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Reliability and efficiency of pollution removal during long-term operation of a one-stage constructed wetland system with horizontal flow

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a b s t r a c t

The paper presents the results of a study of the reliability and efficiency of pollutant removal during long term operation of a one-stage constructed wetland system with horizontal flow. The flow rate of the wastewater treatment plant was 1.2 $m^3\ d^{-1}$ during the research period. Physical and chemical analyses of raw wastewater and treated effluent were carried out in the years 1997–2010 (14 years). During this study period, 56 series of analyses were performed and 112 wastewater samples were collected. The average efficiencies of BOD_5 (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand) and TSS (Total Suspended Solids) removal in the investigated facility during the 14 years of its operation were respectively: 84.7%, 80.9%, and 62.4%. The average values of these parameters in the treated wastewater were significantly lower than the values deemed acceptable by relevant regulations in Poland. The reli-abilities of the wastewater treatment plant, based on the Weibull reliability theory for acceptable values of pollution parameters in the effluent of the treatment plant, were as follows: BOD_5 – 92%, COD – 98%, TSS – 90%. The conducted analysis showed that the operational reliability of the one-stage horizontal sub-surface flow constructed wetland (HSFCW) over the operation period was insufficient according to the Polish standards. Improvement of the reliability of the analyzed system by introduction of additional purification elements, such as irrigated biological beds or a constructed wetland with vertical wastewater flow, was recommended.

Keywords: Reliability, Pollution removal, Wastewater treatment, Constructed wetland, Horizontal flow

1. Introduction

Constructed wetlands (CWs) have been used for wastewater treatment in Poland for over 25 years [1] and for more than 60 years worldwide [2,3]. The first experiments on the viability of constructed wetland wastewater treatment systems were carried out in Germany in the second half of the 20th century by Seidel [4]. In her later works, Seidel [5] presented multi-stage wetland systems with vertical (VF-CWs) and horizontal flow (HF-CWs), in which she used filtering substrates of high hydraulic conductivities such as gravel, planted with macrophytes such as bulrush, iris, and cattail [6]. Another type of system, known as the Kickuth-type reed system, was developed by Kickuth [7,8], who used soil with a high clay content to fill a bed planted only with common reed (*Phragmites australis)* [6]. The results of the research done by Seidel [4,5] and Kickuth [7,8] led to large-scale introduction of constructed wetland systems in the 1980's in Denmark [9], Austria [10], and the United Kingdom [11]. In the 1990's, constructed wetland systems started to be built in the majority of European countries and around the world [12], including Poland [1,13,14]. Initially, single-stage systems with horizontal (and only occasionally with vertical) wastewater flow were used [12]. Those systems mostly employed the common reed *Phragmites australis*

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[6,15–17]. In the 1990's, the willow species *Salix viminalis* also began to be used [18–20]. It has been shown that such systems can be used not only for wastewater treatment, but also for production of biomass for energy generation purposes [21]. Initially, Horizontal Flow type (HF-type) beds were mostly filled with small-grain filtration material (0–4 mm). However, in the recent years, these systems have mostly utilized gravel (2–8 mm) or materials with 10–20 mm grain diameter [12].

HF-type beds have most commonly been used for the treatment of domestic and municipal wastewater [1,6,9,10,11,16,17,19,22]. Moreover, systems of this type have also been employed in the treatment of other types of wastewater, e.g. industrial and landfill leachates, as well as for the creation of plant buffer zones for contaminated areas. Examples of applications of HF-type CWs for the treatment of various types of wastewater were described by Vymazal and Kröpfelová [12] and Vymazal [2,3,23].

The efficiencies of removal of Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD) in one-stage Horizontal-Flow (HF) constructed wetlands recorded by various authors were 56–83%, 75–85%, and 66–82%, respectively [2,17,22,24–27]. Jucherski and Walczowski [18], who studied one-stage HF systems planted with the willow *Salix viminalis* L., found that the highest efficiencies of wastewater treatment were obtained in a wetland with a bed filled with sand and gravel. In those systems the efficiencies of removal of TSS, BOD_5 and COD were 52.0–74.6%, 87.7–95.9%, and 88.0–92.5%, respectively. Also, it was shown that removal of NH_4^+-N was below 40%, the concentration of this pollutant in the effluent was sometimes even higher than 43 mg/l [18].

The principal mechanism responsible for NH_4^+-N removal in the initial phase of system operation is ion exchange adsorption on a bed-filling material, which is a reversible process that depends on the sorption capabilities of such materials [28]. Currently, one-stage HF type wetlands are of limited use for NH_4^+-N removal, but they could be applied effectively for denitrification and dephosphatation after mineralization of organic matter and nitrification [29,30].

Recent research has been focused mainly on the assessment of wetland treatment efficiency, and much fewer papers have been published on the problem of reliability of such systems over a longer time of operation.

Reliability is an important aspect in the evaluation of wastewater treatment plant operation [31–33]. To properly evaluate the reliability of a wastewater treatment plant, a Reliability Coefficient (RC), specifying the technical reliability of the facility, or technological efficiency coefficients can be used. In evaluating the operational reliability of a facility, statistical probability distributions are used to establish the probability of occurrence of selected values and concentrations of contamination parameters. Recent research findings shown that the Weibull distribution is an accurate and precise "tool" for the evaluation of reliability of wastewater treatment plants. This methodology has been applied in studies by Bugajski et al. [34,35].

