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Reliability analysis of a rural wastewater treatment plant: A study of pollutant removal

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ABSTRACT

The study implements the Weibull reliability theory and reliability coefficient (RC) to analyze the rural municipal wastewater treatment plant performance (WWTP), considering the removal of several pollution indicators covering organic compounds, suspended solids and bio-genes. Full-scale technical tests were carried out at a facility with an average throughput of 450 m^3/d and analysis of the reliability of their removal, up to the maximum discharge levels, resulted as follows – the installation achieved 100% in the case of BOD_5, COD and TSS, while only 10% for TN and 3% for TP. These results were confirmed by RC analysis amounted to 0.2 for BOD_5 and TSS, 0.4 for COD, 1.8 for TN and 4.9 for TP, showing that for organics and suspended solids, the concentrations in the treated effluent did not exceed the normative values throughout the five years; however, the technology did not provide an effective removal of biogenic substances, hence TN and TP concentrations remained below or equal to the normative values for 36 and 11 days per year, respectively.

Keywords: municipal wastewater treatment plant, Weibull technological reliability, reliability coefficient, rural area.

INTRODUCTION

The maintenance of high standards of water environment protection should be mentioned among the indicators of sustainable development of countryside. Domestic wastewater, the production of which cannot be avoided at the current technological development stage, is considered one of the main threats. Centrally-managed collective water-wastewater systems with high-efficiency wastewater treatment plants (WWTPs) at the "end-of-pipe" are generally accepted as the best solution for meeting the growing sanitation standards needs of the rural population, without significant reduction of environmental quality. Apart from environmental indicators, such as biogenic nitrogen and phosphorus compounds as well as a growing share of household chemistry components, faecal microorganisms remain the major hazards to public health, including pathogenic ones, and pharmaceutical micro-pollutants, especially when transferred into reservoirs of drinking water due to the technical inability of effective removal (Yang et al., 2017; Kibuye et al., 2019; Józwiakowski et al., 2021). Maintaining the development of water and wastewater technology in rural areas seems necessary in the face of current challenges in the exploitation of continually reducing water resources.

Stricter legal standards and the availability of funding, associated with Poland's presence in European structures, have resulted in a visible improvement in the state of wastewater treatment infrastructure in the recent two decades, especially those operating on a small-scale (Kubiak-Wójcicka and Kielik, 2021). According to Statistics Poland (GUS, 2023), the volume of industrial and municipal wastewater that required treatment in Poland only between 2000 and 2022 decreased by approximately 14% (from 2502 hm^3 to 2148 hm^3), while the volume of untreated decreased by as much as approximately 54% (from 301 hm^3 to 138 hm^3). The share of only mechanically treated wastewater decreased by 49% (from 733 hm^3 to 372 hm^3) and the volume of wastewater treated with increased removal of biogenic substances more than doubled (from 460 hm^3 to 1.186 hm^3). In 2022, most MWWPs were based on biological treatment methods (75%) and a quarter (25%) had the option of increased removal of biogenic substances. Only the share of the population connected to the WWTP-ended sanitation system, increased from 53% in 2000 to 76% in 2022, with an increase from 11% to 47% respectively, in rural areas. Within the Podkarpackie province, 76.2 hm^3 of wastewater required treatment, 99.2% of which was treated; 783,000 rural residents (63.3% of the total countryside population) were served by 194 operational WWTPs, mainly based on biological technology (89.7%).

The technological reliability of a WWTP installation is considered an objectively appropriate tool for assessing the quality of treatment processes at a given time and place. This indicator helps to determine the statistical probability of exceeding the discharge limits for quality parameters. Among the methods previously proposed by Niku et al. (1982), Oliveira and Von Sperling, (2008), the method proposed by Bugajski et al. (2022) is gaining popularity. Due to the requirement of obtaining a large body of data, the analyses are based on mathematical modelling using probability distributions (Chaisee et al., 2024). One approach is the Weibull distribution, which is increasingly implemented in reliability analyses, and lifespan prediction concerning various processes, due to its probabilistic nature.

The analyzed process can be considered, for example, operational damage to electromechanical devices (Hua et al., 2023), but the Weibull coefficient can also illustrate the reliability of biogenic compounds removal from wastewater (Jóźwiakowska and Marzec, 2020; Bugajski et al., 2022; Jucherski et al., 2024). This paper is a novel attempt to assess the reliability coefficient (RC) to compare it with the Weibull technological reliability (WTR) on the example of small-scale WWTP operating in a rural area.

MATERIALS AND METHODS

The analyzed WWTP is located in the Podkarpackie (Subcarpathian) province (south-eastern Poland) and was commissioned in 1996, then upgraded in 2010. The installation was designed as a mechanical-biological system for a load of PE = 4600, with the capacity given in Table 1. Figure 1 shows a schematic diagram and description of the technological line. The receiver of treated wastewater is a nearby foothill river characterized by lower limit of medium flows Q ≈ 1 m/s.

During normal mode of operation, the treated effluent must meet the conditions specified in the national regulations for treated effluent (Ordinance of Minister of Environment, 2019): BOD_5 – 25 mg/L, COD – 125 mg/L, total suspended solids (TSS) – 35 mg/L, total nitrogen (TN) – 15 mg/L and total phosphorus (TP) – 2 mg/L.

The study covers the period from January 2016 to December 2020. Raw wastewater was sampled in the flume after the buffer tank, upstream of the drum screen, and treated wastewater was sampled in the discharge channel to the receiver. The removal efficiency analysis was made on the quarterly mean raw and treated wastewater indices values. Physicochemical analyses of wastewater were performed according to the methodology provided by APHA (2012).

