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Evaluation of the Effectiveness of a Wastewater Treatment Plant with MBBR Technology

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1. Introduction

As environmental protection requirements have become more stringent in recent years, one consequence has been a search for more effective ways of treating wastewater biologically. Among the new solutions are ones based around the increased concentration of biomass in biological reactors as compared with conventional activated sludge. Examples of such solutions are:

- MBBR (Moving Bed Biofilm Reactor) technology, in which the reactor additionally contains carriers, e.g. of plastic, on which biofilm may form,
- AGS (Aerobic Granular Sludge) technology, in which microorganisms are concentrated in a compact spherical biomass resistant to variable loads of pollution,
- MBR (Membrane Biological Reactor) technology, in which membrane separation of treated wastewater from activated sludge is applied (Czarnota et al. 2016, Gromiec 2016).

The development of the MBBR process was based on the idea of bringing together, within a single system, the best characteristics of the activated sludge and biofilm processes, with the undesirable characteristics of each process eliminated (Barwal & Chaudhary 2014, Bassin & Dezotti 2018). The resultant technology is compact and easy to operate, and is often used as a retrofit of existing activated sludge tanks, in order to increase capacity in an existing system (Barwal & Chaudhary 2014). With biomass immobilised on free-support media, the retention of solids in the biological reactor is enhanced (Bassin & Dezotti 2018). The advantages of this technology as compared with activated-sludge systems are: a higher effective sludge retention time (SRT) that favours nitrification, more limited production of sludge, more limited requirements as regards area, and resilience to toxic shock. Moreover, this technology does not need recirculation of sludge, which is the case with activated-sludge systems, so process performance is independent of a secondary clarifier (Burton et al. 2013). It is concluded that MBBR is efficient in removing from municipal wastewater 60-90% of COD, 75-97% of BOD_5, 40-85% of TKN and other nutrients up to a certain extent (Barwal & Chaudhary 2014). A process based on a biofilm and activated sludge in the same tank favours nitrification, since the issue of the retention time for solids becomes partly uncoupled from the hydraulic retention time. This is particularly important where a WWTP is operating at low temperatures, as under these conditions, the sludge age needed to support nitrification is relatively great, due to the low growth rates achieved by nitrifying bacteria (Bassin & Dezotti 2018).

Regardless of the technology deployed, the stability and efficiency of any wastewater treatment plant are affected by factors over which the operator has no influence, has limited influence or has full control. Among the factors on which an operator has only limited influence is the quantitative and qualitative variability of the effluent flowing into the treatment plant. Quantitative and qualitative changes in wastewater are due to the specificity of the catchment area, the presence of industrial plants, the season, the day of the week or even the hours of the day. A detailed analysis of the quality and quantity of raw sewage allows the operator to select appropriate parameters to ensure proper operation of a facility (Piaskowski & Kołacz 2011, Bugajski et al. 2016, Krupicz & Masłoń 2016).

The aim of the article is to evaluate the work of the wastewater treatment plant in Nowa Wieś operating in the MBBR technology in the aspect of effective wastewater treatment. Due to the low stability of biogenic compounds removal from wastewater in the MBBR system, an analysis was made of the impact of wastewater temperature and the quality of raw wastewater and water drained from the lagoon on nitrification, denitrification and biological dephosphatation processes.

2. Characteristics of the Nowa Wieś WWTP

The mechanical-biological wastewater treatment plant in Nowa Wieś was commissioned in 1997. While the facility was extended and modernised in the 2003-2005 period the biological wastewater treatment technology based on the Bardenpho method emerged over time as no longer effective. This necessitated further modernisation of the plant between 2013 and 2015. The target capacity of the extended wastewater treatment plant is now of 2800 $m^3 \cdot d^{-1}$, while the population equivalent is 21000. The receiving water for treated wastewater is the Mrowla stream at km 2+700 along its length, and the discharge of the treated wastewater is regulated by a permit dated 28 June 2013 (Decyzja... 2013) issued on the basis of the 2017 Water Law Act. The quality requirements for treated wastewater specified in this document (in line with the applicable law), are as presented in Table 1. The technological system of the WWTP consists of an expansion chamber, sieve, grit chamber, separation chamber 1, two Moving Bed Biofilm Reactors, separation chamber 2 and two secondary settling tanks. The system is as presented in Fig. 1.

Table 1. Minimum percentage reduction in pollution[1] (Decyzja… 2013 & RMŚ 2014)

Highest permissible concentrations of pollutants in treated wastewater	Parameter				
	BOD_5 [%]	COD_{Cr} [%]	TSS [%]	TN [%]	TP [%]
Water Law permit	90.0	75.0	90.0	80.0	85.0
Regulation of the Minister for Environment	90.0	75.0	90.0	70.0-80.0	80.0

[1] the minimum percentage reduction of pollution levels is determined in relation to the pollutant load in the influent

Wastewater inflowing into the WWTP is discharged through pressure collectors to the expansion chamber (KRP), from where it flows to the Mechanical Treatment Building via a gravitational channel. The mechanical part of the plant is equipped with a sieve and a grit chamber. The sieve cooperates with the press to dewater screenings. The grit chamber, which is integrated with the sieve, works together with a sand separator. Following mechanical treatment, wastewater flows through the gravity channel to separation chamber 1 (KR1), from where it is directed for biological wastewater treatment along with the recirculated sludge flowing from the pre-denitrification sludge chamber (KPDN).

The processes removing compounds of carbon, nitrogen and phosphorus take place with the participation of activated sludge and MBBR technology, in two independent sequences. In the biological part of the treatment plant, wastewater in turn flows through:

- a denitrification chamber (BIO-DN) with submersible agitator, measuring sludge density, temperature, pH and oxygen (total chambers volume is 1123 m^3),
- a dephosphatation chamber (BIO-P) filled with EvU-Perl carrier (Fig. 2) (target filling at the level of 72 m^3), with submersible agitators and a deposit agitation grid (total volume 288.4 m^3),
- a nitrification chamber (BIO-N) equipped with an aeration grate, internal recirculation system (RW), agitators of the "mill wheel" type, and filling with EvU-Perl carrier (target filling of 114 m^3), a system to retain elements of this filling and a system to measure levels of dissolved oxygen (total chambers volume 1628 m^3).

