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Analysis of wastewater treatment efficiency in the region of Lake Czorsztyn

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Abstract

The aim of this study was to analyze the efficiency of wastewater treatment processes in fifteen wastewater treatment plants located in the region of Lake Czorsztyn, which functions as both a direct and indirect receiver of treated effluents from these facilities. The analyzed wastewater treatment plants are situated in the following localities: Czarny Dunajec, Czorsztyn, Dębno, Frydman, Kluszkowce, Krempachy, Krościenko, Łopuszna, Maniowy, Niedzica, Sromowce Niżne, Sromowce Wyżne, Szczawnica, Trute, and Trybsz. The assessment of treatment efficiency in these facilities was performed based on the calculation of the average reduction degree (η) of selected pollution indicators (BOD_5, COD_{Cr}, total suspended solids, total nitrogen, and total phosphorus), as well as on the analysis of the number of exceedances of their permissible values in treated wastewater. The evaluation was based on analytical results from two years (2023–2024). High wastewater treatment efficiency was found for BOD_5, COD_{Cr}, and total suspended solids (the reduction range for the analyzed contaminants was: $\eta_{BOD_5} = 91.2\%–99.1\%$, $\eta_{COD_{Cr}} = 80.9\%–96.7\%$, $\eta_{TSS} = 88.5\%–98.3\%$). For total nitrogen, the average reduction efficiency ranged from 48.2% to 96.6%, and for total phosphorus from 55.6% to 95.7%. Exceedances of permissible total nitrogen concentrations were observed in 40% of the analyzed samples from the Niedzica wastewater treatment plant, as well as single exceedances of total phosphorus limit valuess in Czarny Dunajec, Czorsztyn, and Niedzica.

Keywords: wastewater treatment plant, treatment efficiency, pollutant reduction rate

1. Introduction

Ensuring high water quality in rivers, streams, and water reservoirs in the Czorsztyn Lake region is of key ecological, social, and economic importance for the entire Podhale area. Currently, an increasing trend in environmental pollution is being observed, mainly caused by the growing pace of urbanization, industrialization, and the global rise in population (Migdał et al., 2022). Moreover, due to socio-economic development and climate change, the quality of global water resources is becoming increasingly threatened, with inadequately managed wastewater being a major contributing factor to this deterioration (Jones, et al. 2022). Watercourses are particularly vulnerable to contamination, as they often serve as receivers of treated effluents discharged from wastewater treatment processes. This makes the issue of proper wastewater treatment one of the most crucial aspects of protecting aquatic environments, since insufficiently treated wastewater remains a key source of water pollution (Pssarou et al., 2018; Taheriyoun and Moradinejad, 2015; Jones et al., 2022). Untreated or insufficiently treated domestic wastewater is a source of biogenic compounds, also referred to as eutrophic pollutants (Anielak, 2006). When these compounds enter receiving waters, they trigger eutrophication processes, leading to overgrowth, reduced water retention capacity, and even the complete disappearance of water bodies (Kaczor and Bugajski, 2006).

The discharge of treated wastewater into aquatic reservoirs significantly affects the chemical and ecological quality of rivers by introducing a wide range of pollutants and altering the composition of aquatic microbiomes (Marizzi Del Olmo et al., 2025). Riverine microbiomes can serve as indicators of urban wastewater pollution and are influenced by contaminants such as heavy metals, which impact the health of the entire aquatic ecosystem (Chaturvedi et al., 2025). According to Heindrich and Witkowski (2005), treated wastewater discharged from treatment plants into the natural environment should not alter the physicochemical or biological properties of the receiving waters. Any hydrological disturbances are highly detrimental to both society and the natural environment.

In light of this knowledge, it is crucial to ensure the effective reduction of pollutants during wastewater treatment in every operating treatment facility, which constitutes a key component of the regional water and wastewater management system. Moreover, the landscape and recreational values of the studied Podhale area necessitate particular attention to maintaining the cleanliness of surface waters within the upper Dunajec catchment (Stawski, 1995). Any operational disruptions in wastewater treatment plants, manifested by insufficient pollutant removal efficiency, have a direct and adverse impact on the natural environment, and consequently on human health, quality of life, and in this specific case the further tourism development of the Czorsztyn Lake region. Minimizing this negative impact of wastewater discharge is possible only through the proper functioning of wastewater treatment plants that ensure high treatment efficiency (Chmielowski, Satora and Wałęga, 2009).

