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The efficiency of municipal sewage treatment plants inspiration for water recovery

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Abstract

This article presents a detailed analysis of the functioning of municipal sewage treatment plants. The presented findings are based on questionnaires from over seventy wastewater treatment facilities, covering from several hundred to several hundred thousand inhabitants. The required quality of treated sewage and the necessary efficiency level of the treatment plant were determined in the context of the content of the applicable regulations, and were then compared with the actual data obtained from sewage treatment plants. The findings provided the basis for formulating an evaluation of the efficiency of municipal sewage treatment plants and for further analyses of the possibility of the recovery of water from sewage and its reuse.

Keywords: municipal sewage treatment plants, the efficiency of sewage treatment plants, sewage, water recovery

1. Introduction

The analysis results presented in this paper concerning the quality of treated sewage and the efficiency of municipal sewage treatment plants provide the inspiration to undertake actions aimed at water recovery and its reuse. Moreover, it is an issue that arouses interest in the face of dwindling water resources in many countries, including Poland. It is estimated that around one-third of the world's population live in countries facing moderate to severe levels of water scarcity (Levine, Asano, 2004). In 1990, scientists from Wrocław University of Science and Technology, under the supervision of A. L. Kowal, prepared a book entitled "Water renewal" (Kowal et al., 1997). It contains essential information on technological processes intended for use in sewage treatment plants. This work discusses such processes as coagulation, sedimentation and flotation, filtration, adsorption, reverse osmosis, and disinfection.

In his latest publication on the protection of water resources against pollution, M. Gromiec divides the types of sewage recycling into direct recycling, which constitutes a combination of a treatment and receiving system, and indirect recycling, in which the renewed water is subjected to mixing and dilution processes in natural waters before collection. The author also presents a classification based on the purpose of the renewed water, listing its use for consumption and non-consumption purposes, such as municipal (irrigation of green areas, fire protection, recreation), industrial and agricultural purposes (Gromiec, 2021). The use of renewed water should pay particular attention to irrigating farmland. This issue is gaining popularity, especially in countries struggling with water shortages. For farmers, sewage reuse is a very beneficial solution due to the high content of nutrients in sewage, eliminating the need for expensive chemical fertilisers (Jaramillo, Restrepo, 2017). However, pathogenic microorganisms and unknown chemical components in sewage are of great concern (Angelakis et al., 2018). In this case, it is necessary to carry out a risk analysis of contaminants from reclaimed water entering the soil, which could cause a severe public health problem resulting from the transfer of these compounds to crops and then to the human food chain (Zaidi, 2007; Hashem, Qi, 2021).

The key to the successful implementation of sewage recovery programs is social support. Research in China showed that, despite the general public's limited knowledge of water resources, the awareness and acceptance of sewage reuse were very high. The vast majority of respondents are willing to accept reclaimed water for toilet flushing, fire protection, landscape irrigation or street cleaning. However, respondents tend to be more cautious of body-contact and potable reuses (Chen et al., 2015). Activities in community education may be necessary because, at present, wastewater treatment technologies are so advanced and effective that it is possible to produce water from a sewage stream of a quality similar to clean water (Burgess, Meeker, Minton, O'Donohue, 2015). It is worth noting that the unplanned use of sewage for drinking purposes has continued for a long time. This situation happens in agglomerations where the sewage receiver also acts as a water source for the community downstream. Rivers as environmental buffers remove any remaining contaminants during natural physical and biological processes (Rodriguez et al., 2009).

A book prepared and published in 2003 under the supervision of Tchobanoglous presents a lot of information on the recovery of water from sewage (Tchobanoglous, Burton, Stensel, 2003).

2. Materials and methods

The primary indicator of the operation of the sewage treatment plant is its efficiency in lowering the value of the pollution indicators included in the water law permit. This indicator is the quotient of the pollutant load retained

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in the sewage treatment plant to the pollutant load introduced into the sewage treatment plant, which is expressed by the following formula:

$$\eta_{\alpha} = (\Delta L_{\alpha} : L_{\alpha}) \cdot 100 = \left[(L_{\alpha} - L_{d\alpha}) : L_{\alpha}\right] \cdot 100 [\%]$$

where:

η_{α} – sewage treatment plant efficiency based on the pollution indicators included in the water law permit, %;

ΔL_{α} – pollutant load retained in the sewage treatment plant, kg/d;

L_{α} – pollutant load in the sewage supplied to the sewage treatment plant, kg/d;

$L_{d\alpha}$ – pollutant load contained in the sewage discharged from the sewage treatment plant, kg/d.

