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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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13 ABSTRACT

14 In this paper, we analysed the pollutant removal efficiency and reliability of a vertical and 15 horizontal flow hybrid constructed wetland (CW) planted with giant miscanthus and 16 Jerusalem artichoke. The wastewater treatment plant, located in south-eastern Poland, treated domestic sewage at an average flow rate of 1.2 $\text{m}^3 \cdot \text{d}^{-1}$. The tests were carried out during 17 5-years of operation of the sewage treatment plant (2011–2016). During this period, sewage 18 19 samples were collected from three stages of wastewater treatment in four seasons (winter -20 February, spring – May, summer – August, and autumn – November). The following 21 parameters were measured: BOD₅, COD, total suspended solids, total nitrogen, and total phosphorus. The average effectiveness of organic pollutant removal expressed by BOD₅ and 22 23 COD was 98.8 and 97.6%, respectively, and the removal efficiency for total suspended solids 24 was 93%. The average values of BOD₅, COD, and total suspended solids in wastewater discharged to the receiver were significantly lower than the limit values required in Poland. 25 26 The efficiency of total nitrogen and total phosphorus removal was 64.1 and 68.1%, 27 respectively, and the average values of these components in the outflow from the treatment 28 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 29 30 was very high for BOD₅ and COD (100%). It was also demonstrated that the tested CW did 31 not provide effective elimination of biogenic elements (nitrogen and phosphorus), as 32 evidenced by the low reliability values -32 and 28%, respectively. The investigated hybrid 33 CW system with giant miscanthus and Jerusalem artichoke removed organic and biogenic 34 pollutants with a similar efficiency as systems using classic plant species such as reed and 35 willow.

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37 Key words: wastewater treatment, hybrid constructed wetlands, vertical flow, horizontal

- 38 flow, pollutant removal, efficiency and reliability
- 39

40 **1. Introduction**

41 Domestic wastewater treatment plants are an optimal solution for the disposal of small 42 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; 43 44 Jóźwiakowski et al., 2015). Issues related to the operational reliability of low capacity 45 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 46 47 treatment plants and their control during operation. Such a situation is not conducive to the 48 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 49 50 untreated wastewater into the ground, and therefore, their application for waste water 51 treatment raises serious questions (Jóźwiakowski et al., 2015, Zhang et al., 2015). Moreover, 52 many solutions applied in small sewage treatment plants, including those based on 53 conventional methods, in conditions of high variability of hydraulic load, pollution load and 54 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 55 56 applied, the risk of their negative impact on water quality increases (Bugajski, 2014; Pawełek 57 and Bugajski, 2017).

58 Therefore, the reliability of small sewage treatment plants should be an important criterion 59 in planning the development of technical infrastructure in rural areas, which will enable the 60 selection of optimal and environmentally safe solutions (Jóźwiakowski et al., 2015; Jucherski 61 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 62 63 same time, the popularity of constructed wetland systems, which can be used in various 64 conditions, including protected areas and areas of high landscape value, is increasing due to 65 their high pollutant removal efficiency (Vymazal, 2011; 2013; Jóźwiakowski, 2012; Paruch et al., 2011; Jóźwiakowski et al., 2017; Gajewska et al., 2015). 66

67 Constructed wetlands, and in particular hybrid treatment plants consisting of at least two 68 beds with different sewage flows (vertical and horizontal), ensure effective removal of organic 69 matter (BOD₅ and COD) (Vymazal, 2011) and slightly less effective removal of nutrients 70 (Kadlec and Wallace, 2008; Vymazal and Kropfelova, 2008). The removal of contaminants in 71 constructed wetland systems is related to the functioning of the biological membrane formed 72 during the flow of wastewater through the material filling the beds. The plants growing in the 73 wetland support the process of treatment (Vymazal, 2013; Foladori et al., 2012; Vymazal and 74 Březinová, 2014; Wu et al., 2015). The rhizosphere produces an oxygenated microenvironment, while other layers of the bed provide anaerobic or anoxic conditions. 75 76 Roots and rhizomes of plants increase the hydraulic permeability of the soil and loosen its 77 structure (Birkedal et al., 1993). Until now, depending on the climatic conditions, different 78 plant species have been used in constructed wetland systems, mainly common reed and 79 willow (Vymazal, 2011; Jóźwiakowski, 2012). These plants are characterized by quite 80 intensive growth, even on a very poor substrate (Gruenewald et al., 2007), hence the 81 possibility of using constructed wetland systems not only for wastewater treatment, but also 82 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 83 84 Jerusalem artichoke, in constructed wetland systems may be of interest (Gizińska-Górna et al., 85 2016). The high energy potential of these plants is a result of high yield and biomass calorific 86 value, which depends on its chemical composition (Bridgwater and Peacocke, 2000; Bellamy 87 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 88 artichoke from 9 to 25 Mg DM·ha⁻¹ (Baldini et al., 2004; Gunnarsson et al., 2014). The 89 calorific value of dried biomass of giant miscanthus varies from 14 to 17 MJ·kg DM⁻¹, and for 90 Jerusalem artichoke varies from 15 to 19 MJ·kg DM⁻¹ (Szulczewski et al., 2018; 91 92 Gizińska-Górna et al., 2016). The possibilities of their use in wastewater treatment are less 93 recognized, especially in moderate climate conditions. Jerusalem artichoke has not been used 94 in constructed wetland systems yet, while research on the use giant miscanthus has been 95 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 96 97 those found in the case of classical plant species, including common reed (Toscano et al., 98 2015; Barbagallo et al., 2014).

99 The aim of the present study is to analyse the reliability and effectiveness of pollutant 100 removal in a hybrid constructed wetland wastewater treatment plant with giant miscanthus 101 (*Miscanthus giganteus x* Greef et Deu) and Jerusalem artichoke (*Helianthus tuberosus L.*) 102 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

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108 2011 and its planned capacity is $2.5 \text{ m}^3 \cdot \text{d}^{-1}$. In the analyzed system, sewage from the building 109 was drained into a three-chamber preliminary settling tank, where it was pre-treated in 110 physical and biological processes.

The tank is made of concrete, and its active capacity is 8.64 m³. In the next stage, the 111 sewage flows through a system of two VF-HF type soil and plant beds (biological treatment). 112 A first bed, with vertical sewage flow (VF), has an area of 96 m^2 and a depth of 0.8 m. and the 113 second bed, with horizontal sewage flow (HF), has an area of 80 m^2 and a depth of 1.2 m. The 114 beds have been isolated from the native soil by a PEHD waterproofing geomembrane of 1 mm 115 116 thickness. The VF bed was filled with a layer of sand (1-2 mm) with a height of about 0.8 m. 117 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 118 119 construction of the sewage treatment plant (Figures 1, 2). The first bed was planted with giant 120 miscanthus (Miscanthus x giganteus Greef et Deu.), the second with Jerusalem artichoke 121 (Helianthus tuberosus L.) (Photo 1). Every year, after the winter season, the aboveground 122 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). 123





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

136 During the study period, the amount of wastewater discharged to the treatment plant 137 represented only about half of the design value, as the actual number of inhabitants served by 138 the plant had decreased since its construction. The amount of sewage inflow to the treatment 139 plant was determined on the basis of water meters readings in the building and average water 140 consumption. In addition, the amount of sewage introduced into the VF-HF system was 141 measured by using a flow meter installed on the discharge pipe between the preliminary 142 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 143 wastewater was pumped into the first bed (VF) twice a day, about 0.6 m³ each time, and then 144 145 it flowed gravitationally to the second bed (HF), and finally to the receiver. At the outflow 146 from the HF bed a tilting pipe was installed, which allowed to raise the level of sewage in this 147 field during summer. Theoretical wastewater retention time was determined on the basis of the 148 parameters of the beds (horizontal dimensions, porosity of the material used to fill the bed, the 149 height of the layer filled with sewage) and average daily wastewater inflow (Conley et al., 150 1991) and for the VF bed it was 4.8 d. Thanks to the use of a tilting pipe behind the HF bed, 151 the wastewater retention time in this bed was about 21.2 d in the vegetation period and 10.6 d 152 in the winter period.

154 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

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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.