The applicable legal acts, including the regulation (Dz. U. 2019 poz. 1311) and water law permits issued individually for each wastewater treatment plant, enable operators to monitor the quality and efficiency of wastewater treatment processes, thereby ensuring the proper protection of the receiving water bodies (Śliz and Bugajski, 2022).To assess treatment efficiency in terms of compliance with permissible pollutant levels in treated effluents, it is common practice to compare the measured values of pollution indicators after treatment with the threshold values specified in the relevant legal regulations. This approach remains one of the fastest and least complex methods for verifying the operational performance of wastewater treatment plants in this respect (Śliz, 2020, 2024). Furthermore, comparing pollutant indicator values in treated effluents with those in raw sewage allows for the evaluation of a treatment plant's operational effectiveness by determining the degree of reduction of the analyzed contaminants (Chmielowski, Młyńska and Młyński, 2015).

The subject of this study was the analysis of wastewater treatment efficiency in 15 treatment plants operated by the Podhale Municipal Enterprise, which is responsible for maintaining the good quality of rivers and streams in the Podhale, Orava, Spiš, and Pieniny regions. The receiving body for the treated effluents from these facilities either directly or indirectly is Lake Czorsztyn, which represents the main tourist center of the region. Ensuring high treatment efficiency in the analyzed facilities is particularly important given that the upper Dunajec catchment constitutes the source area of the river basin supplying clean water to the inhabitants of settlements located both upstream and downstream of the Czorsztyn Reservoir (Stawski, 1995).

The analysis of selected pollutant indicators in raw and treated wastewater, taking into account the limit values specified in the applicable legal regulations, allowed for determining the degree of reduction of the analyzed contaminants and identifying the number of exceedances of permissible limits in treated wastewater at the examined facilities during the years 2023–2024. The applied analytical tools enabled an efficient verification of wastewater treatment performance and, consequently, an assessment of the protective function against the negative impact of treated effluents on the aquatic environment of the upper Dunajec catchment and, by extension, the Czorsztyn Reservoir.

2. Characteristics of the analysed facility

The analyzed wastewater treatment plants operated by the Podhale Municipal Enterprise are located in the following municipalities: Czarny Dunajec, Czorsztyn, Dębno, Frydman, Kluszkowce, Krempachy, Krościenko, Łopuszna, Maniowy, Niedzica, Sromowce Niżne, Sromowce Wyżne, Szczawnica, Trute, and Trybsz (Fig. 1). The design and construction of these treatment plants were closely linked to the protection of water quality within the upper Dunajec River basin and the Czorsztyn Reservoir.

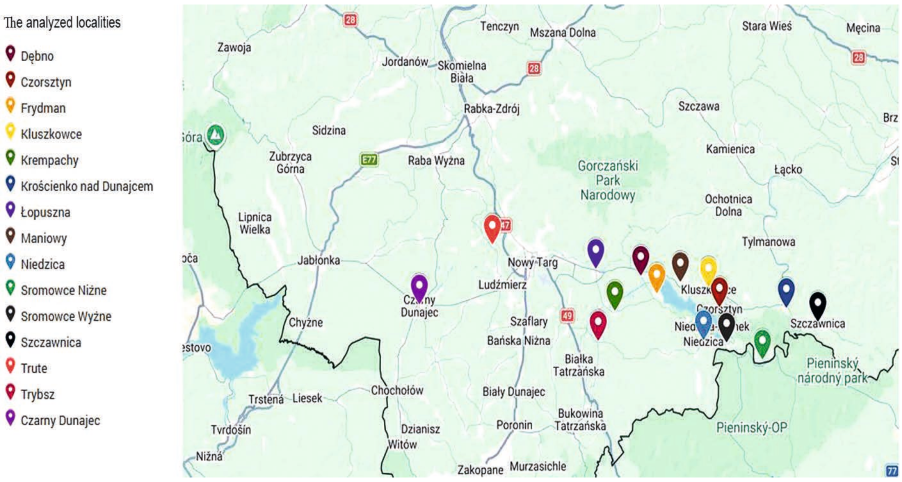

Fig. 1. Location of the localities hosting the analyzed wastewater treatment plants. Source: own elaboration based on Google Maps (accessed: 25 February 2026)

The technical characteristics and operational parameters of the analyzed wastewater treatment plants are presented in Table 1.