The reliability of conventional wastewater treatment plants with the application of activated sludge has been investigated, among others, by Eisenberg et al. [36], Oliveira and Von Sperling [37], Taheriyoun and Moradinejad [38], and Bugajski et al. [39]. The problems of reliability of wetland treatment systems have been discussed, among others, in the following papers: Wen et al. [40], Alfiya et al. [41], Nastawny and Jucherski [42], Garfi et al. [43], Alderson et al. [44], Thomas et al. [45], and Wojciechowska et al. [46].

The purpose of the present study was to analyze the reliability and efficiency of pollution removal in a one-stage horizontal subsurface flow constructed wetland (HSFCW) for a period of 14 years.

2. Methods

2.1. Characteristics of the experimental facility

The facility studied was located in the commune of Jastków, in southeastern Poland (51°18′N, 22°26′E), and had been used for treatment of domestic wastewater for over 14 years. The flow rate the treatment plant was 1.2 $m^3\ d^{-1}$ during the whole research period. The plant consisted of a two-chamber preliminary sedimentation tank, having an active volume of 13.7 m^3, and a 1.2-meter-deep HSFCW with a surface area of 186 m^2 and a bottom slope of 1%. A 1-mm PEHD impermeable layer lining had been used to seal the bed. The bed was filled with medium-size sand with a top layer of humus, in which Common Osier Willow, *Salix viminalis L.*, had been planted (Fig. 1). Effluent from the plant was diverted to a pond with a surface area of 1190 m^2.151917406711950151917406711950.

2.2. Analytical methods

Analysis of quality of raw wastewater and treated effluent were carried out in the years 1997–2010. During this study period, 56 sampling events were carried out and 112 wastewater samples (averaged over 24 h) were collected to analyze TSS, BOD_5 and COD. Samples were collected four times a years in accordance to the seasons: in February (winter), in May (spring), in August (summer), and in November (autumn).

Total suspended solids were determined by the standard paper filtration and direct gravimetric method. BOD_5 was measured by the dilution method using a WTW Oxi 538 portable meter (after Siwiec [48]). COD was determined using a PC Spectro spectrophotometer manufactured by AQUALYTIC, after oxidation of the samples at 148 °C in a WTW CR4200 thermo reactor.

Sampling, sample transportation, processing and analysis have been done according to relative Polish Standards of Wastewater Examination which are compatible with APHA 1992 and 2005 [49,50].

2.3. Experimental procedures

The Weibull distribution is a probability function (1) with the assumption that $\theta < x$, $b > 0$, $c > 0$.

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

where: x is a variable defining the concentration of a given contamination parameter in treated wastewater, b – scale, c – shape, θ – location.

Weibull distribution parameters were estimated using the maximum likelihood method. The quality of fit of the Weibull distribution to empirical data was assessed with the Hollander-Proschan test. The results were initially analyzed using STATISTICA 8 software. As a next step of the reliability analysis, the results of operation of the treatment plant was analyzed with regard to the following three parameters: BOD_5, COD, and TSS. A hypothesis assuming that the Weibull distribution can be used for the approximation of empirical data was verified for the estimated distribution parameters. Results of the analysis of reliability p for all parameters shown that the empirical data can be described with the Weibull distribution. This is assumed to be a zero hypothesis.

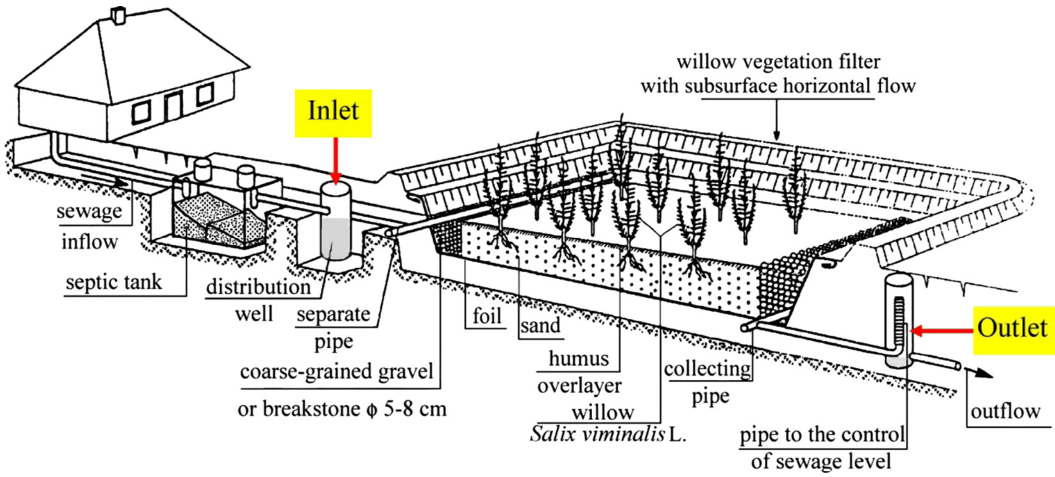

Fig. 1. Technological scheme of one-stage constructed wetland with subsurface horizontal flow (based on a project by Drupka et al. [47]).

