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Assessment of the technological reliability of a hybrid constructed wetland for wastewater treatment in a mountain eco-tourist farm in Poland

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ABSTRACT

The aim of the present study was to assess the technological reliability of a domestic hybrid wastewater treatment installation consisting of a classic three-chambered (volume 6m^3) septic tank, a vertical flow (VF) trickling bed filled with granules of a calcinated clay material (KERAMZYT), a special wetland bed constructed on a slope, and a permeable pond used as a receiver. The test treatment plant was located at a mountain eco-tourist farm on the periphery of the spa municipality of Krynica-Zdrój, Poland. The plant's operational reliability in reducing the concentration of organic matter measured as BOD_5 and COD, was 100% when modelled by both the Weibull and the lognormal distributions. The respective reliability values for total nitrogen removal were 76.8% and 77.0%, total suspended solids – 99.5% and 92.6 %, and PO_4-P – 98.2% and 95.2%, with the differences being negligible. The installation was characterized by a very high level of technological reliability when compared to other solutions of this type. The Weibull method employed for statistical evaluation of technological reliability can also be used for comparison purposes. From the ecological perspective, the facility presented in the study has proven to be an effective tool for protecting local aquifer areas.

Key words: mountain aquifers; rural areas; cold climate; hybrid constructed wetland; technological reliability

INTRODUCTION

Evaluation of the technological reliability of individual wastewater treatment systems should be an important part of planning and decision-making in water and wastewater management, particularly now, when a wide range of technological solutions are available (Jóźwiakowski et al. 2015). Reliable operation of wastewater treatment units must be ensured due to both environmental and human health protection concerns (Eisenberg et al. 2001; Wojciechowska et al 2016). Reliable operation of domestic wastewater treatment plants is especially important in mountain aquifer areas, which are very sensitive to pollution. Mountainous regions in Poland play a key role in developing and sustaining vital socio-economical and environmental functions which intertwine in the activities of spa and tourist resorts, forest management, environment-friendly farming and especially in hydrology.

Although Polish mountainous areas have a high water production potential, as manifested by an almost 40% regional surplus in relation to the water discharged by all the rivers, Poland occupies one of the last positions in Europe in terms of the total freshwater resources, which are estimated at 1630 $m^3 \cdot year^{-1} \cdot person^{-1}$. Therefore, it is essential that groundwater and the upper reaches of local streams and mountain rivers should be protected against biological, chemical and bacteriological pollution resulting from the discharge of untreated domestic sewage to the environment in rural areas. One of the key issues in technological progress in wastewater management in rural, environmentally valuable areas, is the construction of small domestic or local wastewater treatment plants with a high, long-term reliability and effectiveness in reducing wastewater pollutions (Jucherski & Walczowski 2012; Masi et al. 2013; Jóźwiakowski et al. 2016; Gajewska et al. 2015).

Nowadays, more and more innovative wastewater treatment systems are being designed and offered on the market, which spurs the need for developing a universal method of assessing the reliability of the various treatment processes and facilities. Such a method would be helpful in planning and comparing the levels of protection offered by the various technologies (Jóźwiakowski et al. 2015).

The methods for determining the reliability of individual wastewater treatment systems have been described in more detail by Eisenberg et al. (2001). Lately Djeddou & Achour (2015) have proposed a method for predicting reliability using artificial neural networks.

A comprehensive and useful assessment of the reliability of domestic wastewater treatment plants should be based on a series of measurements and observations of treatment variability under normal and critical operating conditions as well as the probability of mechanical failures and their impact on the quality of the treated wastewater (Eisenberg et al. 2001).

Reliability is defined as the probability of achieving required performance of a wastewater treatment plant (WWTP) over a specific time and under specific conditions (Oliveira & Sterling 2008). To assess WWTP, a coefficient of reliability (CR) which relates mean pollutant concentrations to effluent standards (Niku et al. 1982) can also be used.

The statistical step in the assessment of WWTP reliability presented in this article is based on the normal (Niku et al. 1982), the lognormal (Oliveira & Sterling 2008) and the Weibull distributions (Bugajski et al. 2012; Nastawny & Jucherski 2013; Wałęga 2009). Statistical distributions of probability are used to establish the probability of occurrence of selected values of pollutants. Recent findings reported in the literature (Bugajski et al. 2012; Bugajski

2014; Nastawny & Jucherski 2013; Wałęga 2009) show that the Weibull distribution is an accurate and precise tool for evaluation of WWTP reliability.

Systems for domestic wastewater management are individual facilities with technical and quasi-technical treatment devices designed to collect and treat wastewater to the extent required by specific regulations (Regulation of the Polish Minister of Environment 2014) as well as discharge it to receivers without adversely affecting the soil–water complex in the place where the facilities are located. In rural areas, individual treatment facilities usually operate without constant supervision and are therefore particularly exposed to fluctuations in efficiency due to a variable load pattern (Massoud et al. 2009; Platzer & Mauch 1997); in consequence, the quality of effluent often does not meet the requirements stipulated in the regulations in force.

Hybrid wetland systems have recently been more and more frequently used for the treatment of domestic wastewater from museum buildings and forester or mountain shelters, including those located in national parks. When well designed and properly maintained, they can achieve high pollutant removal efficiencies (Masi et al. 2007; Osaliya et al. 2011; Jóźwiakowski et al. 2014; Sanchez-Ramos et al. 2015; Gizińska-Górna et. 2016; Jóźwiakowski et al. 2016). The literature, however, provides little data on the reliability of pollutant removal processes in such CWS over long periods (years) of operation.

The aim of the present study was to assess the range of long-term fluctuations in treatment reliability in a domestic hybrid wastewater treatment plant. The plant had been built over ten years before on an eco-tourist farm in the mountain municipality and spa of Krynica-Zdrój in Poland and had been continuously operating since that time. The following indicators of wastewater contamination were measured: (i) BOD_5 and COD for contamination with organic matter, (ii) total suspended solids, (iii) total nitrogen (TN), and (iv) phosphorus PO_4-P. The indicators results (pollutant concentrations) were compared to the Polish standards for treated wastewater (Regulation of the Polish Minister of Environment 2014) discharged into water and soil from treatment plants below 2000 PE.

MATERIAL AND METHODS

The subject of the study was a hybrid wastewater treatment plant described in detail by Jucherski & Walczowski (2012). The plant was operated by an eco-tourist farm located in the rural peripheries of the spa town of Krynica-Zdrój, Poland. The plant had been monitored over the years 2005–2015. A schematic of the facility with the sampling points is presented in Fig. 1.

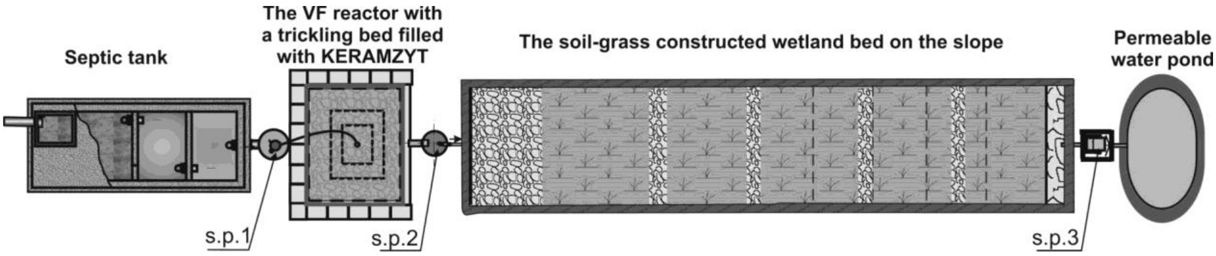


Figure 1. Schematic of the wastewater treatment installation (sampling points: s.p.1, s.p.2, s.p.3)

The installation consisted of a classic three-chamber septic tank, a vertical flow reactor (filter) followed by a special constructed wetland (SCW), and a permeable water pond as a receiver of the final effluent. The septic tank, with a capacity of $6m^3$, was a monolithic concrete structure designed to receive sewage with a seasonal variability from 3 to 15 persons (with an average of PE=5). The substrate used in the vertical flow reactor were granules of a sintered clay material (KERAMZYT). To improve biological treatment and nitrification at the vertical stage, the wastewater was sprayed onto the surface of the reactor. Due to the harsh climate, it was necessary to use a cover to insulate the reactor from freezing in winter. Downstream of the reactor, there was a special filter bed (wetland) with subsurface flow, planted with a mix of reed sweet grass (*Glyceria maxima*), reed canary grass (*Phalaris arundinacea*) and other grasses spontaneously inhabiting the bed. The bed was constructed on a slope for tertiary treatment and removal of the remaining nutrients (N and P). The installation ended with a permeable pond for receiving and infiltration of the treated wastewater into the soil complex surrounding the treatment unit.

The average hydraulic load of the treatment plant in the investigation period was 621.2 $dm^3 \cdot day^{-1}$, and the average concentrations of pollutants in raw sewage were 271.7 mg $O_2 \cdot dm^{-3}$ for BOD_5, 390.8 mg $O_2 \cdot dm^{-3}$ for COD, 75.4 $mg \cdot dm^{-3}$ for total suspended solids, 110.5 $mg \cdot dm^{-3}$ for total nitrogen, and 12.3 $mg \cdot dm^{-3}$ for phosphorus PO_4-P (Table 1). The flow of treated wastewater was calculated based on the water consumption reading of a water meter. BOD_5 was determined using the OxiTop respirometric measuring system from WTW. COD, total nitrogen and phosphate phosphorus were determined using a Merck SQ118 photometer and a Merck thermoreactor TR-200. The total suspended solids were determined by a gravimetric method, in accordance with the standard PN-72/C-04559/02.