The construction of the analyzed wastewater treatment plants took place between 1993 and 2019 and was initiated in connection with the development of the Czorsztyn–Niedzica and Sromowce Wyżne Water Reservoir Complex, which brought about a number of positive changes in the wastewater management of the region. This was associated with the implementation of a surface water protection program for the inflows to the reservoir complex, which included the construction of local wastewater treatment plants and sewage systems (Stawski, 1995). Based on Table 1, it is evident that most of the treatment plants underwent modernization between 2000 and 2023. The technological processes in these facilities are primarily based on flow-through activated sludge systems and SBR biological reactors. Analysis of Table 1 also reveals a significant disparity in the size of the investigated facilities. The average daily capacity of the analyzed wastewater treatment plants ranges from 255 $m^3 \cdot d^{-1}$ in Dębno, with an Equivalent Population (EP) of 1,000, to 3,600 $m^3 \cdot d^{-1}$ in Szczawnica, with an EP of 15,500. Lake Czorsztyn serves as a direct receiver of treated wastewater for the treatment plants in Dębno, Czorsztyn, Kluszkowce, and Frydman, and as an indirect receiver through a network of streams and rivers in the remaining cases (as shown in Table 1).

Table 1. Characteristics of the wastewater treatment plant parameters of the analyzed wastewater treatment plants

No.	Name of treatment plant	Year of commissioning/ modernization	Technology	Average daily capacity Q [$m^3 \cdot d^{-1}$], value of EP [–]	Receiver of treated wastewater
1	Czarny Dunajec	2001/2021	flow-through biological reactor	Q = 1,600, EP = 10,500	Czarny Dunajec Stream at km 215+320
2	Czorsztyn	1993/2014	SBR, 2 reactors	Q = 380, EP = 1,175	Wronie Stream at km 0+100, then Czorsztyn Reservoir
3	Dębno	1994	activated sludge, flow-through system	Q = 255, EP = 1,000	Drainage ditch, then Dębniczanka Stream, then Czorsztyn Reservoir
4	Frydman	1994/2000	SBR, 2 reactors	Q = 300, EP = 1,668	Pumping station reservoir, then Czorsztyn Reservoir
5	Kluszkowce	1994/2021	flow-through biological reactor	Q = 630, EP = 3,150	Unnamed watercourse, then Czorsztyn Reservoir
6	Krempachy	2019	SBR	Q = 500, EP = 3,767	Stream (right-bank tributary of the Białka River)
7	Krościenko n. Dunajcem	2000/2020	SBR, 2 reactors	Q = 1,320, EP = 8,756	Dunajec River at km 148+050 via the Ciemny (Głęboki) Stream
8	Łopuszna	1998/2017	activated sludge, flow-through system	Q = 1,600, EP = 8,426	Dunajec River at km 192+020
9	Maniowy	1999/2023	multifunctional biological reactor	Q = 920, EP = 3,850	Limierzyska Stream at km 0+060
10	Niedzica	1995/2008	SBR, 3 reactors	Q = 1,250, EP = 9,000	Sromowce Wyżne Reservoir
11	Sromowce Niżne	2008	SBR, 2 reactors	Q = 266, EP = 1,320	Macelowy Stream at km 0+550
12	Sromowce Wyżne	1996	SBR	Q = 171, EP = 1,480	Dunajec River at km 172+400 via an unnamed watercourse
13	Szczawnica	1995/2015	activated sludge, flow-through system	Q = 3600, EP = 15,500	Dunajec River at km 151+000
14	Trute	2013/2022	Multi-chamber SBR reactor	Q = 900, EP = 7,500	Lepietnica Stream at km 2+565
15	Trybsz	1998/2022	Multi-chamber SBR reactor	Q = 137, EP = 700	rybska Rzeka Stream at km 2+200

Source: own work based on www. ppkpodhale.pl/nasza-dzialalnosc/sekcje-utrzymania-sieci (date of access: 2025/10/24).