3. Results

3.1. Pollutant concentrations

Results of the analysis of raw wastewater and treated effluent are shown in Table 1. Statistical analysis took into account statistically large errors, i.e. those beyond the Gaussian curve range ($\bar{x}$ - 3 · s, $\bar{x}$ + 3 · s). Moreover, technologically impossible results, in which BOD_5 was higher than COD, were excluded from the pool of the results.

These two cases were analyzed statistically employing the 3-sigma rule, which can be applied when a pool of data is $n > 30$ [51]. The normality of distribution was analyzed with the Shapiro–Wilk test [52]. It was shown that the values of BOD_5 and COD of the influent were normally distributed, and those of the effluent were close to the normal distribution. Also, the ratio of BOD_5 to COD was normally distributed for both influent and effluent. Only TSS deviated a little from normality and showed a weak bimodal character.

Comparison of minimal and maximal values varied greatly between the samples. For the influent, these differences could be explained by the functioning of the septic tank. The mixture of fresh and stabilized sludge and its fermentation could have caused flotation of sludge, decreased the sedimentation effect, and increased the concentration of pollutants in the wastewater flowing out from the tank. This was observed for both BOD_5 and COD, and particularly for TSS.

For the effluent from the HSFCW, the ratio between minimal and maximal values was even higher, which could be explained by the changing meteorological conditions such as temperatures in winter and summer, and precipitation (snow and rain). The influent was characterized by an asymmetric distribution of the investigated parameters, as reflected by significant differences between their average and median values. This was particularly visible for COD and TSS, and could be explained by the specific technological functioning of the septic tank. For the effluent, there were significant differences between average and median values of COD and smaller differences for BOD_5, with TSS values being closest to normal distribution.

The average pollutant removal efficiency was high at 85.4%, 81.1% and 60.8% for BOD_5, COD and TSS respectively. These results comply with the Polish regulation related to small wastewater treatment plants [54]. The distribution of efficiency values was close to normal.

To analyze wastewater susceptibility to biological decomposition, the distribution of the BOD_5/COD ratio was calculated for both influent and effluent. The following values were obtained for the influent: average x = 0.5, median Me = 0.51, min = 0.21, max = 0.86, and standard deviation s = 0.11. The corresponding values for the effluent were: x = 0.41, Me = 0.36, min. = 0.07, max 0.92, and s = 0.19. These results shown a good, symmetric distribution, however, the average ratio, which was around 0.5, was low compared to the ration in raw domestic sewage cited in literature [53]. It happened probably due to sedimentation of biodegradable pollutants in the septic tank. The septic tank was designed with too high volume which resulted in prolonged time of wastewater retention in the tank and in consequence easy removal of organic matter flotated from sediment.

Variations in these ratios for the influent and the effluent seemed to be a logical consequence of the processes of wastewater mineralization in the treatment plant, particularly when looking at the decrease in average and median values of these ratios. Relationships between BOD_5 and COD in influent and effluent are shown in Fig. 2.

Developed equation for the influent was similar to typical one, and positive value of intercept in the equations may be a result of presence of biodegradable chemical compounds which are not sensible for chemical oxidation used in analytical method for COD

Table 1
Composition of treated wastewater and pollutant removal efficiency in the investigated HSFCW system during long-term operation (data for the years 1997–2010).

Parameters	Inflow					Outflow					Efficiency [%]				
	Min	Max	$\bar{x}$	Me	s	Min	Max	$\bar{x}$	Me	s	Min	Max	$\bar{x}$	Me	s
BOD_5 [mg O_2/l]	62.0	309.0	**163.2**	161.0	54.1	6.0	61.0	**21.7**	20.0	12.7	41.9	97.4	**85.4**	87.9	9.7
COD [mg O_2/l]	101.0	580.0	**329.8**	338.0	97.2	9.0	134.0	**57.8**	52.0	29.0	47.8	97.4	**81.1**	83.9	10.6
TSS [mg/l]	10.9	239.0	**89.9**	72.5	56.8	4.2	57.0	**29.7**	29.0	15.2	11.1	89.5	**60.8**	66.6	20.2

Explanations: BOD_5 – Biochemical Oxygen Demand; COD – Chemical Oxygen Demand; TSS – Total Suspended Solids; min – minimum; max – maximum; $\bar{x}$– average; Me – median; s – standard deviation.

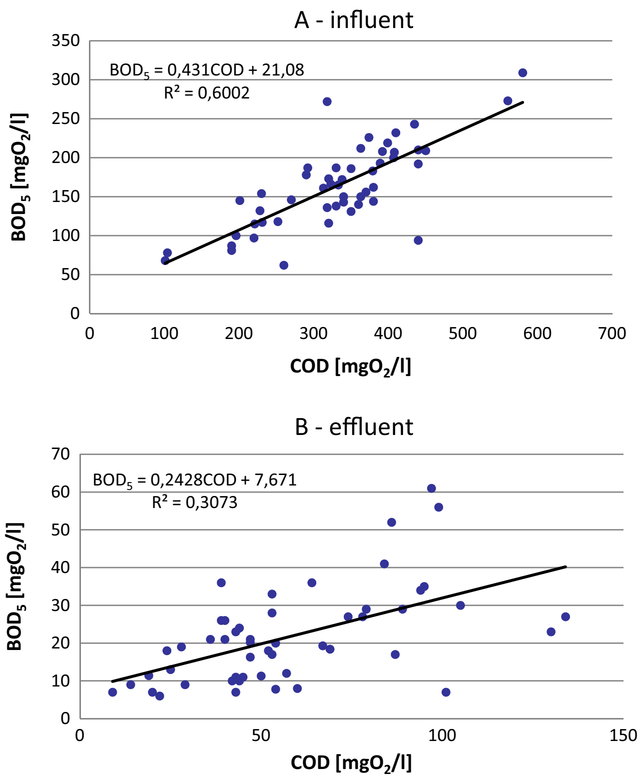

Fig. 2. Relationships between BOD_5 and COD for A) influent and B) effluent.