Another way to determine the efficiency of a sewage treatment plant is the quotient of the difference in concentrations of pollutants in the sewage flowing into the sewage treatment plant (C_{α}) and flowing out of it ($C_{k\alpha}$) to the concentration (C_{α}), which is:

$$\eta_{\alpha} = \left[(C_{\alpha} - C_{d\alpha}) : C_{\alpha}\right] \cdot 100 [\%]$$

where:

C_{α}, expressed in g/m^3 or kg/m^3.

It is worth remembering that the concentrations of pollutants result from the quotient of loads to the average daily amount of sewage (Q_{ad} in m^3/d), which is:

$$C_{\alpha} = L_{\alpha} : Q_{ad} \text{ and } C_{d\alpha} = L_{d\alpha} : Q_{ad}$$

In the case of municipal sewage treatment plants, achieving the required effect of sewage treatment involves the use of mechanical treatment (straining, sedimentation, and flotation), biological processes (decomposition of organic compounds and removal of biogenic compounds) and chemical processes (precipitation or volumetric coagulation). Maintaining the technological parameters of the operation of sewage treatment devices at the appropriate level guarantees the achievement of the expected level of pollutant concentrations in the treated medium. As a result, treated sewage of quality that is compliant with the requirements of the water law permit may be discharged into stagnant or flowing waters without significantly increasing the degree of contamination. The concentration of pollutants in the sewage resulting from applying the processes mentioned above can be considerably reduced through the use of volumetric coagulation, filtration, sorption, nanofiltration, reverse osmosis, and disinfection. All of these processes concern the recovery of water from sewage. Not only cities can use reclaimed water (municipal purposes, i.e. washing streets and pavements, watering green areas, fire-fighting cells, or washing vehicles), but also country areas (irrigation of crops – protection against drought). Sewage reuse minimises the environmental risk associated with its discharge and alleviates the pressure on ecosystems resulting from freshwater withdrawal. In this case, sewage becomes an additional resource helping to achieve sustainable water management (Tong, Elimelech, 2016).

According to the Regulation of the Minister of Maritime Economic and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging sewage into waters or soil and discharging rainwater or meltwater into waters or water facilities (Dz. U. 2019 poz. 1311) sewage treatment plants must meet certain conditions regarding permissible concentrations of pollutants. These concentrations depend upon the number of inhabitants served and the type of receiver, and also if it is sewage treatment plant for single city or agglomeration. The basic requirements apply to pollution indicators such as BOD5, COD, total suspended solids, total nitrogen, and total phosphorus. This list may be extended in the water law permit, for example, by such indicators as pH, colour, turbidity, or the presence of heavy metals.

The required quality of treated sewage (Dz. U. 2019 poz. 1311) and the necessary efficiency of the treatment plant were determined taking into account the number of inhabitants served by the treatment plant above 15 000. The input data was identified assuming concentrations of pollutants in the sewage flowing into the treatment plant on the basis of results from own research conducted in 2018 (Wójcicka, Heidrich, 2018; 2019): BOD5 = 440 g/m^3, COD = 945 g/m^3, total suspended solids = 436 g/m^3, total nitrogen = 82 g/m^3 and total phosphorus = 12 g/m^3. These values are similar to the data set obtained as a result of analyses performed by scientists from the Warsaw University of Technology in 2015 (Sytek--Szmeichel, Heidrich, Stańko, 2016). Table 1 summarises the final requirements.

Table 1. Requirements for treated sewage from urban settlement units based on applicable legal regulations (Dz. U. 2019 poz. 1311)

Sewage pollution indicators	Requirements for the quality of sewage			
	For I = 15 000 – 100 000		For I > 100 000	
	permissible concentrations [g/m^3]	required efficiency [%]	permissible concentrations [g/m^3]	required efficiency [%]
BOD5	15	96.6	15	96.6
COD	125	86.8	125	86.8
Total suspended solids	35	92.0	35	92.0
Total nitrogen	15	81.7	10	87.8
Total phosphorus	2	83.3	1	91.7

The actual data on the quality of treated sewage and the efficiency of the operation of sewage treatment plants were determined based on an analysis of over seventy wastewater treatment facilities, serving from approx. 3,000 up to approx. 900,000 inhabitants, with a hydraulic load from 650 to 200,000 m^3/d. All analysed sewage treatment plants operate using activated sludge technology, ensuring a reduction of organic pollutants (BOD5 and COD) and biogenic compounds.

