Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.29051

278 (2022) 13–22
December

Reliability and probability of organic and biogenic pollutants removal in a constructed wetland wastewater treatment plant in the aspect of its long-term operation

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Received 3 July 2022; Accepted 19 October 2022

ABSTRACT

The aim of the study was to determine the technological reliability and to forecast the efficiency of wastewater treatment in a constructed wetland wastewater treatment plant (CW WWTP) in long-term operation. The research was conducted at a facility which in the mechanical part had a 3-chamber settling tank and the biological stage consisted of 4 constructed wetland beds with horizontal sewage flow, planted with common reed (*Phragmites australis*). During 12 years of the study, the WWTP was hydraulically loaded up to 97.7% of the designed mean daily inflow, equal to $Q_{d,av.}$ = 116 m^3/d. The study showed that despite the high degree of reduction of such parameters as biochemical oxygen demand (BOD_5) (90.0%), chemical oxygen demand (COD) (88.4%) and total suspended solids (TSS) (93.5%) the achieved reliability with respect to the limit values determined by the Weibull distribution model amounted to 48%, 62% and 77% for BOD_5, COD and TSS, respectively. In the case of biogenic parameters, the technological reliability with respect to permissible values was 3% for total nitrogen and 13% for total phosphorus. Based on the performed analysis, it was concluded that the analyzed technological system did not guarantee the concentrations of pollutants in treated wastewater to reach the admissible levels defined in the related Polish legal act. In order to increase the efficiency of pollutants removal in the discussed wastewater treatment plant, the application of additional constructed wetland bed with vertical sewage flow (VF) preceding the horizontal beds (HF) was suggested.

Keywords: Constructed wetland; Horizontal flow; Vertical flow; Reliability and probability of pollutants removal; Organic and biogenic pollutants; Wastewater treatment

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1. Introduction

Currently it is of utmost importance for the management of water resources to be in accordance with the principle of sustainable development. This means that it is forbidden to deplete water resources either in quantity or quality, because water must be preserved in good condition for future generations [1,2]. It is essential to prevent water reservoirs from pollution with different substances, such as suspended solids. Also organic and biogenic pollutants, such as nitrogen (major element regulating biological productivity in waters) or phosphorus compounds can pose a big threat to the environment because they contribute to water eutrophication and contamination [3–5].

Urban and rural areas inhabited by people living in either single-family houses or block of flats should be always equipped with some wastewater collection and disposal system. There are many different solutions of wastewater treatment including big collective wastewater treatment plants used in places with high housing density and small household devices that are recommended in rural areas with scattered buildings. Depending on the type of terrain and various individual circumstances, different methods of local wastewater treatment are possible [6,7]. While choosing the most appropriate wastewater disposal system there is a strong need to discuss some criteria for its selection. These are for example criteria connected with economy (investment and operational costs), ecology (purification efficiency), reliability (reliable operation of the facility), technical aspects (modern solutions, simplicity and ease of use) as well as criteria related to the natural environment (environmental impact) [8].

Recently, constructed wetland wastewater treatment plants have become increasingly popular. This method of wastewater treatment involves the use of sorption processes of pollutants, chemical redox reactions, and biological activity of soil microorganisms and selected plants that inhabit the marsh ecosystems [9]. The first stage of most constructed wetland systems is a primary sedimentation tank which for pretreatment by sedimentation, flotation and fermentation of settled solids. Then wastewater is directed to constructed wetlands planted with vascular plants, for biological treatment. There have been already tested many different plant genus at constructed wetland systems with subsurface sewage flow, including common reed (*Phragmites australis*), willow (*Salix viminalis*), giant miscanthus (*Miscanthus giganteus*), Jerusalem artichoke (*Helianthus tuberosus*), Virginia mallow (*Sida hermaphrodita*) or manna grass (*Glyceria maxima*) [10]. Based on many years of studies constructed wetland systems have been found to provide some of the highest level of pollutants removal efficiency for domestic wastewater treatment, which allows to meet the quality requirements for treated wastewater discharged to the environment [11]. Research conducted to date shows that the highest levels of wastewater purification efficiency and operational reliability are achieved for hybrid constructed wetland systems, combining the use of different types of wastewater flow and different plant species [10,12,13].

The aim of this research was to analyze the efficiency and operational reliability of removal of pollutants such as total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) at the Kickuth-type constructed wetland wastewater treatment plant during its long-term operation (2006–2017).