measurement. Greater variations between BOD_5 and COD were observed for the effluent, (see Fig. 2). This could be explained by possible presence in wastewater of excessive quantities of poorly biodegradable organic matter such as paper, starches, etc.

The results of the Hollander-Proschan goodness-of-fit test and the estimated distribution parameters are shown in Table 2.

The limit values for BOD_5, COD and TSS defined in the Regulation of the Polish Ministry of Environment [54] (40 mgO_2/l, 150 mg O_2/l and 50 mg/l, respectively) were used as the limit values for the distribution parameters. The Regulation not only sets limits on pollution indexes but also on the number of samples per year in which the limit values can be exceeded.

3.2. Reliability of BOD_5 removal

The average BOD_5 reduction during the long-term operation of HSFCW was 84.7%. The average value of this parameter in the effluent was 21.7 mgO_2/l (Table 1), which was almost two times lower than the value 40 mgO_2/l, limited by the Regulation of the Polish Minister of Environment [54]. It was also detected that during the 14 years of operation, samples from 4 events, out of 56 samplings exceeded the BOD_5 limit for wastewater discharged to the environment. However, it should be noted that in 3 of these 4 events, the BOD_5 limit (40 mg O_2/ l) was exceeded only negligibly (from 1 to 16 mg O_2/l above the limit) (Fig. 2b).

The probability of measured BOD_5 exceeding the standard limit value was 8% (Fig. 3). Therefore, in the analyzed wastewater treatment plant, the values of BOD_5 could exceed the limit value over a period of 29 days.

As shown in Fig. 3, the reliability of the efficiency of the analyzed plant in regard to BOD_5 was 92%, what correspond to 335 days in year. In practice this means 335 days with concentration of BOD_5 in effluent below the limit value. According to the recommendations proposed by Andraka and Dzienis [55], wastewater treatment plants up to 2000 PE in Poland should operate at a reliability of at least 97.3% with operator risk at statistical significance level α = 0.05. It means that there is 5% of acceptable risk that plant effluent will not compliant with the limits defined by the Regulations for 10 days (2.7% of 365 days). Another words, as per these recommendations, the acceptable failure rate for such a facility is only 10 day per year.

A comparison of the numbers of days during which BOD_5 in the effluent of the treatment plant did not exceed the acceptable value, to the number of days during which the exceeded BOD_5 limit did not result in unacceptable plant performance, has shown that BOD_5 in the effluent exceeded the acceptable value 20 days per year.

To summarize, the reliability of the analyzed wastewater treatment plant in regard to BOD_5 removal was 92%, and was not sufficient to meet the recommendation proposed by Andraka and Dzienis [55]. But still in our opinion it should be consider as satisfactory due to the localization of the analyzed facility in the region of Europe where the winter with temperatures much below 0 °C could last longer than 60 days.

3.3. Reliability of COD removal

The study showed that the average efficiency of COD removal was 81.1%, and the average concentration in the effluent was 57.8 mg/l (see Tab.1), which was much below the limit value of 150 mg/l defined in the Regulation of the Minister of Environment [54]. Also it was shown that during the 14 years of operation the limit for COD had never been exceeded (Table 1).

Therefore, the reliability of the operation of the wastewater treatment plant was very high (nearly 100%) with respect to reducing the value of this parameter (Figs. 2b and 4).

3.4. Reliability of TSS removal

The study showed that the average efficiency of TSS removal during the long- term operation of the plant was 60.8%, with an average value of 29.7 mg/l of TSS in the effluent, which was much lower than the limit of 50 mg/l specified in the Regulation of the Minister of Environment [54]. During the 14 years of operation, TSS exceeded the standard limits for wastewater discharged to the environment only 5 times.

Table 2
Results of the estimation of the Weibull distribution parameters together with the measures of goodness of fit to empirical data.

Index	Distribution parameters			Hollander–proschan test	
	b	c	θ	Test value	p
BOD_5	26.113	1.5808	5.7879	0.267034	0.78944
COD	66.546	1.8068	4.5556	0.212757	0.83152
TSS	32.992	2.0768	0.56061	−0.102986	0.91707

Explanations: BOD_5 – Biochemical Oxygen Demand; COD – Chemical Oxygen Demand; TSS – Total Suspended Solids; b – scale: c – shape; θ – location; p – statistical significance level α=0,05.