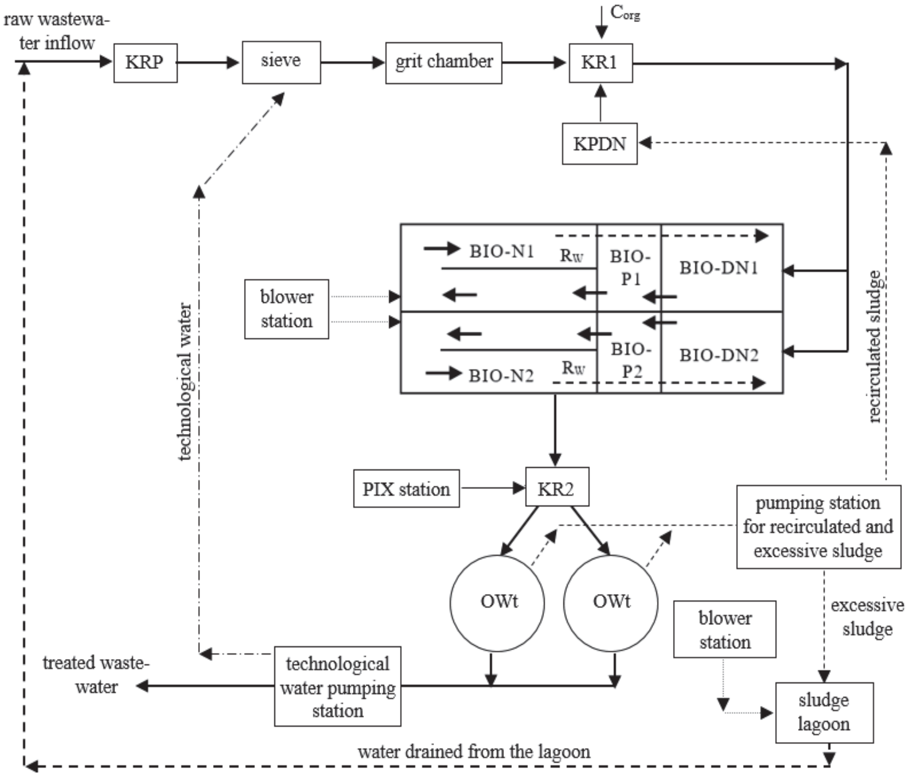

Fig. 1. Scheme presenting the technology used by the wastewater treatment plant in Nowa Wieś: KRP – expansion chamber, KR1 and KR2 – separation chamber 1 and 2, KPDN – pre-denitrification sludge chamber, BIO-DN – denitrification chamber, BIO-P – dephosphatation chamber, BIO-N – denitrification chamber, OWt – secondary settling tank

Fig. 2. The carrier EvU-Perl from Nowa Wieś WWTP (without and with biomass) (own photography)

The project assumes the following sludge technological parameters: sludge concentration – 3.7 kg·m^{-3}, sludge age – 20 days, and organic load – 0.0625 kg BOD_5·kg MLVSS^{-1}·d^{-1}. The volume load of the activated sludge chamber was assumed to be 0.231 kg BOD_5·m^{-3}·d^{-1}. The BOD_5 load on the surface of the deposit is 2.50 g BOD_5·m^{-3}·d^{-1}, for the specific surface of 700 m^2·m^{-3} and with a 14% volumetric share of carrier in the biological reactor. Moreover, it was assumed that if the ratio of TN/BOD_5 in the inflowing wastewater were to be unfavourable, an external source of organic compounds would be used. From the biological reactor, wastewater is discharged into separation chamber 2 (KR2), from where it flows into two radial settling tanks (OWt), where it is separated from biomass. PIX 122 coagulant is dosed into separation chamber 2, before the secondary settling tanks. From the latter, treated sewage flows through the chamber serving in monitoring and measurement prior to its being discharged to the receiving water.

Excessive sludge produced during biological wastewater treatment is directed to a sludge lagoon of cubic capacity 6329 m^3, which takes the form of an earth tank lined with PEHD film. In the balance of excessive sludge an increase in amount at the level of 0.8 kg MLVSS·kg BOD_5^{-1} was taken into account. At current loading of the Nowa Wieś WWTP, retention time for sludge in the lagoon is of 2 years and 3 months. The sludge in the lagoon is aerated using tubular fine-bubble diffusers. Periodic emptying of the lagoon of its accumulated sludge is carried out by means of a mobile press. Water drained from the lagoon is directed to the beginning of the purification system.

The study includes an analysis of the efficiency of operation of the Nowa Wieś WWTP in the 2016-2018 period. The assessment of the plant's efficiency was based on values for pollution indicators in raw and treated sewage made available by the plant operator (i.e. in relation to BOD_5, COD, TSS, TN and TP), as well as on the calculated efficiency of removal of particular pollutants. Chemical analyses for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) entailed measurement methods in line with Polish Standard Methods. Basic descriptive statistics such as minimum, maximum, average and median, along with standard deviation and coefficient of variation, were all determined for the aforementioned indicators.

3. Results and discussion

3.1. Hydraulic load of the WWTP

In the period under consideration, the Nowa Wieś WWTP operated under variable hydraulic conditions (Table 2, Fig. 3). Values for average daily flow ranged between 1482.0 $m^3 \cdot d^{-1}$ and 3617.0 $m^3 \cdot d^{-1}$. Both minimum and maximum flows were recorded in 2017. The mean daily flow in the three consecutive years was of 1965.9 $m^3 \cdot d^{-1}$, 1907.1 $m^3 \cdot d^{-1}$ and 1895.9 $m^3 \cdot d^{-1}$.

Table 2. Quantitative characteristics of wastewater flowing into the Nowa Wieś WWTP in 2016-2018

$Q_{av\,d}$ [$m^3 \cdot d^{-1}$]	Average	Median	Minimum	Maxi-mum	Standard deviation	Percentile 15%	Percentile 85%	Mean range
2016	1965.9	1905.0	1488.0	3235.0	265.4	1730.8	2222.5	1747.0
2017	1907.1	1859.0	1482.0	3617.0	239.7	1694.2	2145.2	2135.0
2018	1895.9	1848.5	1543.0	2857.0	213.1	1711.3	2109.0	1314.0

The mean hydraulic load in relation to the design hydraulic load of the treatment plant (2800.0 $m^3 \cdot d^{-1}$) was thus of about 70.0%, 68.0% and 67.7%, respectively. However, at different times over the analysed period, the amount of wastewater entering the plant oscillated between 53% and 129% of design capacity. Nevertheless, higher-than-planned flows were only noted 8 times, involving just 0.73% of all observations. They were a consequence of snowmelt and/or intensive precipitation (Fig. 3).