2. Materials and methods

The studied wastewater treatment plant (WWTP) is located in the Lesser Poland Voivodeship, Southern Poland. Treated sewage is discharged the Stawki creek, which is a tributary of the Frydrychówka creek, in the Skawa river basin. The WWTP was designed to served local community of 790 Population Equivalent (P.E.), with an average daily inflow of $Q_{d,av.}$ = 116 m^3/d and a maximum daily inflow of $Q_{d,max.}$ = 180 m^3/d. The plant is a facility with primary mechanical wastewater treatment by a cage-type screen with a clearance of 30 mm, on which coarse contaminants are stopped and retained. Next stage of treatment consists of a three-chamber reinforced concrete settling tank, which total active volume is 200 m^3. The fourth chamber of the tank is a retention tank with submersible pumps for pumping the sewage to constructed wetland with appropriate timing (intervals) and capacity volume intervals. There are electromagnetic throttles installed on distribution pipes delivering wastewater to the beds, for control of uniform hydraulic loading on each bed. The biological part of the treatment plant is made up of 4 constructed wetland beds with horizontal wastewater flow (HF), planted with common reed (*Phragmites australis*). The total area of the 4 constructed wetland beds is 3,000 m^2. The wetland beds are isolated from the native soil by a geomembrane. Each bed has thickness of 0.6 m and was made according to guidelines proposed by Kickuth: consists of local soil mixed with sawdust with addition of dolomite and with straw layer in the lower part. The top layer on which reeds are planted consists of local soil mixed with peat. The construction of inflow and outflow parts of each bed is made of a layer of stones, in which PVC pipes with a diameter of 100 mm are placed to distribute inflowing and collect outflowing sewage uniformly. During the study period, the wastewater treatment plant was operated correctly and in accordance with recommendations. The accumulated bottom sludge from the settling tank was taken out once a year by a septic tank truck for disposal in a collective wastewater treatment plant. In addition, once a month there was carried out an inspection in the settling tank regarding the scum forming on the surface of the wastewater, and if necessary, the scum was removed. In the case of the constructed wetland bed, the above-ground part of the vegetation was mechanically removed once a year in March.

The scheme of the technological system of the analyzed wastewater treatment plant was presented in Fig. 1.

The studies concerning wastewater quality were conducted over a 12-year period, that is, from January 2006 to December 2017. During the study period, 141 samples of both raw and treated wastewater were collected and analyzed once a month. Raw wastewater samples were collected at the inflow to the first chamber of the settling tank (No. 3 in Fig. 1), while treated wastewater samples were collected from the collection and control well before discharging wastewater to the creek (No. 9 in Fig. 1).

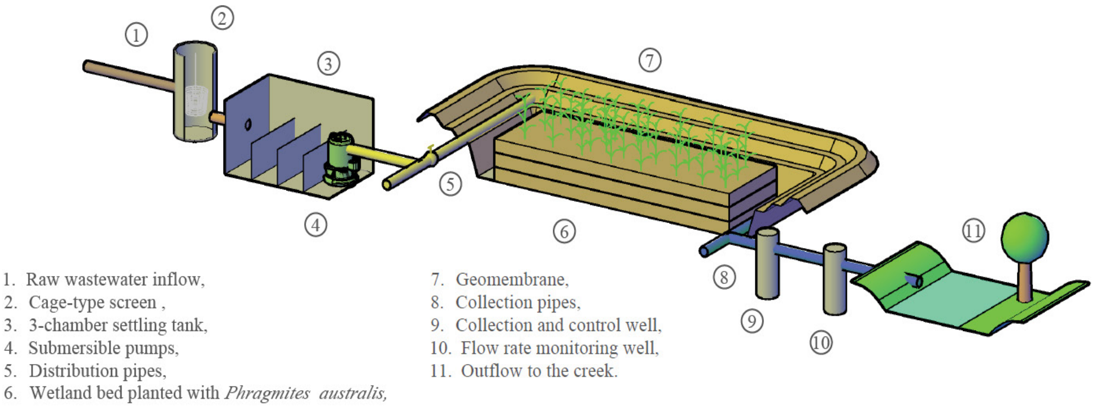

Fig. 1. Scheme of the technological system of the studied wastewater treatment plant.

The technological reliability of the wastewater treatment plant was developed using the reliability model with Weibull distribution. This method, as shown in the studies conducted among others by Bugajski and Nowobilska-Majewska [14] and Jóźwiakowska and Marzec [4], is a general probability distribution that is applicable in determining the technological reliability of wastewater treatment plants operation. The Weibull distribution can be used when the intensity of exceedances of the limit values for the studied pollution indicators is a monotonic variable. The Weibull distribution is characterized by a probability density function Eq. (1) with parameters b, c and θ:

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

where x – variable defining the concentration of a pollutant indicator in treated wastewater, b – scale parameter, c – shape parameter, θ – position parameter.

Under the assumptions: $\theta < x$, $b > 0$, $c > 0$.

A reliability function R(x), as the complement of the distribution function F(x) to unity, was calculated from Eq. (2):

$$R(x)=1-f(x) \quad (2)$$

where:

$$F(x)=1-\exp\left[-\left(\frac{x-\theta}{b}\right)^{c}\right] \quad (3)$$

Estimation of the Weibull distribution parameters was performed using the maximum likelihood method. The quality of fit of the Weibull distribution to the empirical data was carried out using the Hollander–Proschan test. The analysis of this part of the study was performed using the STATISTICA 8 program.

The technological reliability was developed for the parameters determined in the legal act in force in Poland [15]. The discussed wastewater treatment plant belongs to a group of facilities of serving up to 2,000 P.E., therefore, there are following permissible values of pollution parameters at the effluent from the researched wastewater treatment plant:

- BOD_5 – 40 mg/L,
- COD – 150 mg/L,
- TSS – 50 mg/L,
- Total nitrogen – 30 mg/L,
- Total phosphorus – 5 mg/L.