162 The samples were analysed to determine pH, dissolved oxygen, ammonium nitrogen, 163 nitrate and nitrite nitrogen, total nitrogen, total phosphorus, total suspended solids (TSS), 164 biochemical oxygen demand (BOD₅) and chemical oxygen demand (COD). The concentration 165 of dissolved oxygen and the pH were determined using a WTW Multi 340i meter. Nitrate and 166 nitrite nitrogen were determined with a Slandi LF 300 photometer, and ammonium nitrogen 167 was measured with a PC Spectro spectrophotometer from AQUALYTIC. This latter 168 instrument was also used to determine total nitrogen after oxidation of the samples in a 169 thermoreactor at 100°C. Total phosphorus was determined with WTW's MPM 2010 170 spectrophotometer after oxidation of the samples at 120°C. BOD₅ was measured by the 171 dilution method using WTW Multi 340i, and COD was estimated by the same method with a 172 WTW MPM 2010 spectrophotometer after oxidation at 148°C. Total suspended solids were 173 determined by filtration through paper filters. Sampling, transport and processing of the 174 samples and their analysis were carried out in accordance with Polish standards (PN-74/C-175 04620/00; PN-EN 25667-2; PN-EN 1899-1:2002; PN-ISO 15705:2005; PN-EN ISO 176 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 m². 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.

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193 On the basis of the average values of the pollution parameters in the incoming (C_{in}) and 194 outgoing (C_{out}) wastewater, the average pollutant removal efficiency was calculated according 195 to equation 1:

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

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):

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

where: A – surface area of the constructed wetland system [m²], Q_{in} and Q_{out} – average inflow and outflow of wastewater [m³·d⁻¹], C_{in} and C_{out} – average concentrations of pollutants in the wastewater flowing into and out of the system [g·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 (BOD₅, 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:

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

214 where: x - a variable describing the concentration of a pollution parameter in the treated 215 effluent, b – scale parameter, c – shape parameter, θ – position parameter.

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

217 The reliability analysis was based on the estimation of Weibull distribution parameters 218 using the method of highest reliability. The null hypothesis that the analyzed variable could be 219 described by the Weibull distribution was verified with the Hollander-Proschan test at the 220 significance level of 0.05% (Bugajski et al., 2012). The values of basic pollution parameters 221 in treated wastewater discharged to the receiver were analysed. Reliability was determined 222 from the distribution figures, taking into account the normative values of the parameters 223 specified in the Regulation of the Minister of the Environment (2014) for wastewater discharged from treatment plants of less than 2000 p.e.: BOD₅ - 40 mgO₂·dm⁻³, COD -224

150 mgO₂·dm⁻³, total suspended solids - 50 mg·dm⁻³, total nitrogen - 30 mg·dm⁻³, and total phosphorus - 5 mg·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.

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231 **3. Results and discussion**

232 **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.

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241 **Pollutant concentrations in sewage flowing into the treatment plant**

242 The average values of pollution indicators in raw sewage outflowing from the building to the preliminary settling tank were respectively: 704 mgO₂·dm⁻³ for BOD₅, 1486 mgO₂·dm⁻³ 243 for COD, 710 mg·dm⁻³ for total suspended solids, 172 mg·dm⁻³ for total nitrogen and 23.5 244 $mg \cdot dm^{-3}$ for total phosphorus (Table 1). These values were clearly higher than those reported 245 246 in typical domestic wastewater (Heidrich et al., 2008; Bugajski and Bergel, 2008). This may 247 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 248 249 facilities and the need for economical water management, its unit consumption in the building 250 was at a low level, which could result in an increase in the concentration of pollutants in the 251 sewage. In the preliminary settling tank, mainly solid fractions were removed. As a result of 252 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 BOD₅ (by 23%) 253 254 and COD (by 12%) as well as total nitrogen (by 9%) and total phosphorus (by 11%). 255 Nevertheless, the concentration of pollutants in the sewage outflowing from the settling tank 256 to the system of VF-HF beds was high. The average values of these parameters at this stage of treatment were: 537 mgO₂·dm⁻³ for BOD₅, 1309 mgO₂·dm⁻³ for COD, 297 mg·dm⁻³ for total 257 suspended solids, 157 mg·dm⁻³ for total nitrogen, and 21.0 mg·dm⁻³ for total phosphorus 258

259 (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 \cdot dm⁻³. The average 260 contents of ammonium nitrogen, nitrate nitrogen, and nitrite nitrogen in mechanically treated 261 wastewater were 136 mg·dm⁻³, 2.87 mg·dm⁻³, and 0.23 mg·dm⁻³, respectively. The recorded 262 values were significantly higher than those reported in the literature for mechanically treated 263 264 wastewater from single-family buildings (Jucherski et al., 2017; Jóźwiakowski et al., 2017; 265 Jóźwiakowski et al., 2018; Bugajski and Bergel, 2008). This was associated with low water 266 consumption, leading to the formation of highly concentrated wastewater.

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

Donomotoro				Stat	tistic		
Farameters		Average	Median	Min	Max	SD	Cv
D: 1 1	S 0	0.35	0.22	0.08	1.19	0.31	89.51
Dissolved oxygen [mgO ₂ ·dm ⁻³]	S 1	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
	S 3	5.58	5.55	1.27	11.42	2.69	48.24
	S 0	7.26	7.29	6.50	7.89	0,44	6.04
ъU	S 1	7.17	7.13	6.67	7.94	0.29	4.06
рН	S2	7.10	7.08	6.68	7.55	0.24	3.37
	S 3	7.47	7.42	6.93	8.70	0.49	6.51
	S 0	704.0	690.5	376.0	1262.0	202.9	28.82
BOD ₅	S 1	537.0	471.0	310.0	862.0	172.4	32.10
$[mgO_2 \cdot dm^{-3}]$	S2	18.2	16.3	1.8	58.0	15.1	82.60
	S 3	6.6	3.1	0.1	36.9	9.1	137.40
	S 0	1486.9	1485.0	990.0	1920.0	249.8	16.80
COD	S 1	1309.0	1295.0	910.0	1740.0	237.4	18.08
$[mgO_2 \cdot dm^{-3}]$	S2	68.4	52.0	11.0	170.0	43.4	63.52
	S 3	31.8	29.0	8.0	81.0	20.3	63.83
	S 0	710.9	523.2	136.0	2052.0	520.4	73.20
TSS	S 1	297.0	235.0	60.0	1390.0	284.7	95.67
[mgO ₂ ·dm ⁻³] pH BOD ₅ [mgO ₂ ·dm ⁻³] COD [mgO ₂ ·dm ⁻³] TSS [mg·dm ⁻³] Total nitrogen [mg·dm ⁻³] Ammonium nitrogen [mg·dm ⁻³] Nitrate nitrogen [mg·dm ⁻³]	S2	39.0	28.5	1.9	114.0	31.1	79.77
	S 3	18.0	10.2	1.8	65.1	20.2	112.45
	S 0	172.3	171.0	114.0	238.0	32.2	18.70
Total nitrogen	S 1	157.0	150.5	120.0	216.0	22.7	14.45
[mg·dm ⁻³]	S 2	82.4	83.0	34.0	134.0	25.1	30.42
	S 3	56.4	39.0	10.0	150.0	43.7	77.46
	S 0	147.2	139.5	47.0	230.0	42.7	29.02
Ammonium	S 1	136.0	134.5	43.0	204.0	31.3	23.06
[mg·dm ⁻³]	S2	21.3	18.2	1.6	65.2	18.7	87.77
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.1	47.1	16.4	127.44			
	S 0	2.11	0.99	0.03	17.11	3.64	172.89
Nitrate nitrogen	S 1	2.87	0.86	0.28	29.67	6.47	225.24
[mg·dm ⁻³]	S2	24.48	24.96	2.71	57.70	16.07	65.65
-	S 3	20.25	13.48	0.86	58.20	19.89	98.22

	S 0	0.28	0.270	0.08	0.471	0.15	55.07
Nitrite nitrogen	S 1	0.23	0.19	0.08	0.43	0.13	56.71
[mg·dm ⁻³]	S 2	1.03	0.73	0.06	4.04	1.02	98.99
	S 3	0.50	0.13	0.03	3.62	1.00	198.99
	S 0	23.5	23.1	15.3	30.2	4.6	19.69
	S 1	21.0	21.1	17.2	23.9	1.9	8.89
[mg·dm ⁻³]	S2	12.0	11.6	8.5	21.0	3.0	24.83
	S 3	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 272 273 concentrations, grouped in different ranges. BOD₅ in the wastewater flowing into the hybrid VF-HF system did not fall below 300 mgO₂·dm⁻³ across measurements. The most common 274 values were in the range of $300-400 \text{ mgO}_2 \cdot \text{dm}^{-3}$ (30% of cases), 400-500 and 700-800 275 $mgO_2 \cdot dm^{-3}$ (25% each), and 500–600 $mgO_2 \cdot dm^{-3}$ (10%). The COD values were very high and 276 277 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 278 $mgO_2 \cdot dm^{-3}$ (Figure 3). Differentiation of COD values in mechanically treated sewage could be 279 280 the result of variability in the composition of raw sewage and also the operation of the settling 281 tank. Lower COD values were recorded during the tank's working phase, when the 282 sedimentation process played a major role. A similar effect could occur after each removing of 283 scum and some part of sludge from the tank, which was one of the operating works. In other 284 periods, sludge fermentation could have caused sludge flotation, decreased the sedimentation 285 effect and increased the concentration of pollutants in sewage flowing out from the settling 286 tank.