Table 2 presents the permissible values of the analyzed pollution indicators in treated wastewater that may be discharged into receiving water bodies in accordance with the valid water law permits. According to the provisions of the valid water law permits (Pozwolenie...2013,..., Pozwolenie...2024) presented in Table 2, the values of pollution indicators for treated wastewater discharged into receiving bodies from individual facilities must not exceed the following permissible limit valuess: 25.0–40.0 $mgO_2 \cdot dm^{-3}$ for BOD_5, 125.0–150.0 $mgO_2 \cdot dm^{-3}$ for COD_{Cr}, 35.0–50.0 $mgO_2 \cdot dm^{-3}$ for total suspended solids, 15.0–30.0 mgN·dm^{-3} for total nitrogen, and 2.0–5.0 mgP·dm^{-3} for total phosphorus.

Table 2. Permissible values of selected pollution indicators in treated wastewater in the analyzed wastewater treatment plants

Wastewater treatment plant	The limit values of wastewater pollution indicators discharged into receiving waters				
	BOD$_5$ [mgO$_2$·dm^{-3}]	COD$_{Cr}$ [mgO$_2$·dm^{-3}]	total suspended solids [mg·dm^{-3}]	total nitrogen [mgN·dm^{-3}]	total phosphorus [mgP·dm^{-3}]
Czarny Dunajec	25	125	35	15	2
Czorsztyn	25	125	35	15	2
Dębno	40	150	50	30	5
Frydman	25/40	125/150	35/50	15/30	2/5
Kluszkowce	25	125	35	15	2
Krempachy	25	125	35	–	–
Krościenko	25	125	35	–	–
Łopuszna	25	125	35	–	–
Maniowy	25	125	35	15	2
Niedzica	25	125	35	15	2
Sromowce Niżne	40	150	50	–	–
Sromowce Wyżne	40	150	50	–	–
Szczawnica	25/25	125	35	15	2
Trute	25	125	35	–	–
Trybsz	40	150	50	–	–

Source: own work based on (Pozwolenie...2013, 2024).

3. Materials and methodology

To determine the parameters of wastewater treatment efficiency in the analyzed treatment plants, the results of physicochemical analyses of raw and treated wastewater from the study period 2023–2024 were used. The scope of the analysis included the main wastewater pollution indicators, i.e., BOD$_5$, COD$_{Cr}$, total suspended solids, total nitrogen, and total phosphorus. Furthermore, for each facility, the obtained concentrations of pollutants in the treated wastewater were compared with the permissible limit values, and the number of exceedances of these limit values was identified.

The reduction rate of the analysed pollutant indicators in the treated wastewater, which was used to directly determine the treatment efficiency, was calculated according to the following formula:

$$\eta = \frac{S_S - S_o}{S_s} \cdot 100\% \tag{1}$$

where: η – reduction of a particular pollutant index in treated sewage [%], S_s – value of the pollution index in raw sewage [mg·dm^{-3}], S_o – value of the pollution index in treated sewage [mg·m^{-3}].

Subsequently, the average reduction values of individual pollution indicators were calculated for the analyzed wastewater treatment plants.

3.1. Results

Table 3 presents the number of exceedances of limit values for the analyzed pollution indicators, in relation to the stipulations of the applicable water permits (Pozwolenie...2013, 2024), which are listed in Table 2. Analysis of Table 3 shows that no exceedances of permissible values for BOD_5, COD_{Cr}, or total suspended solids were recorded for any of the studied wastewater treatment plants.