3. Results and discussion

3.1. Characteristics of inflowing wastewater

During the studied period, the actual average daily hydraulic loading of the wastewater treatment plant was 113 m^3/d, which was 97.5% of the designed loading (116 m^3/d). A detailed characteristics of flow rates of wastewater flowing into the researched facility was presented by Mucha et al. [16]. According to the design assumptions, the technological system of the treatment plant should ensure a high degree of reduction of concentration of organic and biogenic pollutants, guaranteeing that pollution parameters will be below permissible values for facilities of this size. As reported by Jucherski et al. [17], Jóźwiakowski et al. [18], Gajewska et al. [19] and Araújo Almeida et al. [20] constructed wetland wastewater treatment plants provide high efficiency of organic and biogenic pollutants removal from domestic wastewater. In the above-mentioned papers, the authors point out that one of the main factors affecting the efficiency of pollutants removal in constructed wetland systems is their proper operation. Another important factor influencing the efficiency of pollutants removal is variability of the quality and quantity of wastewater flowing into the treatment plant [21]. Therefore, the concentrations of pollution parameters in raw wastewater were analyzed in order to compare them with typical concentrations for domestic wastewater reported in the literature [22–24]. In the case of the pollution parameters selected for this research, it was found that the concentrations of these parameters in raw sewage in the analyzed 141 samples were at highly variable levels, as indicated by coefficients of variation Cv oscillating from 67% to 94% and their standard deviations [25]. This high unevenness of the BOD_5, COD and TSS values is noticed when comparing the arithmetic mean to the median. The median is considered to be the authoritative value reflecting the mean values of pollution indicators. In raw wastewater, the median value of BOD_5, COD, and TSS were 380.0, 939.0 and for 291.0 mg/L, respectively. The median values of these 3 parameters are comparable to typical values of these parameters in domestic wastewater. However, the arithmetic mean values of these parameters were 579.7 mg/L for BOD_5, 1,351.9 mg/L for COD, and 846.0 mg/L for TSS. This indicates that the arithmetic mean concentrations of the discussed parameters were higher than in typical domestic wastewater. For the biogenic parameters such as $N–NH_4$, TN, $P–PO_4$ and TP, it was found that the level of variation of their concentrations in raw sewage was high, but definitely lower than for BOD, COD and TSS [25]. The median of most of these parameters differed slightly from the arithmetic mean, however it was at the same level for TP. The median for $N–NH_4$ was 65.5 mg/L, 83.4 mg/L for TN, 10.8 mg/L for $P–PO_4$ and 13.9 mg/L for TP. Overall, concentrations of biogenic parameters in raw wastewater were similar to typical domestic sewage. The characteristic values of the analyzed parameters in inflowing wastewater are presented in Table 1.

One of basic activities essential for proper operation of any wastewater treatment plant, regardless of its size and the type of used technology, is the constant and systematic monitoring of treatment processes [26–28]. Monitoring of wastewater treatment processes should begin with constant control of the concentration of pollutants in inflowing wastewater. It is also important that wastewater quality control should be efficient, that is, the operator shall have information on the wastewater quality at each treatment stage very quickly. Taking into account the methodology of determining the values of individual parameters, it was assumed that the results of chemical analyses of parameters such as COD and $N–NH_4$ are available after just a few hours after taking wastewater samples. Therefore, these two parameters, were selected as authoritative for determining the concentrations of organic and biogenic pollutants in wastewater flowing into the treatment plant. As stated by Abdalla and Hammam [29] and Bhat et al. [30] on the basis of the concentration of one parameter it is possible to accurately estimate the values of other pollutants in wastewater. In the discussed case COD and $N–NH_4$, may be a simplified measure of concentrations of over five parameters, provided that they are mutually correlated. In order to confirm this correlation, a detailed analysis was carried out to show the mutual correlations between the discussed parameters.

In order to characterize and illustrate the mutual correlation of the analyzed parameters, a correlation matrix was developed (Table 2). According to the scale proposed by Stanisz [31], a very high correlation between organic parameters in raw sewage was found. The correlation between COD and BOD_5 was $r_{x,y} = 0.88$, and the correlation between COD and TSS was $r_{x,y} = 0.77$. For the biogenic parameters, the correlations between both $N–NH_4$ and $P–PO_4$ and $N–NH_4$ and TP were $r_{x,y} = 0.57$ and $r_{x,y} = 0.66$, respectively. The correlation between $N–NH_4$ and TN was $r_{x,y} = 0.79$, which is a very high level according to the scale proposed by Stanisz [31].

It was important to determine the range of changes of COD and TSS concentration in raw wastewater in relation to changes of BOD_5 values. For this reason, a scatter plot was developed and is presented in Fig. 2, along with a regression line and an equation describing the correlation relationship that occurred. It can be concluded from the equations describing the regression lines in Fig. 2, that a 1 mg/L change in COD causes a 0.36 mg/L change in BOD_5 (blue line) and a 0.85 mg/L change in TSS (red line). The correlation relationship described was confirmed by the student's t-test at a significance level of $\alpha = 0.05$.