Fig. 3. Frequency histogram of influent parameter values (BOD₅, COD, TSS, total nitrogen, total phosphorus)

As a rule, total suspended solids did not exceed 400 mg \cdot 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/BOD₅, BOD₅/TN, and BOD₅/TP. It was found that the wastewater flowing into the tested VF-HF hybrid system was characterized by unfavourable COD/BOD₅ (2.4) and BOD₅/TN (3.0) ratios; the BOD₅/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

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BOD ₅ /TP	≥25	25.6
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309 Pollutant concentrations in the effluent from the VF bed

After treatment of the wastewater in the VF bed , the average BOD₅ and COD values were 310 18 mgO₂·dm⁻³ and 68.4 mgO₂·dm⁻³, respectively. The average concentration of total 311 suspended solids was 39.0 mg·dm⁻³, total phosphorus 12.0 mg·dm⁻³, total nitrogen 312 313 82.4 mg·dm⁻³. The average values of BOD₅, COD, and total suspended solids in wastewater treated in the VF bed met the requirements specified in the Regulation of the Minister of 314 315 Environment (2014) for wastewater discharged to waters or to the ground from treatment 316 plants above 2000 p.e. (Figure 4). These results indicate that the VF bed provided favourable 317 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⁻³ 318 compared to the mechanically treated wastewater, while the average concentration of 319 ammonia nitrogen slightly exceeded 20 mg·dm⁻³. The total nitrogen balance in the VF bed 320 indicates the existence of processes leading to the permanent removal of this component from 321 322 the wastewater, including, mainly, the process of denitrification and uptake by vegetation. 323 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 324 nitrogen suggests that a significant part of ammonia nitrogen after transformation to the 325 326 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). 327 328 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 329 330 were more than twice as high as the level stipulated by the law as acceptable for treatment 331 plants up to 2000 p.e. discharging sewage into standing waters (Regulation of the Minister of 332 the Environment, 2014).

334 Pollutant concentrations in the effluent from the HF bed

An HF bed in a hybrid system is designed to optimise total nitrogen and organic 336 compounds removal in anaerobic and oxidised conditions (Vymazal, 2007; Saeed and Sun, 337 2012). The average concentrations of BOD₅, 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 338 18.0 mg·dm⁻³, respectively (Table 1). The respective median values were 3.1, 29.0, and 339 10.2 mg·dm⁻³. These values were significantly lower than the limit values stipulated in the

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341 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, 342 343 respectively) did not meet the above requirements (Figure 4). The average value of total 344 nitrogen in treated wastewater was most strongly affected by the results collected during the 345 initial period of operation of the plant (about 18 months), when the vegetation was not yet 346 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 347 348 parameters of wastewater outflowing from the VF-HF system. Because the concentrations of 349 contaminants in the effluent were low, the results may have been much more strongly 350 influenced by environmental factors, precipitation and temperature, or random changes in 351 operating conditions compared with the results for S1 and S2.



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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)

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3.2. Pollutant removal efficiency

363 The results indicate that the investigated CW had a high efficiency of removal of organic 364 pollutants and total suspended solids, and a lower efficiency of elimination of biogenic 365 compounds (total nitrogen and total phosphorus). The differences between the various stages 366 of treatment were clear-cut. The largest proportion of the investigated pollutants were 367 eliminated in the VF bed. This bed provided favourable conditions for the biodegradation of 368 organic pollutants and moderately good conditions for the removal of biogenic pollutants. 369 Several factors may have been of significance here, including the way the bed was fed with 370 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 371 bed (an average of 12.5 mm $\cdot d^{-1}$) ensured optimal time of contact of sewage with the 372 microorganisms forming the biological membrane on the filling material (Saeed and Sun, 373 374 2012). In addition, cyclic feeding of wastewater to the bed and alternating dry and wet 375 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 376 377 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 BOD₅ and 97.6% for COD (Figure 5). The effects of BOD₅ and COD removal were similar to or higher than those recorded by other authors in hybrid constructed wetland systems operating under similar climatic conditions

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

The largest part of the pollution load was eliminated in the first stage of treatment in the 384 385 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 386 387 amounted to 6.7 g·m⁻²·d⁻¹ (BOD₅) and 16.4 g·m⁻²·d⁻¹ (COD), respectively. Moreover, the wastewater flowing into the VF bed was characterised by an unfavourable BOD₅/COD ratio 388 389 (2.4), which testified to the lower susceptibility of the tested wastewater to biological 390 decomposition. Despite this, nearly 97% of BOD₅ and 95% COD were removed from the VF 391 bed, which is a very good result. The system under investigation was rather insensitive to the 392 high concentrations of organic compounds and their degradability. Caselles-Osorio and Garcia 393 (2006) observed a similar relationship in their studies. Research carried out under similar 394 climatic conditions has shown that the removal efficiency of VF reservoirs with regard to 395 BOD₅ is in the range of 86–98% (Obarska-Pempkowiak et al., 2010; Gajewska et al., 2011; 396 Vymazal, 2010). On the other hand, the efficiency of COD reduction in VF beds, according to 397 various authors, may vary from 79 to 94% (Obarska-Pempkowiak, 2009; Sharma et al., 2010; 398 Masi and Martinuzzi, 2007).



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

In the HF bed, the elimination of organic pollutants (BOD₅ 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.

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406 The average efficiency of removal of total suspended solids in the analysed system was 407 94%. The VF bed removed nearly 87% of total suspended solids, while the HF bed removed 408 54% of the solids. The efficiency of the tested system in removing total suspended solids was 409 higher than demonstrated by other authors. For comparison, a HF-VF system investigated by 410 Masi and Martinuzzi (2007) had a total suspended solids removal efficiency of 84% a result 411 that was identical to that obtained by Krzanowski et al. (2005). Hybrid systems analysed by 412 Gajewska and Obarska-Pempkowiak (2009) reached an average total suspended solids 413 removal efficiency of 89%.

414 The average total nitrogen removal efficiency for the analysed hybrid system was 64.1%, 415 with 47.5% of nitrogen removed in the VF bed and 31.6% in the HF bed. According to 416 Gajewska and Obarska-Pempkowiak (2011), the efficiency of total nitrogen removal in hybrid 417 constructed wetland systems may range from 23 to 80%, depending on the configuration and 418 operating conditions of the beds. In the light of these reports, the effectiveness of the facility 419 tested in this present study was moderately high, but not high enough to obtain stable results 420 at the outflow that would meet the requirements set out in the Polish regulations (Regulation 421 of the Minister of the Environment, 2014). The incomplete removal of nitrogen may have 422 been caused by a lack of appropriate conditions for effective denitrification in the HF bed, 423 especially the deficit of organic compounds and the unfavourable BOD₅/TN ratio inhibiting 424 the denitrification process, or thermal conditions (Vymazal, 2010). The analysis of 425 meteorological conditions in the area of the conducted research (meteorological station in 426 Radawiec near Lublin) showed that the significance of this last factor could have been 427 smaller. Against the background of some long-term data, there can be observed a tendency of 428 increasing the average air temperature (Figure 6). Throughout the entire research period 429 (2011-2016) average annual temperatures were higher than the long-term average 430 (1970-2000) by 0.7–2.0°C. In the six-month period covering the growing season (from April 431 to September) the average differences ranged from 1.0 to 1.8°C, in the remaining period (from 432 October to March) - from 0.4 to 2.5°C (IMWM 2011-2016; CSO, 2017). On this basis, it can 433 be concluded that, apart from periods that are considered to be unfavorable in a moderate 434 climate (December-February) temperature should not be a limiting factor for microbial 435 removal processes.