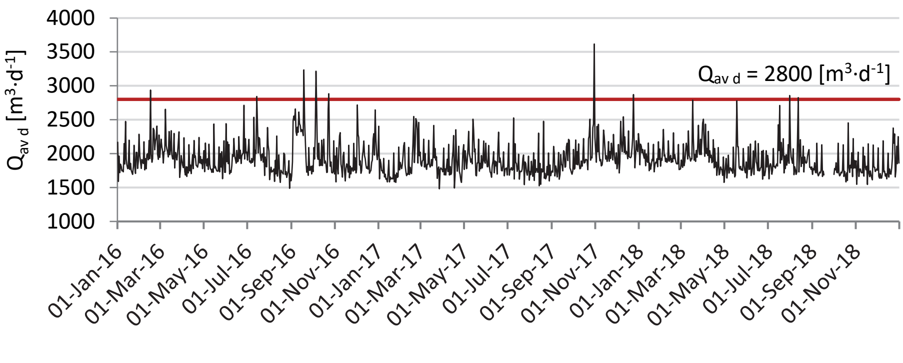

Fig. 3. Average daily flow into the WWTP, 2016-2018

The percentile of 85% of the recorded daily flows for each year is lower than the design flow. This indicates a reserve of hydraulic capacity of the plant at a level of about 640 $m^3 \cdot d^{-1}$. The total monthly flow varied from 53462 to 65745 $m^3 \cdot month^{-1}$. The months with the lowest and highest flows in the analysed period were November 2018 and September 2016 respectively.

3.2. Quality of raw wastewater

There were significant differences in the quality of wastewater flowing into the Nowa Wieś WWTP and the loads of individual pollutants (Table 3). Furthermore, significant change from year to year was to be noted in the content of pollutants in raw wastewater. The highest noted concentrations of organic compounds, as determined by BOD_5 and COD indices, and of total nitrogen, occurred in 2018 and were of 726.0 mg $O_2 \cdot dm^{-3}$, 1778.0 mg $O_2 \cdot dm^{-3}$ and 146.0 mg $TN \cdot dm^{-3}$ respectively.

Table 3. Values of selected descriptive statistics for concentrations and loads of individual pollutants noted in the 2016-2018 period

Parameter	Year	Pollution concentration [$mg \cdot dm^{-3}$]	Pollution load [$kg \cdot d^{-1}$]
		$\frac{\text{minimum} - \text{average} - \text{maximum}}{\text{standard deviation} - \text{coefficient of variation}}$	
BOD_5	2016	$\frac{296.0 - 387.3 - 513.0}{55.2 - 0.14}$	$\frac{580.2 - 742.6 - 913.7}{105.6 - 0.14}$
	2017	$\frac{339.0 - 408.5 - 490.0}{52.2 - 0.13}$	$\frac{616.0 - 767.9 - 983.4}{109.0 - 0.14}$
	2018	$\frac{296.0 - 459.8 - 726.0}{123.0 - 0.27}$	$\frac{529.5 - 876.3 - 1395.3}{252.0 - 0.29}$
COD	2016	$\frac{642.0 - 938.9 - 1293.0}{168.9 - 0.18}$	$\frac{1268.0 - 1810.0 - 2632.5}{391.3 - 0.22}$
	2017	$\frac{613.0 - 868.9 - 1061.0}{141.0 - 0.16}$	$\frac{1318.8 - 1627.4 - 1986.6}{244.4 - 0.15}$
	2018	$\frac{725.0 - 1068.9 - 1778.0}{275.6 - 0.26}$	$\frac{1286.2 - 2030.0 - 3134.6}{509.3 - 0.25}$
Total suspended solids	2016	$\frac{259.0 - 395.0 - 720.0}{128.5 - 0.33}$	$\frac{409.5 - 782.5 - 1758.2}{360.5 - 0.46}$
	2017	$\frac{146.0 - 307.4 - 470.0}{104.8 - 0.34}$	$\frac{246.6 - 573.4 - 859.6}{183.5 - 0.32}$
	2018	$\frac{183.0 - 475.3 - 920.0}{233.4 - 0.49}$	$\frac{324.6 - 904.0 - 1713.6}{437.0 - 0.48}$
Total nitrogen	2016	$\frac{72.1 - 93.8 - 121.0}{16.0 - 0.17}$	$\frac{128.7 - 180.1 - 227.1}{31.7 - 0.18}$
	2017	$\frac{72.9 - 98.3 - 123.0}{13.4 - 0.14}$	$\frac{149.6 - 184.0 - 217.7}{20.7 - 0.11}$
	2018	$\frac{70.5 - 98.2 - 146.0}{19.0 - 0.19}$	$\frac{150.7 - 188.1 - 312.7}{49.1 - 0.26}$
Total phosphorus	2016	$\frac{7.3 - 15.9 - 32.5}{8.2 - 0.52}$	$\frac{15.7 - 31.4 - 79.4}{19.6 - 0.62}$
	2017	$\frac{10.4 - 18.9 - 47.8}{10.2 - 0.54}$	$\frac{19.4 - 34.9 - 82.1}{17.1 - 0.49}$
	2018	$\frac{8.8 - 16.6 - 35.6}{7.1 - 0.43}$	$\frac{15.1 - 32.4 - 76.3}{16.5 - 0.51}$

The lowest values were in turn the 296.0 mg $O_2 \cdot dm^{-3}$ noted for BOD_5 (in 2016 and 2018), 613.0 mg $O_2 \cdot dm^{-3}$ for COD (2017) and 70.5 mg $TN \cdot dm^{-3}$ for total nitrogen (2018). In the case of total phosphorus, the highest concentration was the 47.8 mg $TP \cdot dm^{-3}$ recorded in 2017, while the lowest characterised 2016 (7.3 mg $TP \cdot dm^{-3}$). Higher concentrations of organic compounds, total nitrogen and total phosphorus in raw wastewater were to be observed in the April-June periods of each year, as a consequence of the introduction of water drained from the sludge lagoon, the quality of which changed in line with both ambient temperature and lagoon mixing.