3. Analysis

Figure 1 presents histograms of the considerations concerning the concentration of pollutants in treated sewage, and the summary results are provided in Table 2. By analysing the results of the calculations, it can be concluded that the average annual values of BOD5 and COD, as well as the concentration of total suspended solids, are approx. three times lower than the permissible values, and the maximum values in no case exceed the requirements resulting from legal regulations (see Table 1) and specified in water law permits. These statements also apply to the concentration of biogenic compounds. Both total nitrogen and total phosphorus concentrations are several dozen per-centage points lower than the permissible values.

Finally, it can be stated that the annual average concentrations of pollutants in treated sewage discharged from municipal sewage treatment plants are: BOD5 = 5.2 g/m^3, COD = 39.8 g/m^3, total suspended solids = 8.3 g/m^3, total nitrogen = 10.1 g/m^3 and total phosphorus = 0.63 g/m^3. The analysis of the tested concentrations is supplemented by the data on the dominant ranges, presented in Table 2. It is worth noting that these ranges are quite narrow, and their concentrations constitute a significant part of the entire data set.

The obtained data set on the quality of sewage flowing into the treatment plant and discharged to the receiving body enables the determination of the

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efficiency of all treatment plants, taking into account five fundamental pollution indicators. The results of the calculations are presented in the form of the histograms in Figure 2. The data introduced in Table 2 are the summary of the presented findings. Comparing the data in Table 2 with the data in Table 1, it can be seen that the average actual efficiency related to BOD5 is 2.1% higher than the permitted limit. For COD this value is 8.7% higher than required and for total suspended solids – 5.9% higher. Total nitrogen is characterized by the average actual efficiency on the level 4.9% higher than permitted, for I = 15,000 – 100,000, and 1.2 lower than permitted for I > 100,000. In the case of total phosphorus, this value is over 10% higher than required in the regulations for treatment plants serving 15,000 – 100,000 inhabitants and 2.2% higher for I > 100,000. Generally, it can be concluded that the actual operating efficiency of the analysed sewage treatment plants significantly exceeds the efficiency resulting from the applicable legal regulations.

Analysing the data set presented in Table 3 shows that after supplementing the treatment with devices such as sand filter, sorption filter and reverse osmosis, BOD5 will not exceed 1 g/m^3. The same applies to microfiltration and reverse osmosis. With regard to the total nitrogen, the appropriate concentrations are 5 – 10 g/m^3 and ≤ 0.1 g/m^3, and in the case of orthophosphates, appropriate concentrations are 5 – 10 g/m^3 and ≤ 0.5 g/m^3. It is also worth paying attention to the turbidity of the sewage and of the recovered water, which is 5 – 15 NTU and 0.01 – 1 NTU, respectively. Compared to other methods, reverse osmosis ensures higher levels of safety of using renewed water for various purposes due to simultaneously removing a wide range of contaminants, such as dissolved solids, pathogens and low-molecular-weight chemical pollutants (Tang, 2018).

4. Results

Table 2. Actual data from municipal wastewater treatment plants related to the quality of treated sewage and operating efficiency (Wójcicka, Heidrich, 2020)

Sewage pollution indicators	Concentrations and efficiency	Characteristic concentrations [g/m^3]			Dominant range	
		min.	max.	average	range	participation [%]
BOD5	S_{BOD5}	0.4	12.3	5.2	2,0 – 6,0	72.4
	η_{BOD5}	96.4	99.9	98.7	98 – 99	50.0
COD	S_{COD}	23.0	89.0	39.8	30 – 40	46.1
	η_{COD}	90.1	98.4	95.5	95 – 97	60.5
Total suspended solids	S_{tss}	0.0	36.4	8.3	3.0 – 9.0	68.4
	η_{tss}	92.4	100.0	97.9	98 – 99	43.4
Total nitrogen	S_{N_t}	3.1	38.3	10.1	6.0 – 12.0	69.4
	η_{N_t}	26.6	95.7	86.6	85 – 95	65.3
Total phosphorus	S_{P_t}	0.19	5.9	0.63	0.2 – 0.6	72.2
	η_{P_t}	46.4	99.1	93.9	94 – 98	58.3