Table 3. Number of exceedances of permissible limits for selected pollution indicators in the studied wastewater treatment plants

Wastewater treatment plant	Number of exceedances of limit values in treated wastewater in 2023–2024					Number of samples
	BOD_5	COD_{Cr}	total suspended solids	total nitrogen	total phosphorus	
Czarny Dunajec	0	0	0	0	1	24
Czorsztyn	0	0	0	0	1	8
Dębno	0	0	0	0	0	6
Frydman	0	0	0	0	0	5
Kluszkowce	0	0	0	0	0	8
Krempachy	0	0	0	no data	no data	11
Krościenko	0	0	0	no data	no data	8
Łopuszna	0	0	0	0	0	15
Maniowy	0	0	0	0	0	13
Niedzica	0	0	0	6	1	15
Sromowce Niżne	0	0	0	no data	no data	4
Sromowce Wyżne	0	0	0	no data	no data	4
Szczawnica	0	0	0	0	0	24
Trute	0	0	0	no data	no data	11
Trybsz	0	0	0	no data	no data	4

Source: own work.

Exceedances of limit values in treated wastewater were recorded only for biogenic compounds in the studied facilities. Regarding total nitrogen, exceedance of the permissible value occurred in the Niedzica treatment plant 6 times out of 15 samples, accounting for as much as 40% of all analyses. Single cases of exceeding permissible total phosphorus values were observed in the treatment plants in Czarny Dunajec, Czorsztyn, and Niedzica, representing approximately 4%, 13%, and 7% of the analyzed samples, respectively. In the treatment plants of Krempachy, Krościenko, Sromowce Niżne, Sromowce Wyżne, Trute, and Trybsz, monitoring of nitrogen and phosphorus compounds was not required. The occurrence of exceedances of permissible total nitrogen values could be related to the instability of nitrification and denitrification processes, during which nitrogen compounds are removed in the biological reactor. According to Bugajski et al. (2015), the inflow of raw wastewater characterized by large fluctuations in nitrogen concentrations, as well as the decrease in wastewater temperature in the reactors during the winter period, negatively affects the metabolism of activated sludge microorganisms and may lead to increased values of these indicators in treated wastewater.

Based on the analysis of Figure 2, it was determined that the average reduction efficiency (η) of the analyzed indicator for each studied wastewater treatment plant demonstrates compliance with the requirements specified

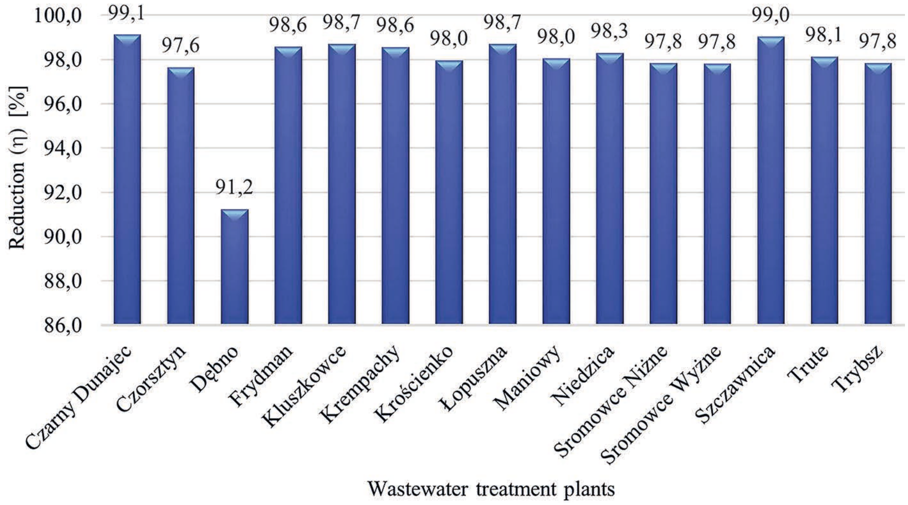

Fig. 2. Average BOD_5 reduction efficiency [%].
Source: own work

in the applicable regulation (Dz. U. 2019 poz. 1311) regarding the minimum BOD_5 reduction in wastewater discharged into receiving waters. This reduction ranges from 70–90% for treatment plants with value of EP between 2,000 and 9,999, and is set at 90% for plants with a EP > 9,999. The lowest reduction value was achieved by the treatment plant in Dębno (91.2%), while the highest was recorded in Czarny Dunajec (99.1%). The smallest facilities, i.e., treatment plants with EP < 2,000 (Dębno, Trybsz, Frydman, Czorsztyn, Sromowce Niżne, Sromowce Wyżne), although not subject to this requirement, also showed high pollutant reduction effectiveness, exceeding 90%.

