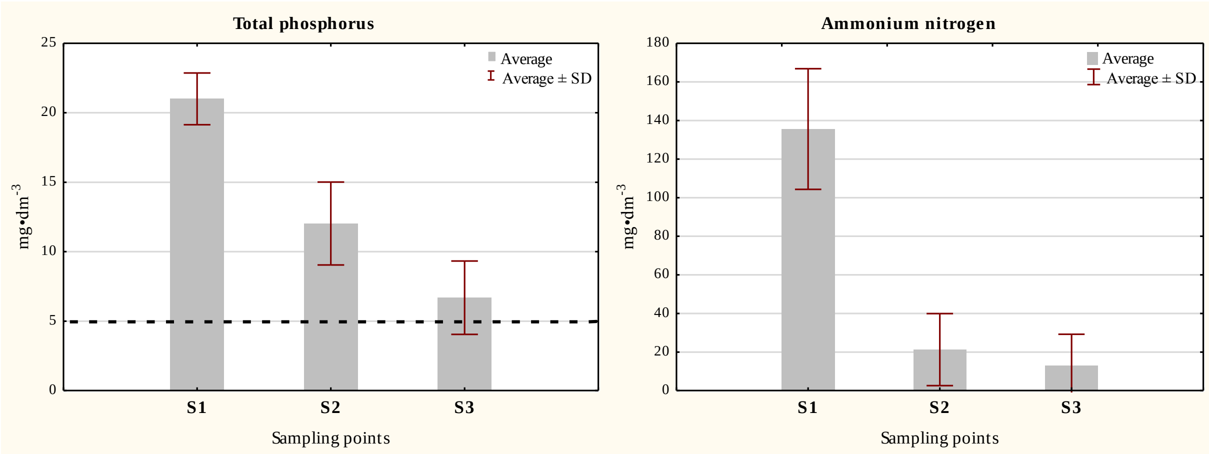


Fig. 4. Dynamics of reduction of pollutant concentrations in the successive stages of treatment

Notation: dashed black line – Polish legal requirements for wastewater discharged into water and soil from treatment plants below 2000 p.e.

(Regulation of the Minister of the Environment, 2014)

3.2. Pollutant removal efficiency

The results indicate that the investigated CW had a high efficiency of removal of organic pollutants and total suspended solids, and a lower efficiency of elimination of biogenic compounds (total nitrogen and total phosphorus). The differences between the various stages of treatment were clear-cut. The largest proportion of the investigated pollutants were eliminated in the VF bed. This bed provided favourable conditions for the biodegradation of organic pollutants and moderately good conditions for the removal of biogenic pollutants. Several factors may have been of significance here, including the way the bed was fed with sewage and the associated availability of oxygen, the hydraulic and pollution loads on the bed, the vegetation, and air and wastewater temperature. The low hydraulic load of the VF bed (an average of 12.5 $mm\cdot d^{-1}$) ensured optimal time of contact of sewage with the microorganisms forming the biological membrane on the filling material (Saeed and Sun, 2012). In addition, cyclic feeding of wastewater to the bed and alternating dry and wet periods, may have, in accordance with generally accepted opinions, increased the diffusion of atmospheric oxygen and improved the conditions for the oxidation of organic pollutants and the course of the nitrification process (Jia et al., 2010; Gervin and Brix, 2001).

The average efficiency of the entire VF-HF system in removing organic pollutants from wastewater in the 5-year research period was 98.8% for BOD_5 and 97.6% for COD (Figure 5). The effects of BOD_5 and COD removal were similar to or higher than those recorded by other authors in hybrid constructed wetland systems operating under similar climatic conditions

(Krzanowski et al., 2005; Gajewska and Obarska-Pempkowiak, 2009; Vymazal and Kröpfelová, 2009).

The largest part of the pollution load was eliminated in the first stage of treatment in the VF bed. Although the amount of sewage flowing into the treatment plant constituted about 50% of the designed value, the load of organic pollutants in the first bed, was quite high and amounted to 6.7 $g \cdot m^{-2} \cdot d^{-1}$ (BOD_5) and 16.4 $g \cdot m^{-2} \cdot d^{-1}$ (COD), respectively. Moreover, the wastewater flowing into the VF bed was characterised by an unfavourable BOD_5/COD ratio (2.4), which testified to the lower susceptibility of the tested wastewater to biological decomposition. Despite this, nearly 97% of BOD_5 and 95% COD were removed from the VF bed, which is a very good result. The system under investigation was rather insensitive to the high concentrations of organic compounds and their degradability. Caselles-Osorio and Garcia (2006) observed a similar relationship in their studies. Research carried out under similar climatic conditions has shown that the removal efficiency of VF reservoirs with regard to BOD_5 is in the range of 86–98% (Obarska-Pempkowiak et al., 2010; Gajewska et al., 2011; Vymazal, 2010). On the other hand, the efficiency of COD reduction in VF beds, according to various authors, may vary from 79 to 94% (Obarska-Pempkowiak, 2009; Sharma et al., 2010; Masi and Martinuzzi, 2007).