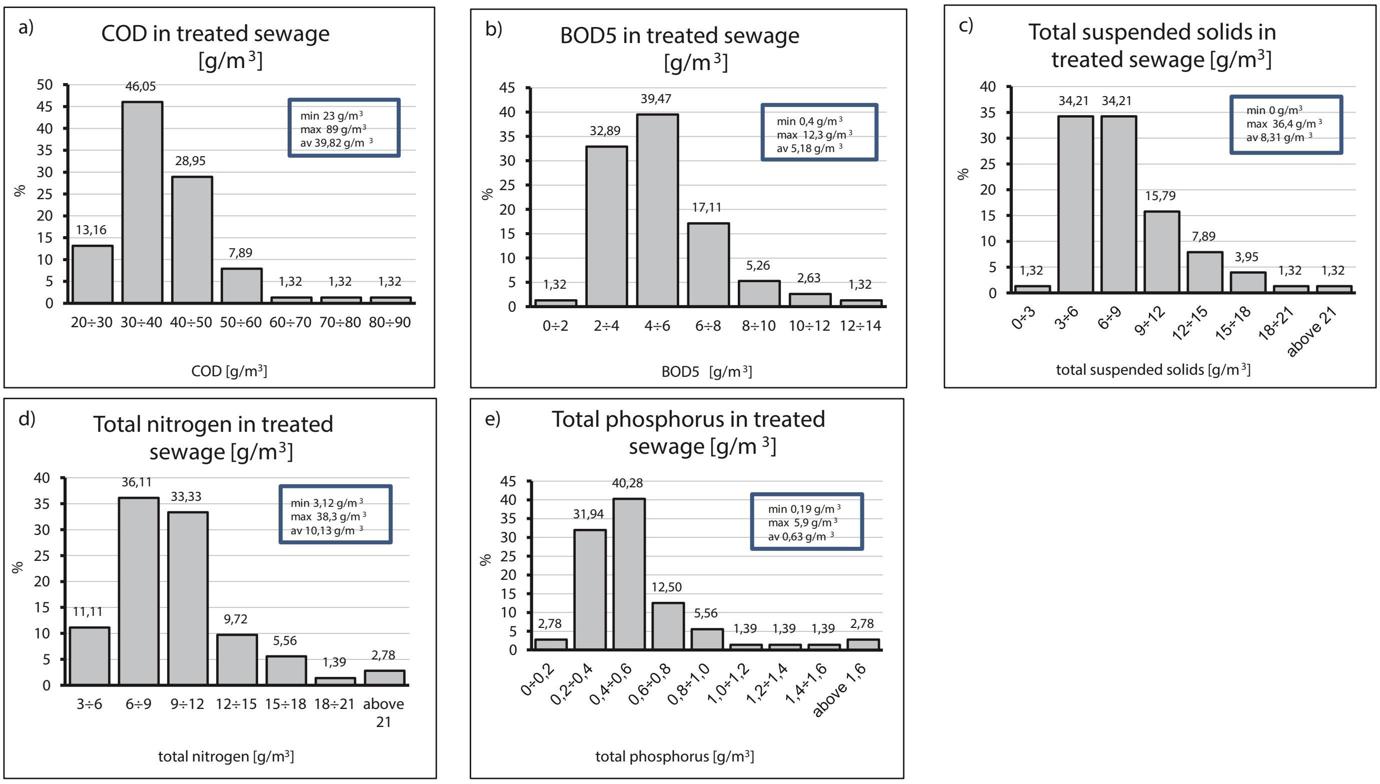

Fig. 1. Histograms representing contaminant concentrations in municipal sewage treatment plant effluent, based on actual data: a) COD, b) BOD5, c) total suspended solids, d) total nitrogen, e) total phosphorus (Wójcicka, Heidrich, 2020)