The pollutant load in inflow and outflow was calculated according to Equation 1

$$L = C \cdot Q \tag{1}$$

where: L – inflow or outflow load [kg/d], C – concentration of pollutant [kg/m^3] and Q – flow rate [m^3/d].

Removal efficiency was calculated according to Equation 2

$$E = \frac{C_0 - C_e}{C_e} \cdot 100 \tag{2}$$

where: E – efficiency [%], C_0 – concentration in influent [mg/L] and C_e – concentration in effluent [mg/L].

Reliability analysis is based on matching the distribution of the mentioned indicators with the Weibull distribution. The changing concentrations of individual indicators such as BOD_5, COD, TSS, TN and TP were analyzed. Since the rate of change is not constant over time, the

Table 1. Permissible capacity of the analyzed wastewater treatment plant

Flow	Rain-free period	Rain period
$Q_{śrd}$	450 m^3/d	500 m^3/d
Q_{maxd}	653 m^3/d	600 m^3/d
Q_{maxh}	47 m^3/d	-
Q_{maxa}	164259 m^3/a	-

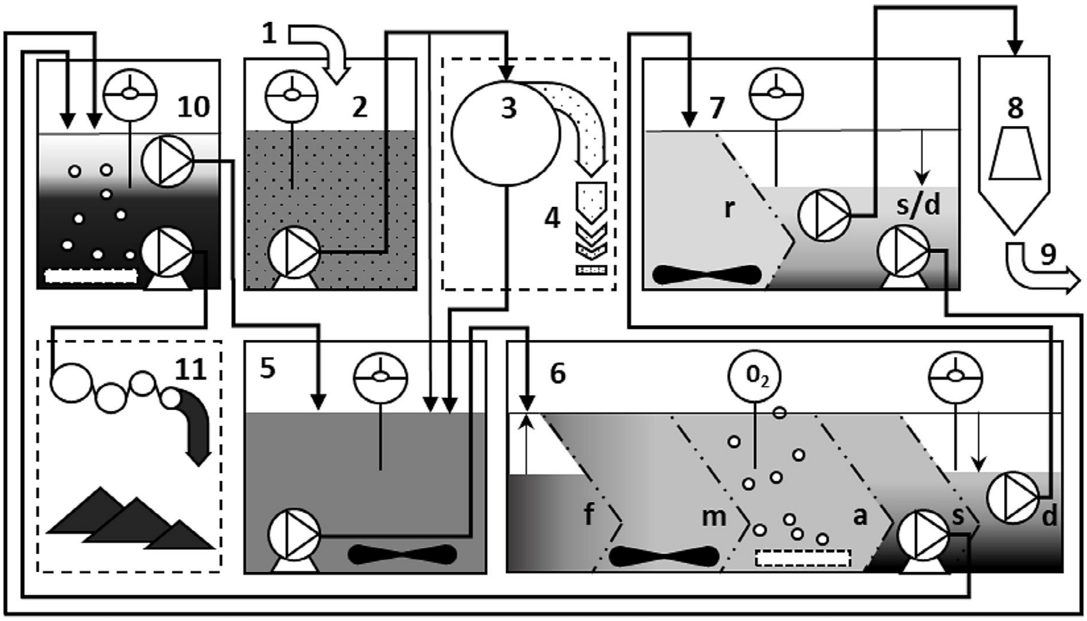

Figure 1. Technological line of the analyzed small municipal WWTP: raw wastewater from the collector (1) flows to the pumping station/buffer chamber (2) protected with automatic level control, from where is pumped to the mechanical treatment station (optionally bypassed), consisting of slotted, rotary drum sieve (3) integrated with press of screenings (4), then directed to the mechanically mixed equalization/buffer tank (5) with a maximum active capacity of 320 m^3, from where pumped to a rectangular biological chamber (6) with an active capacity of 1000 m^3, equipped with a fine bubble aeration system with DO probe and mechanical mixing, operating in the SBR mode consisted of: (f)illing, (m)ixing/denitrification, (a)eration/nitrification, (s)edimentation and final (d)ecantation to the buffer chamber (7) with a capacity of 480 m^3, with the optional feeding of a coagulant and mechanical (m)ixing in a mode of chemical reactor, then (s)edimentation/decantation to the outlet chamber with continuous flow measurement (8), from where they are directed to the receiver (9). Excessive active and chemical sludge (6s and 7s/d) are pumped to the sludge stabilization aerobic chamber (10) with a capacity of 150 m^3 where supernatant water is returned to the wastewater treatment line, and the mixed sludge is directed to the dewatering station (11) consisting of polyelectrolyte dosing and double-belt press

Weibull distribution is a useful and widely used analysis (StatSoft Electronic StatisticsTextbook 1984–2024). The probability density function of the Weibull distribution is illustrated by the Equation 3.

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

where: x – a variable that describes the concentration of a pollution parameter in the treated effluent, b – scale parameter, c – shape parameter, θ – position parameter, and e – constant (2.71828...), assuming: $\theta < x$, $b > 0$, $c > 0$.

The reliability function of the Weibull distribution is described as follows:

$$R(x) = 1 - F(x) \quad (4)$$

where:

$$Fx = 1 - exp\left[-(\frac{x-\theta}{b})^{c}\right] \quad (5)$$

Reliability was determined from distribution charts, considering the normative values of the parameters specified in the above-mentioned regulations for discharged wastewater from WWTP with PE of 2000 to 9999. The fitting of distribution to the empirical data was verified by the Hollander-Proschan test (goodness of fit), using Statistica 13.1 (StatSoft) software package.