440 The efficiency of total phosphorus removal for the whole VF-HF system was 68.1%. The 441 two beds had similar average phosphorus removal rates, in the range of 42–45%. To compare, 442 the average total phosphorus removal efficiencies for hybrid CW systems studied by other 443 authors range from 70 to 89% (Krzanowski et al., 2005; Sharma et al., 2010). In our study, the 444 highest phosphorus removal rates were found in the initial period of the plant's operation, 445 which confirms the observation that the kind of filling of beds plays an important role in the 446 process of total phosphorus elimination. A useful tool to compare the efficiency of pollutant 447 removal in different facilities or in different units of the same system is the mass removal rate 448 (MRR), which provides a measure of the amount of a component removed per unit area of 449 a constructed wetland systems. Table 3 presents theoretical indicators of main pollutants mass 450 removal (according to formula 2) in each bed and in the whole VF-HF system of the sewage 451 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 452 453 equal to the inflow. In fact, these quantities may vary more or less, which is primarily due to 454 evapotranspiration and precipitation (Chazarenc et al., 2003; 2010). The evapotranspiration 455 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 456 457 natural bog systems with common reed in northern Germany, in the full vegetation period, it may exceed 10 mm·d⁻¹, but in other periods (from November to April) it approaches zero. 458 459 These researchers also found that under certain conditions (cloudy and rainy weather) the

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460 efficiency of evapotranspiration during the year may be similar or even lower than the total 461 precipitation. Also Chazarenc et al. (2003) in the research conducted on the HF field of the 462 multi-stage constructed wetland confirmed the possibility of maintaining balance of beds 463 evapotranspiration by precipitation. In the case of the analyzed sewage treatment plant, 464 factors limiting the efficiency of evapotranspiration could be the proximity of high plants at 465 the south-western side, which cause periodic shading of beds and reduce air movement. 466 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 467 468 conditions, is clearly lower than on the beds with common reed.

469 Despite the lower than planned hydraulic load, the pollution load in the investigated system 470 was comparable to those found in other constructed wetlands tested in Poland (Gajewska and 471 Obarska-Pempkowiak, 2011). The MRR mass removal ratios of organic pollutants were 472 relatively high, similar to those recorded in two- and three-stage constructed wetland systems, 473 described by Gajewska and Obarska-Pempkowiak (2011).

474 Similarly, in the case of total nitrogen, the MRR value did not differ significantly from the
475 values determined for other plants (Gajewska and Obarska-Pempkowiak, 2011; Brix et al.,
476 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).

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Table 3. Mass removal rates of BOD₅, COD, total nitrogen (TN) and total phosphorus (TP)

Paramete	ers	VF	HF	VF-HF
ROD	Load $[g \cdot m^{-2} \cdot d^{-1}]$	6.71	0.27	3.66
BOD_5	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
COD -	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
111	Mass Removal Rate $[g \cdot m^{-2} \cdot d^{-1}]$	0.93	0.39	0.68
тр	Load $[g \cdot m^{-2} \cdot d^{-1}]$	0.26	0.18	0.14
11	Mass Removal Rate [g·m ⁻² ·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

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487 conditions for the activity of microorganisms and the course of biochemical processes in the 488 bed (Langergraber, 2005; Wu et al., 2013 a, b). This is confirmed by the research carried out 489 on the treatment plant in Skorczyce, including the lack of seasonal variability of treatment 490 effects, mainly organic pollutants. In the case of the VF bed and the entire VF-HF system, the 491 average removal effects were constant during the whole year (Figure 7). Higher variability 492 was found on the HF field, however, it is difficult to relate this to seasonal conditions, because 493 the average efficiency of BOD₅ decreasing was the highest in autumn and winter. Most researchers point to the reverse regularity (Zhao et al., 2011; Saeed and Sun, 2012), although 494 495 some studies did not show differences between the removal of these compounds in the 496 summer and winter (Bulc, 2006). The lack of a clear influence of seasonal conditions on 497 microbial removal processes can be associated with the dominance of physical processes. In 498 addition, Plamondon et al. (2006) suggested that the factor that balances the dependence of 499 kinetics on biological reactions on temperature in a cooler climate can be favorable oxygen 500 conditions.

501 The average efficiency of nitrogen and phosphorus removal from wastewater was slightly 502 higher in August and November. However, the share of plants in the uptake of pollutants from 503 sewage, expressed as nitrogen and phosphorus content in biomass was relatively small. The 504 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 505 the limits of 3.55-4.43 kg DM·m⁻² and was clearly higher than the yields recorded in field 506 507 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), 508 approximately 2.5 kg of nitrogen were accumulated in the biomass. At the content of 509 phosphorus – 0.26 g·kg DM⁻¹ its mass accumulated in aboveground parts of giant miscanthus 510 511 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 $DM \cdot m^{-2}$ in 2013 to 1.43 kg $DM \cdot m^{-2}$ 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.

523 In the years which were most favorable in terms of yield of giant miscanthus and 524 Jerusalem artichoke (2015 and 2016), the share of nitrogen accumulated in the biomass of 525 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 526 527 plant activity associated with biomass production is limited to the growing season (in south-528 eastern Poland it usually lasts from April to September), it can be concluded that real 529 contribution of the plants to nutrient removal by uptake was higher and exceeded 10% in the 530 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).

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537 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 (BOD₅, COD, TSS, total nitrogen, total phosphorus) in the wastewater discharged from the VF-HF constructed wetland system to the receiver.

547 The null hypothesis was confirmed. The results of the Hollander-Proschan goodness-of-fit548 test along with the estimated parameters, are presented in Table 4.

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

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Parameter	Parameter	rs of Weibull dis	tribution	Hollander	-Proschan
				goodness-	-of-fit test
-	heta	С	b	stat	р
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

goodness-of-fit test

Symbols: stat – value of the test statistic, p – significance level of the test; when $p \le 0.05$ 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 mgO₂·dm⁻³, respectively). This

leads to the conclusion that, with an operator risk of $\alpha = 0.05$, 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).



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determined for each pollution parameter Notation: dashed red line – reliability function, <u>continuous red line – confidence intervals</u>,

Fig. 86. Weibull cumulative distribution functions and the technological reliabilities

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 $5 \text{ mg} \cdot \text{dm}^{-3}$ 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.

598 The reliability levels obtained indicate that the hybrid constructed wetland with giant 599 miscanthus and Jerusalem artichoke performed very well in terms of organic pollutant 600 removal. The facility guaranteed stable low BOD₅ and COD results for the treated wastewater, 601 which meant it was highly likely to be positively evaluated in the case of an inspection. These 602 conclusions are consistent with the reports of other authors, which indicate that hybrid 603 systems are very reliable with respect to BOD₅ and COD reduction (Jucherski et al., 2017; 604 Jóźwiakowski, 2012). At the same time, the reliability of the tested VF-HF system was higher 605 than that of single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et 606 al., 2017) or other small sewage treatment plants using other technological solutions. For 607 comparison, the organic pollutant removal reliabilities (expressed as BOD₅ and COD) of 608 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).

611 The reliabilities of removal of nutrient contaminants (nitrogen and phosphorus) for the 612 tested facility were 32 and 28%, respectively, which indicates that treated wastewater was 613 highly likely to contain excessive nitrogen and total phosphorus concentrations. Therefore, the 614 performance of the system was not satisfactory in this respect. Tests carried out in other 615 facilities show that similar or higher levels of nutrient removal reliability are reached in 616 single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et al., 2018). 617 Jucherski et al. (2017) reported that the reliabilities of nitrogen and phosphorus removal in the 618 hybrid constructed wetland they studied were significantly higher at 76.8% for total nitrogen 619 and 95.2% for total phosphorus. It should be noted, however, that the normative values for 620 nitrogen and total phosphorus used in reliability assessment refer only to specific cases when 621 treated wastewater is discharged to lakes and their tributaries and directly to artificial water 622 reservoirs situated in flowing waters (Regulation of the Minister of the Environment, 2014). 623 Moreover, according to the Polish law, there is no obligation to control the operation of 624 domestic sewage treatment plants or to perform quality tests of sewage discharged to the 625 environment. In this light, the assessment of nutrient removal reliability of domestic treatment 626 plants is a theoretical issue, which does not mean that it should not become a common part of 627 wastewater management practice in the future. In combination with an analysis of the 628 effectiveness of wastewater treatment, the assessment of the pollutant removal reliability of 629 wastewater treatment plants allows to determine what technological solutions should be 630 promoted when building sewage systems in rural areas to support water protection against 631 pollution and eutrophication. The use of highly efficient and reliable wastewater treatment 632 systems can reduce the use of the cheapest solutions, which instead of protecting the 633 environment pose a potential threat to it. According to the emerging suggestions, it also seems 634 necessary to create administrative and legal instruments in Poland which would enable control 635 of all sewage treatment plants, regardless of their size and type of receiver (Jóźwiakowski et 636 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.

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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 (BOD₅ 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

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676 constructed wetland systems, and, owing to their high biomass production potential, they can677 also be exploited as energy yielding materials.