The statistical analysis was based on the normal, lognormal and Weibull distributions. Statistica v. 13.0 software was employed to define the characteristics of the distribution of the empirical data using the Kolmogorov-Smirnov goodness-of-fit test. Data were tested for normality of distribution by measuring the distance between the empirical distribution and the theoretical distribution. The following null hypothesis was tested at 0.05 level of significance: distribution of the variable is normal/lognormal/Weibull. Furthermore the quality of fit of the Weibull distribution to empirical data was assessed using the Hollander–Proschan test for the significance level of 0.05. The reliability function R(*x*) was calculated as a complement to the cumulative distribution function using the following formula:

$$R(x) = 1 - F(x) \quad [1]$$

where *x* is an indicator of the concentration of pollutants in treated wastewater (Bugajski et al. 2012).

Reliability was determined from cumulative distribution plots, taking into consideration pollutant concentrations in treated wastewater permitted by the Regulation of the Polish Minister of Environment (2014) , i.e.: $BOD_5 \leq 40$ mg $O_2 \cdot dm^{-3}$, COD ≤ 150 mg $O_2 \cdot dm^{-3}$, total suspended solids ≤ 50 $mg \cdot dm^{-3}$, total nitrogen ≤ 30 $mg \cdot dm^{-3}$, total phosphorus ≤ 5 $mg \cdot dm^{-3}$.

RESULTS AND DISCUSSION

The many-year means of effluent contaminant concentrations in wastewater treated in the investigated installation (BOD_5 – 3.49 $mgO_2 \cdot dm^{-3}$, COD – 28.0 $mgO_2 \cdot dm^{-3}$, suspended solids – 15.8 $mg \cdot dm^{-3}$, total nitrogen – 20.9 $mg \cdot dm^{-3}$, and phosphorus $P\text{-}PO_4$ – 1.70 $mg \cdot dm^{-3}$) (Table 1) were much lower than required by the Regulation (2014) on discharging wastewater into the soil or surface waters including lakes and their tributaries, and artificial water reservoirs situated on flowing waters.

Table 1 shows the basic statistics for pollutant concentration in wastewater.

Table 1. Basic statistics for pollutant concentrations in wastewater

Parameter		Number of samples	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation
			$mg \cdot dm^{-3}$	$mg \cdot dm^{-3}$	$mg \cdot dm^{-3}$	$mg \cdot dm^{-3}$	$mg \cdot dm^{-3}$	%
BOD_5	inlet	57	271.7	230	90	580	132.9	48.8
	outlet	49	3.49	2.5	0	13	2.92	83.6
COD	inlet	61	391	353	214	641	114.9	29.4
	outlet	55	28	25	5	112	17.6	63
Suspended solids	inlet	48	75.4	66	19	218.6	40.5	53.7
	outlet	41	15.8	14	0	44.6	10.9	69.2
Total nitrogen N_{tot}	inlet	61	110.5	105.5	70.3	193.8	19.5	17.6
	outlet	55	20.9	19.5	1.6	64.8	16.4	78.5
Phosphorus PO_4-P	inlet	65	12.3	11.1	7.6	24.9	3.97	32.3
	outlet	59	1.7	1.5	0.14	5.46	1.23	72.2

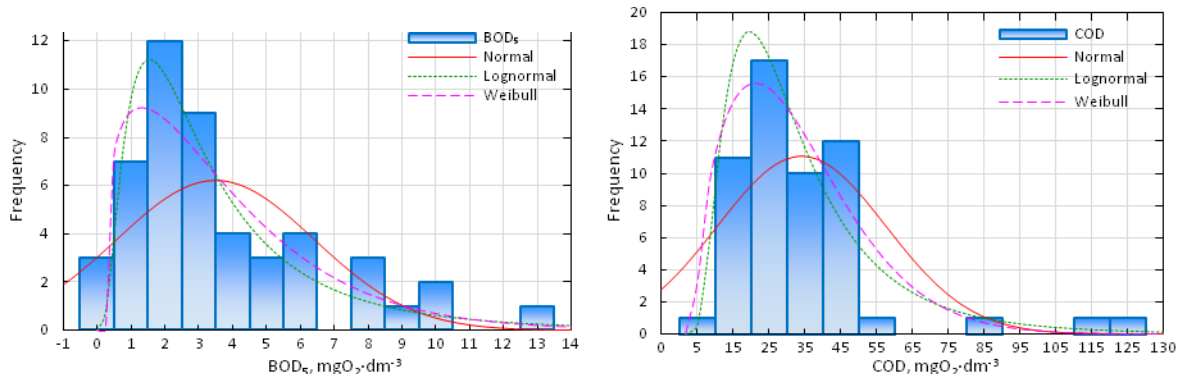
The effluent quality indicators were characterized by high coefficients of variation (Table 1) which, though statistically significant (and therefore useful for the evaluation of the treatment processes in the installation), were too low to have any relevance from the point of view of environmental protection. To determine the technological reliability of the treatment plant, a detailed statistical analysis was performed based on the distributions of the empirical data of each effluent contaminant. The normal, lognormal and Weibull distributions (Table 2, Fig. 2) were adjusted to data sets obtained during the 10-year study.

Table 2. The Kolmogorov-Smirnov goodness-of-fit statistics and significance levels for the analyzed empirical distributions

Distribution	Normal		Lognormal		Weibull	
	stat	p	stat	p	stat	p
BOD_5	0.2076	0.0324	0.1118	0.5751	0.1354	0.3371
COD	0.1388	0.2183	0.0970	0.6427	0.1157	0.4208
TSS	0.0944	0.8454	0.1416	0.3786	0.1067	0.7262
Total nitrogen N_{tot}	0.1422	0.1960	0.1604	0.1056	0.1085	0.5028
Phosphorus PO_4-P	0.1093	0.4501	0.0926	0.6585	0.0507	0.9962

Symbols: stat – value of the statistic test, p – significance level of the test; when p is greater than 0.05, the distribution of empirical data can be described by the analyzed distribution

Statistical analysis using the Kolmogorov-Smirnov goodness-of-fit test showed that the Weibull and lognormal distributions could be well fitted to the empirical distributions of each pollution indicator, whereas the normal distribution gave a much worse fit, although it could also be used for most of the parameters, except BOD_5 (Table 2).



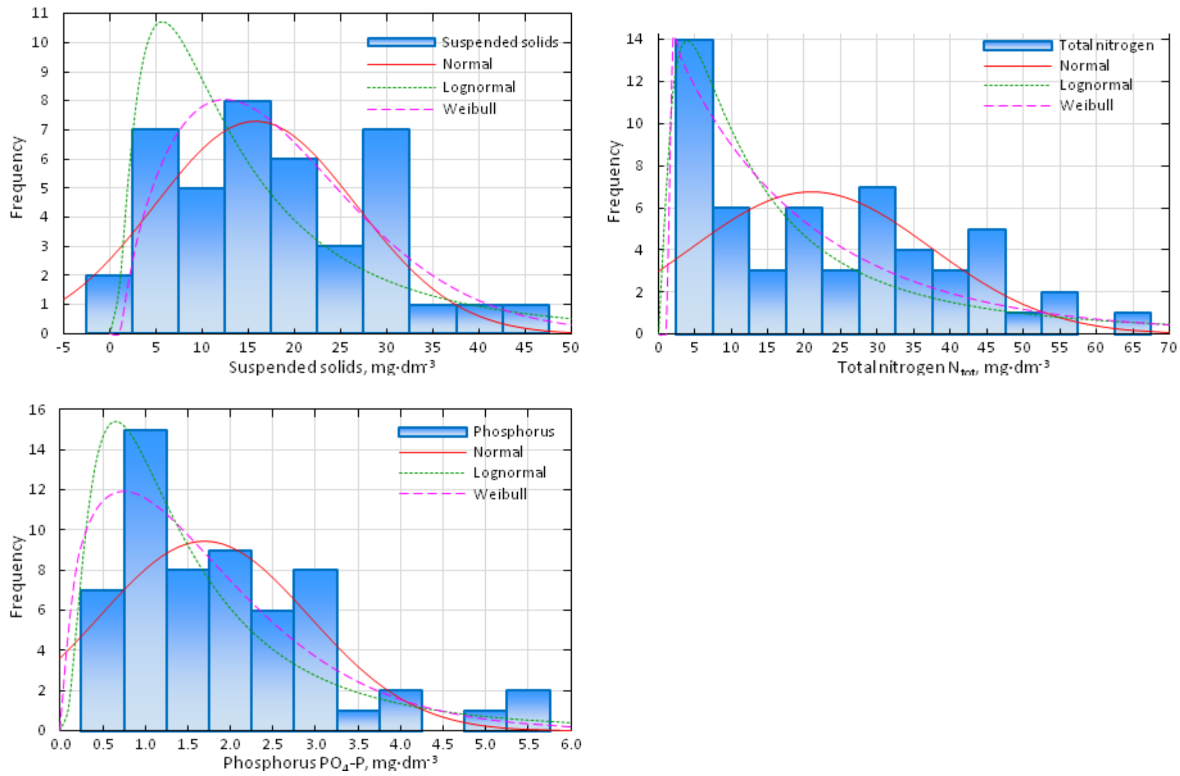


Figure 2. Histograms of the normal, lognormal and Weibull distributions of the empirical data

Based on the detailed analysis and evaluation of the WWTP, as reported above, its reliability was modelled using the Weibull distribution (Table 3, Fig. 3). This allowed us to compare our results with those obtained by other authors (Bugajski et al. 2012; Nastawny & Jucherski 2013; Wałęga 2009) who had used the same distribution. In addition, the indicators of the technological reliability of the treatment plant were also compared to values obtained from the lognormal distribution. The parameters of the Weibull distribution were calculated using the maximum likelihood estimation. In order to determine the goodness of fit of the Weibull distribution to the empirical data described by the distribution parameters (Table 3), the Hollander–Proschan test was applied. As can be seen from Table 3, the goodness of fit of the obtained distributions was high and ranged from 72 to 98% at a significance level of 0.05 (Table 3).