The reliability coefficient (RC) was also calculated according to Equation 6

$$RC = \frac{C_y}{C_L} \quad (6)$$

where: C_y – mean concentration of a pollutant indicator in raw wastewater [mg/L], C_L – mean concentration of a pollutant indicator in treated wastewater [mg/L] and C – limit concentration of a pollutant indicator in treated wastewater [mg/L].

Basic descriptive statistics (Statistica 13.1) are shown in Table 2.

RESULTS AND DISCUSSION

In the analyzed WWTP, as is usually the case with small-scale installations (Mažeikienė and Vaiškūnaitė, 2018; Rizzardini et al., 2012), mainly domestic wastewater was treated. During the analysis period (2016–2020), the total monthly inflows to the treatment plant ranged from 9745 m^3 in May 2020 to 14992 m^3 in December 2017, while the mean annual flow ranged from 369 m^3 in 2020 to 388 m^3 in 2017.

To characterize the dynamics of wastewater composition changes the values of individual statistical parameters for pollutant concentrations in raw and treated wastewater were determined. The descriptive statistics for these pollutant indices are presented in Table 2. However, in analyzing the impact of treated wastewater on the environment, it is not sufficient to rely on pollutant concentrations only (Figure 2). A measure of the amount (mass) of a specific pollutant inflowing into a receiving body in a given time is defined as a load (Equation 1). Figure 3 shows the loadings of individual pollution indicators in the wastewater flowing in and out the treatment plant.

The data covering five years of the treatment plant operation shows that in raw wastewater, the concentrations of organic compounds expressed as BOD_5 changed significantly, with a range of 106 mg/L (Q4 2017) to the maximum reached in Q3 2018 (as high as 655 mg/L). In all cases, the concentration of easily biodegradable organic compounds met the conditions laid down in the Regulation of the Minister responsible for the environment of 12 July 2019. Therefore, although the mean load of biodegradable compounds inflowing the installation amounted to 141.2 kg/d and the coefficient of variation of this parameter reached almost 18%, in the wastewater discharged to the receiver, the biological oxygen demand load decreased to a mean value of 1.9 kg/d, with a similar coefficient of variation (16.4%). The concentration of organic compounds expressed as chemical oxygen demand (COD) in raw wastewater ranged from 277 mg/L (Q4 2017) to 1358 mg/L (Q3 2018), and after the treatment, from 27 mg/L (Q4 2017) to 90 mg/dm^3 (Q4 2020) hence, the treatment efficiency ranged from 78.9% to 96.4%, with a coefficient of variation of influent and effluent loads of 15.1 and 11.6%, respectively. There was also no observed exceedance of the limiting value of 125 mg/L in the outflow.

The BOD_5/COD ratio, which indicates the biodegradability potential of organic compounds, in raw wastewater varied considerably, from 0.3 (Q3 2017) to 0.53 (Q2 2018 and Q1 2019), and after

Table 2a. Values of descriptive statistics of contamination parameters in raw wastewater and effluent from WWTP during years 2016–2020

Parameter	BOD_5			COD			TSS			BOD_5/COD	
	Raw	Treated	E [%] RC	Raw	Treated	E [%] RC	Raw	Treated	E [%] RC	Raw	Treated
	C [mg/L] L [kg/d]			C [mg/L] L [kg/d]			C [mg/L] L [kg/d]				
Mean	348.4	4.6	98.4	766.1	51.8	92.2	259.5	7.3	96.8	0.44	0.10
	131.53	1.8	0.2	104.6	10.2	0.4	98.0	2.8	0.2	-	-
Min.	106.0	1.8	95.9	277.0	27.0	78.9	87.6	2.0	93.5	0.30	0.04
	40.01	0.7	0.1	104.6	10.2	0.2	33.1	0.8	0.1	-	-
25th prcl	228.3	2.9	98.1	544.0	40.0	90.6	202.0	3.8	95.3	0.41	0.06
	86.17	1.09	0.1	205.4	15.1	0.3	76.3	1.4	0.1	-	-
Median	374.0	5.0	98.7	764.0	53.2	92.9	223.0	6.9	97.2	0.46	0.09
	141.2	1.9	0.2	288.4	20.1	0.4	84.2	2.6	0.2	-	-
75th prcl	448.3	6.0	99.1	930.3	57.8	94.7	324.0	9.4	98.8	0.48	0.11
	169.2	2.3	0.3	351.2	21.8	0.5	122.3	3.5	0.3	-	-
Max.	655.0	8.7	99.3	1358.0	90.0	96.4	540.0	18.2	99.2	0.53	0.18
	247.3	3.3	0.3	512.7	34.0	0.7	203.9	6.9	0.5	-	-
Coefficient of variation	46.6	43.3	-	40.1	30.7	-	45.8	62.7	-	-	-
	17.6	16.4	-	15.1	11.6	-	17.3	23.7	-	-	-
Spread	470.0	6.9	-	1081.0	63.0	-	452.4	16.2	-	0.23	0.17
	207.3	2.6	-	408.1	23.8	-	170.8	6.1	-	-	-

Table 2b. Values of descriptive statistics of contamination parameters in raw wastewater and effluent from WWTP during years 2016-2020