For the effects of $N–NH_4$ concentration on TN, $P–PO_4$ and TP concentrations, a graph presented in Fig. 3 was developed. It can be concluded from the equations describing the regression lines (Fig. 3), that a 1 mg/L change in $N–NH_4$ concentration in raw wastewater results in a 1.05 mg/L change in TN concentration (blue line), a 0.12 mg/L change in $P–PO_4$ concentration (red line) and a 0.15 mg/L change in TP concentration (green line). The correlation relationship described was confirmed by the student's t-test at a significance level of $\alpha = 0.05$.

3.2. Susceptibility of wastewater to biological decomposition

In the processes of nitrification and denitrification, that is, nitrogen compounds removal processes occurring in constructed wetland beds, the amount of dissolved organic matter in wastewater plays an important role [32,33]. In order to determine whether the amount of readily decomposable organic matter in wastewater undergoing biological treatment was at the optimum level in terms of the susceptibility of sewage to biological decomposition, an analysis on this issue at the studied treatment plant was performed. For this purpose, the ratios of COD/BOD_5 as well as BOD_5/TN and BOD_5/TP were determined. Based on the guidelines adopted by Heidrich and Witkowski [34] and Liu et al. [35], it was assumed that biological treatment processes occur most effectively if sewage flowing into the constructed wetland is characterized by following appropriate relationships: $COD/BOD_5 \le 2$, $BOD_5/TN \ge 4$, and $BOD_5/TP \ge 20$. In order to illustrate the number of

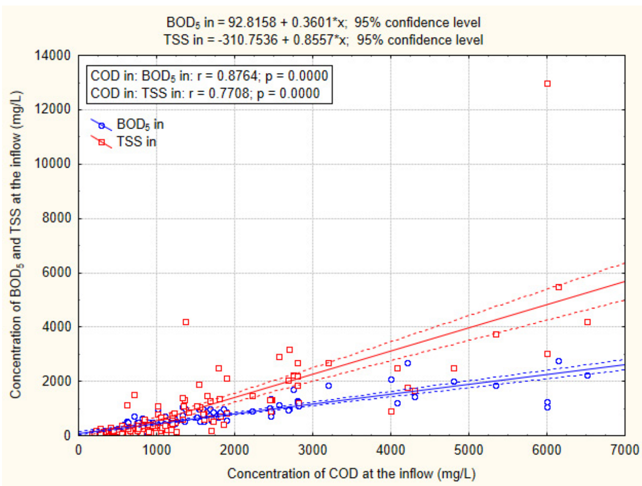

Fig. 2. Scatter plot with a regression line and a 95% confidence level for interdependencies between the concentration of BOD_5 and TSS and the concentration of COD in inflowing wastewater.

wastewater samples in which these relationships were met, histograms of the frequency of occurrence of each parameter ratios were prepared and shown in Fig. 4. In each case of the 3 analyzed relationships, 4 class intervals were proposed with an interval of 1 for the COD/BOD_5 ratio, with an interval of 2.5 for the BOD_5/TN ratio, and with an interval of 10 for the BOD_5/TP ratio. In the histograms shown in Fig. 4A–C characteristic percentage of the analyzed relationships were presented. Analyzing the COD/BOD_5 relationship (Fig. 4A), it was found that only 31.2% of the analyzed cases were below the value of 2, that is, met the condition of biodegradability of organic compounds. In the case of the relationship between the amount of organic compounds expressed by BOD_5, and the concentration of biogenic compounds expressed by TN and TP (Fig. 4B and C), it was found that in 46.1% of cases the ratio of BOD_5/TN and in 67.4% of cases the ratio of BOD_5/TP were adequate and guaranteed high efficiency of biological treatment.

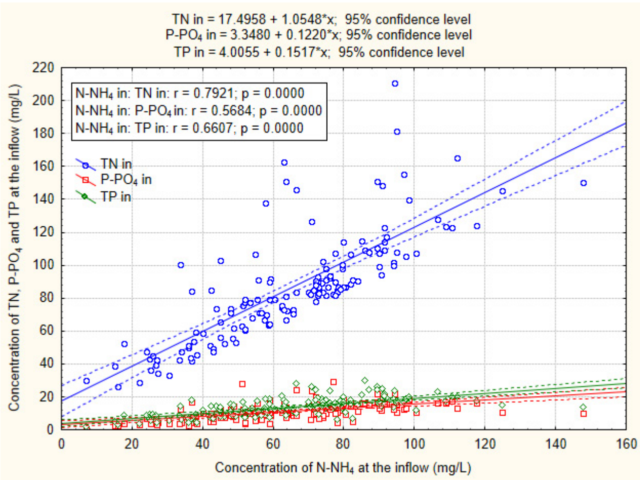

Fig. 3. Scatter plot with a regression line and a 95% confidence level for interdependencies between the concentration of TN, P–PO_4 and TP and the concentration of N–NH_4 in inflowing wastewater.