Table 3. Parameters of the Weibull distribution and the Hollander–Proschan goodness-of-fit test

Parameter	Parameters of Weibull distribution			Hollander–Proschan goodness-of-fit test	
	Location	Shape	Scale	stat	p
BOD_5	0.3182	1.2479	3.6602	0.2150	0.8297
COD	2.4697	1.5798	28.5112	0.0200	0.9840
Suspended solids	−0.6212	1.6638	19.2133	−0.1235	0.9017
Total nitrogen N_{tot}	1.2364	0.9844	19.5929	−0.3558	0.7220
Phosphorus PO_4-P	0.0707	1.3664	1.7796	0.0411	0.9672

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

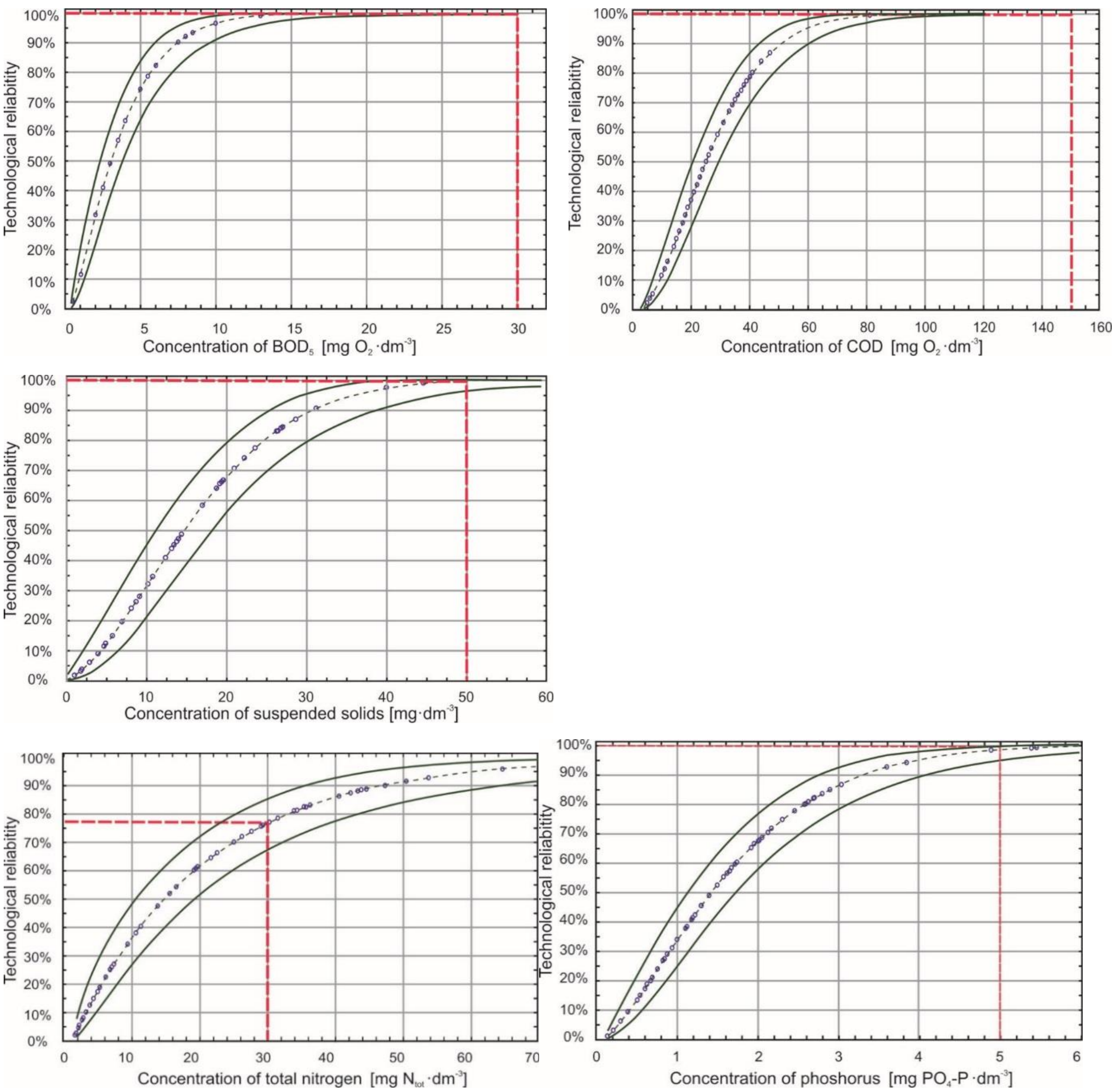


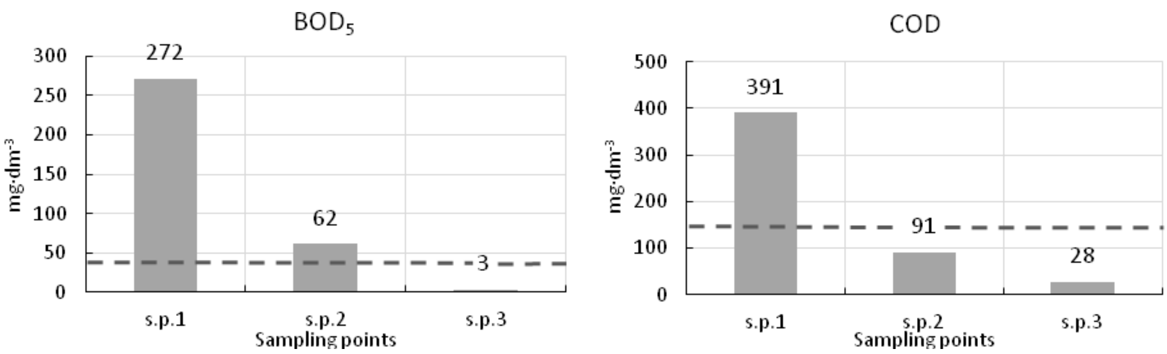
Figure 3. Weibull cumulative distribution functions and the technological reliabilities determined for each pollution parameter with estimated confidence intervals of 95.0%

The technological reliabilities of the installation determined by the Weibull distribution function compared to the lognormal distribution are given in Table 4. It was shown that the reliability of reducing BOD_5 and COD concentrations was 100% both for the lognormal as well as the Weibull distribution functions. For other pollutants, the reliabilities of the treatment plant described by the lognormal distribution and the Weibull distribution were slightly lower at 92.6% and 99.5% for TSS, 77.0% and 76.8% for Ntot, and 95.2% and 98.2% for phosphorus PO_4-P, respectively (Fig. 3, Table 4).

Table 4. The technological reliability of the facility for wastewater treatment [in %] determined using the Weibull and the lognormal distribution functions

Parameter	Weibull distribution	Lognormal distribution
BOD_5	100	100
COD	100	100
Suspended solids	99.5	92.6
Total nitrogen N_{tot}	76.8	77.0
Phosphorus PO_4-P	98.2	95.2

The results of this study demonstrate that the wastewater treatment processes were stable and reliable as well as very effective. As shown by the graphs in Figure 4 and the Helsinki Commission Recommendation (HELCOM 2007) data in Table 5, the average values of the parameters of the treated wastewater met the Polish requirements (Regulation of the Polish Minister of Environment 2014).Therefore, treated wastewater could be discharged into the environment throughout the year, with soil receiver sites being preferred over other receiver bodies.