The determination of BOD_5/COD, BOD_5/TN, COD/TN, BOD_5/TP and COD/TP ratios is important in assessing the susceptibility of wastewater inflow to a WWTP, e.g. to denitrification and biological dephosphatation processes (Cyganecka et al. 2008, Klaczyński 2012, Mazurkiewicz 2012, Klaczyński 2013, Młyńska et al. 2017, Sytek-Szmeichel et al. 2016). The BOD_5/COD value for example indicates susceptibility or resistance to biological decomposition on the part of organic compounds present in wastewater. In the period in question, 63.9% of the observations corresponded to average susceptibility of organic compounds to biochemical decomposition. The results indicating the presence of easily degradable organic compounds in wastewater are 19.4% (Fig. 4a). On the other hand, the most frequent BOD_5/TN ratios in raw wastewater were of between 3 and 5 (in 72.2% of cases), with this indicating a favourable influence of raw wastewater on the effectiveness of the denitrification process and numbers of nitrifying bacteria in activated sludge. BOD_5/TN values below 3 in turn indicate that the nitrification process may dominate in a reactor, but were noted in just 2.3% of observations (Fig. 4b). In the case of the COD/TN ratio, values above 8 (Cyganecka et al. 2008) and above 9 (Klaczyński 2012) were noted in 88.9 and 63.9% of cases respectively. In the case of the BOD_5/TP ratio, over 72% of cases involved values greater than 20 (Fig. 4c). On the other hand, almost 78% of COD/TP values were higher than the minimum recommended value, i.e. 40, indicating the most favourable conditions for effective phosphorus removal by way of the biological phosphorus-removal process.

Changes in the amount of wastewater flowing into the wastewater treatment plant and different concentrations of particular pollutants translate into pollutant loads in the years analysed. The distribution of organic pollutant loads expressed as BOD_5 and COD indexes oscillated in the 529.5-1395.3 kg $O_2 \cdot d^{-1}$ range, and between 1268.0 and 3134.6 kg $O_2 \cdot d^{-1}$ respectively. The load of biogenic compounds was from 128.7 to 312.7 kg $TN \cdot d^{-1}$ and from 15.1 to 82.1 kg $TP \cdot d^{-1}$. The load of total suspended solids was in turn between 246.6 and 1758.2 $kg \cdot d^{-1}$.

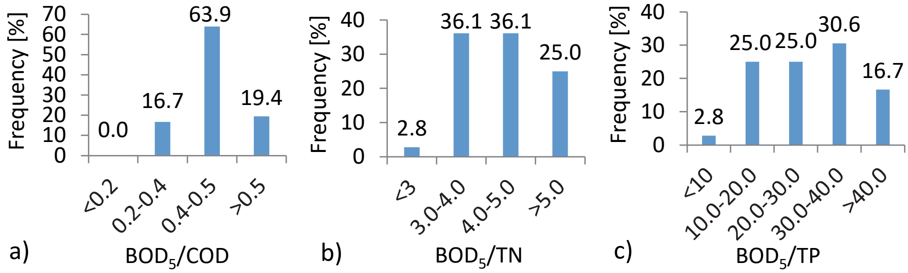

Fig. 4. Frequency of occurrence of specific values of selected ratios

3.3. Efficiency of wastewater treatment

The criterion for evaluation the efficiency of the wastewater treatment plant in Nowa Wieś form the percentage reduction of organic compounds, biogenic compounds and suspension. Selected descriptive statistics on the effectiveness of removal of particular pollutants from wastewater and the quality of treated wastewater are presented in Tab. 4.

The analysis of the results shows that the percentage of reduction of organic compounds and total suspended solids in the wastewater treatment plant in question was higher than the minimum percentage of reduction of pollution specified in the water-rights permit. The effectiveness of organic compounds removal for BOD_5 and COD ranged from 96.9 to 99.7% and from 90.1 to 98.9%, respectively. The concentration of organic compounds in treated wastewater oscillated between 1.2 and 10.4 mg $O_2 \cdot dm^{-3}$ and between 10.0 and 76.0 mg $O_2 \cdot dm^{-3}$, respectively for BOD_5 and COD (Table 4, Fig. 5a and b).

The efficiency of reduction of total suspended solids from wastewater was from 91.5 to 99.8%, as a result the concentration of the suspended solids in the outflow varied in the range of 2.0-18.4 $mg \cdot dm^{-3}$ (Table 4, Fig. 5c).

In the analysed period of operation of the WWTP, reductions in levels of biogenic compounds proved to be insufficient. The efficiency of total nitrogen removal ranged from 8.4 to 93.8%, and the concentration of this pollutant in the outflow from the wastewater treatment plant ranged from 6.3 to 83.7 mg $TN \cdot dm^{-3}$ (Table 4, Fig. 5d). The efficiency of TN removal below the required reduction efficiency specified in the water-rights permit (80.0%) was recorded 13 times within 3 years. Insufficient removal of nitrogen compounds in each of the analysed years was observed in the period from January to April (in 2017 year also in May). Both the lowest and the highest reduction of nitrogen compounds was recorded in 2017 year.

Table 4. Values of selected descriptive statistics for the concentration and efficiency of removal of individual pollutants in the years 2016-2018