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1 The efficiency and reliability of pollutant removal in a hybrid constructed

2 wetland with giant miscanthus and Jerusalem artichoke in Poland

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13 ABSTRACT

14 In this paper, we analysed the pollutant removal efficiency and reliability of a vertical and 15 horizontal flow hybrid constructed wetland (CW) planted with giant miscanthus and 16 Jerusalem artichoke. The wastewater treatment plant, located in south-eastern Poland, treated domestic sewage at an average flow rate of 1.2 m³·d⁻¹. The tests were carried out during 17 5-years of operation of the sewage treatment plant (2011–2016). During this period, sewage 18 samples were collected from three stages of wastewater treatment in four seasons (winter -19 20 February, spring – May, summer – August, and autumn – November). The following 21 parameters were measured: BOD₅, COD, total suspended solids, total nitrogen, and total 22 phosphorus. The average effectiveness of organic pollutant removal expressed by BOD₅ and 23 COD was 98.8 and 97.6%, respectively, and the removal efficiency for total suspended solids 24 was 93%. The average values of BOD₅, COD, and total suspended solids in wastewater 25 discharged to the receiver were significantly lower than the limit values required in Poland. 26 The efficiency of total nitrogen and total phosphorus removal was 64.1 and 68.1%, 27 respectively, and the average values of these components in the outflow from the treatment 28 plant exceeded the standard levels. A reliability analysis performed using the Weibull 29 probability model showed that the reliability of pollutant removal in the tested CW system 30 was very high for BOD₅ and COD (100%). It was also demonstrated that the tested CW did 31 not provide effective elimination of biogenic elements (nitrogen and phosphorus), as 32 evidenced by the low reliability values -32 and 28%, respectively. The investigated hybrid 33 CW system with giant miscanthus and Jerusalem artichoke removed organic and biogenic 34 pollutants with a similar efficiency as systems using classic plant species such as reed and 35 willow.

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37 Key words: wastewater treatment, hybrid constructed wetlands, vertical flow, horizontal

38 flow, pollutant removal, efficiency and reliability

40 **1. Introduction**

41 Domestic wastewater treatment plants are an optimal solution for the disposal of small 42 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; 43 44 Jóźwiakowski et al., 2015). Issues related to the operational reliability of low capacity 45 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 46 47 treatment plants and their control during operation. Such a situation is not conducive to the 48 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 49 50 untreated wastewater into the ground, and therefore, their application for waste water 51 treatment raises serious questions (Jóźwiakowski et al., 2015, Zhang et al., 2015). Moreover, 52 many solutions applied in small sewage treatment plants, including those based on 53 conventional methods, in conditions of high variability of hydraulic load, pollution load and 54 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 55 56 applied, the risk of their negative impact on water quality increases (Bugajski, 2014; Pawełek 57 and Bugajski, 2017).

58 Therefore, the reliability of small sewage treatment plants should be an important criterion 59 in planning the development of technical infrastructure in rural areas, which will enable the 60 selection of optimal and environmentally safe solutions (Jóźwiakowski et al., 2015; Jucherski 61 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 62 63 same time, the popularity of constructed wetland systems, which can be used in various 64 conditions, including protected areas and areas of high landscape value, is increasing due to 65 their high pollutant removal efficiency (Vymazal, 2011; 2013; Jóźwiakowski, 2012; Paruch et al., 2011; Jóźwiakowski et al., 2017; Gajewska et al., 2015). 66

67 Constructed wetlands, and in particular hybrid treatment plants consisting of at least two 68 beds with different sewage flows (vertical and horizontal), ensure effective removal of organic 69 matter (BOD₅ and COD) (Vymazal, 2011) and slightly less effective removal of nutrients 70 (Kadlec and Wallace, 2008; Vymazal and Kropfelova, 2008). The removal of contaminants in 71 constructed wetland systems is related to the functioning of the biological membrane formed 72 during the flow of wastewater through the material filling the beds. The plants growing in the 73 wetland support the process of treatment (Vymazal, 2013; Foladori et al., 2012; Vymazal and 74 Březinová, 2014; Wu et al., 2015). The rhizosphere produces an oxygenated microenvironment, while other layers of the bed provide anaerobic or anoxic conditions. 75 76 Roots and rhizomes of plants increase the hydraulic permeability of the soil and loosen its 77 structure (Birkedal et al., 1993). Until now, depending on the climatic conditions, different 78 plant species have been used in constructed wetland systems, mainly common reed and 79 willow (Vymazal, 2011; Jóźwiakowski, 2012). These plants are characterized by quite 80 intensive growth, even on a very poor substrate (Gruenewald et al., 2007), hence the 81 possibility of using constructed wetland systems not only for wastewater treatment, but also 82 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 83 84 Jerusalem artichoke, in constructed wetland systems may be of interest (Gizińska-Górna et al., 85 2016). The high energy potential of these plants is a result of high yield and biomass calorific 86 value, which depends on its chemical composition (Bridgwater and Peacocke, 2000; Bellamy 87 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 88 artichoke from 9 to 25 Mg DM·ha⁻¹ (Baldini et al., 2004; Gunnarsson et al., 2014). The 89 calorific value of dried biomass of giant miscanthus varies from 14 to 17 MJ·kg DM⁻¹, and for 90 Jerusalem artichoke varies from 15 to 19 MJ·kg DM⁻¹ (Szulczewski et al., 2018; 91 92 Gizińska-Górna et al., 2016). The possibilities of their use in wastewater treatment are less 93 recognized, especially in moderate climate conditions. Jerusalem artichoke has not been used 94 in constructed wetland systems yet, while research on the use giant miscanthus has been 95 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 96 97 those found in the case of classical plant species, including common reed (Toscano et al., 98 2015; Barbagallo et al., 2014).

99 The aim of the present study is to analyse the reliability and effectiveness of pollutant 100 removal in a hybrid constructed wetland wastewater treatment plant with giant miscanthus 101 (*Miscanthus giganteus x* Greef et Deu) and Jerusalem artichoke (*Helianthus tuberosus L.*) 102 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

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108 2011 and its planned capacity is $2.5 \text{ m}^3 \cdot \text{d}^{-1}$. In the analyzed system, sewage from the building 109 was drained into a three-chamber preliminary settling tank, where it was pre-treated in 110 physical and biological processes.

The tank is made of concrete, and its active capacity is 8.64 m³. In the next stage, the 111 sewage flows through a system of two VF-HF type soil and plant beds (biological treatment). 112 A first bed, with vertical sewage flow (VF), has an area of 96 m^2 and a depth of 0.8 m. and the 113 second bed, with horizontal sewage flow (HF), has an area of 80 m^2 and a depth of 1.2 m. The 114 beds have been isolated from the native soil by a PEHD waterproofing geomembrane of 1 mm 115 116 thickness. The VF bed was filled with a layer of sand (1-2 mm) with a height of about 0.8 m. 117 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 118 119 construction of the sewage treatment plant (Figures 1, 2). The first bed was planted with giant 120 miscanthus (Miscanthus x giganteus Greef et Deu.), the second with Jerusalem artichoke 121 (Helianthus tuberosus L.) (Photo 1). Every year, after the winter season, the aboveground 122 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). 123





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

136 During the study period, the amount of wastewater discharged to the treatment plant 137 represented only about half of the design value, as the actual number of inhabitants served by 138 the plant had decreased since its construction. The amount of sewage inflow to the treatment 139 plant was determined on the basis of water meters readings in the building and average water 140 consumption. In addition, the amount of sewage introduced into the VF-HF system was 141 measured by using a flow meter installed on the discharge pipe between the preliminary 142 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 143 wastewater was pumped into the first bed (VF) twice a day, about 0.6 m³ each time, and then 144 145 it flowed gravitationally to the second bed (HF), and finally to the receiver. At the outflow 146 from the HF bed a tilting pipe was installed, which allowed to raise the level of sewage in this 147 field during summer. Theoretical wastewater retention time was determined on the basis of the 148 parameters of the beds (horizontal dimensions, porosity of the material used to fill the bed, the 149 height of the layer filled with sewage) and average daily wastewater inflow (Conley et al., 150 1991) and for the VF bed it was 4.8 d. Thanks to the use of a tilting pipe behind the HF bed, 151 the wastewater retention time in this bed was about 21.2 d in the vegetation period and 10.6 d 152 in the winter period.

154 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

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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.