Parameter	TN			TP		
	Raw	Treated	E [%] RC	Raw	Treated	E [%] RC
	C [mg/L] L [kg/d]			C [mg/L] L [kg/d]		
Mean	90.3	27.4	67.8	9.8	5.8	39.8
	34.1	10.3	1.8	3.7	2.2	4.9
Min.	37.7	10.8	39.8	3.2	1.4	0.1
	14.2	4.1	0.7	1.2	0.5	1.6
25^{th} prcl	70.4	19.1	61.0	8.0	4.2	33.6
	26.6	7.2	1.3	3.0	1.6	4.0
Median	89.9	27.6	69.2	10.4	6.1	40.4
	33.9	10.4	1.8	3.9	2.3	5.2
75^{th} prcl	115.5	36.0	79.2	12.2	7.3	45.8
	43.6	13.6	2.4	4.6	2.8	6.1
Max.	132.0	51.0	89.0	15.2	9.7	77.7
	49.8	19.3	3.4	5.7	3.6	7.6
Coefficient of variation	33,5	41,2	-	34.5	40.7	-
	12,6	15,5	-	13,0	15,4	-
Spread	94.3	40.2	-	12.0	8.3	-
	35.6	15.2	-	4.5	3.1	-

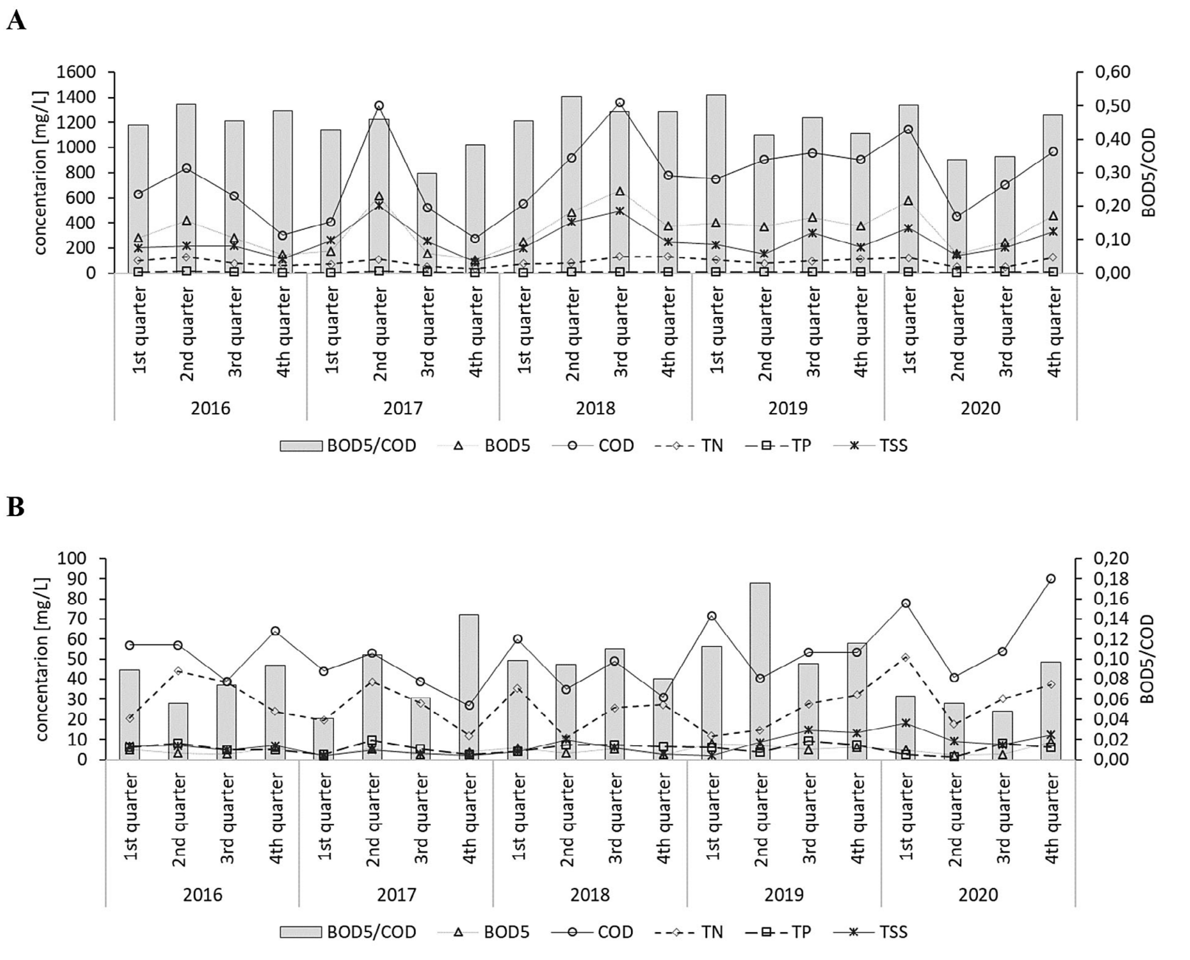

Figure 2. The concentration of pollution indicators: TSS, TN, TP, and organic substances expressed as BOD_5 and COD, in raw (A) and treated wastewater (B). BOD_5/COD ratios are shown on bars