Parameter	Year	Pollution concentration [mg·dm^{-3}]	Efficiency [%]
		$\frac{\text{minimum} - \text{average} - \text{maximum}}{\text{standard deviation} - \text{coefficient of variation}}$	
BOD_5	2016	$\frac{1.8 - 3.4 - 5.5}{1.3 - 0.38}$	$\frac{98.2 - 99.1 - 99.6}{0.4 - 0.00}$
	2017	$\frac{1.2 - 4.2 - 10.4}{2.7 - 0.63}$	$\frac{96.9 - 98.9 - 99.7}{0.7 - 0.01}$
	2018	$\frac{1.9 - 5.2 - 7.3}{1.9 - 0.36}$	$\frac{97.7 - 98.7 - 99.7}{0.6 - 0.01}$
COD	2016	$\frac{10.0 - 39.7 - 60.0}{16.9 - 0.43}$	$\frac{91.0 - 95.7 - 98.9}{2.1 - 0.02}$
	2017	$\frac{17.0 - 46.9 - 76.0}{22.2 - 0.47}$	$\frac{90.1 - 94.6 - 98.1}{2.6 - 0.03}$
	2018	$\frac{29.0 - 43.3 - 56.0}{9.1 - 0.21}$	$\frac{92.9 - 95.6 - 98.3}{1.5 - 0.02}$
Total suspended solids	2016	$\frac{3.8 - 8.3 - 15.4}{3.1 - 0.38}$	$\frac{96.0 - 97.8 - 98.8}{1.0 - 0.01}$
	2017	$\frac{3.0 - 7.6 - 16.8}{4.2 - 0.55}$	$\frac{91.5 - 97.3 - 98.9}{2.0 - 0.02}$
	2018	$\frac{2.0 - 9.0 - 18.4}{5.5 - 0.61}$	$\frac{95.6 - 97.7 - 99.8}{1.4 - 0.01}$
Total nitrogen	2016	$\frac{7.52 - 20.8 - 49.7}{17.8 - 0.85}$	$\frac{41.5 - 78.7 - 91.3}{17.5 - 0.22}$
	2017	$\frac{6.3 - 34.0 - 83.7}{32.6 - 0.96}$	$\frac{8.4 - 65.6 - 93.8}{33.1 - 0.50}$
	2018	$\frac{7.0 - 21.3 - 59.9}{19.8 - 0.93}$	$\frac{29.9 - 76.7 - 93.1}{22.9 - 0.30}$
Total phosphorus	2016	$\frac{0.21 - 2.1 - 9.2}{2.7 - 1.27}$	$\frac{70.0 - 89.4 - 97.3}{9.7 - 0.11}$
	2017	$\frac{0.1 - 3.4 - 14.8}{4.2 - 1.23}$	$\frac{69.0 - 85.6 - 99.1}{11.8 - 0.14}$
	2018	$\frac{0.32 - 2.1 - 7.31}{2.0 - 0.95}$	$\frac{56.5 - 87.2 - 97.3}{11.5 - 0.13}$

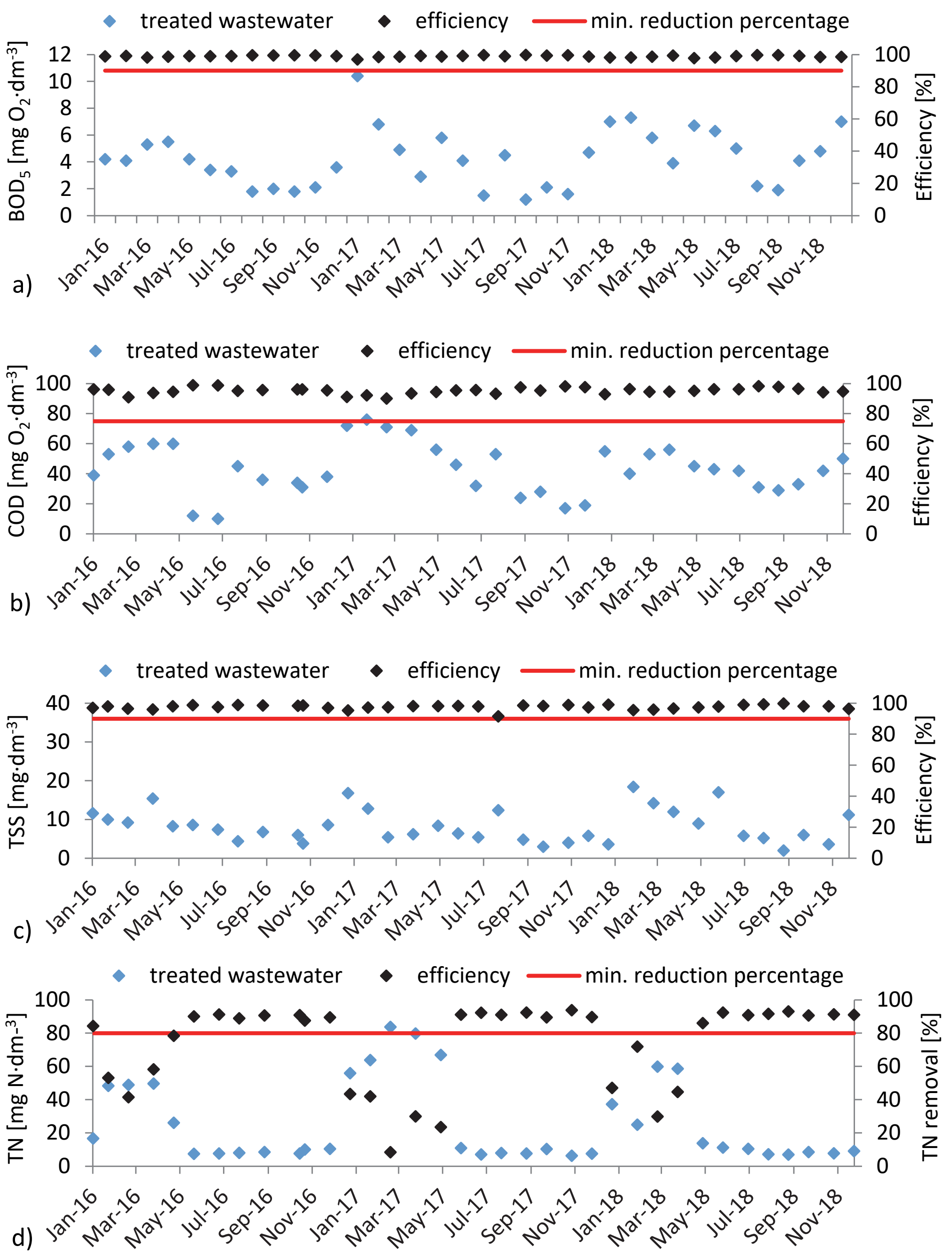

Fig. 5. The quality of treated wastewater and removal efficiency of individual pollutants

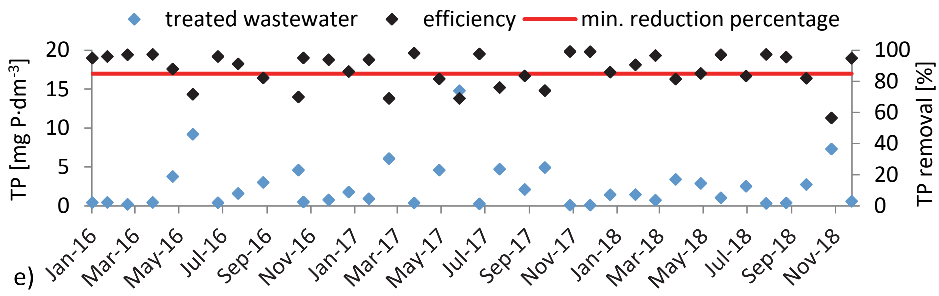

Fig. 5. cont.