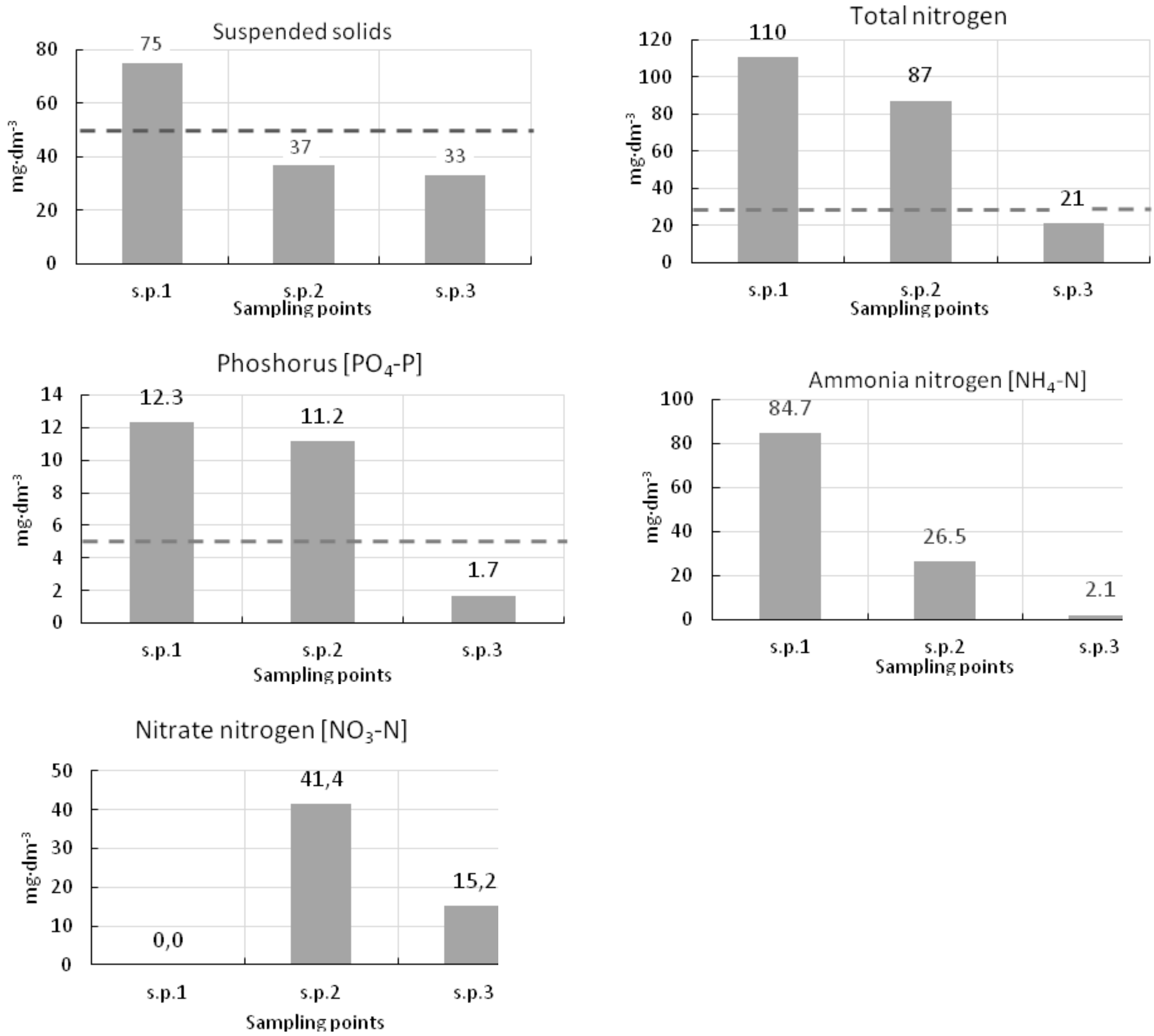


Figure 4. Dynamics of reduction of the mean pollutant concentrations in the successive treatment steps .

Table 5. The specific loads of pollutants in treated wastewater – median values [$g \cdot PE^{-1} \cdot d^{-1}$]

Specification	Sampling points		
	s.p.1	s.p.2	s.p.3
BOD_5	35	7	0.4*
COD	354	13	3.8
N_{tot}	16.0	13.4	3.0*
NH_4-N	12.6	3.8	0.06
PO_4-P	1.7	1.5	0.23*

*/HELCOM Recommendation 28E/6 (2007): BOD_5, 8 $g \cdot PE^{-1} \cdot d^{-1}$; N_{tot} ,10 $g \cdot PE^{-1} \cdot d^{-1}$; P_{tot}, 0.65 $g \cdot PE^{-1} \cdot d^{-1}$

Compared to the technological reliabilities of domestic wastewater treatment plants evaluated by other authors (Bugajski et al. 2012, Wałęga et al. 2008), the installation investigated in this study was much more efficient and reliable as far as the removal of pollutants was concerned. The reliability of reducing the levels of organic matter in wastewater was 100% for BOD_5 and COD and more than 92% for suspended solids. The corresponding values for the treatment plant Biocompact BCT S-12 (with activated sludge) were 68% (BOD), 88% (COD) and 62% (suspended solids) (Bugajski et al. 2012). In the case of the domestic treatment plant RetroFAST (with an aerated biological filter) the reliability values were 85%, 89% and 92%, respectively (Wałęga et al. 2008). Wastewater from individual rural households collected in septic tanks is characterized by several times higher concentrations of pollutants than wastewater discharged by municipal sewage systems. The results of a two-year monitoring study of the quality of wastewater, conducted in one of Polish villages are shown in Table 6.

Table 6. Data on pollutant concentrations in wastewater outflowing from septic tanks in a village in Poland. A two-year monitoring study.

Parameter	Number of samples	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation	Mean values in municipal wastewater
		mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	%	mg dm^{-3}
BOD_5	147	521.1	460.0	100.0	1300.0	236.0	45.3	197
COD	149	866.3	811.0	251.0	1754.0	295.6	34.1	393
Suspended solids	149	205.5	140.0	45.6	3060.0	272.9	132.8	116
Total nitrogen N_{tot}	149	150.1	145.7	28.3	323.5	50.1	33.4	36
Ammonia nitrogen NH_4-N	149	109.9	101.9	18.4	280.1	40.3	36.7	25
Phosphorus PO_4-P	149	16.5	15.9	2.5	30.7	5.3	32.1	6

Due to this fact, the technological set up of a single-family WWTP (below 50 PE) needs to be characterized by a very high pollutant removal efficiency as well as a very high resistance to the these fluctuations. Such requirements are practically impossible to meet using container WWTPs with activated sludge or trickling filters. By contrast, hybrid systems equipped with beds built as treatment wetlands can easily adapt to such fluctuations and ensure stable removal of pollutants from wastewater.

As far as BOD_5 and COD are concerned, the analyzed installation worked without technological failures over the whole 10-year study period. For suspended solids, the probability of occurrence of failure events (effluent quality parameters higher than permitted) was 2 days per year and for phosphorus 7 days per year. The technological reliability of total nitrogen removal was much lower (76.8%), with as many as 85 failure days during the whole year. The hybrid treatment plant had operated continuously for more than 10-years and had been maintained to ensure constant operational availability. The yearly removal efficiency of pollutants was sensitive only to a slight periodic variability of both hydraulic and pollution loads caused by tourists staying at the farm during vacation periods. The plant had never been observed to freeze in winter thanks to the snow cover, and the only decrease in average efficiency in the cold season concerned the removal of N_{tot}.(18%) (Jucherski & Walczowski 2012). These malfunctions occurred in winter when the weather conditions were not conducive to efficient denitrification of NO_3-N, which was the dominant form of nitrogen in the effluent (Fig. 4). By contrast, the installation showed a very high rate of conversion of ammonium nitrogen. The average concentration of NH_4-N did not exceed 2.1 mg·dm^{-3} over the entire research period. In order to increase the efficiency of tertiary wastewater treatment in winter seasons and thereby improve the overall pollutant removal efficiency of the WWTP, further efforts have to be made at re-designing and re-building the existing filter bed.

To summarize, the installation tested can be particularly recommended for use in mountainous regions, where streams and rivers as well as underground waters are very sensitive to pollution and, therefore, require higher levels of protection. The high reliability of this type of wastewater treatment plants is a consequence of the application of a hybrid configuration of facilities which is characterized by an increased technological inertia in the multi-staged wastewater treatment process (Jucherski 2007). The number and configuration of the facilities constituting the wastewater treatment installation have been chosen so as to ensure the stability of the process under changeable weather conditions and variable pollutant loads in raw wastewater. The advantages of the investigated installation include simple operation, low power consumption and low operating costs. One disadvantage is that, compared to a container WWTP, the system occupies a slightly larger surface area, which, however, does not limit its application, especially in rural (Nastawny & Jucherski 2013) or protected areas (Jóźwiakowski et al. 2014, Jóźwiakowski et al. 2016). The design and structure of the test facility make it especially suitable for use in sloping terrain with large inclines typical of mountainous regions.

CONCLUSIONS

This study showed that the technological solutions applied in the investigated installation for the treatment of wastewater produced by an eco-tourist mountain farm, proved to be very effective and reliable during the whole 10-year period of operation. The long-term median concentration values of effluent pollutants (BOD_5 – 2.5 mg $O_2 \cdot dm^{-3}$, COD – 25.0 mg $O_2 \cdot dm^{-3}$, N_{tot} – 19.5 mg$\cdot dm^{-3}$, PO_4-P – 1.5 mg$\cdot dm^{-3}$ and suspended solids – 14.0 mg$\cdot dm^{-3}$) were lower than permitted by the Polish Regulation (2014). At the same time, the specific loads of pollutants in the effluent were much lower than those specified in the HELCOM Recommendation.

The technological reliability of the tested installation (100% for both BOD_5 and COD removal, over 90% for the removal of PO_4-P and total suspended solids, and 77% for total-nitrogen removal) calculated with the Weibull method, confirmed that the treatment plant could be used as an effective tool for protecting the quality of local water resources (especially in ecologically valuable mountainous areas) regardless of changeable weather conditions and variable loads of pollutants characteristic of individual wastewater management in rural regions.

The statistical methods based on the Weibull as well as the lognormal data distributions describe very well the degree of stability and technological reliability of treatment processes, and the differences between them in estimating reliability are negligible.

The Weibull method is especially well-suited for comparing the specific functional features of various types of rural domestic wastewater treatment plants, but the log-normal distribution can also be used.