Figure 3 presents the analysis of the next wastewater pollution indicator (COD_{Cr}). Based on the analysis of the research results, it was concluded that the average reduction efficiency of the COD_{Cr} indicator in the studied wastewater treatment plants ranged from 80.9% (Dębno) to 96.7% (Czarny Dunajec, Szczawnica). The achieved reduction was significantly higher than the value required for the safe discharge of treated wastewater into the aquatic ecosystem, which is 75% for treatment plants with EP > 2,000.

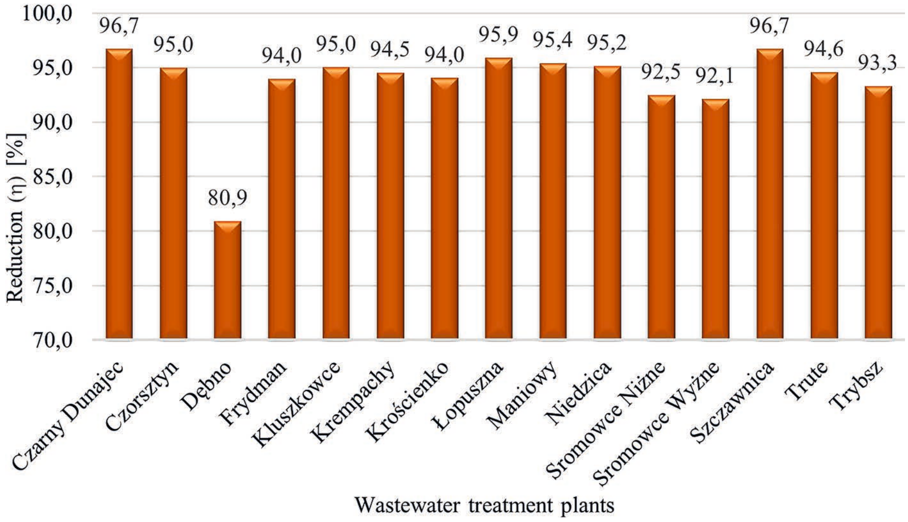

Fig. 3. Average COD_{Cr} reduction efficiency [%].
Source: own work

Figure 4 presents the average values of total suspended solids reduction in treated wastewater in the studied wastewater treatment plants.

Based on the analysis of Figure 4, it can be stated that the effectiveness of total suspended solids removal remained at a high level, ranging from 88.5% in the wastewater treatment plant in Dębno to 98.3% in the treatment plant in Łopuszna. According to the applicable regulation (Dz. U. 2019 poz. 1311), for

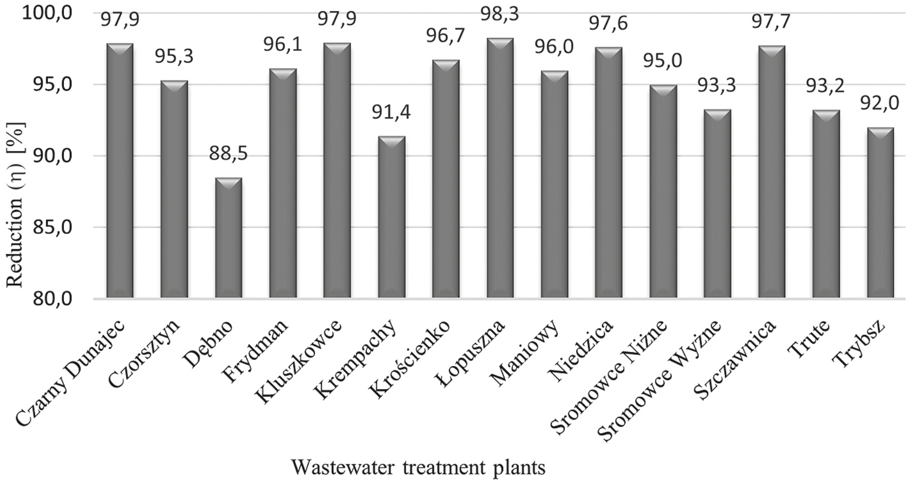

Fig. 4. Average total suspended solids reduction efficiency [%]. Source: own work