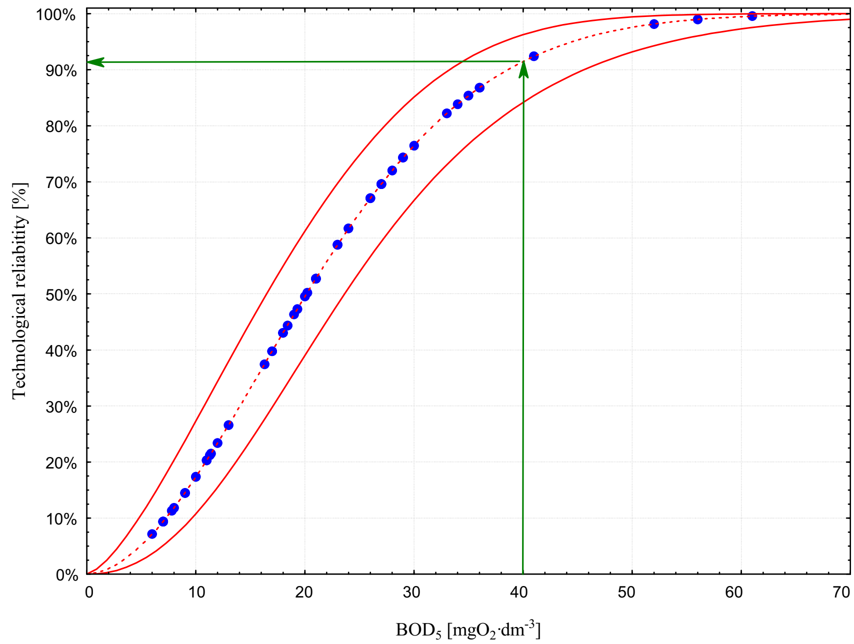

Fig. 3. Results of the Weibull reliability analysis for BOD_5 in treated wastewater. Legend: punctuated red color line - reliability function, continuous red color – confidence intervals, green arrows – probability of occurrence of BOD_5 limit value in the effluent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

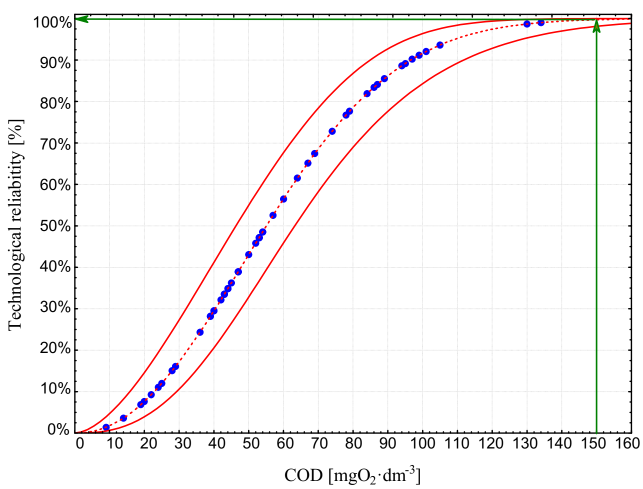

Fig. 4. Results of the Weibull reliability analysis for COD in the treated wastewater. Legend: punctuated red color line - reliability function, continuous red color - confidence intervals, green arrows - probability of occurrence of COD limit value in effluent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

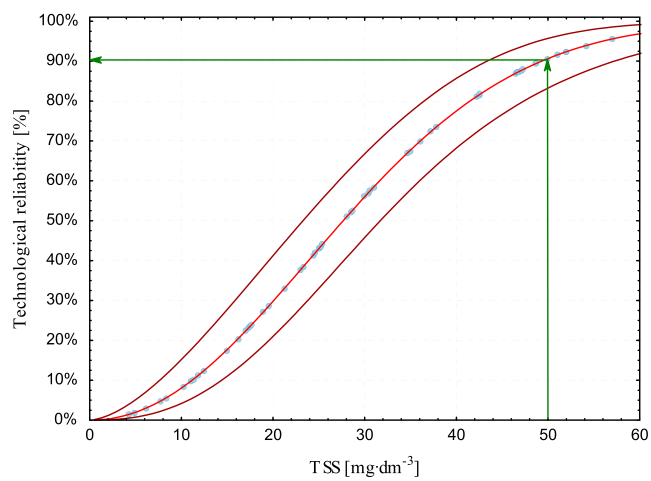

Fig. 5. Results of the Weibull reliability analysis for TSS in the treated wastewater. Legend: punctuated red color line - reliability function, continuous red color - confidence intervals, green arrows - probability of occurrence of TSS limit value in effluent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The probability of TSS exceeding the permitted value was approx. 10%, which meant that this parameter could exceed the acceptable value approx. 36 days per year. This was 27 days more than the acceptable number of days per year given in the recommendations for treatment plants of this size [54].

The reliability of the studied treatment plant with respect to TSS was 90% (Fig. 5) and was a little lower than recommended in Poland by Andraka and Dzienis [55].

4. Discussion

The data concerning the operation of the treatment plant described in this study showed that the reliability and efficiency of removal of organics and suspended solids was lower than that found in similar plants using the CW technology [22,42,56].

A reliability analysis of another wetland treatment system of this type performed by Nastawny and Jucherski [42] with the application of the Weibull method showed 100% reliability of BOD_5 and COD removal, and 99.8% reliability of TSS removal. In a study by Bugajski et al. [34], the reliability of a small compacted wastewater treatment plant using activated sludge was 67% for BOD_5, 88% for COD, and 92% for TSS. Walega et al. [57] investigated the reliability of a small wastewater treatment plant with an aerated biofilm reactor, and reported the following reliability values: 85% for BOD_5, 89% for COD, and 92% for TSS.