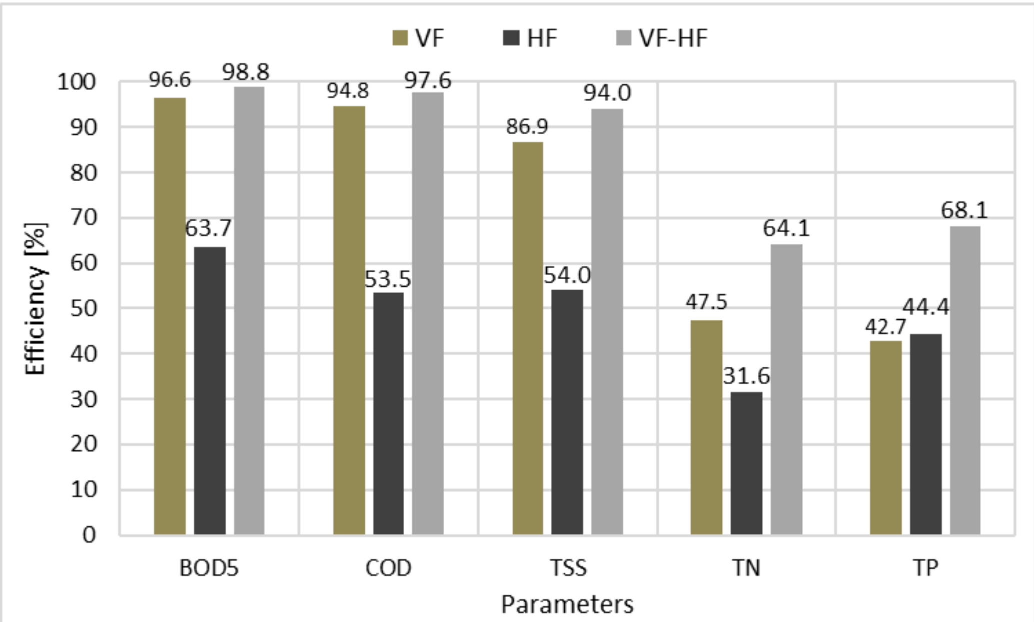


Fig. 5. Average pollutant removal efficiency of the investigated system

In the HF bed, the elimination of organic pollutants (BOD_5 and COD) was 63.7% and 53.5%, respectively. Research carried out by Obarska-Pempkowiak et al. (2010) indicates that HF type systems can provide a higher degree of COD reduction, but at higher contaminant loads.

The average efficiency of removal of total suspended solids in the analysed system was 94%. The VF bed removed nearly 87% of total suspended solids, while the HF bed removed 54% of the solids. The efficiency of the tested system in removing total suspended solids was higher than demonstrated by other authors. For comparison, a HF-VF system investigated by Masi and Martinuzzi (2007) had a total suspended solids removal efficiency of 84% a result that was identical to that obtained by Krzanowski et al. (2005). Hybrid systems analysed by Gajewska and Obarska-Pempkowiak (2009) reached an average total suspended solids removal efficiency of 89%.

The average total nitrogen removal efficiency for the analysed hybrid system was 64.1%, with 47.5% of nitrogen removed in the VF bed and 31.6% in the HF bed. According to Gajewska and Obarska-Pempkowiak (2011), the efficiency of total nitrogen removal in hybrid constructed wetland systems may range from 23 to 80%, depending on the configuration and operating conditions of the beds. In the light of these reports, the effectiveness of the facility tested in this present study was moderately high, but not high enough to obtain stable results at the outflow that would meet the requirements set out in the Polish regulations (Regulation of the Minister of the Environment, 2014). The incomplete removal of nitrogen may have been caused by a lack of appropriate conditions for effective denitrification in the HF bed, especially the deficit of organic compounds and the unfavourable BOD_5/TN ratio inhibiting the denitrification process, or thermal conditions (Vymazal, 2010). The analysis of meteorological conditions in the area of the conducted research (meteorological station in Radawiec near Lublin) showed that the significance of this last factor could have been smaller. Against the background of some long-term data, there can be observed a tendency of increasing the average air temperature (Figure 6). Throughout the entire research period (2011-2016) average annual temperatures were higher than the long-term average (1970-2000) by 0.7–2.0°C. In the six-month period covering the growing season (from April to September) the average differences ranged from 1.0 to 1.8°C, in the remaining period (from October to March) - from 0.4 to 2.5°C (IMWM 2011-2016; CSO, 2017). On this basis, it can be concluded that, apart from periods that are considered to be unfavorable in a moderate climate (December-February) temperature should not be a limiting factor for microbial removal processes.