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Assessment of the technological reliability of a hybrid constructed wetland for wastewater treatment in a mountain eco-tourist farm in Poland

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ABSTRACT

The aim of the present study was to assess the technological reliability of a domestic hybrid wastewater treatment installation consisting of a classic three-chambered (volume 6m^3) septic tank, a vertical flow (VF) trickling bed filled with granules of a calcinated clay material (KERAMZYT), a special wetland bed constructed on a slope, and a permeable pond used as a receiver. The test treatment plant was located at a mountain eco-tourist farm on the periphery of the spa municipality of Krynica-Zdrój, Poland. The plant's operational reliability in reducing the concentration of organic matter measured as BOD_5 and COD, was 100% when modelled by both the Weibull and the lognormal distributions. The respective reliability values for total nitrogen removal were 76.8% and 77.0%, total suspended solids – 99.5% and 92.6 %, and PO_4-P – 98.2% and 95.2%, with the differences being negligible. The installation was characterized by a very high level of technological reliability when compared to other solutions of this type. The Weibull method employed for statistical evaluation of technological reliability can also be used for comparison purposes. From the ecological perspective, the facility presented in the study has proven to be an effective tool for protecting local aquifer areas.

Key words: mountain aquifers, rural areas, cold climate, hybrid constructed wetland, technological reliability

INTRODUCTION

Evaluation of the technological reliability of individual wastewater treatment systems should be an important part of planning and decision-making in water and wastewater management, particularly now, when a wide range of technological solutions are available (Jóźwiakowski et al. 2015). Reliable operation of wastewater treatment units must be ensured due to both environmental and human health protection concerns (Eisenberg et al. 2001; Wojciechowska et al 2016). Reliable operation of domestic wastewater treatment plants is especially important in mountain aquifer areas, which are very sensitive to pollution. Mountainous regions in Poland play a key role in developing and sustaining vital socio-economical and environmental functions which intertwine in the activities of spa and tourist resorts, forest management, environment-friendly farming and especially in hydrology.

Although Polish mountainous areas have a high water production potential, as manifested by an almost 40% regional surplus in relation to the water discharged by all the rivers, Poland occupies one of the last positions in Europe in terms of the total freshwater resources, which are estimated at 1630 $m^3 \cdot year^{-1} \cdot person^{-1}$. Therefore, it is essential that groundwater and the upper reaches of local streams and mountain rivers should be protected against biological, chemical and bacteriological pollution resulting from the discharge of untreated domestic sewage to the environment in rural areas. One of the key issues in technological progress in wastewater management in rural, environmentally valuable areas, is the construction of small domestic or local wastewater treatment plants with a high, long-term reliability and effectiveness in reducing wastewater pollutions (Jucherski & Walczowski 2012; Masi et al. 2013; Jóźwiakowski et al. 2016; Gajewska et al. 2015).

Nowadays, more and more innovative wastewater treatment systems are being designed and offered on the market, which spurs the need for developing a universal method of assessing the reliability of the various treatment processes and facilities. Such a method would be helpful in planning and comparing the levels of protection offered by the various technologies (Jóźwiakowski et al. 2015).

The methods for determining the reliability of individual wastewater treatment systems have been described in more detail by Eisenberg et al. (2001). Lately Djeddou & Achour (2015) have proposed a method for predicting reliability using artificial neural networks.

A comprehensive and useful assessment of the reliability of domestic wastewater treatment plants should be based on a series of measurements and observations of treatment variability under normal and critical operating conditions as well as the probability of mechanical failures and their impact on the quality of the treated wastewater (Eisenberg et al. 2001).

Reliability is defined as the probability of achieving required performance of a wastewater treatment plant (WWTP) over a specific time and under specific conditions (Oliveira & Sterling 2008). To assess WWTP, a coefficient of reliability (CR) which relates mean pollutant concentrations to effluent standards (Niku et al. 1982) can also be used.

The statistical step in the assessment of WWTP reliability presented in this article is based on the normal (Niku et al. 1982), the lognormal (Oliveira & Sterling 2008) and the Weibull distributions (Bugajski et al. 2012; Nastawny & Jucherski 2013; Wałęga 2009). Statistical distributions of probability are used to establish the probability of occurrence of selected values of pollutants. Recent findings reported in the literature (Bugajski et al. 2012; Bugajski

2014; Nastawny & Jucherski 2013; Wałęga 2009) show that the Weibull distribution is an accurate and precise tool for evaluation of WWTP reliability.

Systems for domestic wastewater management are individual facilities with technical and quasi-technical treatment devices designed to collect and treat wastewater to the extent required by specific regulations (Regulation of the Polish Minister of Environment 2014) as well as discharge it to receivers without adversely affecting the soil–water complex in the place where the facilities are located. In rural areas, individual treatment facilities usually operate without constant supervision and are therefore particularly exposed to fluctuations in efficiency due to a variable load pattern (Massoud et al. 2009; Platzer & Mauch 1997); in consequence, the quality of effluent often does not meet the requirements stipulated in the regulations in force.

Hybrid wetland systems have recently been more and more frequently used for the treatment of domestic wastewater from museum buildings and forester or mountain shelters, including those located in national parks. When well designed and properly maintained, they can achieve high pollutant removal efficiencies (Masi et al. 2007; Osaliya et al. 2011; Jóźwiakowski et al. 2014; Sanchez-Ramos et al. 2015; Gizińska-Górna et. 2016; Jóźwiakowski et al. 2016). The literature, however, provides little data on the reliability of pollutant removal processes in such CWS over long periods (years) of operation.

The aim of the present study was to assess the range of long-term fluctuations in treatment reliability in a domestic hybrid wastewater treatment plant. The plant had been built over ten years before on an eco-tourist farm in the mountain municipality and spa of Krynica-Zdrój in Poland and had been continuously operating since that time. The following indicators of wastewater contamination were measured: (i) BOD_5 and COD for contamination with organic matter, (ii) total suspended solids, (iii) total nitrogen (TN), and (iv) phosphorus PO_4-P. The indicators results (pollutant concentrations) were compared to the Polish standards for treated wastewater (Regulation of the Polish Minister of Environment 2014) discharged into water and soil from treatment plants below 2000 PE.

MATERIAL AND METHODS

The subject of the study was a hybrid wastewater treatment plant described in detail by Jucherski & Walczowski (2012). The plant was operated by an eco-tourist farm located in the rural peripheries of the spa town of Krynica-Zdrój, Poland. The plant had been monitored over the years 2005–2015. A schematic of the facility with the sampling points is presented in Fig. 1.

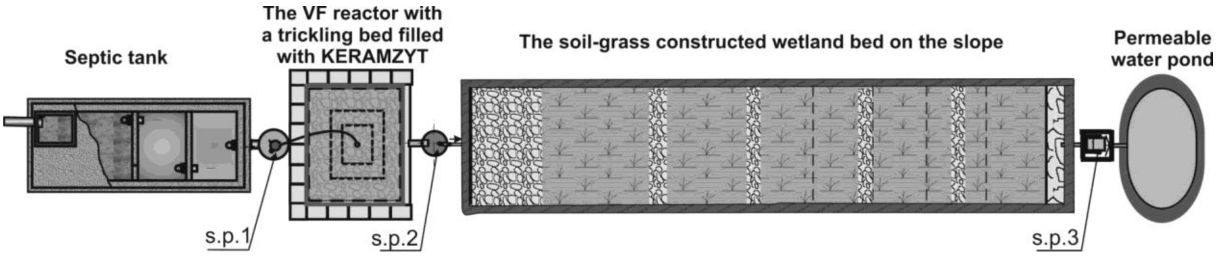


Figure 1. Schematic of the wastewater treatment installation (sampling points: s.p.1, s.p.2, s.p.3)

The installation consisted of a classic three-chamber septic tank, a vertical flow reactor (filter) followed by a special constructed wetland (SCW), and a permeable water pond as a receiver of the final effluent. The septic tank, with a capacity of $6m^3$, was a monolithic concrete structure designed to receive sewage with a seasonal variability from 3 to 15 persons (with an average of PE=5). The substrate used in the vertical flow reactor were granules of a sintered clay material (KERAMZYT). To improve biological treatment and nitrification at the vertical stage, the wastewater was sprayed onto the surface of the reactor. Due to the harsh climate, it was necessary to use a cover to insulate the reactor from freezing in winter. Downstream of the reactor, there was a special filter bed (wetland) with subsurface flow, planted with a mix of reed sweet grass (*Glyceria maxima*), reed canary grass (*Phalaris arundinacea*) and other grasses spontaneously inhabiting the bed. The bed was constructed on a slope for tertiary treatment and removal of the remaining nutrients (N and P). The installation ended with a permeable pond for receiving and infiltration of the treated wastewater into the soil complex surrounding the treatment unit.

The average hydraulic load of the treatment plant in the investigation period was 621.2 $dm^3 \cdot day^{-1}$, and the average concentrations of pollutants in raw sewage were 271.7 mg $O_2 \cdot dm^{-3}$ for BOD_5, 390.8 mg $O_2 \cdot dm^{-3}$ for COD, 75.4 $mg \cdot dm^{-3}$ for total suspended solids, 110.5 $mg \cdot dm^{-3}$ for total nitrogen, and 12.3 $mg \cdot dm^{-3}$ for phosphorus PO_4-P (Table 1). The flow of treated wastewater was calculated based on the water consumption reading of a water meter. BOD_5 was determined using the OxiTop respirometric measuring system from WTW. COD, total nitrogen and phosphate phosphorus were determined using a Merck SQ118 photometer and a Merck thermoreactor TR-200. The total suspended solids were determined by a gravimetric method, in accordance with the standard PN-72/C-04559/02.