The HSFCW presented in this paper had higher reliability than treatment plants with activated sludge [34] and the plant's with aerated submerged fixed bed biofilm reactors [57]. However, the plant's reliability was lower than that of hybrid VF-HF wetland systems as studied by Jóźwiakowski [22] and of hybrid plants with trickling filter and wetland studied by Krzanowski et al. [58] and Nastawny and Jucherski [42]. High reliability in these systems was achieved by a multistage configuration of the treatment technology [22,53,59].

Although the treatment efficiency of the investigated HSFCW, reflected by the average values of BOD_5, COD and TSS, met the criteria defined in the Polish Regulations [54], the process reliability, measured as the number of days when the standards were exceeded, was lower for both TSS and BOD_5 than that recommended by Andraka and Dzienis [55]. However, some other authors allow lower reliability of wastewater treatment plant operation. For example, Eisenberg et al. [36] recommend 97%, Oliveira and Von Sperling [37] 95%, while Charles et al. [60] and Alderson et al. [44] 80%. Taking into account the aforementioned limits of reliability, the studied wetland system complies only with the standards assuming the criterion of 80% recommended by Charles et al. [60] and Alderson et al. [44]. Its low reliability is similar to all other horizontal flow wetland treatment systems [22,53,57].

5. Conclusions

The average efficiencies of BOD_5, COD and TSS removal in this one-stage HSFCW during 14 years of its operation were: 85.4%, 81.9%, and 60.8%, respectively. The average values of pollutants in the effluent measured by BOD_5, COD and TSS were 23.3 mgO_2/l; 58.9 mgO_2/l and 22.2 mg/l, respectively, and were much below the requirements of the Polish Regulation [54], which are 40 mg/l for BOD_5, 150 mg/l for COD, and 50 mg/l for TSS.

The reliabilities of the wastewater treatment plant, based on the Weibull reliability theory of acceptable values of pollution parameters in the effluent of a treatment plant, were as follows: BOD_5 – 92%, COD – 100%, TSS – 90%. The 92% reliability for BOD_5 means that the concentration of this parameter in treated wastewater could exceed the permissible limit on 29 days each year. In the case of TSS, the permissible limit was 36 days per year.

The reliability of the investigated one-stage HSFCW during the exploitation period of 14 years was insufficient in accordance with Polish standards.