wastewater treatment plants with a EP > 2,000, the minimum reduction rate of total suspended solids should be 90%. All treatment plants subject to this requirement due to their EP value met the required level of total suspended solids reduction, as only the treatment plant in Dębno showed a value below 90%, which, due to its EP < 2,000, is not subject to this requirement.

Figure 5 presents the degree of total nitrogen reduction in individual wastewater treatment plants, excluding those facilities that, according to their applicable water permits, are not required to monitor this parameter in treated wastewater.

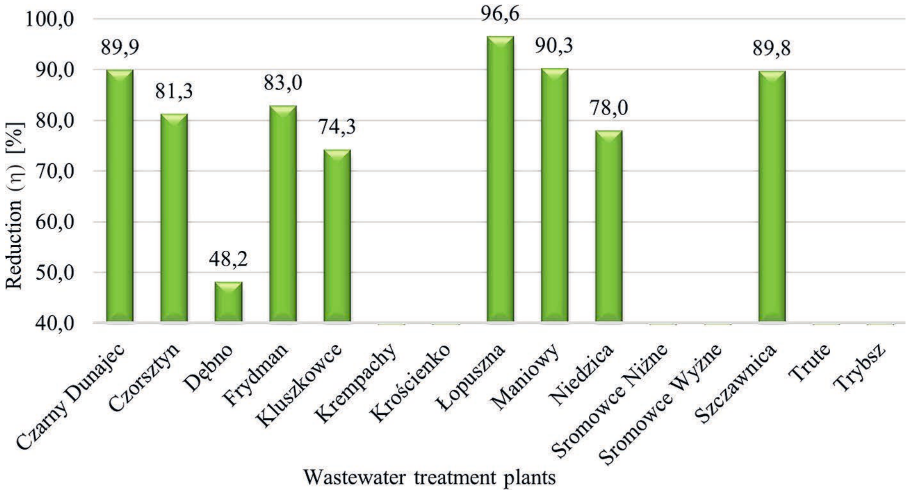

Fig. 5. Average total nitrogen reduction efficiency [%]. Source: own work

According to the requirements specified in the regulation (Dz. U. 2019 poz. 1311), the minimum total nitrogen reduction rate should be between 70–80% and applies to treatment plants with a EP > 10,000 (Szczawnica, Czarny Dunajec). From Figure 5, it is evident that the only treatment plant with a lower reduction rate is the facility in Dębno, which is significantly smaller than the other plants (EP = 1,000) and therefore not subject to this requirement. The facilities in Szczawnica and Czarny Dunajec, which are obligated to meet this condition, exhibit much higher total nitrogen reduction rates than required (η = 89.8% and 89.9%, respectively).

The analysis of total phosphorus reduction in the individual wastewater treatment plants subject to monitoring requirements is presented in Figure 6, excluding those facilities that, according to their applicable water permits, are not required to monitor this parameter in treated wastewater.