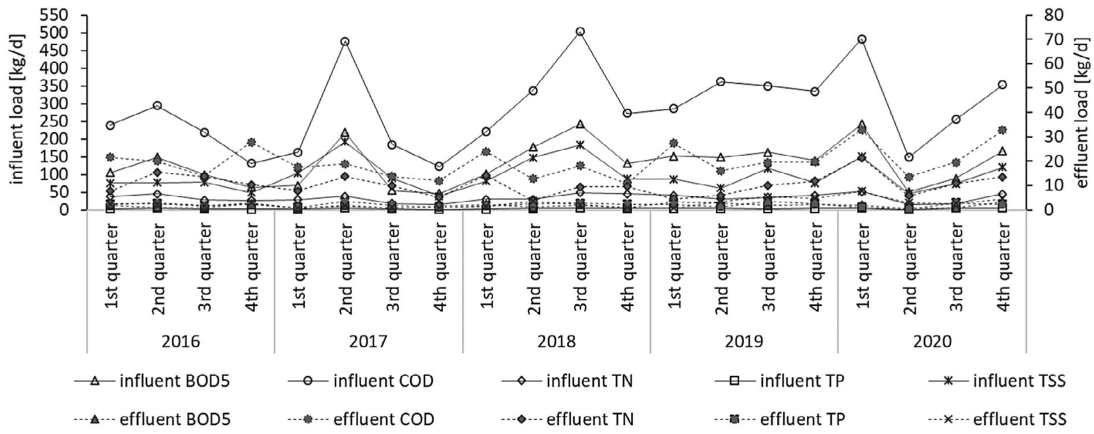

Figure 3. Loads of pollution indicators in influent and effluent from analyzed WWTP

treatment, the mean value decreased from 0.46 to even 0.09. This shows the good performance of the treatment plant and the effective removal of organics, including easily degradable compounds. On the basis on the ratios proposed in the literature, including Młyński et al. (2020), wastewater with a BOD_5/COD quotient > 0.5–0.6 can be effectively disposed of by appropriate technological conditions of biological treatment processes. If BOD_5/COD in wastewater lies within the range of 0.4–0.5 or 0.2–0.4, moderate or slow biodegradation is possible, respectively. Below < 0.2, wastewater is considered not susceptible to biodegradation.

The third pollutant parameter, the TSS concentration, is a measure of the total solids suspended in a wastewater sample that are possible to retain by filtration, and indicating its clarity (Johal et al. 2014; Showkat and Najar 2019). The concentration of TSS in the effluent entering the treatment plant ranged from 87.6 mg/L (Q4 2017) to 540 mg/L (Q2 2017), and in the treated effluent, from 2 mg/L (Q1 and Q4 2017 and Q1 2019) to 18.2 mg/L (Q1 2020). The coefficient of variation of the TSS load in raw wastewater was lower compared to treated wastewater, amounting to 17.3% and 23.7%, respectively. As in the case of organic compounds, there were no exceedances of limited concentration of TSS in discharged wastewater, specified in Polish legislation - 35 mg/L.

In contrast, an analysis of the TN and TP concentration revealed that almost all values in treated wastewater exceeded Polish limitation, that is, 15 mg/L for TN and 2 mg/L for TP.

The TN concentration in raw wastewater ranged from 37.7 mg/L in Q4 2017 to 132 mg/L in Q1 2020, while in treated wastewater it ranged from 10.8 in Q2 2018, to 51 mg/L in Q1 2020. The mean TN load entering the treatment plant amounted to 34.1 kg/d with a coefficient of variation of 12.6%, while after the treatment was decreased to 10.3 kg/d (coefficient of variation of 15.5%). TP concentrations in raw wastewater ranged from 3.17 mg/L (Q4 2017) to 15.2 mg/L (Q2 2017) and after treatment, from 1.4 (Q2 2020) to 9.7 (Q2 2017). The coefficients of the TP load variation in the raw and treated wastewater were similar to the corresponding coefficients for the TN. Both TN and TP concentrations did not meet the conditions specified for treated effluent discharged to water bodies and ground. The prerequisite for effective biological denitrification and dephosphatation of the wastewater is a suitable ratio of $BOD_5/TN \geq 4$ and $BOD_5/TP \geq 20$. In the study, BOD_5/TN ranged from 2.34 (Q4 2016) to 5.93 (Q2 2018) (mean 3.77), while BOD_5/TP ranged from 18.33 (Q3 2017) to 50 (Q3 2018) (mean 34.85). The low BOD_5/TN ratio indicates the mineralization of organic matter during treatment, limiting the efficiency of biological nitrogen removal (Jucherski et al. 2024). Despite the relatively high BOD_5/TP ratio in the wastewater inflowing the treatment plant, the phosphorus removal efficiency was still low, contrary to expectations. In an SBR, it is usually possible to set up conditions favorable for microbial anaerobic and aerobic dephosphatation, to absorb and remove phosphates with the excess sludge.

Reliability and efficiency factors

An additional criterion for assessing the performance of a wastewater treatment plant is to determine the reliability of the plant operation in terms of achieving the required quality of treated wastewater. Figure 4 shows the removal efficiency of the pollutant indicators tested and the RC of the plant operation. Very high efficiency was found for the removal of organic pollutants as well as TSS from wastewater (Figure 4 A) throughout the analysis period. In removing TN and TP, the treatment efficiency was low and insufficient for effective wastewater treatment (Figure 4B). The operational efficiency of WWTP, in terms of organic matter and TSS removal, was similar, or even higher than in facilities operating with similarly designed activated sludge-based multiphase systems. During the analysis period (2016–2020) no technological malfunctions were recorded in all stages of treatment. The analysis shows that the highest treatment efficiency was achieved in the spring and early summer months (March to June). The efficiency of removal of all considered pollutants remained at the same level, regardless of inflow changes. The results of these studies are consistent with those on installations with similar technological layouts, although calculations for higher throughput WWTPs dominate the literature. Łagożny et al. (2015) analyzed the technological efficiency of a mechanical-biological wastewater treatment plant with a throughput exceeding 35000 m/d, and the BOD_5, COD, and TSS content indices at the outflow showed comparable values. The mean pollutant removal efficiency was for BOD_5 – 97.9%, COD – 91.0% and TSS – 97.5%. On the other hand, Budkowska et al. (2012) assessed the performance of WWTP designed to enhance the potential for the removal of biogenic substances by characterization of unit processes and the efficiency of pollutants removal rating, they revealed, that the plant met the requirements in terms of values of parameters of wastewater discharged into the receiver, with a mean reduction of 93.2% BOD_5, 91.2% COD, and 93.9% TSS, when the concentration of TN and TP in the treated effluent did not meet the limits set out in the national regulations.