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References

[1] M. Gajewska, H. Obarska-Pempkowiak, 20 years of experience of hybrid constructed wetlands exploitation in Poland, Rocz Ochr Sr. 11 (2009) 875–888.
[2] J. Vymazal, Constructed wetlands for wastewater treatment, Water 2 (3) (2010) 530–549.
[3] J. Vymazal, Constructed wetlands for wastewater treatment: five decades of experience, Environ. Sci. Technol. 45 (2011) 61–69.
[4] K. Seidel, Die Flechtbinse Scirpus lacustris. Ökologie, Morphologie und Entwicklung, ihre Stellung bei den Volkern und ihre wirtschaftliche Bedeutung. Schweizerbartïsche Verlags-buchnadlung, Stuttgart, Germany (1955) 37–52.
[5] K. Seidel, Neue Wege zur Grundwasseranreicherung in Krefeld, vol. II. Hydrobotanische Reinigungsmethode. GWF Wasser/Abwasser (1965) 831–833.
[6] R. Haberl, R. Perfler, H. Mayer, Constructed wetlands in Europe, Water Sci. Technol. 32 (3) (1995) 305–315.
[7] R. Kickuth Höhere, Wasserpflanzen und Gawässerreinhaltung, Schiftenreihe der Vereinigung Deutscher Gewässerschutz EV-VDG 19 (1969) 3–14.
[8] R. Kickuth, Degradation and incorporation of nutrients from rural wastewaters by plant rhizosphere under limnic conditions. In: Utilization of Manure by Land Spreading. Comm. Europ. Commun., EUR 5672e, London, UK (1977) 335–343.
[9] H. Brix, H.H. Schierup, Sewage treatment in constructed wetlands – Danish experience, Wat. Sci. Tech. 21 (1989) 1665–1668.
[10] R. Haberl, R. Perfler, Seven years of research work and experience with wastewater treatment by a reed bed system. In: Constructed wetlands in Water Pollution Control, Advances in Water Pollution Control No. 11, Cooper P. F. and Findlater B. C. (eds.), Pergamon Press, Oxford (1990) 529-534.
[11] P. Cooper, B. Green, Reed bed treatment systems for sewage treatment in the United Kingdom – The first 10 years experience, Water Sci. Technol. 32 (3) (1995) 317–327.
[12] J. Vymazal, L. Kröpfelová, Wastewater treatment in constructed wetlands with horizontal sub-surface flow, Environmen. pollut. 14 (2008) 556.
[13] A. Jucherski, Sewage treating efficiency of ground and soil-vegetable treatment plants situated in a mountain region. Zeszyty Naukowe Akademii Rolniczej im. H. Kołłątaja w Krakowie 365 (2000) 371-380 (in Polish).
[14] M. Gajewska, K. Jóźwiakowski, A. Ghrabi, F. Masi, Impact of influent wastewater quality on nitrogen removal rates in multistage treatment wetlands, Environ. Sci. Pollut. Res. 22 (2015), 12840 1284.
[15] H. Brix, Functions of macrophytes in constructed wetlands, Water Sci. Technol. 29 (1994) 71–78.
[16] P. Kowalik, H. Obarska-Pempkowiak, Polish experience, with sewage purification in constructed wetlands. Constructed Wetlands for Wastewater Treatment in Europe, ed. J. Vymazal, H. Brix, P.F. Cooper, M.B. Green & R. Haberl, Backhuys Publishers, Leiden, The Netherlands (1998) 217-225.
[17] J. Vymazal, Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment, Ecol. Eng. 25 (5) (2005) 478–490.
[18] A. Jucherski, A. Walczowski, Implementation of energy-saving methods of disposing domestic wastewater in mountain farms. Annual report from IBMER's (Poland) research work. Krynica – Bradowiec (1994) (in Polish).
[19] K.L. Perttu, Biomass production and nutrient removal from municipal wastes using willow vegetation filters, J. Sustain. For. 1 (3) (1994) 57–70.
[20] K.L. Perttu, P.J. Kowalik, Salix vegetation filters for purification of waters and soils, Biom. Bioene. 12 (1) (1997) 9–19.
[21] M. Gizińska-Górna, W. Czekała, K. Jóźwiakowski, A. Lewicki, J. Dach, M. Marzec, A. Pytka, D. Janczak, A. Kowalczyk-Juśko, A. Listosz, The possibility of using plants from hybrid constructed wetland wastewater treatment plants for energy purposes, Ecol. Eng. 95 (2016) 534–541.
[22] K. Jóźwiakowski, Studies on the efficiency of sewage treatment in chosen constructed wetland systems, Infr. Ecol. of Rur. Are. 1 (2012) 232 (in Polish).
[23] J. Vymazal, The use constructed wetlands with horizontal sub-surface flow for various types of wastewater, Ecol. Eng. 35 (2009) 1–17.
[24] A. Albuquerque, M. Arendacz, M. Gajewska, H. Obarska-Pempkowiak, P. Randerson, P. Kowalik, Removal of organic matter and nitrogen in an horizontal subsurface flow (HSSF) constructed wetland under transient loads, Water Sci. Technol. 60 (7) (2009) 1677–1682.
[25] T. Börner, Einflußfaktoren für die Leistungfähigkeit von Pflanzenkläranlegen, TH Darmstadt, Schriftenreihe WAR, 1992, p. 58.
[26] H.H. Schierup, H. Brix, B. Lorenzen, Wastewater treatment in constructed reed beds in Denmark - state of the art, in: P.F. Cooper, B.C. Findlater (Eds.), Constructed wetlands in water pollution control, Pergamon Press, Oxford, 1990, pp. 495–504.
[27] J. Vymazal, Types of constructed wetlands for wastewater treatment: their potential for nutrient removal, in: J. Vymazal (Ed.), Transformations on Nutrients in Natural and Constructed Wetlands, Backhuys Publishers, Leiden, The Netherlands, 2001, pp. 1–93.
[28] P.F. Cooper, G.D. Job, M.B. Green, R.B.E. Shutes, Reed beds and constructed wetlands for wastewater treatment. WRc Publications, Severn Trent Water Workshop. WRc Swidon (1996) 17-18.
[29] N.H. Johansen, H. Brix, Design criteria for a two-stage constructed wetlands. In: Proc. 5th Int. Conf. Wetland System for Water Pollution Control. Universität Für Bodenkultur. Wien, Austria. Chapter IX/3 (1996).
[30] R. Ciupa, The experience in the separation of constructed wetlands in north Poland. In: Proc. 5th Int. Conf. Wetland System for Water Pollution Control. Universität Für Bodenkultur. Wien, Austria. Chapter IX/6 (1996).
[31] K. Jóźwiakowski, Z. Mucha, A. Generowicz, S. Baran, J. Bielińska, W. Wójcik, The use of multi-criteria analysis for selection of technology for a household WWTP compatible with sustainable development, Arch. Environ. Prot. 3 (2015) 76–82.
[32] J. Mikosz, Wastewater management in small communities in Poland, Desalinat. Water Treat. 51 (10–12) (2013) 2461–2466.
[33] K. Kołecka, M. Gajewska, H. Obarska-Pempkowiak, Treatment Wetlands in Rural Areas of Poland for Baltic Sea Protection Chapter Role Natur. Construct. Wetlands Nut. Cycl. Retent. Lands. 18 (2015) 259–273.
[34] P. Bugajski, A. Wałęga, G. Kaczor, Application of the Weibull reliability analysis of household sewage treatment plant. Gaz, Woda i Technika Sanitarna 2 (2012) 56-58 (in Polish).
[35] P. Bugajski, Analysis of reliability of the treatment plant Bioblok PS-50 using the method of Weibull, Infr. Ecol. of Rur. Are. II (3) (2014) 667–677.
[36] D. Eisenberg, J. Soller, R. Sakaji, A. Olivieri, A methodology to evaluate water and wastewater treatment plant reliability, Water Sci. Technol. 43 (10) (2001) 91–99.