162 The samples were analysed to determine pH, dissolved oxygen, ammonium nitrogen, 163 nitrate and nitrite nitrogen, total nitrogen, total phosphorus, total suspended solids (TSS), 164 biochemical oxygen demand (BOD₅) and chemical oxygen demand (COD). The concentration 165 of dissolved oxygen and the pH were determined using a WTW Multi 340i meter. Nitrate and 166 nitrite nitrogen were determined with a Slandi LF 300 photometer, and ammonium nitrogen 167 was measured with a PC Spectro spectrophotometer from AQUALYTIC. This latter 168 instrument was also used to determine total nitrogen after oxidation of the samples in a 169 thermoreactor at 100°C. Total phosphorus was determined with WTW's MPM 2010 170 spectrophotometer after oxidation of the samples at 120°C. BOD₅ was measured by the 171 dilution method using WTW Multi 340i, and COD was estimated by the same method with a 172 WTW MPM 2010 spectrophotometer after oxidation at 148°C. Total suspended solids were 173 determined by filtration through paper filters. Sampling, transport and processing of the 174 samples and their analysis were carried out in accordance with Polish standards (PN-74/C-175 04620/00; PN-EN 25667-2; PN-EN 1899-1:2002; PN-ISO 15705:2005; PN-EN ISO 176 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 m². 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.

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193 On the basis of the average values of the pollution parameters in the incoming (C_{in}) and 194 outgoing (C_{out}) wastewater, the average pollutant removal efficiency was calculated according 195 to equation 1:

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

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):

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

where: A – surface area of the constructed wetland system [m²], Q_{in} and Q_{out} – average inflow and outflow of wastewater [m³·d⁻¹], C_{in} and C_{out} – average concentrations of pollutants in the wastewater flowing into and out of the system [g·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 (BOD₅, 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:

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

214 where: x - a variable describing the concentration of a pollution parameter in the treated 215 effluent, b – scale parameter, c – shape parameter, θ – position parameter.

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

217 The reliability analysis was based on the estimation of Weibull distribution parameters 218 using the method of highest reliability. The null hypothesis that the analyzed variable could be 219 described by the Weibull distribution was verified with the Hollander-Proschan test at the 220 significance level of 0.05% (Bugajski et al., 2012). The values of basic pollution parameters 221 in treated wastewater discharged to the receiver were analysed. Reliability was determined 222 from the distribution figures, taking into account the normative values of the parameters 223 specified in the Regulation of the Minister of the Environment (2014) for wastewater discharged from treatment plants of less than 2000 p.e.: BOD₅ - 40 mgO₂·dm⁻³, COD -224

150 mgO₂·dm⁻³, total suspended solids - 50 mg·dm⁻³, total nitrogen - 30 mg·dm⁻³, and total phosphorus - 5 mg·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.

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231 **3. Results and discussion**

232 **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.

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241 **Pollutant concentrations in sewage flowing into the treatment plant**

242 The average values of pollution indicators in raw sewage outflowing from the building to the preliminary settling tank were respectively: 704 mgO₂·dm⁻³ for BOD₅, 1486 mgO₂·dm⁻³ 243 for COD, 710 mg·dm⁻³ for total suspended solids, 172 mg·dm⁻³ for total nitrogen and 23.5 244 $mg \cdot dm^{-3}$ for total phosphorus (Table 1). These values were clearly higher than those reported 245 246 in typical domestic wastewater (Heidrich et al., 2008; Bugajski and Bergel, 2008). This may 247 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 248 249 facilities and the need for economical water management, its unit consumption in the building 250 was at a low level, which could result in an increase in the concentration of pollutants in the 251 sewage. In the preliminary settling tank, mainly solid fractions were removed. As a result of 252 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 BOD₅ (by 23%) 253 254 and COD (by 12%) as well as total nitrogen (by 9%) and total phosphorus (by 11%). 255 Nevertheless, the concentration of pollutants in the sewage outflowing from the settling tank 256 to the system of VF-HF beds was high. The average values of these parameters at this stage of treatment were: 537 mgO₂·dm⁻³ for BOD₅, 1309 mgO₂·dm⁻³ for COD, 297 mg·dm⁻³ for total 257 suspended solids, 157 mg·dm⁻³ for total nitrogen, and 21.0 mg·dm⁻³ for total phosphorus 258

259 (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 \cdot dm⁻³. The average 260 contents of ammonium nitrogen, nitrate nitrogen, and nitrite nitrogen in mechanically treated 261 wastewater were 136 mg·dm⁻³, 2.87 mg·dm⁻³, and 0.23 mg·dm⁻³, respectively. The recorded 262 values were significantly higher than those reported in the literature for mechanically treated 263 264 wastewater from single-family buildings (Jucherski et al., 2017; Jóźwiakowski et al., 2017; 265 Jóźwiakowski et al., 2018; Bugajski and Bergel, 2008). This was associated with low water 266 consumption, leading to the formation of highly concentrated wastewater.

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

Donomotoro				Stat	tistic		
Farameters		Average	Median	Min	Max	SD	Cv
D: 1 1	S 0	0.35	0.22	0.08	1.19	0.31	89.51
Dissolved oxygen [mgO ₂ ·dm ⁻³]	S 1	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
	S 3	5.58	5.55	1.27	11.42	2.69	48.24
	S 0	7.26	7.29	6.50	7.89	0,44	6.04
ъU	S 1	7.17	7.13	6.67	7.94	0.29	4.06
рН	S2	7.10	7.08	6.68	7.55	0.24	3.37
	S 3	7.47	7.42	6.93	8.70	0.49	6.51
	S 0	704.0	690.5	376.0	1262.0	202.9	28.82
BOD ₅	S 1	537.0	471.0	310.0	862.0	172.4	32.10
$[mgO_2 \cdot dm^{-3}]$	S2	18.2	16.3	1.8	58.0	15.1	82.60
	S 3	6.6	3.1	0.1	36.9	9.1	137.40
	S 0	1486.9	1485.0	990.0	1920.0	249.8	16.80
COD	S 1	1309.0	1295.0	910.0	1740.0	237.4	18.08
$[mgO_2 \cdot dm^{-3}]$	S2	68.4	52.0	11.0	170.0	43.4	63.52
	S 3	31.8	29.0	8.0	81.0	20.3	63.83
	S 0	710.9	523.2	136.0	2052.0	520.4	73.20
TSS	S 1	297.0	235.0	60.0	1390.0	284.7	95.67
[mgO ₂ ·dm ⁻³] pH BOD ₅ [mgO ₂ ·dm ⁻³] COD [mgO ₂ ·dm ⁻³] TSS [mg·dm ⁻³] Total nitrogen [mg·dm ⁻³] Ammonium nitrogen [mg·dm ⁻³] Nitrate nitrogen [mg·dm ⁻³]	S2	39.0	28.5	1.9	114.0	31.1	79.77
	S 3	18.0	10.2	1.8	65.1	20.2	112.45
	S 0	172.3	171.0	114.0	238.0	32.2	18.70
Total nitrogen	S 1	157.0	150.5	120.0	216.0	22.7	14.45
[mg·dm ⁻³]	S 2	82.4	83.0	34.0	134.0	25.1	30.42
	S 3	56.4	39.0	10.0	150.0	43.7	77.46
	S 0	147.2	139.5	47.0	230.0	42.7	29.02
Ammonium	S 1	136.0	134.5	43.0	204.0	31.3	23.06
[mg·dm ⁻³]	S2	21.3	18.2	1.6	65.2	18.7	87.77
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	0.1	47.1	16.4	127.44			
	S 0	2.11	0.99	0.03	17.11	3.64	172.89
Nitrate nitrogen	S 1	2.87	0.86	0.28	29.67	6.47	225.24
[mg·dm ⁻³]	S2	24.48	24.96	2.71	57.70	16.07	65.65
-	S 3	20.25	13.48	0.86	58.20	19.89	98.22

	S 0	0.28	0.270	0.08	0.471	0.15	55.07
Nitrite nitrogen	S 1	0.23	0.19	0.08	0.43	0.13	56.71
[mg·dm ⁻³]	S 2	1.03	0.73	0.06	4.04	1.02	98.99
	S 3	0.50	0.13	0.03	3.62	1.00	198.99
	S 0	23.5	23.1	15.3	30.2	4.6	19.69
	S 1	21.0	21.1	17.2	23.9	1.9	8.89
[mg·dm ⁻³]	S2	12.0	11.6	8.5	21.0	3.0	24.83
	S 3	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 272 273 concentrations, grouped in different ranges. BOD₅ in the wastewater flowing into the hybrid VF-HF system did not fall below 300 mgO₂·dm⁻³ across measurements. The most common 274 values were in the range of $300-400 \text{ mgO}_2 \cdot \text{dm}^{-3}$ (30% of cases), 400-500 and 700-800 275 $mgO_2 \cdot dm^{-3}$ (25% each), and 500–600 $mgO_2 \cdot dm^{-3}$ (10%). The COD values were very high and 276 277 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 278 $mgO_2 \cdot dm^{-3}$ (Figure 3). Differentiation of COD values in mechanically treated sewage could be 279 280 the result of variability in the composition of raw sewage and also the operation of the settling 281 tank. Lower COD values were recorded during the tank's working phase, when the 282 sedimentation process played a major role. A similar effect could occur after each removing of 283 scum and some part of sludge from the tank, which was one of the operating works. In other 284 periods, sludge fermentation could have caused sludge flotation, decreased the sedimentation 285 effect and increased the concentration of pollutants in sewage flowing out from the settling 286 tank.