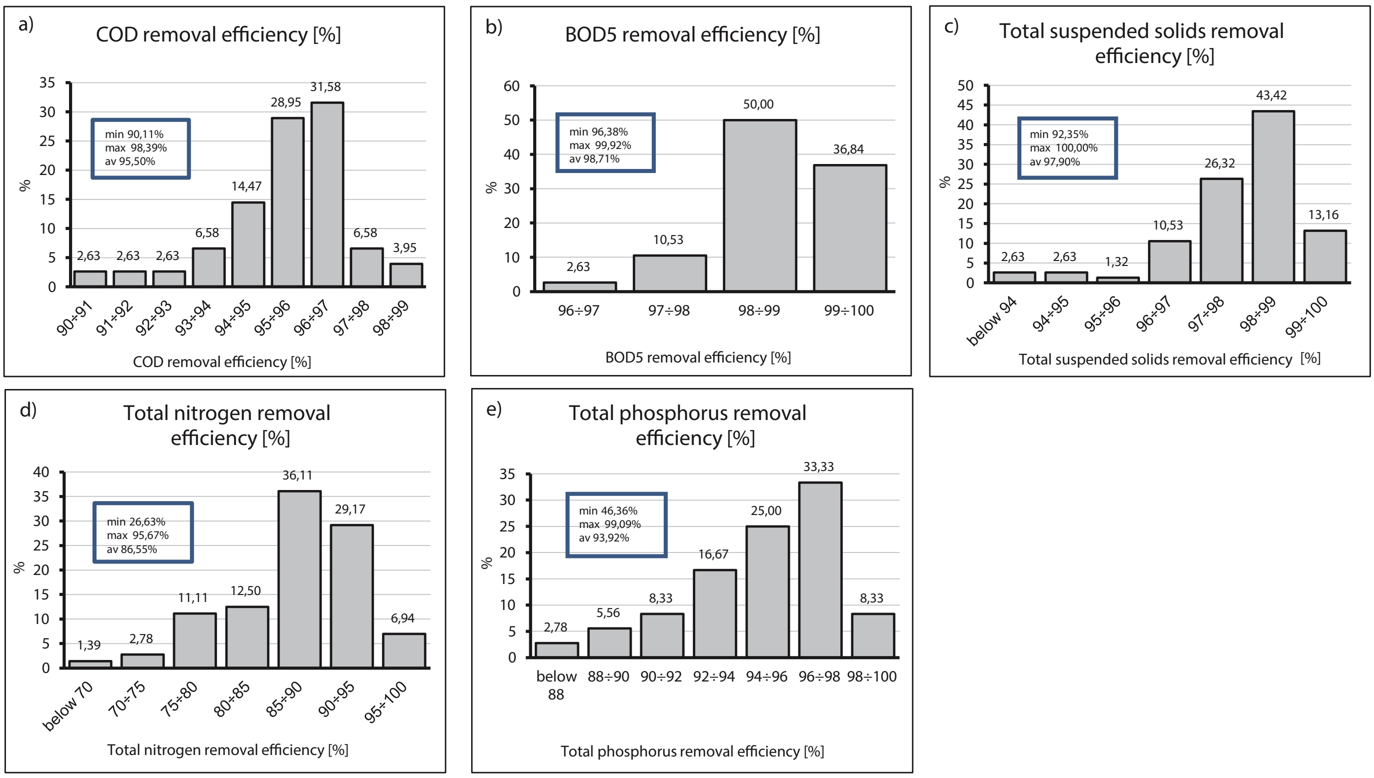

Fig. 2. Histograms representing sewage treatment plant efficiency in relation to: a) COD, b) BOD5, c) total suspended solids, d) total nitrogen, e) total phosphorus (Wójcicka, Heidrich, 2020)

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5. Discussion

Much of the information presented here can be used in planning research and implementation on the issue under consideration. Data on the characteristics of the quality of sewage after various treatment systems are of particular interest. Basic information on this subject is presented in Table 3. The data contained in this table shows that the introduction of additional processes to the conventional sewage treatment system reduces the concentrations of pollutants to a level that allows reuse of the recovered water. It should be noted that the fundamental methods of wastewater treatment preceding its renewal are based on activated sludge technology, which provides for a far-reaching reduction of the concentrations of organic compounds, nitrogen, and phosphorus. In a conventional system, it is possible to lower BOD5 to the level of 5–15 g/m^3.