The statistical analysis was based on the normal, lognormal and Weibull distributions. Statistica v. 13.0 software was employed to define the characteristics of the distribution of the empirical data using the Kolmogorov-Smirnov goodness-of-fit test. Data were tested for normality of distribution by measuring the distance between the empirical distribution and the theoretical distribution. The following null hypothesis was tested at 0.05 level of significance: distribution of the variable is normal/lognormal/Weibull. Furthermore the quality of fit of the Weibull distribution to empirical data was assessed using the Hollander–Proschan test for the significance level of 0.05. The reliability function R(*x*) was calculated as a complement to the cumulative distribution function using the following formula:

$$R(x) = 1 - F(x) \quad [1]$$

where *x* is an indicator of the concentration of pollutants in treated wastewater (Bugajski et al. 2012).

Reliability was determined from cumulative distribution plots, taking into consideration pollutant concentrations in treated wastewater permitted by the Regulation of the Polish Minister of Environment (2014) , i.e.: $BOD_5 \le 40$ mg $O_2 \cdot dm^{-3}$, COD ≤ 150 mg $O_2 \cdot dm^{-3}$, total suspended solids ≤ 50 mg$\cdot dm^{-3}$, total nitrogen ≤ 30 mg$\cdot dm^{-3}$, total phosphorus ≤ 5 mg$\cdot dm^{-3}$.

RESULTS AND DISCUSSION

The many-year means of effluent contaminant concentrations in wastewater treated in the investigated installation (BOD_5 – 3.49 mg$O_2 \cdot dm^{-3}$, COD – 28.0 mg$O_2 \cdot dm^{-3}$, suspended solids – 15.8 mg$\cdot dm^{-3}$, total nitrogen – 20.9 mg$\cdot dm^{-3}$, and phosphorus P-PO_4 – 1.70 mg$\cdot dm^{-3}$) (Table 1) were much lower than required by the Regulation (2014) on discharging wastewater into the soil or surface waters including lakes and their tributaries, and artificial water reservoirs situated on flowing waters.

Table 1 shows the basic statistics for pollutant concentration in wastewater.

Table 1. Basic statistics for pollutant concentrations in wastewater

Parameter		Number of samples	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation
			mg$\cdot dm^{-3}$	mg$\cdot dm^{-3}$	mg$\cdot dm^{-3}$	mg$\cdot dm^{-3}$	mg$\cdot dm^{-3}$	%
BOD_5	inlet	57	271.7	230	90	580	132.9	48.8
	outlet	49	3.49	2.5	0	13	2.92	83.6
COD	inlet	61	391	353	214	641	114.9	29.4
	outlet	55	28	25	5	112	17.6	63
Suspended solids	inlet	48	75.4	66	19	218.6	40.5	53.7
	outlet	41	15.8	14	0	44.6	10.9	69.2
Total nitrogen N_{tot}	inlet	61	110.5	105.5	70.3	193.8	19.5	17.6
	outlet	55	20.9	19.5	1.6	64.8	16.4	78.5
Phosphorus PO_4-P	inlet	65	12.3	11.1	7.6	24.9	3.97	32.3
	outlet	59	1.7	1.5	0.14	5.46	1.23	72.2

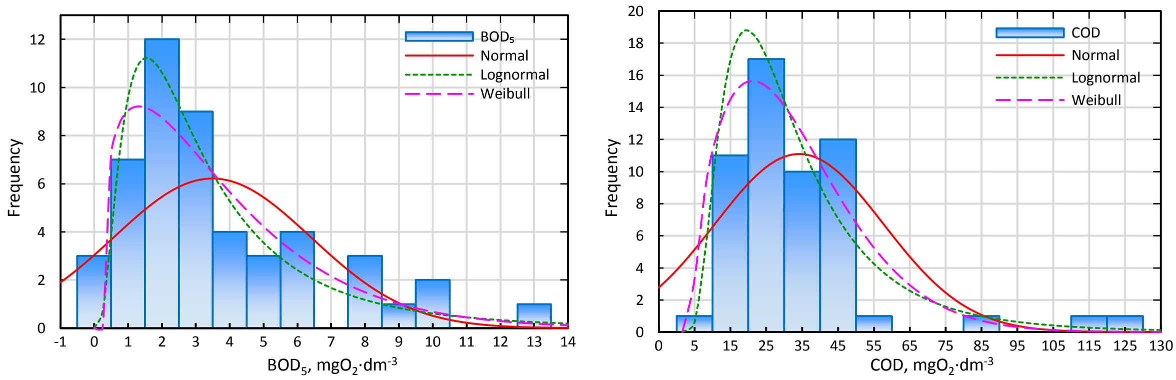
The effluent quality indicators were characterized by high coefficients of variation (Table 1) which, though statistically significant (and therefore useful for the evaluation of the treatment processes in the installation), were too low to have any relevance from the point of view of environmental protection. To determine the technological reliability of the treatment plant, a detailed statistical analysis was performed based on the distributions of the empirical data of each effluent contaminant. The normal, lognormal and Weibull distributions (Table 2, Fig. 2) were adjusted to data sets obtained during the 10-year study.

Table 2. The Kolmogorov-Smirnov goodness-of-fit statistics and significance levels for the analyzed empirical distributions

Distribution	Normal		Lognormal		Weibull	
	stat	p	stat	p	stat	p
BOD_5	0.2076	0.0324	0.1118	0.5751	0.1354	0.3371
COD	0.1388	0.2183	0.0970	0.6427	0.1157	0.4208
TSS	0.0944	0.8454	0.1416	0.3786	0.1067	0.7262
Total nitrogen N_{tot}	0.1422	0.1960	0.1604	0.1056	0.1085	0.5028
Phosphorus PO_4-P	0.1093	0.4501	0.0926	0.6585	0.0507	0.9962

Symbols: stat – value of the statistic test, p – significance level of the test; when p is greater than 0.05, the distribution of empirical data can be described by the analyzed distribution

Statistical analysis using the Kolmogorov-Smirnov goodness-of-fit test showed that the Weibull and lognormal distributions could be well fitted to the empirical distributions of each pollution indicator, whereas the normal distribution gave a much worse fit, although it could also be used for most of the parameters, except BOD_5 (Table 2).



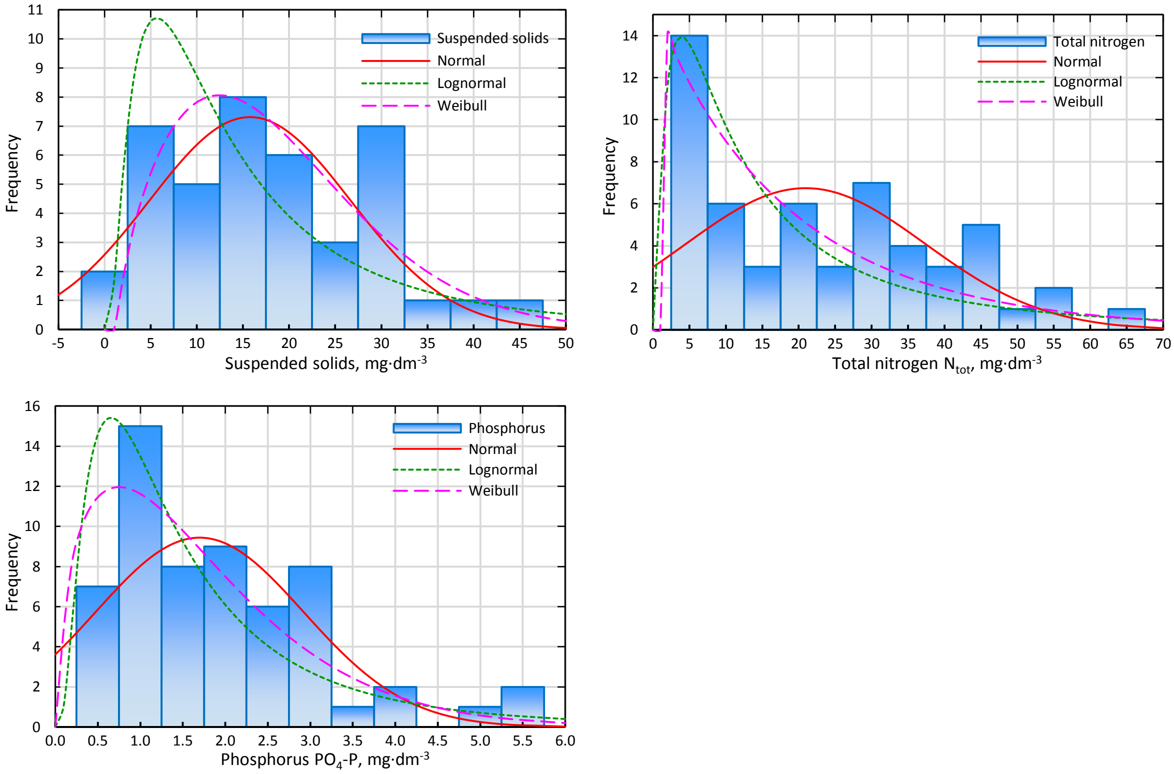


Figure 2. Histograms of the normal, lognormal and Weibull distributions of the empirical data

Based on the detailed analysis and evaluation of the WWTP, as reported above, its reliability was modelled using the Weibull distribution (Table 3, Fig. 3). This allowed us to compare our results with those obtained by other authors (Bugajski et al. 2012; Nastawny & Jucherski 2013; Wałęga 2009) who had used the same distribution. In addition, the indicators of the technological reliability of the treatment plant were also compared to values obtained from the lognormal distribution. The parameters of the Weibull distribution were calculated using the maximum likelihood estimation. In order to determine the goodness of fit of the Weibull distribution to the empirical data described by the distribution parameters (Table 3), the Hollander–Proschan test was applied. As can be seen from Table 3, the goodness of fit of the obtained distributions was high and ranged from 72 to 98% at a significance level of 0.05 (Table 3).