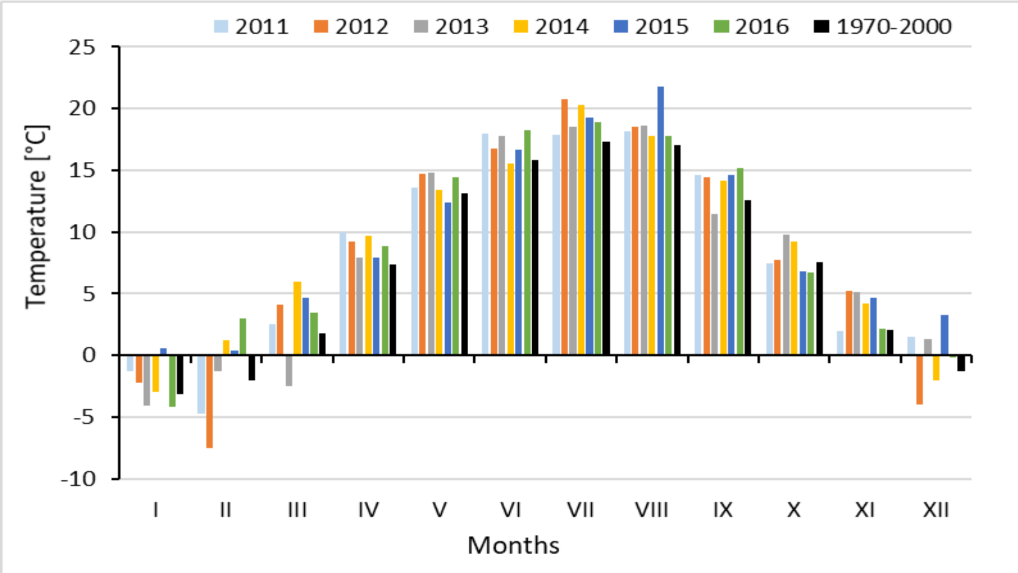


Fig. 6. The average monthly temperatures for Radawiec near Lublin in the years 2011-2016 (IMWM, 2011-2016; CSO, 2017)

The efficiency of total phosphorus removal for the whole VF-HF system was 68.1%. The two beds had similar average phosphorus removal rates, in the range of 42–45%. To compare, the average total phosphorus removal efficiencies for hybrid CW systems studied by other authors range from 70 to 89% (Krzanowski et al., 2005; Sharma et al., 2010). In our study, the highest phosphorus removal rates were found in the initial period of the plant's operation, which confirms the observation that the kind of filling of beds plays an important role in the process of total phosphorus elimination. A useful tool to compare the efficiency of pollutant removal in different facilities or in different units of the same system is the mass removal rate (MRR), which provides a measure of the amount of a component removed per unit area of a constructed wetland systems. Table 3 presents theoretical indicators of main pollutants mass removal (according to formula 2) in each bed and in the whole VF-HF system of the sewage treatment plant in south-eastern Poland. The indicators were determined on the basis of the assumption that the average annual sewage outflow from individual purification stages is equal to the inflow. In fact, these quantities may vary more or less, which is primarily due to evapotranspiration and precipitation (Chazarenc et al., 2003; 2010). The evapotranspiration efficiency in CW is subject to great fluctuations, depending on seasonal conditions, it can range from 0 to 50 $mm \cdot d^{-1}$ (Chazarenc et al. 2010). According to Herbst and Kappen (1999) in natural bog systems with common reed in northern Germany, in the full vegetation period, it may exceed 10 $mm \cdot d^{-1}$, but in other periods (from November to April) it approaches zero. These researchers also found that under certain conditions (cloudy and rainy weather) the efficiency of evapotranspiration during the year may be similar or even lower than the total precipitation. Also Chazarenc et al. (2003) in the research conducted on the HF field of the multi-stage constructed wetland confirmed the possibility of maintaining balance of beds evapotranspiration by precipitation. In the case of the analyzed sewage treatment plant, factors limiting the efficiency of evapotranspiration could be the proximity of high plants at the south-western side, which cause periodic shading of beds and reduce air movement. Moreover, the research of Toscano et al. (2015) indicate that the efficiency of evapotranspiration on the beds planted with giant miscanthus, even under warm climate conditions, is clearly lower than on the beds with common reed.