The results of biochemical tests from the winter period (January 2018) showed a decrease in nitrification rate between two dates, both by the biomass of the activated sludge (by approx. 79.4%) and biomass on the carrier (by approx. 60.0%). In addition, the highest percentage of nitrification conducted by the biofilm was only 17.7%. Also in the assessment of the denitrification rate, between successive dates, a decrease of about 43.0% for active sludge and about 68.0% for biomass on a carrier was observed.

On the other hand, the efficiency of removing total phosphorus from wastewater was from 56.5 to 99.1%, while the average efficiency in subsequent years was 89.4±9.7%, 85.6±11.8% and 87.2±11.5%. The concentration of this pollutant in treated wastewater varied from 0.1 to 14.8 mg TP·dm^{-3} (Table 4, Fig. 5e). The achieved efficiency of total phosphorus removal resulted not only from biological phosphorus removal but also from chemical phosphorus precipitation. The efficiency of TP removal below the required reduction efficiency specified in the water-rights permit (85.0%) was also recorded 13 times within 3 years. However, it was not observed that the decrease of efficiency was in the same months in the subsequent years. Only October was the month in which the decrease in phosphorus reduction observed in all years. Moreover, twice (2016 and 2017) such a dependency was observed in June and September.

According to the literature, there are different levels of efficiency of removal of organic and biogenic compounds using MBBR technology. Chu & Wang (2011) applied MBBR technology to remove organics and nitrogen from wastewater with a low C/N ratio, achieving levels of 90.0 and 65.0% respectively in so doing. Shrestha (2013) reported, that carrier filling rate in a MBBR is important to the removal of organic compounds. In research carried out at 10, 20, 30 and 40% filling rates, the average levels of COD removal efficiency reported were 75.7, 91.1, 85.5 and 79.6% respectively. Ahmadi et al. (2014) reported that the efficiency of an MBBR system as regards COD removal exceeded 80%. In turn, Wang et al. (2006) reported that efficiency of removal of COD from domestic wastewater was in the 71.3-77.1% range. Gani et al. (2016) found levels of removal of total phosphorus and suspended solids ranging from 84.0 to 98.0% and 85.0 to 94.0%, where influent concentrations were 3.3-7.1 mg TP·dm^{-3} and 74.0-356.0 mg·dm^{-3}, respectively. In an MBBR with suspended plastic carriers (AnoxKaldnes K5), and a 50% filling ratio, average phosphorus and total nitrogen removal efficiencies were respectively of 76.8% and 70.0% (almost complete nitrification, with average ammonium removal efficiency equal to 82%) (Mudhaffar et al. 2015). By using a moving bed biofilm process in conditions that were anaerobic or anoxic, or aerobic, total nitrogen and phosphorus removal efficiencies obtained were of 84.6 and 95.8% respectively (Kermani et al. 2008).

The wastewater treatment plant in Nowa Wieś is obliged to remove biogenic compounds, however, the results presented in Table 4 and Fig. 5 confirm the operational problems of the facility in this scope. The data made available by the operator show that the sludge age in these years was maintained at the range of about 5 to 25 days. The concentration of biomass varied from approx. 2.0 to 5.8 kg MLVSS·m^{-3}, while the biomass loading of BOD_5 ranged from 0.04 to 0.11 kg BOD_5·kg MLVSS^{-1}·d^{-1}. The degree of external recirculation was also kept within the recommended limits with the average value of approx. 0.8. In turn, the degree of internal recirculation allowed to maintain the nitrate concentration at the level of 6.0 mg·dm^{-3}.

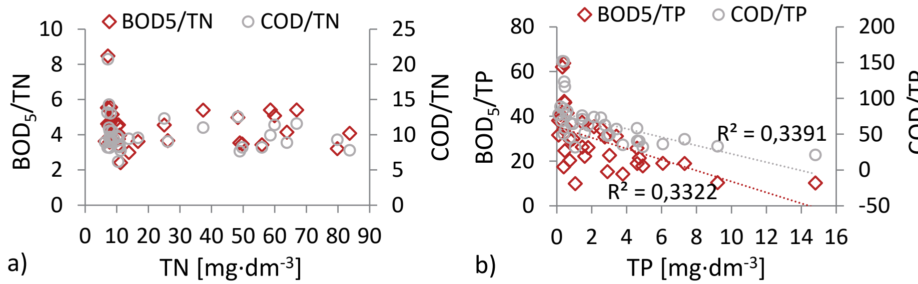

Fig. 6. Relationship between selected ratios and TN or TP concentrations in treated wastewater

The recognizing of the effect of BOD_5/TN and COD/TN ratio of raw wastewater did not show any significant dependencies between these ratios and the degree reduction of total nitrogen and total nitrogen concentration in treated wastewater. However, it can be observed (Fig. 6a) that the concentration of total nitrogen in treated wastewater below 10.0 mg TN·dm^{-3} was most frequently observed at BOD_5/TN values ranging from 3.60 to 5.0. In turn, a high correlation was observed between BOD_5/TP and COD/TP ratio and total phosphorus concentration in treated wastewater (r = 0.5764 and r = 0.5823) (Fig. 6b). The lowest

TP concentrations in treated wastewater, at the level of up to 1.0 mg P·dm^{-3}, were observed for BOD_5/TP ratio values above 30.

Over the whole 2016-2018 period, the temperatures in the BIO-DN1 and BIO-DN2 chambers were in the range 7.5-20.5°C. Assessment of the dependent relationship between TN concentration in outflow and efficiency of removal as set against temperature (Fig. 7) showed a high level of correlation (r = 0.7665 and 0.7647 respectively).

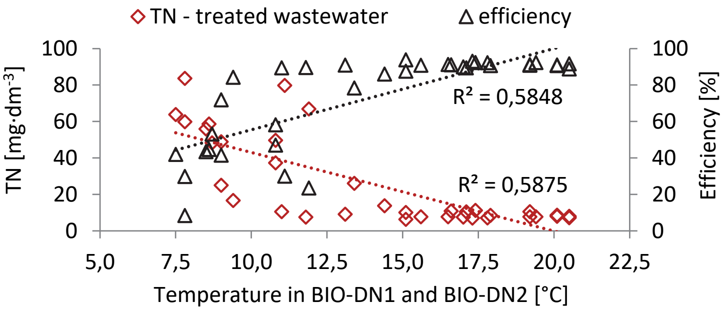

Fig. 7. Relationship between TN concentration in outflow or TN removal efficiency and temperature in the denitrification chamber

Periods of low temperature were indeed associated with increased concentrations of total nitrogen in treated wastewater (typically to about 50.0 mg·dm^{-3} in 2016, 84.0 mg·dm^{-3} in 2017 and 60.0 mg·dm^{-3} in 2018). In addition, WWTP employees report very high winter concentrations of ammonium compounds in outflow, indicative of low efficiency (i.e. inhibition) of the nitrification process. There nevertheless remain points not accounted for readily by reference to this relationship, which may indicate the presence of a further factor influencing nitrification.