3.3. Pollutants removal efficiency

Taking into account the detailed analysis of raw wastewater there were carried out some study concerning the efficiency of pollutants removal in the technological line of the wastewater treatment plant. It was found that the degree of reduction of concentrations of BOD_5, COD and TSS was at a high level and similar to the results reported by other authors [36–38], who also analyzed constructed wetland wastewater treatment plants. The median BOD_5 removal efficiency was 90.0%, COD – 88.4%, and TSS – 93.5%. In the case of parameters from the biogenic group,

Table 1
Statistical characteristics of concentration of contamination indicators in inflowing wastewater

Parameters	Statistics					
	Average	Median	Min.	Max.	Standard deviation	Coefficient of variation
	mg/L					%
BOD_5	579.7	380.0	38.0	2,750.0	524.4	90
COD	1,351.9	939.0	169.0	6,512.0	1,275.9	94
TSS	846.0	291.0	40.0	13,000.0	1,416.4	67
N–NH_4	64.9	65.5	6.9	147.9	24.6	38
TN	86.0	83.4	26.5	210.7	32.8	38
P–PO_4	11.3	10.8	0.94	29.1	5.3	47
TP	13.9	13.9	1.94	30.2	5.7	41

Table 2
Cross-correlation matrix of contamination indicators in inflowing wastewater

Parameters	BOD_5	COD	TSS	N–NH_4	TN	P–PO_4	TP
BOD_5	–	0.88	0.63	0.14	0.40	0.20	0.30
COD	0.88	–	0.77	0.17	0.48	0.30	0.39
TSS	0.63	0.77	–	0.04	0.37	0.27	0.31
N–NH_4	0.14	0.17	0.04	–	0.79	0.57	0.66
TN	0.40	0.48	0.37	0.79	–	0.62	0.75
P–PO_4	0.20	0.30	0.27	0.57	0.62	–	0.81
TP	0.30	0.39	0.31	0.66	0.75	0.81	–

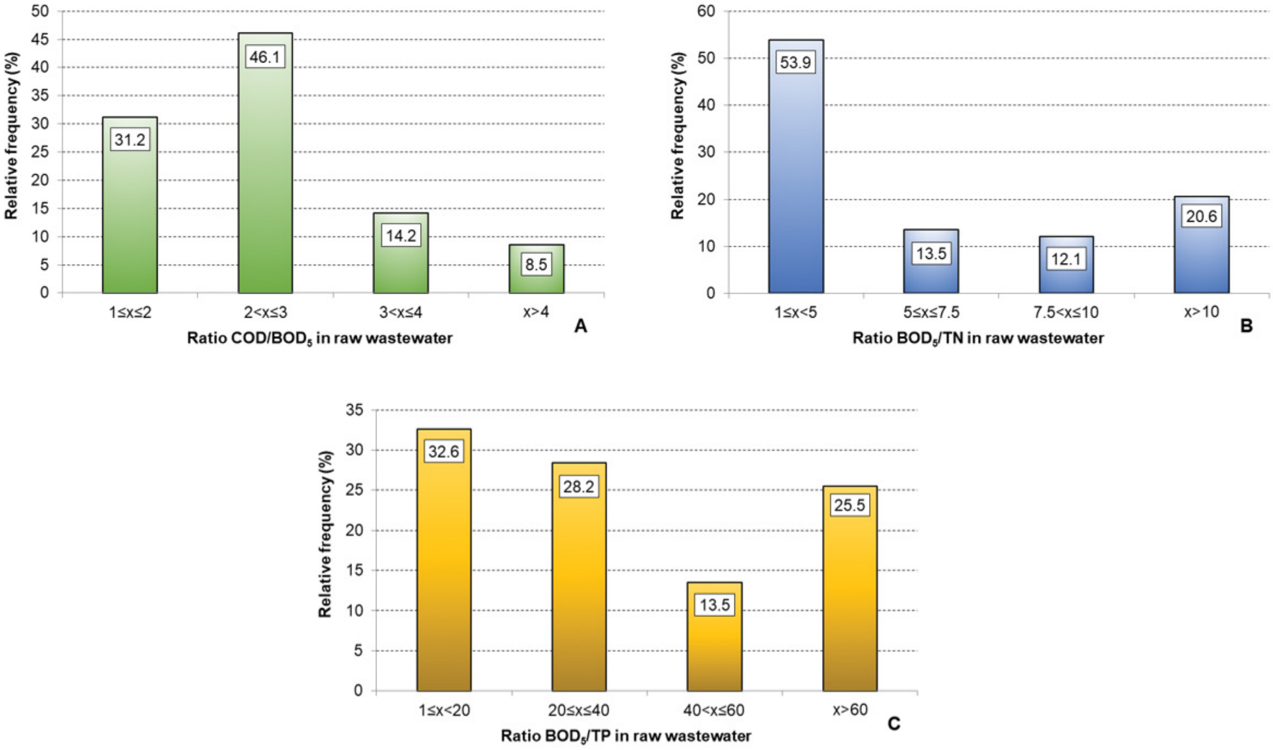

Fig. 4. Histograms of the frequency of ratios of COD/BOD_5 (A), BOD_5/TN (B) and BOD_5/TP (C) in inflowing wastewater.