Despite the lower than planned hydraulic load, the pollution load in the investigated system was comparable to those found in other constructed wetlands tested in Poland (Gajewska and Obarska-Pempkowiak, 2011). The MRR mass removal ratios of organic pollutants were relatively high, similar to those recorded in two- and three-stage constructed wetland systems, described by Gajewska and Obarska-Pempkowiak (2011).

Similarly, in the case of total nitrogen, the MRR value did not differ significantly from the values determined for other plants (Gajewska and Obarska-Pempkowiak, 2011; Brix et al., 2003).

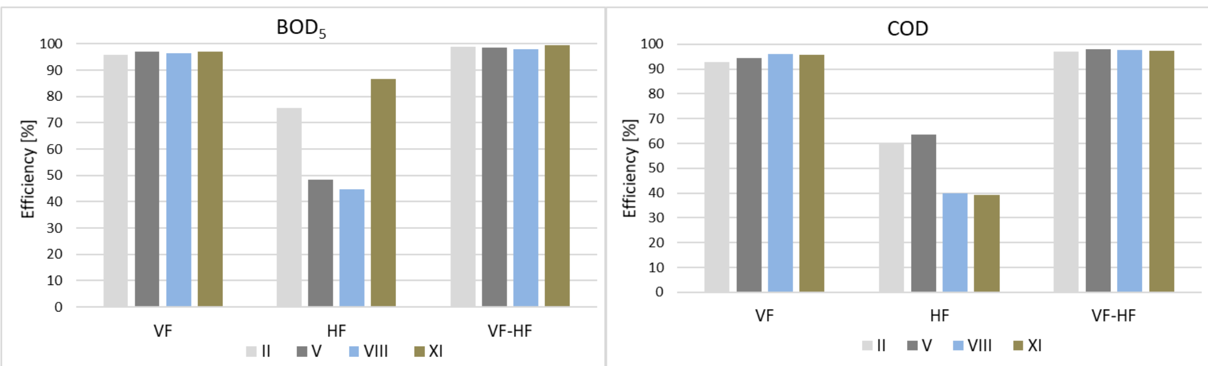
The VF bed played a decisive role in the removal of organic pollutants. The mass removal rates determined for this field were many times higher than in the case of the HF bed (Table 3).

Table 3. Mass removal rates of BOD_5, COD, total nitrogen (TN) and total phosphorus (TP)

Parameters		VF	HF	VF-HF
BOD_5	Load [$g \cdot m^{-2} \cdot d^{-1}$]	6.71	0.27	3.66
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	6.49	0.17	3.62
COD	Load [$g \cdot m^{-2} \cdot d^{-1}$]	16.36	1.02	8.93
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	15.51	0.54	8.70
TN	Load [$g \cdot m^{-2} \cdot d^{-1}$]	1.96	1.23	1.07
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	0.93	0.39	0.68
TP	Load [$g \cdot m^{-2} \cdot d^{-1}$]	0.26	0.18	0.14
	Mass Removal Rate [$g \cdot m^{-2} \cdot d^{-1}$]	0.11	0.08	0.10

The investigated wastewater treatment plant in south-eastern Poland, with giant miscanthus and Jerusalem artichoke, provided efficiency in the area of organic and biogenic compounds removal similar to other systems using classic plant species that function under similar operating conditions. In such systems, plants perform an auxiliary role, creating favorable conditions for the activity of microorganisms and the course of biochemical processes in the bed (Langergraber, 2005; Wu et al., 2013 a, b). This is confirmed by the research carried out on the treatment plant in Skorczyce, including the lack of seasonal variability of treatment effects, mainly organic pollutants. In the case of the VF bed and the entire VF-HF system, the average removal effects were constant during the whole year (Figure 7). Higher variability was found on the HF field, however, it is difficult to relate this to seasonal conditions, because the average efficiency of BOD_5 decreasing was the highest in autumn and winter. Most researchers point to the reverse regularity (Zhao et al., 2011; Saeed and Sun, 2012), although some studies did not show differences between the removal of these compounds in the summer and winter (Bulc, 2006). The lack of a clear influence of seasonal conditions on microbial removal processes can be associated with the dominance of physical processes. In addition, Plamondon et al. (2006) suggested that the factor that balances the dependence of kinetics on biological reactions on temperature in a cooler climate can be favorable oxygen conditions.