Over the analysed period, water drained from the sludge lagoon was also introduced into the technological process of wastewater treatment. This represents an additional load of biogenic compounds also capable of impacting upon treatment efficiency. Values for TN and TP loads in raw wastewater and water drained from the sludge lagoon on selected dates were as presented in Fig. 8.

The nitrogen load introduced with water drained from the sludge lagoon was in the range 6.9-30.8 kg TN·d^{-1}, in this way accounting for between 3.0 and 20.0% of the load in raw wastewater (Fig. 8a). Total nitrogen concentrations varied from 67.8 to 145.0 mg TN·dm^{-3} in the case of raw wastewater, from 38.0 to 197.5 mg TN·dm^{-3} in water draining from sludge lagoon and from 11.0 to 92.0 mg TN·dm^{-3} in treated wastewater. However, it should be emphasised further that on days when a high concentration of TN in water draining from sludge lagoon was observed and the ambient temperature was propitious, the TN concentration in treated wastewater was low. This suggests that temperature was indeed the main factor limiting effective removal of nitrogen compounds.

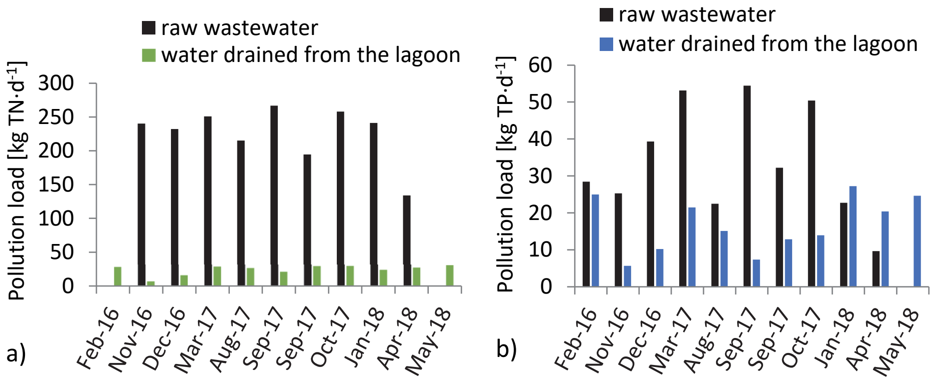

Fig. 8. Values for loads of biogenic pollutants in raw wastewater and water drained from the sludge lagoon

On the other hand, the total phosphorus load varied from 5.6 to 27.2 kg $TP \cdot d^{-1}$ and made up from 13.5% to 210.0% load of raw wastewater (Fig. 8b). Phosphorus concentration ranged from 4.9 to 29.6 mg $TP \cdot dm^{-3}$ – raw wastewater; from 31.0 to 158.0 mg $TP \cdot dm^{-3}$ – water drained from sludge lagoon and from 1.0 to 10.7 mg $TP \cdot dm^{-3}$ – treated wastewater. It should be emphasized that in the sludge lagoon anaerobic conditions prevail, which causes the release of phosphorus embedded in the biomass in the biological part of the treatment plant. Therefore, the primarily removed phosphorus is released back and returned with water drained from sludge lagoon to the wastewater part. It is worth emphasizing that on the days when very high concentrations of TP in water drained from sludge lagoon were observed, the concentration in the effluent from WWTP was usually above 5.0 mg $TP \cdot dm^{-3}$. Thus, it was one of the causes of increased phosphorus concentration in the effluent from the wastewater treatment plant.

4. Conclusions

The hydraulic load of the wastewater treatment plant in Nowa Wieś is 68.6% of the planned load, which is 2800.0 m^3-d^{-1}. The hydraulic capacity reserve of the plant, estimated by reference to the percentile value of 85% of recorded daily flows, is approximately 640 $m^3 \cdot d^{-1}$. The interpretation of the plant's efficiency in relation to the requirements set out in the permit issued under the Water

Law Act indicates correct operation of the facility in terms of the removal of organic compounds and elimination of total suspended solids.

The average level of efficiency determined for the removal of organic compounds from sewage was 98.9±0.6% for BOD_5 and 95.3±2.1% for COD, denoting that the average concentration of these compounds in outflow was of 4.3±2.1 and 43.3±16.7 mg $O_2 \cdot dm^{-3}$ respectively. The average value for the efficiency of removal of total suspended solids was in turn 97.6±1.5%, with the average concentration on discharge equal to 8.3±4.3 $mg \cdot dm^{-3}$. Unfortunately, in the analysed years, a dozen or so times (in about 36% of the results) the reduction of biogenic compounds proving achievable was below the level laid down by the permit, i.e. 80.0% for TN and 85.0% for TP. The average efficiencies of removal of nitrogen and phosphorus compounds from wastewater in the analysed period were in fact of 73.7±25.3% and 87.4±10.8% respectively. This denotes that the average concentration of biogenic compounds in treated wastewater was 25.4±24.4 mg $TN \cdot dm^{-3}$ and 2.5±3.1 mg $TP \cdot dm^{-3}$. The evaluation of raw wastewater quality showed that values for the BOD_5/TN, COD/TN, BOD_5/TP and COD/TP ratios are invariably within the range recommended for the proper course of denitrification and nitrification processes. This leaves the typical cause of problems relating to insufficient removal of total nitrogen as low temperature, which is found to restrict nitrification. In addition, it is possible to conclude that water drained from the sludge lagoon may have contained substances also acting to curb the nitrification process. In the case of insufficient reduction of phosphorus compounds, the problem results from additional loading of this pollutant.

If the efficiency of nutrient removal in the Nowa Wieś WTTP is to be raised, sludge management will need to be organised better. It may also be necessary to adapt the nitrification chambers to low winter temperatures by increasing their volume, or by replacing the biofilm carrier. It is also worthwhile assessing the quality of wastewater treated mechanically, with attention paid to the of BOD_5/TN, COD/TN, BOD_5/TP and COD/TP ratios, with a view to noting if these are definitely favourable to biological wastewater treatment processes.