Fig. 3. Frequency histogram of influent parameter values (BOD₅, COD, TSS, total nitrogen, total phosphorus)

As a rule, total suspended solids did not exceed 400 mg \cdot 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/BOD₅, BOD₅/TN, and BOD₅/TP. It was found that the wastewater flowing into the tested VF-HF hybrid system was characterized by unfavourable COD/BOD₅ (2.4) and BOD₅/TN (3.0) ratios; the BOD₅/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

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BOD ₅ /TP	≥25	25.6
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309 Pollutant concentrations in the effluent from the VF bed

After treatment of the wastewater in the VF bed , the average BOD₅ and COD values were 310 18 mgO₂·dm⁻³ and 68.4 mgO₂·dm⁻³, respectively. The average concentration of total 311 suspended solids was 39.0 mg·dm⁻³, total phosphorus 12.0 mg·dm⁻³, total nitrogen 312 313 82.4 mg·dm⁻³. The average values of BOD₅, COD, and total suspended solids in wastewater treated in the VF bed met the requirements specified in the Regulation of the Minister of 314 315 Environment (2014) for wastewater discharged to waters or to the ground from treatment 316 plants above 2000 p.e. (Figure 4). These results indicate that the VF bed provided favourable 317 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⁻³ 318 compared to the mechanically treated wastewater, while the average concentration of 319 ammonia nitrogen slightly exceeded 20 mg·dm⁻³. The total nitrogen balance in the VF bed 320 indicates the existence of processes leading to the permanent removal of this component from 321 322 the wastewater, including, mainly, the process of denitrification and uptake by vegetation. 323 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 324 nitrogen suggests that a significant part of ammonia nitrogen after transformation to the 325 326 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). 327 328 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 329 330 were more than twice as high as the level stipulated by the law as acceptable for treatment 331 plants up to 2000 p.e. discharging sewage into standing waters (Regulation of the Minister of 332 the Environment, 2014).

334 Pollutant concentrations in the effluent from the HF bed

An HF bed in a hybrid system is designed to optimise total nitrogen and organic 336 compounds removal in anaerobic and oxidised conditions (Vymazal, 2007; Saeed and Sun, 337 2012). The average concentrations of BOD₅, 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 338 18.0 mg·dm⁻³, respectively (Table 1). The respective median values were 3.1, 29.0, and 339 10.2 mg·dm⁻³. These values were significantly lower than the limit values stipulated in the

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341 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, 342 343 respectively) did not meet the above requirements (Figure 4). The average value of total 344 nitrogen in treated wastewater was most strongly affected by the results collected during the 345 initial period of operation of the plant (about 18 months), when the vegetation was not yet 346 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 347 348 parameters of wastewater outflowing from the VF-HF system. Because the concentrations of 349 contaminants in the effluent were low, the results may have been much more strongly 350 influenced by environmental factors, precipitation and temperature, or random changes in 351 operating conditions compared with the results for S1 and S2.



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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)

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3.2. Pollutant removal efficiency

363 The results indicate that the investigated CW had a high efficiency of removal of organic 364 pollutants and total suspended solids, and a lower efficiency of elimination of biogenic 365 compounds (total nitrogen and total phosphorus). The differences between the various stages 366 of treatment were clear-cut. The largest proportion of the investigated pollutants were 367 eliminated in the VF bed. This bed provided favourable conditions for the biodegradation of 368 organic pollutants and moderately good conditions for the removal of biogenic pollutants. 369 Several factors may have been of significance here, including the way the bed was fed with 370 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 371 bed (an average of 12.5 mm $\cdot d^{-1}$) ensured optimal time of contact of sewage with the 372 microorganisms forming the biological membrane on the filling material (Saeed and Sun, 373 374 2012). In addition, cyclic feeding of wastewater to the bed and alternating dry and wet 375 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 376 377 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 BOD₅ and 97.6% for COD (Figure 5). The effects of BOD₅ and COD removal were similar to or higher than those recorded by other authors in hybrid constructed wetland systems operating under similar climatic conditions

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

The largest part of the pollution load was eliminated in the first stage of treatment in the 384 385 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 386 387 amounted to 6.7 g·m⁻²·d⁻¹ (BOD₅) and 16.4 g·m⁻²·d⁻¹ (COD), respectively. Moreover, the wastewater flowing into the VF bed was characterised by an unfavourable BOD₅/COD ratio 388 389 (2.4), which testified to the lower susceptibility of the tested wastewater to biological 390 decomposition. Despite this, nearly 97% of BOD₅ and 95% COD were removed from the VF 391 bed, which is a very good result. The system under investigation was rather insensitive to the 392 high concentrations of organic compounds and their degradability. Caselles-Osorio and Garcia 393 (2006) observed a similar relationship in their studies. Research carried out under similar 394 climatic conditions has shown that the removal efficiency of VF reservoirs with regard to 395 BOD₅ is in the range of 86–98% (Obarska-Pempkowiak et al., 2010; Gajewska et al., 2011; 396 Vymazal, 2010). On the other hand, the efficiency of COD reduction in VF beds, according to 397 various authors, may vary from 79 to 94% (Obarska-Pempkowiak, 2009; Sharma et al., 2010; 398 Masi and Martinuzzi, 2007).



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

In the HF bed, the elimination of organic pollutants (BOD₅ 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.

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406 The average efficiency of removal of total suspended solids in the analysed system was 407 94%. The VF bed removed nearly 87% of total suspended solids, while the HF bed removed 408 54% of the solids. The efficiency of the tested system in removing total suspended solids was 409 higher than demonstrated by other authors. For comparison, a HF-VF system investigated by 410 Masi and Martinuzzi (2007) had a total suspended solids removal efficiency of 84% a result 411 that was identical to that obtained by Krzanowski et al. (2005). Hybrid systems analysed by 412 Gajewska and Obarska-Pempkowiak (2009) reached an average total suspended solids 413 removal efficiency of 89%.

414 The average total nitrogen removal efficiency for the analysed hybrid system was 64.1%, 415 with 47.5% of nitrogen removed in the VF bed and 31.6% in the HF bed. According to 416 Gajewska and Obarska-Pempkowiak (2011), the efficiency of total nitrogen removal in hybrid 417 constructed wetland systems may range from 23 to 80%, depending on the configuration and 418 operating conditions of the beds. In the light of these reports, the effectiveness of the facility 419 tested in this present study was moderately high, but not high enough to obtain stable results 420 at the outflow that would meet the requirements set out in the Polish regulations (Regulation 421 of the Minister of the Environment, 2014). The incomplete removal of nitrogen may have 422 been caused by a lack of appropriate conditions for effective denitrification in the HF bed, 423 especially the deficit of organic compounds and the unfavourable BOD₅/TN ratio inhibiting 424 the denitrification process, or thermal conditions (Vymazal, 2010). The analysis of 425 meteorological conditions in the area of the conducted research (meteorological station in 426 Radawiec near Lublin) showed that the significance of this last factor could have been 427 smaller. Against the background of some long-term data, there can be observed a tendency of 428 increasing the average air temperature (Figure 6). Throughout the entire research period 429 (2011-2016) average annual temperatures were higher than the long-term average 430 (1970-2000) by 0.7–2.0°C. In the six-month period covering the growing season (from April 431 to September) the average differences ranged from 1.0 to 1.8°C, in the remaining period (from 432 October to March) - from 0.4 to 2.5°C (IMWM 2011-2016; CSO, 2017). On this basis, it can 433 be concluded that, apart from periods that are considered to be unfavorable in a moderate 434 climate (December-February) temperature should not be a limiting factor for microbial 435 removal processes.