The average efficiency of nitrogen and phosphorus removal from wastewater was slightly higher in August and November. However, the share of plants in the uptake of pollutants from sewage, expressed as nitrogen and phosphorus content in biomass was relatively small. The yield of giant miscanthus on the VF field in the first year of operation was at a low level – 0.42 kg DM·m^{-2} (Gizińska-Górna et al., 2017b). In the following years, it fluctuated within the limits of 3.55–4.43 kg DM·m^{-2} and was clearly higher than the yields recorded in field crops of this plant (Szulczewski et al., 2018). The average nitrogen content in aboveground parts of giant miscanthus was 5.8 g·kg DM^{-1}, which means that with the highest yield (2016), approximately 2.5 kg of nitrogen were accumulated in the biomass. At the content of phosphorus – 0.26 g·kg DM^{-1} its mass accumulated in aboveground parts of giant miscanthus amounted to a maximum level of 0.11 kg.



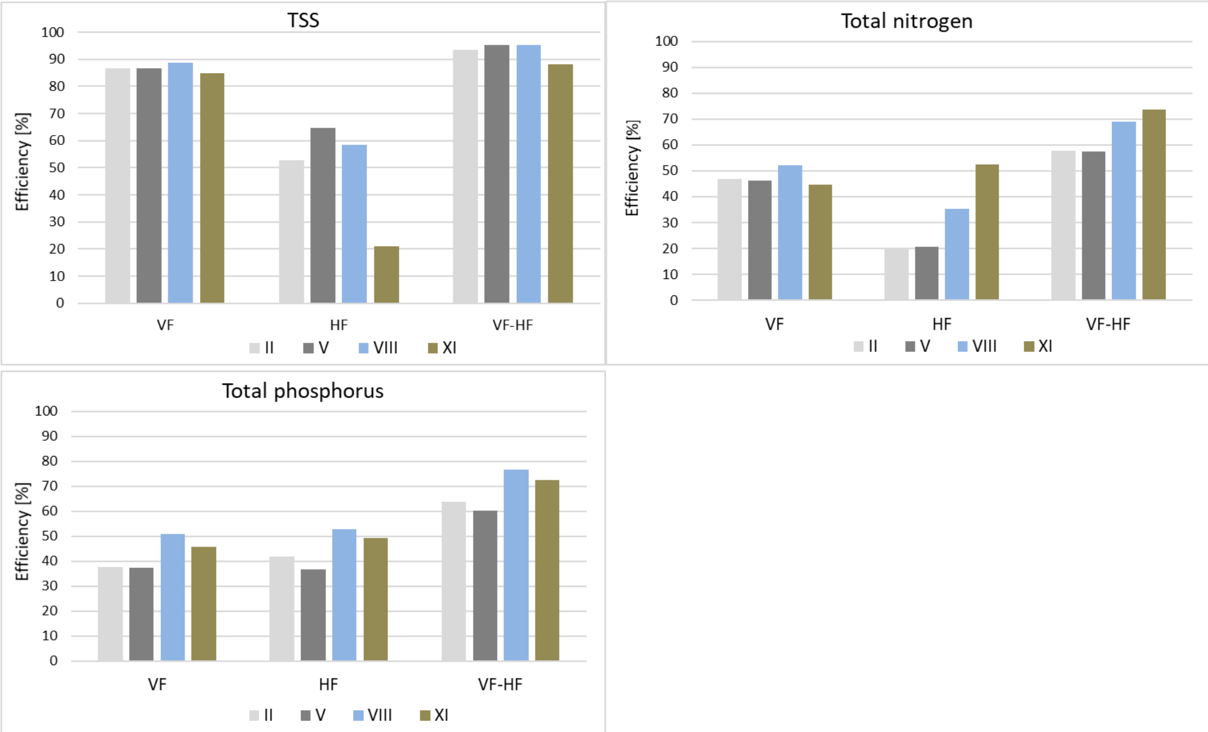


Fig. 7. Average removal efficiency of pollutants in different months of the research. Notation: II – February; V – May; VIII – August; XI – November

The yield of Jerusalem artichoke on the HF bed ranged from 0.83 kg DM·m^{-2} in 2013 to 1.43 kg DM·m^{-2} in 2015. The average nitrogen content in aboveground parts of plants was 3.4 g·kg DM^{-1}, and phosphorus – 0.34 g·kg DM^{-1}. In 2015, the nitrogen and phosphorus masses contained in the aboveground biomass were respectively 0.47 kg and 0.047 kg.