Similarly, Łagożny et al. (2015) pointed out lower efficiencies of TN elimination, oscillating between 56.0 to 92.6% and a mean of 96.6% for TP, although its required concentration in outflow was exceeded occasionally. Budkowska et al. (2012) also reported that the removal

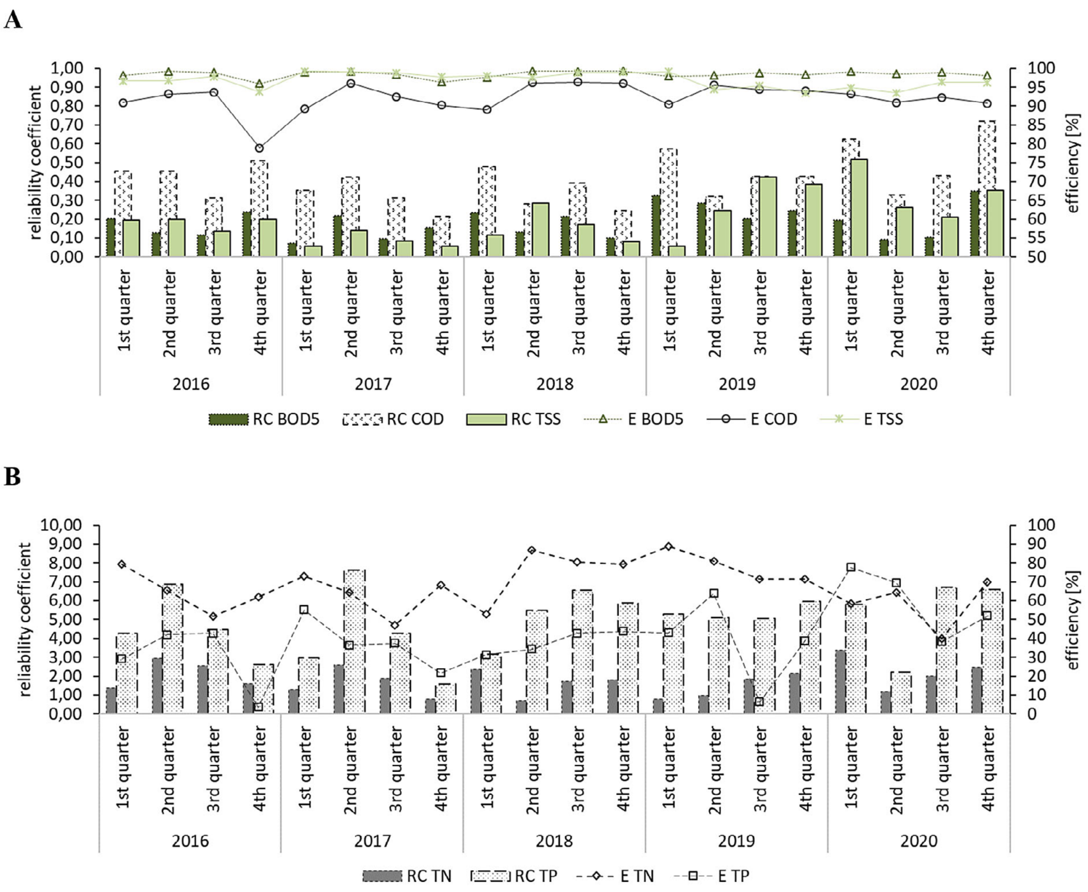

Figure 4. Reliability ratios (RC) for removal efficiencies of: (A) organics (BOD_5, COD) and solids (TSS) and (B) biogenic substances (TN, TP)

efficiencies of TN and TP, which amounted to 57.2% and 84.1%, respectively, were lower anyway compared to organic matter and TSS removal efficiency. In the WWTP analyzed in this paper, the TN removal efficiencies widely ranged from 39.8 to 89%, whereas the TP removal efficiencies ranged even from 0.1 to 77.7% and were found to be insufficient to secure the environment. The efficiency of TN removal in activated sludge systems primarily depends on the fundamental biochemical processes of nitrification and denitrification (Ding et al., 2018). In the activated sludge process phosphorus is mainly removed by assimilation, sorption and chemical precipitation (Myszograj, 2018), so effective biological removal usually requires alternating aerobic and anaerobic conditions to enhance the selective growth of specific microbial communities able to accumulate phosphorus compounds in their cells (Bunce et al., 2018). However, in small-scale WWTPs typically operating in rural areas, the problems of successful nitrogen and phosphorus removal are common. This is most often due to underinvestment, underestimation of investment costs and the need for advanced methods implementation (Shi et al., 2021; Zhang et al., 2024). As reported by Yang et al. (2021), among 146 rural WWTPs surveyed, mean removal efficiencies of 72% COD, 83.6% BOD_5, 73.7% TN and 56.9% TP were achieved, which indicates the priority to improve TP removal technologies on rural areas. Also, Bo and Wen, (2022) reported that rural wastewater disposal requires enhanced public investment, and due to financial problems, most of the WWTPs do not operate properly, posing a long-term risk to the quality of critical environmental resources. As many as 80% of the WWTPs surveyed were operating inefficiently, among others, due to excessively high operating costs. It has also been observed that the relative environmental impact of domestic wastewater is higher in rural areas than in urban ones (Chen et al., 2021).