440 The efficiency of total phosphorus removal for the whole VF-HF system was 68.1%. The 441 two beds had similar average phosphorus removal rates, in the range of 42–45%. To compare, 442 the average total phosphorus removal efficiencies for hybrid CW systems studied by other 443 authors range from 70 to 89% (Krzanowski et al., 2005; Sharma et al., 2010). In our study, the 444 highest phosphorus removal rates were found in the initial period of the plant's operation, 445 which confirms the observation that the kind of filling of beds plays an important role in the 446 process of total phosphorus elimination. A useful tool to compare the efficiency of pollutant 447 removal in different facilities or in different units of the same system is the mass removal rate 448 (MRR), which provides a measure of the amount of a component removed per unit area of 449 a constructed wetland systems. Table 3 presents theoretical indicators of main pollutants mass 450 removal (according to formula 2) in each bed and in the whole VF-HF system of the sewage 451 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 452 453 equal to the inflow. In fact, these quantities may vary more or less, which is primarily due to 454 evapotranspiration and precipitation (Chazarenc et al., 2003; 2010). The evapotranspiration 455 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 456 457 natural bog systems with common reed in northern Germany, in the full vegetation period, it may exceed 10 mm·d⁻¹, but in other periods (from November to April) it approaches zero. 458 459 These researchers also found that under certain conditions (cloudy and rainy weather) the

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460 efficiency of evapotranspiration during the year may be similar or even lower than the total 461 precipitation. Also Chazarenc et al. (2003) in the research conducted on the HF field of the 462 multi-stage constructed wetland confirmed the possibility of maintaining balance of beds 463 evapotranspiration by precipitation. In the case of the analyzed sewage treatment plant, 464 factors limiting the efficiency of evapotranspiration could be the proximity of high plants at 465 the south-western side, which cause periodic shading of beds and reduce air movement. 466 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 467 468 conditions, is clearly lower than on the beds with common reed.

469 Despite the lower than planned hydraulic load, the pollution load in the investigated system 470 was comparable to those found in other constructed wetlands tested in Poland (Gajewska and 471 Obarska-Pempkowiak, 2011). The MRR mass removal ratios of organic pollutants were 472 relatively high, similar to those recorded in two- and three-stage constructed wetland systems, 473 described by Gajewska and Obarska-Pempkowiak (2011).

474 Similarly, in the case of total nitrogen, the MRR value did not differ significantly from the
475 values determined for other plants (Gajewska and Obarska-Pempkowiak, 2011; Brix et al.,
476 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).

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Table 3. Mass removal rates of BOD₅, 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·m ⁻² ·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

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487 conditions for the activity of microorganisms and the course of biochemical processes in the 488 bed (Langergraber, 2005; Wu et al., 2013 a, b). This is confirmed by the research carried out 489 on the treatment plant in Skorczyce, including the lack of seasonal variability of treatment 490 effects, mainly organic pollutants. In the case of the VF bed and the entire VF-HF system, the 491 average removal effects were constant during the whole year (Figure 7). Higher variability 492 was found on the HF field, however, it is difficult to relate this to seasonal conditions, because 493 the average efficiency of BOD₅ decreasing was the highest in autumn and winter. Most researchers point to the reverse regularity (Zhao et al., 2011; Saeed and Sun, 2012), although 494 495 some studies did not show differences between the removal of these compounds in the 496 summer and winter (Bulc, 2006). The lack of a clear influence of seasonal conditions on 497 microbial removal processes can be associated with the dominance of physical processes. In 498 addition, Plamondon et al. (2006) suggested that the factor that balances the dependence of 499 kinetics on biological reactions on temperature in a cooler climate can be favorable oxygen 500 conditions.

501 The average efficiency of nitrogen and phosphorus removal from wastewater was slightly 502 higher in August and November. However, the share of plants in the uptake of pollutants from 503 sewage, expressed as nitrogen and phosphorus content in biomass was relatively small. The 504 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 505 the limits of 3.55-4.43 kg DM·m⁻² and was clearly higher than the yields recorded in field 506 507 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), 508 approximately 2.5 kg of nitrogen were accumulated in the biomass. At the content of 509 phosphorus – 0.26 g·kg DM⁻¹ its mass accumulated in aboveground parts of giant miscanthus 510 511 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 $DM \cdot m^{-2}$ in 2013 to 1.43 kg $DM \cdot m^{-2}$ 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.

523 In the years which were most favorable in terms of yield of giant miscanthus and 524 Jerusalem artichoke (2015 and 2016), the share of nitrogen accumulated in the biomass of 525 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 526 527 plant activity associated with biomass production is limited to the growing season (in south-528 eastern Poland it usually lasts from April to September), it can be concluded that real 529 contribution of the plants to nutrient removal by uptake was higher and exceeded 10% in the 530 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).

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537 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 (BOD₅, COD, TSS, total nitrogen, total phosphorus) in the wastewater discharged from the VF-HF constructed wetland system to the receiver.

547 The null hypothesis was confirmed. The results of the Hollander-Proschan goodness-of-fit548 test along with the estimated parameters, are presented in Table 4.

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

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Parameter	Parameters of Weibull distribution			Hollander-Proschan	
			goodness-of-fit test		
-	heta	С	b	stat	р
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

goodness-of-fit test

Symbols: stat – value of the test statistic, p – significance level of the test; when $p \le 0.05$ 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 mgO₂·dm⁻³, respectively). This

leads to the conclusion that, with an operator risk of $\alpha = 0.05$, 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).



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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

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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.

593 An even lower level of reliability was found for total phosphorus removal. The probability 594 that the concentration of this parameter in treated wastewater would reach a value below 595 $5 \text{ mg} \cdot \text{dm}^{-3}$ was 28%. This means that the plant operated correctly for only 102 days a year, 596 and excessive concentrations of total phosphorus in treated wastewater were recorded on 597 254 days a year.

598 The reliability levels obtained indicate that the hybrid constructed wetland with giant 599 miscanthus and Jerusalem artichoke performed very well in terms of organic pollutant 600 removal. The facility guaranteed stable low BOD₅ and COD results for the treated wastewater, 601 which meant it was highly likely to be positively evaluated in the case of an inspection. These 602 conclusions are consistent with the reports of other authors, which indicate that hybrid 603 systems are very reliable with respect to BOD₅ and COD reduction (Jucherski et al., 2017; 604 Jóźwiakowski, 2012). At the same time, the reliability of the tested VF-HF system was higher 605 than that of single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et 606 al., 2017) or other small sewage treatment plants using other technological solutions. For 607 comparison, the organic pollutant removal reliabilities (expressed as BOD₅ and COD) of 608 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).

611 The reliabilities of removal of nutrient contaminants (nitrogen and phosphorus) for the 612 tested facility were 32 and 28%, respectively, which indicates that treated wastewater was 613 highly likely to contain excessive nitrogen and total phosphorus concentrations. Therefore, the 614 performance of the system was not satisfactory in this respect. Tests carried out in other 615 facilities show that similar or higher levels of nutrient removal reliability are reached in 616 single-stage constructed wetland systems (Jóźwiakowski, 2012; Jóźwiakowski et al., 2018). 617 Jucherski et al. (2017) reported that the reliabilities of nitrogen and phosphorus removal in the 618 hybrid constructed wetland they studied were significantly higher at 76.8% for total nitrogen 619 and 95.2% for total phosphorus. It should be noted, however, that the normative values for 620 nitrogen and total phosphorus used in reliability assessment refer only to specific cases when 621 treated wastewater is discharged to lakes and their tributaries and directly to artificial water 622 reservoirs situated in flowing waters (Regulation of the Minister of the Environment, 2014). 623 Moreover, according to the Polish law, there is no obligation to control the operation of 624 domestic sewage treatment plants or to perform quality tests of sewage discharged to the 625 environment. In this light, the assessment of nutrient removal reliability of domestic treatment 626 plants is a theoretical issue, which does not mean that it should not become a common part of 627 wastewater management practice in the future. In combination with an analysis of the 628 effectiveness of wastewater treatment, the assessment of the pollutant removal reliability of 629 wastewater treatment plants allows to determine what technological solutions should be 630 promoted when building sewage systems in rural areas to support water protection against 631 pollution and eutrophication. The use of highly efficient and reliable wastewater treatment 632 systems can reduce the use of the cheapest solutions, which instead of protecting the 633 environment pose a potential threat to it. According to the emerging suggestions, it also seems 634 necessary to create administrative and legal instruments in Poland which would enable control 635 of all sewage treatment plants, regardless of their size and type of receiver (Jóźwiakowski et 636 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.

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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 (BOD₅ 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

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676 constructed wetland systems, and, owing to their high biomass production potential, they can677 also be exploited as energy yielding materials.

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