In the years which were most favorable in terms of yield of giant miscanthus and Jerusalem artichoke (2015 and 2016), the share of nitrogen accumulated in the biomass of both plants in relation to the mass of nitrogen removed in these years in the VF-HF system ranged from 5% to 6.3%. For phosphorus, it was about 2.6%. Baring in mind the fact that the plant activity associated with biomass production is limited to the growing season (in south-eastern Poland it usually lasts from April to September), it can be concluded that real contribution of the plants to nutrient removal by uptake was higher and exceeded 10% in the case of nitrogen and 5% in the case of phosphorus.

In this case, it can be concluded that the physiochemical processes, such as oxidation or adsorption by the substrate elements, could have a big influence on nitrogen removal (Bulc, 2006; Saeed and Sun, 2012). Physicochemical processes, especially substrate sorption, could also be very important in the elimination of phosphorus from wastewater (Jóźwiakowski et al., 2018; Xu et al., 2006).

3.3. Pollutant removal reliability

The reliability of the tested wastewater treatment plant, defined as its ability to dispose of the expected amount of wastewater to the extent required by the wastewater receiver, was determined using the Weibull method. The method allows a more in-depth analysis of qualitative data than is possible with average values, through the prism of legal requirements for sewage discharged to the environment. The first step was to estimate the parameters of distribution and verify the null hypothesis that empirical data could be described by Weibull's distribution. The data sets were the values of the basic pollution parameters (BOD_5, COD, TSS, total nitrogen, total phosphorus) in the wastewater discharged from the VF-HF constructed wetland system to the receiver.

The null hypothesis was confirmed. The results of the Hollander-Proschan goodness-of-fit test along with the estimated parameters, are presented in Table 4.

Table 4. Parameters of the Weibull distribution and results of the Hollander-Proschan goodness-of-fit test

Parameter	Parameters of Weibull distribution			Hollander-Proschan goodness-of-fit test	
	θ	c	b	stat	p
BOD_5	0.0000	0.8410	5.9731	0.1732	0.8625
COD	5.4646	1.7097	35.8400	0.1496	0.8810
TSS	1.6182	0.9676	17.6798	0.3140	0.7535
Total Nitrogen	9.0606	1.3572	61.8000	0.1807	0.8565
Total Phosphorus	-0.2000	2.8367	7.4737	-0.3043	0.7608

Symbols: stat – value of the test statistic, p – significance level of the test; when $p \leq 0.05$ the distribution of data is not a Weibull distribution

The goodness-of-fit of the obtained distributions was high at 75–88%, at a significance level $\alpha = 0.05$. The technological reliability of the treatment plant was determined on the basis of the distribution functions, taking into account the limit values for the parameters, as specified in the Regulation of the Minister of Environment for WWTPs of less than 2000 p.e. (Regulation of the Minister of the Environment, 2014) (Figure 8).

The organic pollutant removal reliability expressed by BOD_5 and COD was 100% (Figure 8). This means that the plant operated without any problems throughout the testing period, and the values of the tested parameters in the treated wastewater did not exceed the acceptable levels stipulated in the Polish law (40 and 150 $mgO_2 \cdot dm^{-3}$, respectively). This leads to the conclusion that, with an operator risk of α = 0.05, the plant should successfully pass inspection with regard to the parameters concerned throughout the year.

The reliability of removal of total suspended solids from sewage in the tested system was 93%. On this basis, it can be concluded that the plant operated smoothly on average 339 days a year. The period of failure-free operation is equivalent to the period when the concentration of total suspension particles in the wastewater discharged to the receiver was below the required limit (50 mg·dm^{-3}).