the reduction level was low and amounted 9.3%, for $N–NH_4$, 18.9%, for TN, 7.4% for $P–PO_4$, and 17.9% for TP. Moreover, high instability of their removal efficiency was found, as evidenced by the high value of coefficient of variation Cv. According to the interpretation proposed by Mucha [25], the concentrations of these parameters in treated wastewater were characterized by a very high variability ranging from 71% to 88%. In the case of concentrations of nitrogen related parameters in treated wastewater, their variability was recorded at an average level (Cv = 30%–32%), while in the case of the parameters representing phosphorus compounds in treated wastewater, their high variability of Cv = 49%–56% was noted. The permissible value of BOD_5 in treated wastewater was in 42% of cases higher than the limit value listed in the regulation as equal to 40 mg/L. For COD, the limit value of 150 mg/L in the effluent was exceeded in 27% of all the studied cases, and the concentration limit of TSS (50 mg/L) was exceeded in 20% of cases. As far as the permissible concentrations of biogenic parameters in the effluent are concern, the limit concentrations of TN (30 mg/L) and TP (5 mg/L) were exceeded in 98.6% and 84.4% of all the researched cases, respectively. Characteristic concentrations of analyzed parameters of wastewater discharged to the environment are presented in Table 3.

3.4. Pollutants removal reliability

In the further analytical part of the research, there was carried out the determination of the technological reliability of selected pollutants removal, that is, those for which acceptable values were set in the legal act in force in Poland [15].

For the estimated distribution parameters, the hypothesis of assuming Weibull distribution for approximation of empirical data was verified. As a result of the statistical analysis concerning the test probability p for the analyzed parameters, it was found that the empirical data can be described by the Weibull distribution and accepted as the null hypothesis. The results of fitting the distribution with the Hollander–Proschan test along with the estimated parameters are presented in Table 4.

The technological reliability based on the Weibull distribution for the researched wastewater treatment plant, with respect to the permissible concentrations of the analyzed parameters, were as follows:

- BOD_5 – 48%,
- COD – 62%,
- TSS – 77%,
- TN – 3%,
- TP – 13%.

The results of the analysis regarding the technological reliability of the WWTP operation are presented in Fig. 5A, C, G, E and I. It was found that the ability to remove organic (BOD_5, COD and TSS) as well as biogenic (TN and TP) pollutants was insufficient to reach permissible concentrations. The median degree of organic parameters reduction oscillated around 90%. However, despite the high level of reduction of the analyzed organic parameters, it was found that the treatment plant did not guarantee the values of these parameters to be at the acceptable level. In the case of biogenic compounds, the median degree of their reduction oscillated around 18%. As a result of such a low level of nitrogen and phosphorus compounds removal, the concentrations of these parameters in outflowing wastewater were higher than the permissible concentrations in the vast majority of cases.

It is essential from the point of view of both the operation and the controlling authorities to determine the probability (prediction) of occurrence of values of particular parameters exceeding the permissible levels. For this reason, an empirical probability of occurrence of values higher than permissible for a given parameter were determined by means of distribution, calculated on the basis of relative frequencies (Fig. 5B, D, F, H and J). Using descriptive analysis of the data set structure, the curves of cumulative frequencies were determined in relation to relative values of the discussed parameters in the effluent. Probability calculations were carried out on the basis of the size of class intervals for the frequency of occurrence for the analyzed parameters. For each of the discussed pollution parameter, the curves of cumulated values of particular indicators with higher ones were prepared and presented in Fig. 5B, D, F, H and J together with empirical probabilities. The developed histograms provided a rationale for selecting a theoretical distribution to describe the empirical distribution [39].

Calculated distribution functions allow to determine (read) the probability of exceeding the permissible concentrations of particular contamination parameters. For BOD_5 the probability of exceeding permissible 40 mg/L was 33%, for COD the probability of exceeding permissible 150 mg/L was 19%, for TSS the probability of exceeding permissible 50 mg/L was 15%, for TN the probability of exceeding permissible 30 mg/L was 95%, and for TP the probability of exceeding permissible 5 mg/L was almost 83%.