The RC of the analyzed WWTP, calculated from Eq. 6 for the organic matter – BOD_5, COD and TSS meant 0.2, 0.4 and 0.2, respectively, which confirms its operational efficiency. For TN and TP, the mean RCs were 1.8 and 5.2 respectively, indicating that did not operate properly in this regard. On the basis of the values of the above-mentioned indicators in wastewater discharged to the receiver during the operation, parameters of the distribution were estimated, and the null hypothesis that the Weibull distribution can describe empirical data was positively verified and validated – the fit of the obtained distributions was high at 56–98%, with a significance level of $\alpha = 0.05$ (Table 3). A review of the literature confirms that an RC value of less than 1 is an indication that the treatment plant is functioning properly (Al-Shandah et al., 2021; Silva and Rosa, 2022; Atea et al., 2024).

The WTR of the WWTPs tested was established based on the distribution function (Figure 5), taking the limiting values of the indicators defined in the law regulation for WWTPs from 2000 to 9999 PE. In the case of BOD_5, COD, and TSS concentrations, no exceedances of the limitations were observed during the analyzed period meaning that the WTR was achieved 100% (Figure 5A, B, C). The available data in the literature regarding WWTPs mostly sized up to 2000 PE (Table 4). For example, the reliability coefficient reported by Micek et al. (2021) was 76 to 95% for BOD_5, 87–96% for COD and 86 to 95% for TSS. However, Marzec et al. (2018) obtained 100% RCW for the chosen parameters analyzed in the hydrobotanical treatment system. Furthermore, Jóźwiakowska and Marzec (2022) obtained 100% RCW of organic matter and TSS removal in the case of the PE = 2000 to 9999. Analysis of a larger municipal wastewater treatment plant (up to PE = 50000) showed that the WTR for BOD5 may reach 72.5%, for COD 88% and TSS up to 65% (Bugajski and Nowobilska-Majewska 2019). These differences may result from specific wastewater composition when larger-scale WWTPs could occasionally receive

Table 3. Weibull analysis coefficients for selected wastewater treatment parameters and goodness of fit test results

Purification parameters	Distribution parameters			Hollander-Proschan test	
	b	c	ϴ	test value	p value*
BOD_5	6.945	4.206	0.000	0.046	0.963
COD	71.415	5.716	0.000	0.330	0.741
TSS	12.562	2.672	0.000	0.014	0.989
TN	38.318	4.295	0.000	0.077	0.939
TP	8.616	7.246	0.000	-0.157	0.875