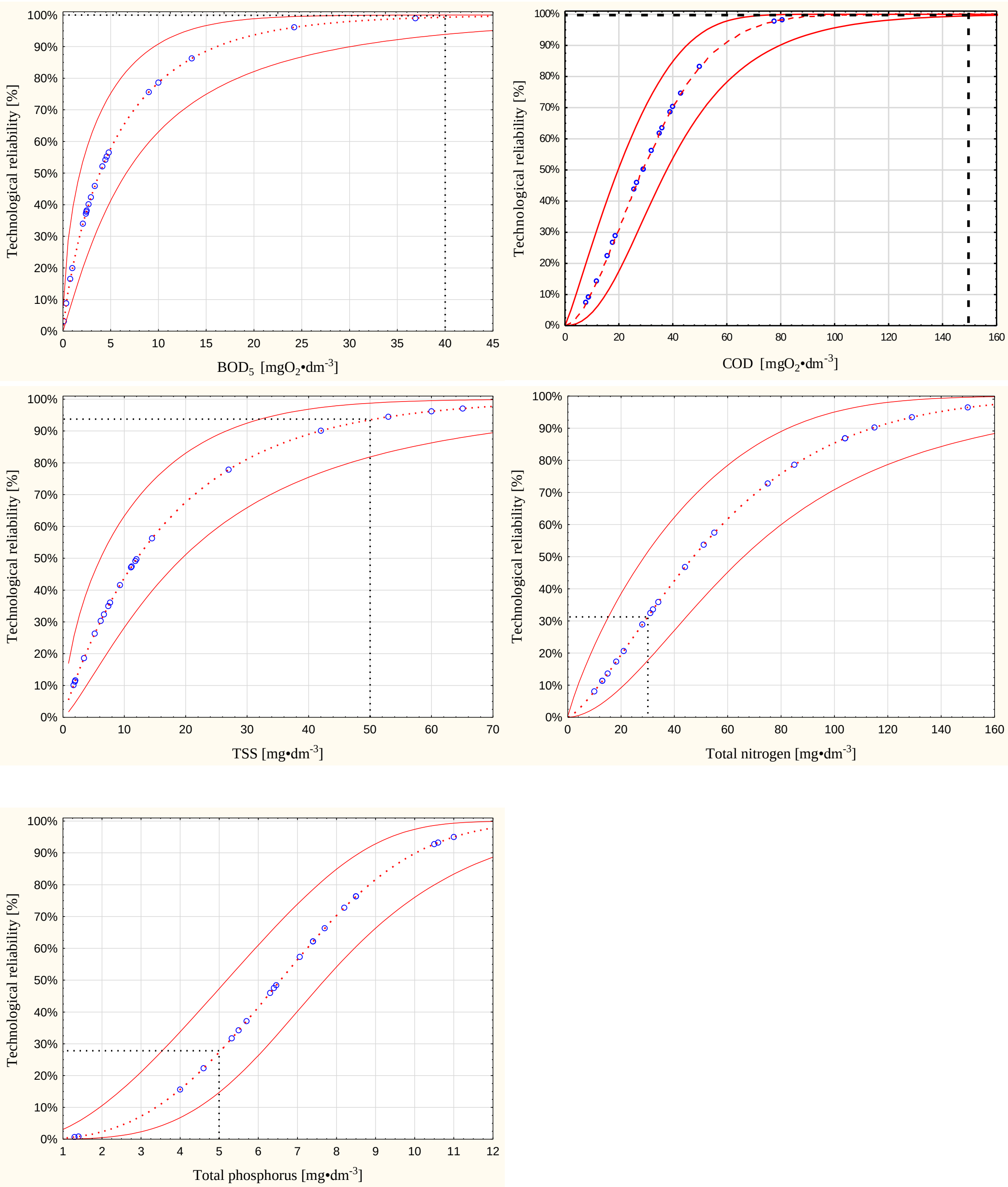


Fig. 8. Weibull cumulative distribution functions and the technological reliabilities determined for each pollution parameter

Notation: dashed red line – reliability function, continuous red line – confidence intervals, dashed black line – probability of reaching the effluent parameter limit

According to the guidelines proposed by Andraka and Dzienis (2003), the minimum reliability level for treatment plants below 2000 p.e. should be 97.27%, which means that these plants, even when operating poorly for 9 days a year, still have a 95% chance of successfully going through inspection procedures. Given these guidelines, it can be assumed that the limit concentrations of total suspended solids in the CW investigated in this present study can be exceeded without affecting the plant's operation on 17 days a year.

The reliability of removal of nutrients was significantly lower than in the case of organic pollutants. The probability that the total nitrogen concentration in treated effluents would reach the limit value (30 $mg \cdot dm^{-3}$) established for effluents discharged from a treatment plant of less than 2000 p.e. to standing waters was 32%. This means that the total nitrogen concentration in treated wastewater exceeded the limit value, and the plant operated incorrectly on 249 days a year.

An even lower level of reliability was found for total phosphorus removal. The probability that the concentration of this parameter in treated wastewater would reach a value below 5 $mg \cdot dm^{-3}$ was 28%. This means that the plant operated correctly for only 102 days a year, and excessive concentrations of total phosphorus in treated wastewater were recorded on 254 days a year.

The reliability levels obtained indicate that the hybrid constructed wetland with giant miscanthus and Jerusalem artichoke performed very well in terms of organic pollutant removal. The facility guaranteed stable low BOD_5 and COD results for the treated wastewater, which meant it was highly likely to be positively evaluated in the case of an inspection. These conclusions are consistent with the reports of other authors, which indicate that hybrid systems are very reliable with respect to BOD_5 and COD reduction (Jucherski et al., 2017; Jóźwiakowski, 2012). At the same time, the reliability of the tested VF-HF system was higher than that of single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et al., 2017) or other small sewage treatment plants using other technological solutions. For comparison, the organic pollutant removal reliabilities (expressed as BOD_5 and COD) of plants operating on the basis of conventional treatment methods (activated sludge, biological bed, hybrid reactor), were 60–88% and 89–92%, respectively, and in extreme cases as low as 30% (Marzec, 2017; Bugajski et al., 2012; Wałęga et al., 2008).