4. Conclusions

The research showed that although the efficiency of pollutants removal at the studied WWTP was high, the BOD_5, COD and TSS in the effluent exceeded permissible values specified in the appropriate legal act in force in Poland in many cases. As far as biogenic parameters of pollution such as TN and TP are concerned, reduction degree was negligible and in most cases the concentrations of these parameters turned out to be higher than the permissible values. The technological reliability of the wastewater treatment plant for the parameters from the oxygen related group oscillated around 60%, while for biogenic parameters amounted to 35% for TN and 13% for TP. It was shown that the treatment technology

Table 3
Statistical characteristics of concentration of contamination parameters in outflowing wastewater

Parameters	Statistics					
	Average	Median	Min.	Max.	Standard deviation	Coefficient of variation
	mg/L					%
BOD_5	45.2	38.0	10.0	280.0	33.3	74
COD	134.7	109.0	36.0	747.0	96.1	71
TSS	33.2	26.0	4.0	169.0	29.2	88
$N–NH_4$	59.3	59.0	21.5	123.0	18.9	32
TN	69.4	70.3	25.9	134.7	20.7	30
$P–PO_4$	9.2	9.8	0.1	21.8	5.2	56
TP	11.2	10.7	1.0	29.4	5.5	49

Table 4
Results of the estimation of the Weibull distribution parameters together with the measures of goodness of fit to empirical data

Sewage quality parameters	Distribution parameters			Hollander–Proschan test	
	b	*c*	θ	Test value	*p**
BOD_5	50.924	1.5811	9.0606	0.552335	0.58072
COD	151.75	1.6037	34.545	0.520349	0.60282
TSS	35.995	1.2566	3.8434	0.616115	0.53782
TN	76.894	3.6232	17.980	0.232495	0.81615
TP	12.668	2.1337	–0.444	–0.191966	0.84777

Notes: b – scale parameter; c – shape parameter; θ – location parameter;
*p – probability value; if p ≤ 0.05 then the zero hypothesis – stating that the empirical data can be described with Weibull distribution – must be rejected.

used did not ensure permissible concentrations of pollutants in the effluent. It is suggested to reconstruct one-stage constructed wetland into a hybrid Vertical Flow-Horizontal flow (VF-HF) system. As shown by operational experience and literature reports, this type of systems is more efficient in terms of both organic and biogenic pollutants disposal [40]. In addition, it is recommended to conduct continuous and systematic monitoring of the quality of both raw wastewater as well as wastewater after mechanical treatment at the sedimentation tank. The quality control of mechanically treated sewage can show whether the sedimentation tank removes and retains an adequate amount of pollutants before carrying wastewater to biological treatment stage. The presented results of the research are really valuable in terms of application aspects due to the long period of the study performed. The 12-year period of measurements allowed the