[37] S.C. Oliveira, M. Von Sperling, Reliability analysis of wastewater treatment plants, Water Res. 42 (4–5) (2008) 1182–1194.
[38] M. Taheriyoun, S. Moradinejad, Reliability analysis of a wastewater treatment plant using fault tree analysis and Monte Carlo simulation, Environ. Monit. Assess. 187 (1) (2015) 4186, http://dx.doi.org/10.1007/s10661-014-4186-7.
[39] P. Bugajski, K. Chmielowski, G. Kaczor, Reliability of a collective wastewater treatment plant, J. Ecol. Eng. 17 (4) (2016) 143–147.
[40] Y. Wen, C. Xu, G. Liu, Y. Chen, Q. Zhou, Enhanced nitrogen removal reliability and efficiency in integrated constructed wetland microcosms using zeolite, Front. Environ. Sci. En. 6 (1) (2012) 140–147.
[41] Y. Alfiya, A. Gross, M. Sklarz, E. Friedler, Reliability of on-site greywater treatment systems in Mediterranean and arid environments - a case study, Water Sci. Technol. 67 (6) (2013) 1389–1395.
[42] M. Nastawny, A. Jucherski, Assessing technical reliability of an on-site sewage treatment plant with filtration bed system, by using modified Weibull's method. Problems of Agricultural Engineering (IV–VI): z. 2 (80) (2013) 165–175.
[43] M. Garfí, A. Pedescoll, J. Carretero, J. Puigagut, J. García, Reliability and economic feasibility of online monitoring of constructed wetlands performance, Desalin. Water Treat. 52 (31–33) (2014) 5848–5855.
[44] M.P. Alderson, A.B. Dos Santos, C.R. Mota, Filho, Reliability analysis of low-cost, full-scale domestic wastewater treatment plants for reuse in aquaculture and agriculture, Ecological Engineering 82 (2015) 6–14.
[45] A. Thomas, R.J. Morrison, P. Gangaiya, A.G. Miskiewicz, R.L. Chambers, M. Powell, Constructed wetlands as urban water constructed wetlands as urban water quality control ponds - studies on reliability and effectiveness, Wetlands Australia Journal 28 (1) (2016) 2–14.
[46] E. Wojciechowska, M. Gajewska, A. Ostojski, Reliability of nitrogen removal processes in multistage treatment wetlands receiving high-strength wastewater, Ecol. Eng. 98 (2017) 365–371.
[47] S. Drupka, M. Sikorski, K. Borys, Technical projects of the root wastewater treatment plant for individual farms in the Jastków village. Manuscript, IMUZ – Falenty (1992) (in Polish).
[48] T. Siwiec, L. Kiedryńska, K. Abramowicz, A. Rewicka, Analysis of chosen models describing the changes in BOD_5 in sewages, Environment Protection Engineering 38 (2) (2012) 61–76.
[49] American Public Health Association (APHA); Standard Methods For Examination of Water And Wastewater. 18th Edition, American Public Health Association, Washington, DC, (1992).
[50] American Public Health Association (APHA); Standard Methods for Examination of Water and Wastewater. 21st edition, American Public Health Association, Washington, DC, (2005).
[51] K. Twardowski, J. Traple, Remarks on dubious measurement results, Wiertnictwo Nafta Gaz 23 (2) (2006) 699–714 (in Polish).
[52] A. Zięba, Data analysis in science and technology, PWN, Warszawa, 2013 (in Polish).
[53] R. Cossu, T. Lai, A. Sandon, Standardization of BOD_5/COD ratio as a biological stability index for MSW, Waste Management 32 (2012) 1503–1508.
[54] Polish standards according limits for discharged sewage and environmental protection from July, 24 2006 (No 137 item 984) and January, 28 2009 (No 27 item 169) and November, 18 2014 (No 2014 item 1800) (in Polish).
[55] D. Andraka, L. Dzienis, Required reliability level of wastewater treatment plants according to European and Polish regulations. Zesz. Nauk. Politechniki Białostockiej, Seria Inżynieria Środowiska, z. 16, Białystok (2003) 24-28 (in Polish).
[56] A. Jucherski, M. Nastawny, A. Walczowski, K. Jóźwiakowski, M. Gajewska, Assessment of the technological reliability of a hybrid constructed wetland for wastewater treatment in a mountain eco-tourist farm in Poland, Water Sci. Technol. (2017), http://dx.doi.org/10.2166/wst.2017.139.
[57] A. Wałęga, W. Miernik, T. Kozień, The efficiency of a domestic sewage treatment plant type RetroFAST, Przemysł Chem. 87 (5) (2008) 210–212 (in Polish).
[58] S. Krzanowski, A. Jucherski, A. Wałęga, Influence of season on technological of reliability of multi-degrees plant-ground adjacent of sewage treatment, Infr. Ecol. of Rur. Are. 1 (2005) 37–55 (in Polish).
[59] A. Jucherski, The quality of farm house-hold wastewater treatment in quasi-technical farmstead installation of IBMER model, in winter period on the mountainous terrain, Prob. Inżynierii Rolniczej 15 (2) (2007) 51–60 (in Polish).
[60] K.J. Charles, N.J. Ashbolt, D.J. Roser, R. McGuinness, D.A. Deere, Effluent quality from 200 on-site sewage systems: design values for guidelines, Water Sci. Technol. 51 (10) (2005) 163–169.