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Abstract

The MBBR technology base on the idea of bringing together, within a single system, the best characteristics of the activated sludge and biofilm processes. With biomass immobilised on free-support media, the retention of solids in the biological reactor is enhanced. The advantages of this technology as compared with activated-sludge systems are: a higher effective sludge retention time (SRT) that favours nitrification, more limited production of sludge, more limited requirements as regards area, and resilience to toxic shock. The MMBR technology does not need recirculation of sludge, which is the case with activated-sludge systems, so process performance is independent of a secondary clarifier. Wastewater treatment based on the MBBR process in the same tank favours nitrification, since the issue of the retention time for solids becomes partly uncoupled from the hydraulic retention time. This is particularly important where a WWTP is operating at low temperatures, as under these conditions, the sludge age needed to support nitrification is relatively great, due to the low growth rates achieved by nitrifying bacteria.

The aim of the paper is the evaluation of the effectiveness of a wastewater treatment plant in Nowa Wieś (Poland). The technological system of the Nowa Wieś WWTP consists of an sieve, grit chamber, two reactors with moving bed biofilm (MBBR reactors with the EvU-Perl carriers) and two secondary settling tanks. The study includes an analysis of the efficiency of operation of the Nowa Wieś WWTP in the 2016-2018 period. The assessment of the plant's efficiency was based on values for pollution indicators in raw and treated sewage made available by the plant operator (i.e. in relation to BOD_5, COD, TSS, TN and TP), as well as on the calculated efficiency of removal of particular pollutants.

The average level of efficiency determined for the removal of organic compounds from sewage was 98.9±0.6% (BOD_5) and 95.3±2.1% (COD), denoting that the average concentration of these compounds in outflow was of 4.3±2.1 and 43.3±16.7 mg $O_2 \cdot dm^{-3}$ respectively. The average value for the efficiency of removal of total suspended solids was in turn 97.6±1.5%, with the average concentration on discharge equal to 8.3±4.3 $mg \cdot dm^{-3}$. Unfortunately, in the analysed years, a dozen or so times (in about 36% of the results) the reduction of biogenic compounds proving achievable was below the level laid down by the permit, i.e. 80.0% for TN and 85.0% for TP. The average efficiencies of removal of nitrogen and phosphorus compounds from wastewater in the analysed period were in fact of 73.7±25.3% and 87.4±10.8% respectively. This denotes that the average concentration of biogenic compounds in treated wastewater was 25.4±24.4 mg $TN{\cdot}dm^{-3}$ and 2.5±3.1 mg $TP{\cdot}dm^{-3}$.

Keywords:
MBBR technology, activated sludge, EvU-Perl carrier material, organic compounds, biogenic compounds

Ocena efektywności działania oczyszczalni ścieków z technologią MBBR

Streszczenie

Technologia złoża ruchomego (MBBR) opiera się na idei połączenia w ramach jednego systemu najlepszych cech osadu czynnego i błony biologicznej. W wyniku unieruchomienia mikroorganizmów na ruchomych nośnikach, retencja biomasy w reaktorze biologicznym jest zwiększona. Zaletami tej technologii w porównaniu do klasycznego osadu czynnego są: wyższy efektywny wiek osadu, który intensyfikuje proces nitryfikacji, mniejszy przyrost osadu nadmiernego oraz odporność układu na dopływ substancji toksycznych. Technologia MBBR nie wymaga recyrkulacji osadu czynnego, co ma miejsce w przypadku systemów osadu czynnego, więc wydajność procesu jest niezależna od osadnika wtórnego. Oczyszczanie ścieków w oparciu o proces MBBR sprzyja nitryfikacji, ponieważ kwestia czasu retencji biomasy zostaje częściowo niezależna od hydraulicznego czasu retencji. Jest to szczególnie ważne, gdy oczyszczalnia ścieków działa w niskich temperaturach, ponieważ w tych warunkach wiek osadu potrzebny do podtrzymania nitryfikacji jest stosunkowo duży, ze względu na niskie tempo wzrostu osiągane przez bakterie nitryfikacyjne.

Celem pracy jest ocena efektywności oczyszczalni ścieków w Nowej Wsi (Polska). Układ technologiczny oczyszczalni w Nowej Wsi składa się z sita i piaskownika, dwóch reaktorów z osadem czynnym i złożem ruchomym w postaci kształtek EvU-Perl oraz dwóch osadników wtórnych. Opracowanie obejmuje analizę efektywności działania oczyszczalni ścieków w Nowej Wsi w latach 2016-2018. Ocenę efektywności przedmiotowej oczyszczalni dokonano w oparciu o wartości wskaźników zanieczyszczeń w ściekach surowych i oczyszczonych udostępnionych przez eksploatatora oczyszczalni (BZT_5, ChZT, zawiesina ogólna, azot ogólny, fosfor ogólny), a także obliczonej efektywności usuwania poszczególnych zanieczyszczeń.

Średnia efektywność usunięcia ze ścieków związków organicznych wyniosła 98.9±0.6% (BZT_5) oraz 95.3±2.1% (ChZT), efektem czego średnie stężenie tych związków w odpływie wynosiło odpowiednio 4.3±2.1 mg $O_2{\cdot}dm^{-3}$ oraz 43.3±16.7 mg $O_2{\cdot}dm^{-3}$. Wartość średnia efektywności usuwania zawiesiny ogólnej była na poziomie 97.6±1.5%, przy średnim stężeniu równym 8.3±4.3 $mg{\cdot}dm^{-3}$. Niestety w analizowanych latach kilkanaście razy (ok. 36% wyników) odnotowano niższy stopień redukcji związków biogennych, niż ten określony pozwoleniem wodno-prawnym tj. 80.0% dla N_{og} i 85.0% dla P_{og}.

Wyznaczona średnia efektywność usunięcia związków azotu i fosforu ze ścieków w rozpatrywanym okresie wyniosła odpowiednio 73.7±25.3% oraz 87.4±10.8%. Średnia wartość stężenia związków biogennych w ściekach oczyszczonych była równa 25.4±24.4 mg $N \cdot dm^{-3}$ oraz 2.5±3.1 mg $P \cdot dm^{-3}$.

Słowa kluczowe:
technologia MBBR, osad czynny, złoże biologiczne EvU-Perl, związki organiczne, związki biogenne