Table 3. Parameters of the Weibull distribution and the Hollander–Proschan goodness-of-fit test

Parameter	Parameters of Weibull distribution			Hollander–Proschan goodness-of-fit test	
	Location	Shape	Scale	stat	p
BOD_5	0.3182	1.2479	3.6602	0.2150	0.8297
COD	2.4697	1.5798	28.5112	0.0200	0.9840
Suspended solids	−0.6212	1.6638	19.2133	−0.1235	0.9017
Total nitrogen N_{tot}	1.2364	0.9844	19.5929	−0.3558	0.7220
Phosphorus PO_4-P	0.0707	1.3664	1.7796	0.0411	0.9672

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

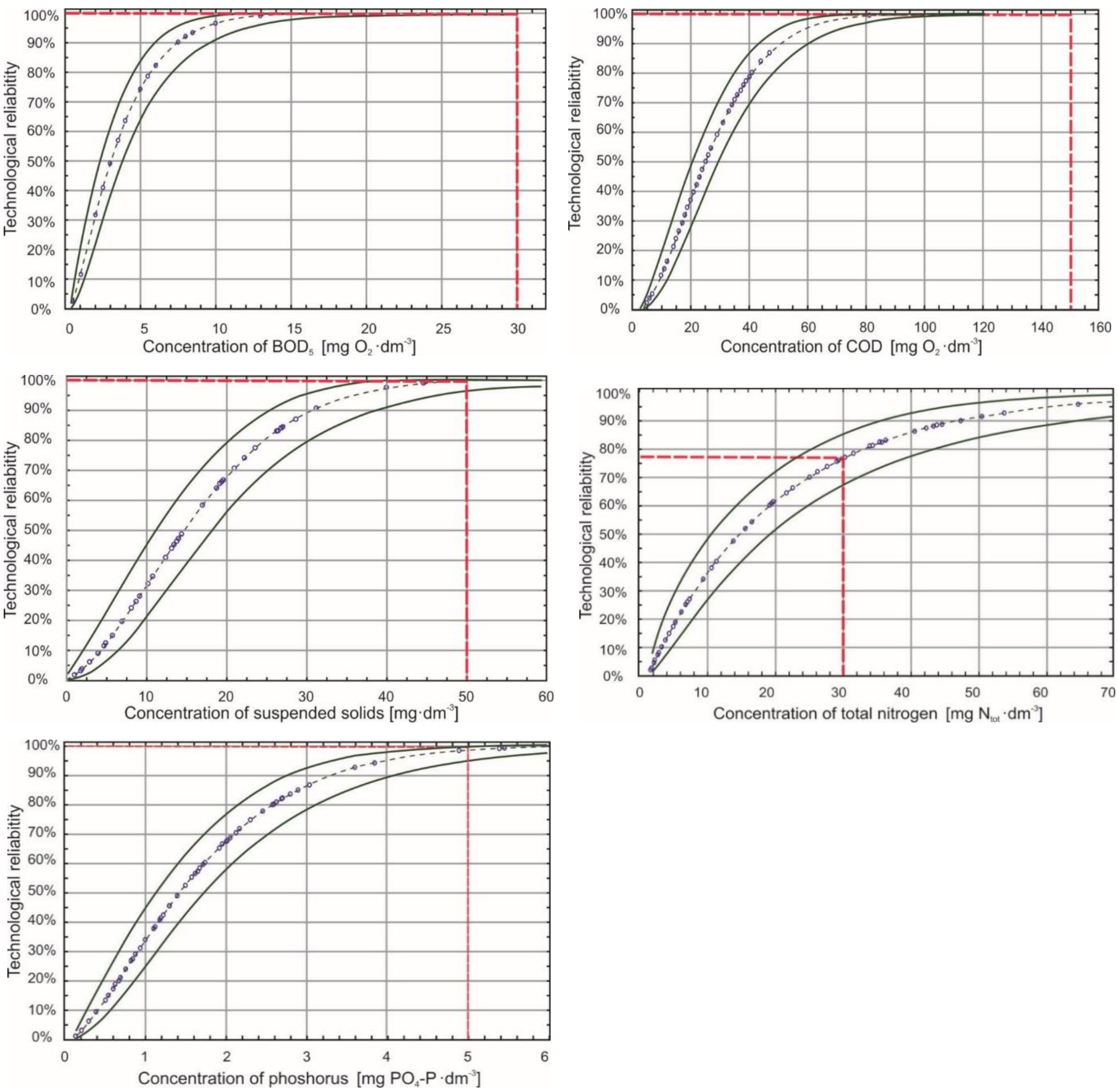


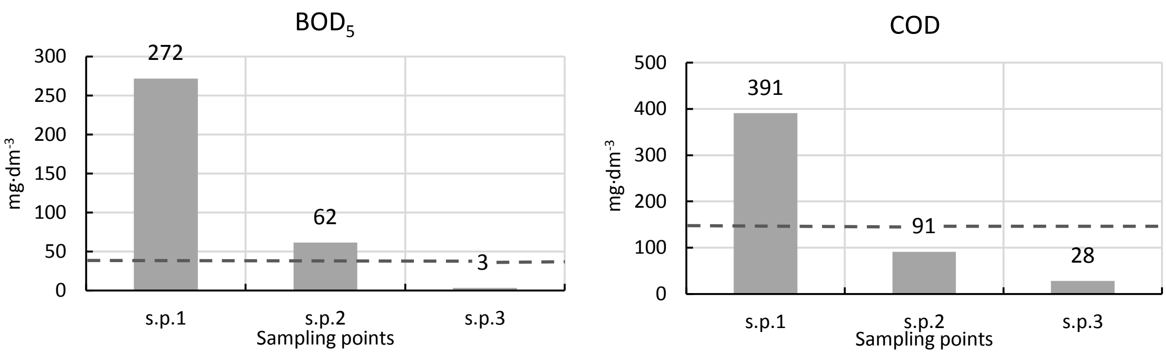
Figure 3. Weibull cumulative distribution functions and the technological reliabilities determined for each pollution parameter with estimated confidence intervals of 95.0%

The technological reliabilities of the installation determined by the Weibull distribution function compared to the lognormal distribution are given in Table 4. It was shown that the reliability of reducing BOD_5 and COD concentrations was 100% both for the lognormal as well as the Weibull distribution functions. For other pollutants, the reliabilities of the treatment plant described by the lognormal distribution and the Weibull distribution were slightly lower at 92.6% and 99.5% for TSS, 77.0% and 76.8% for Ntot, and 95.2% and 98.2% for phosphorus PO_4-P, respectively (Fig. 3, Table 4).

Table 4. The technological reliability of the facility for wastewater treatment [in %] determined using the Weibull and the lognormal distribution functions

Parameter	Weibull distribution	Lognormal distribution
BOD_5	100	100
COD	100	100
Suspended solids	99.5	92.6
Total nitrogen N_{tot}	76.8	77.0
Phosphorus PO_4-P	98.2	95.2

The results of this study demonstrate that the wastewater treatment processes were stable and reliable as well as very effective. As shown by the graphs in Figure 4 and the Helsinki Commission Recommendation (HELCOM 2007) data in Table 5, the average values of the parameters of the treated wastewater met the Polish requirements (Regulation of the Polish Minister of Environment 2014).Therefore, treated wastewater could be discharged into the environment throughout the year, with soil receiver sites being preferred over other receiver bodies.