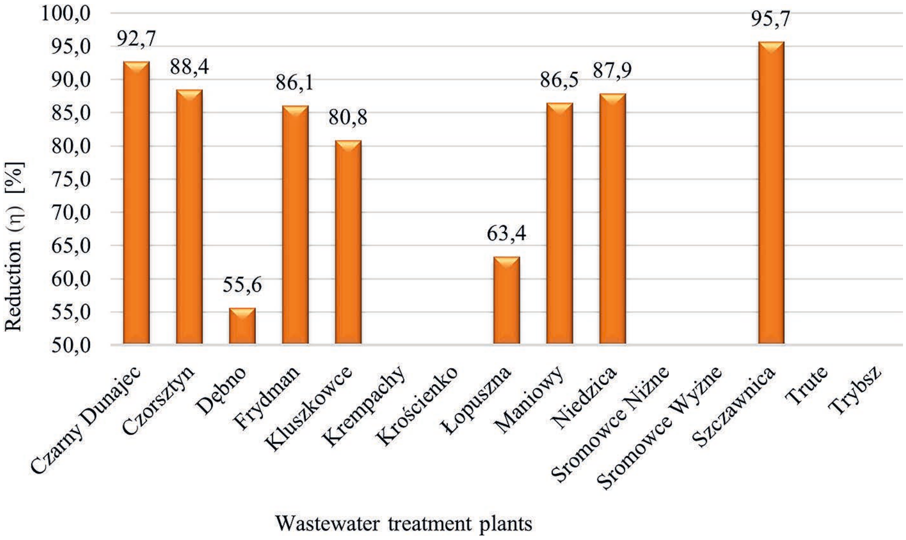

Fig. 6. Average total phosphorus reduction efficiency [%].Source: own work

Similarly to total nitrogen, the minimum total phosphorus reduction requirement of 80%, stipulated by the regulation (Dz. U. 2019 poz. 1311), applies only to large treatment plants with EP > 10,000. In this case, according to Figure 6, besides the treatment plants in Szczawnica (η = 95.7%) and Czarny Dunajec (η = 92.7%), which are subject to this requirement, most of the smaller facilities also met these standards by achieving reduction efficiencies in the range of 80.8% to 88.4%. The exceptions were the treatment plants in Dębno and Łopuszna.

4. Conclusions and summary

This study concerned the assessment of the wastewater treatment efficiency in 15 wastewater treatment plants (Czarny Dunajec, Czorsztyn, Dębno, Frydman, Kluszkowce, Krempachy, Krościenko, Łopuszna, Maniowy, Niedzica, Sromowce Niżne, Sromowce Wyżne, Szczawnica, Trute, Trybsz), whose treated wastewater is discharged directly or indirectly into the Czorsztyn Reservoir. The analysis of treatment efficiency was based on the calculation of the reduction of a particular pollutant index (η) and the analysis of the number of exceedances of limit values in treated wastewater. These activities allowed to verify whether the quality of treated wastewater in the examined facilities met the requirements contained in the applicable legal regulations, thus ensuring proper protection of the water environment of the natural receivers. Based on the conducted analysis, the following conclusions and statements were formulated:

1. In none of the analyzed wastewater treatment plants, in accordance with the provisions of the applicable water permits (Pozwolenie…2013, 2024), were any exceedances of permissible values for BOD_5, COD_{Cr}, and total suspended solids observed in the treated wastewater.
2. Exceedances of permissible total nitrogen values in treated wastewater were recorded only in the wastewater treatment plant in Niedzica, in 40% of the samples (6 out of 15 measurements), which may influence the migration of biogenic compounds from this facility to the natural receiver.
3. In the analysis of permissible total phosphorus values in treated wastewater, single exceedances were recorded in the treatment plants in Czarny Dunajec, Czorsztyn, and Niedzica, constituting approximately 4%, 13%, and 7% of the analyzed samples, respectively.
4. High wastewater treatment efficiency was observed in the studied facilities in terms of organic pollutants (η_{BOD_5}: 91.2–99.1%, $\eta_{COD_{Cr}}$: 80.5–96.7%, η_{TSS}: 88.5–98.3%). For biogenic pollutants, the range of achieved

reductions was lower due to the treatment plant in Dębno (η_{TN}: 48.2–96.6%, η_{TP}: 55.6–95.7%).

5. According to the requirements contained in the regulation (Dz. U. 2019 poz. 1311) regarding the minimum reduction levels for the analyzed pollution indicators, taking into account the EP of individual treatment plants, all analyzed facilities met the specified requirements, thereby ensuring the protection of the aquatic environment, which confirms the effectiveness of employed treatment methods.

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