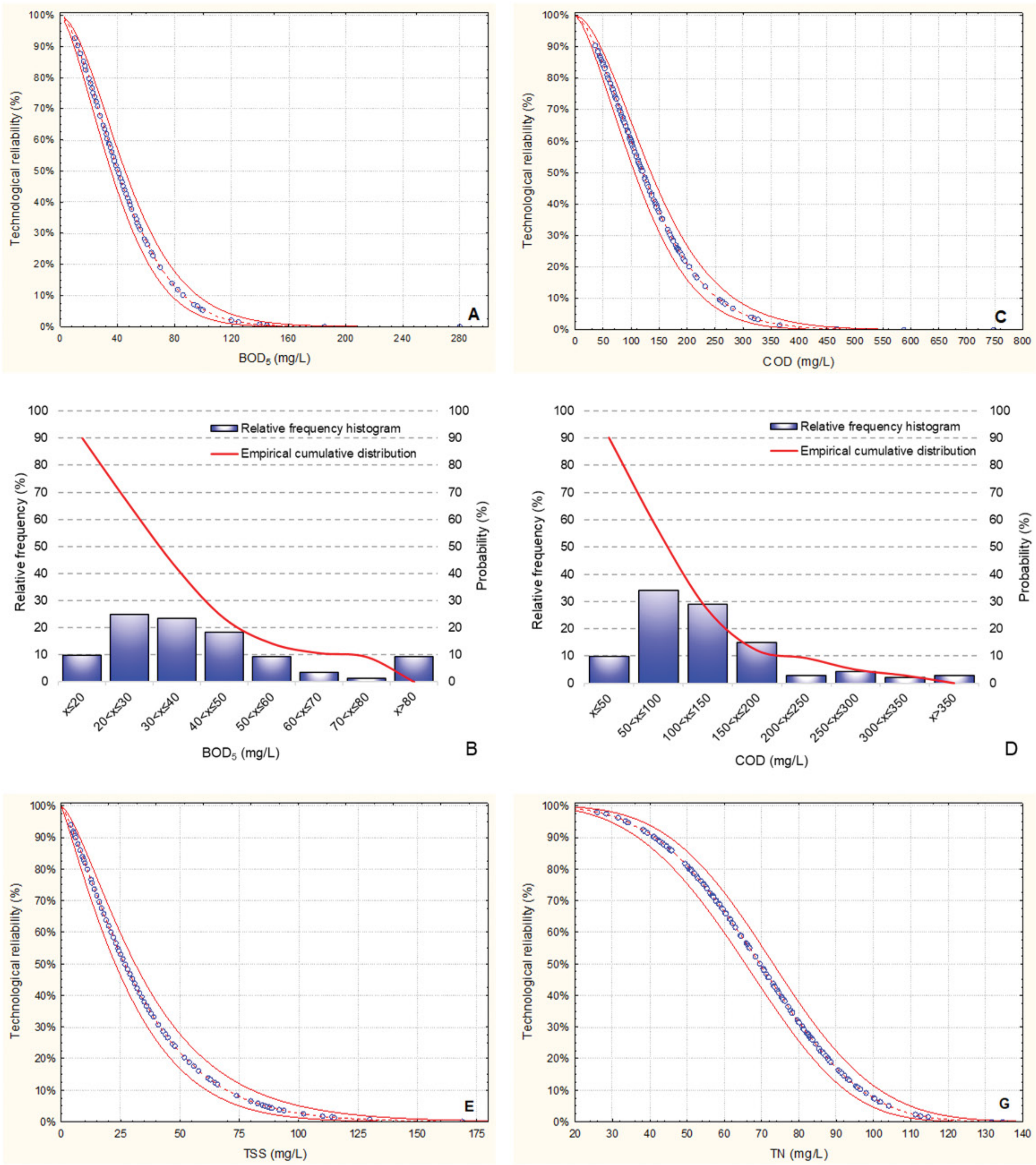

Fig. 5. Continued

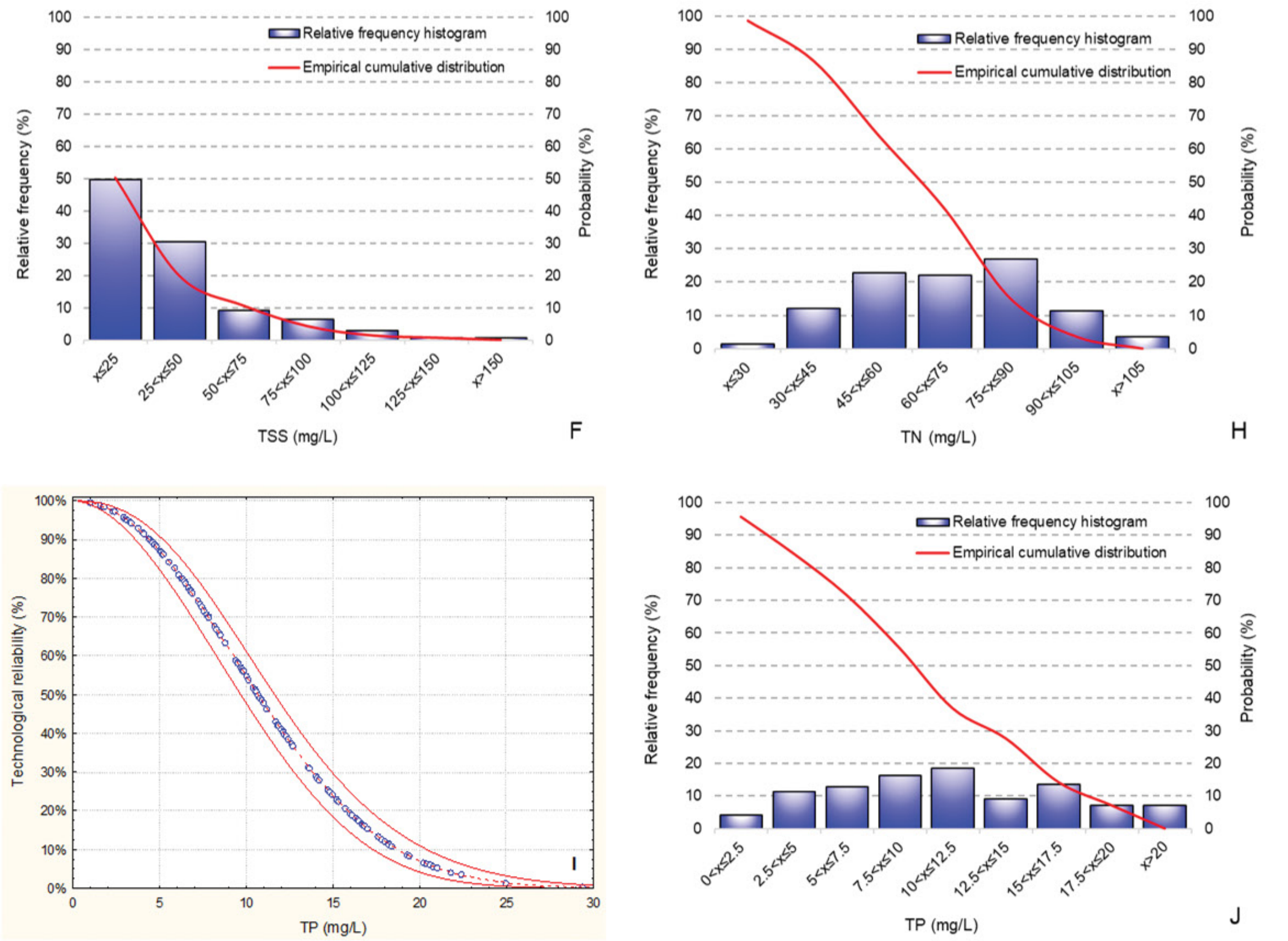

Fig. 5. Reliability of removal (A, C, E, G, I) and probability of exceeding acceptable values (B, D, F, H, J) for the analyzed contamination parameters.

development of detailed conclusions about the stability and efficiency of this type of facilities during operation.

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