The reliabilities of removal of nutrient contaminants (nitrogen and phosphorus) for the tested facility were 32 and 28%, respectively, which indicates that treated wastewater was highly likely to contain excessive nitrogen and total phosphorus concentrations. Therefore, the performance of the system was not satisfactory in this respect. Tests carried out in other facilities show that similar or higher levels of nutrient removal reliability are reached in single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et al., 2018). Jucherski et al. (2017) reported that the reliabilities of nitrogen and phosphorus removal in the hybrid constructed wetland they studied were significantly higher at 76.8% for total nitrogen and 95.2% for total phosphorus. It should be noted, however, that the normative values for nitrogen and total phosphorus used in reliability assessment refer only to specific cases when treated wastewater is discharged to lakes and their tributaries and directly to artificial water reservoirs situated in flowing waters (Regulation of the Minister of the Environment, 2014). Moreover, according to the Polish law, there is no obligation to control the operation of domestic sewage treatment plants or to perform quality tests of sewage discharged to the environment. In this light, the assessment of nutrient removal reliability of domestic treatment plants is a theoretical issue, which does not mean that it should not become a common part of wastewater management practice in the future. In combination with an analysis of the effectiveness of wastewater treatment, the assessment of the pollutant removal reliability of wastewater treatment plants allows to determine what technological solutions should be promoted when building sewage systems in rural areas to support water protection against pollution and eutrophication. The use of highly efficient and reliable wastewater treatment systems can reduce the use of the cheapest solutions, which instead of protecting the environment pose a potential threat to it. According to the emerging suggestions, it also seems necessary to create administrative and legal instruments in Poland which would enable control of all sewage treatment plants, regardless of their size and type of receiver (Jóźwiakowski et al., 2015; Marzec, 2017; Jóźwiakowski et al., 2018).

4. Conclusions

In the five-year research period, the hydraulic load of the analysed VF-HF system with giant miscanthus and Jerusalem artichoke in south-eastern Poland was about 50% of the design value; however, the load of contaminants did not differ significantly from that found in similar constructed wetlands.

The average effectiveness of organic pollutant removal expressed as BOD_5 and COD was 98.8 and 97.6%, respectively; the corresponding value for total suspended solids was 93%. Under the conditions typical for moderate climate, the hybrid VF-HF system provided high and stable effects of organic pollutants removal throughout the whole year. In the VF bed, the concentration of organic pollutants (BOD_5 and COD) in the inflowing sewage was removed on average by over 94%.

Technological reliability of the constructed wetland wastewater treatment plant with giant miscanthus and Jerusalem artichoke concerning BOD_5 and COD amounted to 100%. Under given operating conditions, the facility ensures failure-free operation and the fulfillment of Polish legal requirements throughout the whole year. The reliability of removal of total suspended solids was 93%.

The efficiencies of total nitrogen and total phosphorus removal were 64.1 %. and 68.1%, respectively, and the average values of these components in the outflow from the treatment plant exceeded the standard levels. The lower efficiency of total nitrogen removal was probably caused by unfavourable denitrification conditions in the HF bed, including the deficit of organic compounds.

The CW had low total nitrogen and total phosphorus removal reliabilities (32% and 28%, respectively.

Giant miscanthus and Jerusalem artichoke showed favorable features when it comes to their use in constructed wetlands, also under moderate climate conditions. They were characterized by high resistance to unfavorable environmental conditions, and even at low hydraulic load, high yield potential. Despite the high yield, their share in the uptake of biogenic pollutants from wastewater was relatively small.

Giant miscanthus is characterized by a clearly higher biomass production than Jerusalem artichoke, has a well-developed root system, and the operation of miscanthus beds is simpler. Jerusalem artichoke generates large amounts of tubers, which allow the plant to compact the entire surface of the bed, and after some time their accumulation can affect the balance of pollutants in the bed. To avoid this, there is often a need to remove them during the operation of the facility.

The investigated hybrid constructed wetland system with giant miscanthus and Jerusalem artichoke had organic and biogenic pollutant removal efficiencies that were similar to those obtained in systems using classic plant species such as reed and willow. Giant miscanthus and Jerusalem artichoke can be successfully used to support wastewater treatment processes in constructed wetland systems, and, owing to their high biomass production potential, they can also be exploited as energy yielding materials.

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