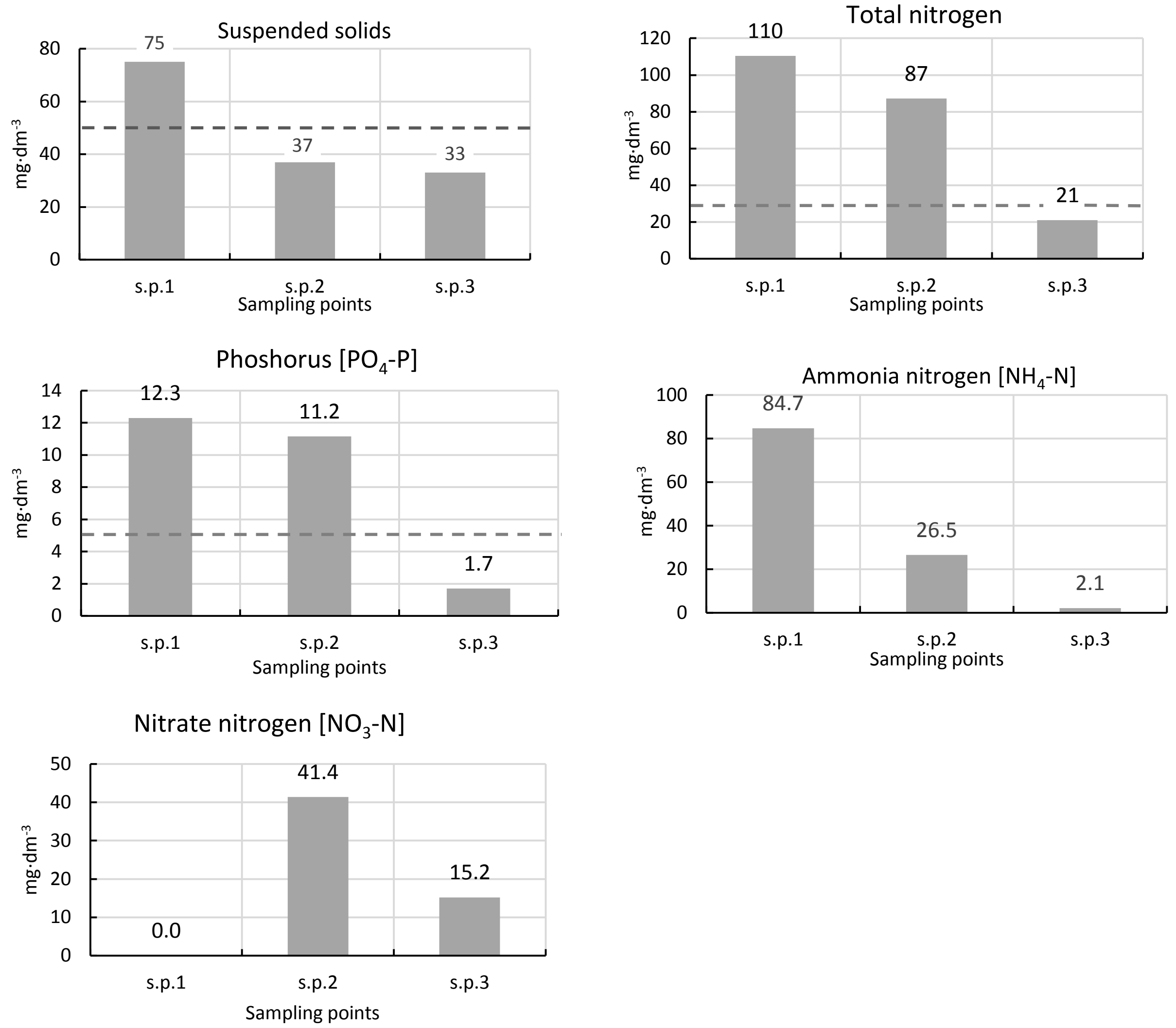


Figure 4. Dynamics of reduction of the mean pollutant concentrations in the successive treatment steps .

Table 5. The specific loads of pollutants in treated wastewater – median values [$g \cdot PE^{-1} \cdot d^{-1}$]

Specification	Sampling points		
	s.p.1	s.p.2	s.p.3
BOD_5	35	7	0.4*
COD	354	13	3.8
N_{tot}	16.0	13.4	3.0*
NH_4-N	12.6	3.8	0.06
PO_4-P	1.7	1.5	0.23*

*/HELCOM Recommendation 28E/6 (2007): BOD_5, 8 $g \cdot PE^{-1} \cdot d^{-1}$; N_{tot} ,10 $g \cdot PE^{-1} \cdot d^{-1}$; P_{tot}, 0.65 $g \cdot PE^{-1} \cdot d^{-1}$

Compared to the technological reliabilities of domestic wastewater treatment plants evaluated by other authors (Bugajski et al. 2012, Wałęga et al. 2008), the installation investigated in this study was much more efficient and reliable as far as the removal of pollutants was concerned. The reliability of reducing the levels of organic matter in wastewater was 100% for BOD_5 and COD and more than 92% for suspended solids. The corresponding values for the treatment plant Biocompact BCT S-12 (with activated sludge) were 68% (BOD), 88% (COD) and 62% (suspended solids) (Bugajski et al. 2012). In the case of the domestic treatment plant RetroFAST (with an aerated biological filter) the reliability values were 85%, 89% and 92%, respectively (Wałęga et al. 2008). Wastewater from individual rural households collected in septic tanks is characterized by several times higher concentrations of pollutants than wastewater discharged by municipal sewage systems. The results of a two-year monitoring study of the quality of wastewater, conducted in one of Polish villages are shown in Table 6.

Table 6. Data on pollutant concentrations in wastewater outflowing from septic tanks in a village in Poland. A two-year monitoring study.

Parameter	Number of samples	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation	Mean values in municipal wastewater
		mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	%	mg dm^{-3}
BOD_5	147	521.1	460.0	100.0	1300.0	236.0	45.3	197
COD	149	866.3	811.0	251.0	1754.0	295.6	34.1	393
Suspended solids	149	205.5	140.0	45.6	3060.0	272.9	132.8	116
Total nitrogen N_{tot}	149	150.1	145.7	28.3	323.5	50.1	33.4	36
Ammonia nitrogen NH_4-N	149	109.9	101.9	18.4	280.1	40.3	36.7	25
Phosphorus PO_4-P	149	16.5	15.9	2.5	30.7	5.3	32.1	6

Due to this fact, the technological set up of a single-family WWTP (below 50 PE) needs to be characterized by a very high pollutant removal efficiency as well as a very high resistance to the these fluctuations. Such requirements are practically impossible to meet using container WWTPs with activated sludge or trickling filters. By contrast, hybrid systems equipped with beds built as treatment wetlands can easily adapt to such fluctuations and ensure stable removal of pollutants from wastewater.

As far as BOD_5 and COD are concerned, the analyzed installation worked without technological failures over the whole 10-year study period. For suspended solids, the probability of occurrence of failure events (effluent quality parameters higher than permitted) was 2 days per year and for phosphorus 7 days per year. The technological reliability of total nitrogen removal was much lower (76.8%), with as many as 85 failure days during the whole year. The hybrid treatment plant had operated continuously for more than 10-years and had been maintained to ensure constant operational availability. The yearly removal efficiency of pollutants was sensitive only to a slight periodic variability of both hydraulic and pollution loads caused by tourists staying at the farm during vacation periods. The plant had never been observed to freeze in winter thanks to the snow cover, and the only decrease in average efficiency in the cold season concerned the removal of $N_{tot.}$(18%) (Jucherski & Walczowski 2012). These malfunctions occurred in winter when the weather conditions were not conducive to efficient denitrification of NO_3-N, which was the dominant form of nitrogen in the effluent (Fig. 4). By contrast, the installation showed a very high rate of conversion of ammonium nitrogen. The average concentration of NH_4-N did not exceed 2.1 $mg{\cdot}dm^{-3}$ over the entire research period. In order to increase the efficiency of tertiary wastewater treatment in winter seasons and thereby improve the overall pollutant removal efficiency of the WWTP, further efforts have to be made at re-designing and re-building the existing filter bed.

To summarize, the installation tested can be particularly recommended for use in mountainous regions, where streams and rivers as well as underground waters are very sensitive to pollution and, therefore, require higher levels of protection. The high reliability of this type of wastewater treatment plants is a consequence of the application of a hybrid configuration of facilities which is characterized by an increased technological inertia in the multi-staged wastewater treatment process (Jucherski 2007). The number and configuration of the facilities constituting the wastewater treatment installation have been chosen so as to ensure the stability of the process under changeable weather conditions and variable pollutant loads in raw wastewater. The advantages of the investigated installation include simple operation, low power consumption and low operating costs. One disadvantage is that, compared to a container WWTP, the system occupies a slightly larger surface area, which, however, does not limit its application, especially in rural (Nastawny & Jucherski 2013) or protected areas (Jóźwiakowski et al. 2014, Jóźwiakowski et al. 2016). The design and structure of the test facility make it especially suitable for use in sloping terrain with large inclines typical of mountainous regions.

CONCLUSIONS

This study showed that the technological solutions applied in the investigated installation for the treatment of wastewater produced by an eco-tourist mountain farm, proved to be very effective and reliable during the whole 10-year period of operation. The long-term median concentration values of effluent pollutants (BOD_5 – 2.5 mg $O_2 \cdot dm^{-3}$, COD – 25.0 mg $O_2 \cdot dm^{-3}$, N_{tot} – 19.5 mg·dm^{-3}, PO_4-P – 1.5 mg·dm^{-3} and suspended solids – 14.0 mg·dm^{-3}) were lower than permitted by the Polish Regulation (2014). At the same time, the specific loads of pollutants in the effluent were much lower than those specified in the HELCOM Recommendation.

The technological reliability of the tested installation (100% for both BOD_5 and COD removal, over 90% for the removal of PO_4-P and total suspended solids, and 77% for total-nitrogen removal) calculated with the Weibull method, confirmed that the treatment plant could be used as an effective tool for protecting the quality of local water resources (especially in ecologically valuable mountainous areas) regardless of changeable weather conditions and variable loads of pollutants characteristic of individual wastewater management in rural regions.

The statistical methods based on the Weibull as well as the lognormal data distributions describe very well the degree of stability and technological reliability of treatment processes, and the differences between them in estimating reliability are negligible.

The Weibull method is especially well-suited for comparing the specific functional features of various types of rural domestic wastewater treatment plants, but the log-normal distribution can also be used.

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