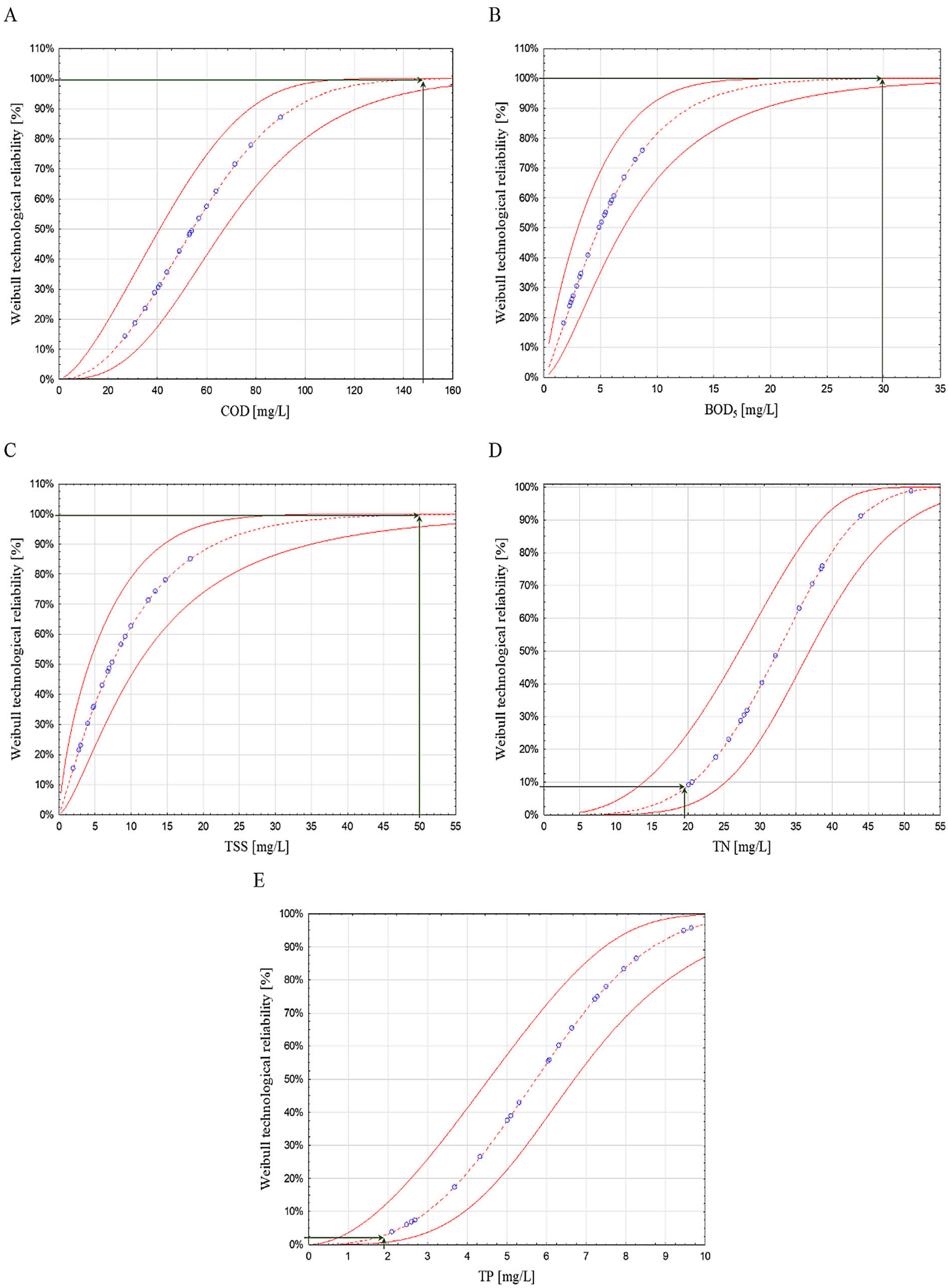

Figure 5. Weibull cumulative distribution functions and the technological reliabilities determined for each pollution parameter. Notation: dashed red line – reliability function, continuous red line – confidence interval, grey area – probability of achieving the indicators limit in the effluent, blue points – probability for variables describing the concentration of given parameter in the effluent

Table 4. The most common ranges of WWTP reliabilities and frequencies of limits exceedance reported in the literature

Parameter and reference	Reliability [%]	Exceedance frequency [%]
BOD [1, 2, 3]	77.5–99.5	17.14–23
COD [1, 2, 3]	87–98.1	3.7–8
TSS [1,2,3, 4]	66–100	0–25.3
TN [1, 2, 5]	12.2–92	2.5–85.2
TP [1, 2,5, 6]	5–88	2–81.2

Note: [1]Jucherski et al., 2019, [2]Bugajski and Nowobilska-Majewska, 2019, [3]Jóźwiakowska and Marzec, 2020; [4]Marzec, 2017, [5]Bugajski et al., 2016; [6]Marzec, 2018.

certain volumes of industrial wastewater affecting the removal. This can be confirmed by the study by Kurek et al. (2019), who – when assessing the performance of WWTP designed for PE = 82200 – obtained WTR values for BOD_5, COD and TSS of 69%, 62% and 94%, respectively.

A WTR value of 100% means that the technology provides the required level of BOD_5, COD and TSS removal reliability throughout the considered time, with a risk level $\alpha = 0.05$. The WWTP operated without any failure and the indicators in outflows did not exceed maximum limits, which gives reason to predict that with the assumed operator's level of risk, the installation passes the control procedures for the indicators of organic pollution throughout the year.

For TN and TP, the biogenic pollution indicators, WTR values of 10 and 3% were obtained, respectively (Figure 5 D and E), meaning that during the season, nitrogen did not exceed the normative for only 36 days, and the TP, just 11 days. When calculating WTR for the household hydrobotanical wastewater treatment plant, Micek et al. (2021) obtained values between 0 and 5% for both biogenic indicators. In contrast, Bugajski and Nowobilska-Majewska (2019), in a WWTP of more than PE > 50.000, obtained a WTR for TN of 97.5% and TP of 98%. Removal of these compounds in WWTPs falling within the 2000–9999 PE range seems to be difficult, in practice. In small-scale WWTPs, the concentrations of TN and TP in the raw inflow can be relatively low compared to those drained from the sewage network of larger towns. Furthermore, the qualitative indicators of the wastewater flowing into small-scale WWTPs have higher coefficients of irregularity, which can affect the instability of the activated sludge process and the removal efficiencies. The technological reliability analysis results of rural WWTPs conducted by the Weibull model confirm literature reports that this methodology quite accurately describes the reliability for a wide range of technological approaches and installations of different scales (Jóźwiakowski et al., 2018; Marzec, 2018) and concomitantly were confirmed by RC analysis.

CONCLUSIONS

Maintaining good water quality requires an efficient network of treatment plants to process the wastewater collected from small towns and villages. Therefore, implementing reliable, effective and well-maintained autonomous wastewater treatment systems in rural areas is an inevitable necessity in many parts of the world, including developing countries and those in Central and Eastern Europe, such as Poland. On the basis of the results obtained from the analysis of the raw and treated wastewater quality, it should be stated unambiguously that the analyzed wastewater treatment plant guarantees a high level of pollution reduction, in the case of organics and suspended solids, and the values of specific indicators were significantly lower than concentrations limits. Unfortunately, the Weibull reliability analysis also revealed that in the case of TN and TP only 10 and 3 percent of the time, respectively, the installation complied with current regulations. When analyzing the causes of failure, which is part of an interconnected sewerage system, it is first necessary to determine which represent operational errors and which are beyond the operator's control and, therefore, which corrective measures must be taken. As it has been seen, the reliability coefficient (RC) results are authoritative in this regard and confirmed by Weibull's (RCW) analysis. This emphasizes the need for constant oversight, improved management strategies and potential technological upgrades to ensure compliance with environmental standards and improve the reliability of treatment facilities. Weibull analysis is a valuable tool for evaluating the effectiveness of municipal wastewater treatment plants. It provides insight into the performance of treatment systems and pinpoints areas for improvement. However, the effective removal of pollutants and the need for corrective action highlight the complexity of reliability assessment in this context. The results of Weibull analysis can be compared with those of other methods and have significant implications for the maintenance and operation of wastewater treatment plants.

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