By analysing the solutions presented in the book (Tchobanoglous, Burton, Stensel, 2003), it is possible to propose different technological systems, which are shown in Fig. 3. The central part of the system involves mechanical and biological treatment using the activated sludge technology with the integrated removal of organic carbon, nitrogen and phosphorus. In the primary system, the sedimentation of the activated sludge separated from the treated sewage takes place in a conventional secondary settling tank. At the same time, the alternative solutions are membrane packages (nanofiltration) or microsieves (microfiltration). In the primary system, the sewage is directed to the volumetric coagulation process, with the recommendation of supporting the process with micro-sand grains, constituting centres for the formation of large, stable flocks, and sedimentation carried out in a lamella (multi-stream) sedimentation tank (Chaitra, 2017). The further purification process includes filtration on sand filters and filtration with activated carbon filling, related to the sorption process. The last stage of treatment (when the water is almost pure) is disinfection with UV rays to improve bacteriological properties.

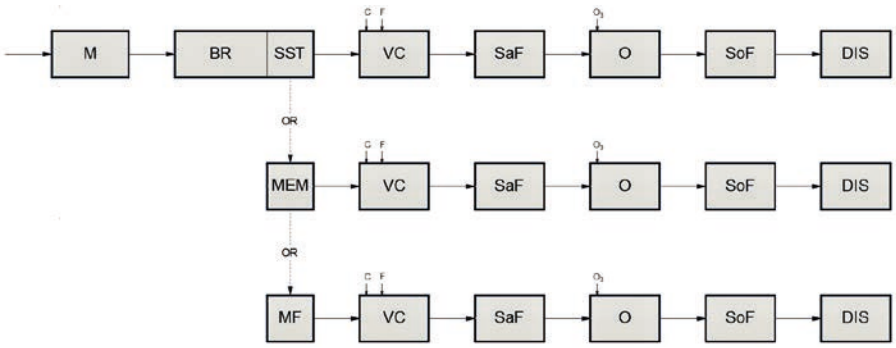

Fig. 3. Technological diagram of a sewage treatment plant with water recovery.
M – mechanical part; BR – biological reactor with active sludge for integrated removal of C, N and P; SST – secondary settlings tank; MEM – membrane packages (nanofiltration); MF – microfiltration (microsieves); VC – volumetric coagulation; SaF – sand filter; O – ozonation; SoF – sorption filter; DIS – UV disinfection; C – coagulant; F – flocculant; O_3 – ozone

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Table 3. Possibility of achieving the specified concentration of pollutants in treated sewage with different technological systems of sewage treatment, according to Tchobanoglous and others (Tchobanoglous, Burton, Stensel, 2003)

Technological system of the sewage treatment plant	Concentrations of pollutants in treated sewage [g/m^3]						Turbidity [NTU]
	Total suspended solids	BOD5	COD	Total nitrogen	NH_3–N	PO_4–P	
Reactor with activated sludge and separate zones of nitrification and denitrification	10–15	5–15	20–35	5–10	1–2	5–10	5–15
Activated sludge reactor with simultaneous precipitation, nitrification and denitrification + sand filter	≤ 5–10	≤ 5–10	20–30	3–5	1–2	≤ 1	0.3–2
Biological removal of nitrogen and phosphorus + sand filter	≤ 10	< 5	20–30	≤ 5	≤ 2	≤ 2	0.3–2
Activated sludge reactor + sand filter + sorption filter + reverse osmosis	≤ 1	≤ 1	5–10	< 2	< 2	≤ 1	0.01–1
Activated sludge reactor with carbon, nitrogen and phosphorus removal + sand filter + sorption filter + reverse osmosis	≤ 1	≤ 1	2–8	≤ 1	≤ 0.1	≤ 0.5	0.01–1
Activated sludge reactor with carbon, nitrogen and phosphorus removal + microfiltration + reverse osmosis	≤ 1	≤ 1	2–8	≤ 0.1	≤ 0.1	≤ 0.5	0.01–1

6. Conclusions

The findings concerning the operation of municipal sewage treatment plants in Poland, based on data from more than seventy wastewater treatment facilities, led to the conclusion that the actual efficiency of these treatment plants is much higher than the required efficiency specified in the applicable legal regulations (Dz. U. 2019 poz. 1311). The annual average concentrations of pollutants in treated sewage discharged from the analysed objects are: BOD5 = 5.2 g/m^3, COD = 39.8 g/m^3, total suspended solids = 8.3 g/m^3, total nitrogen = 10.1 g/m^3 and total phosphorus = 0.63 g/m^3. The average efficiencies of the treatment plant calculated using the data on the concentration of pollutants in the incoming and treated sewage are as follows: η_{BOD5} = 98.7%, η_{COD} = 95.5%, η_{tss} = 97.9%, η_{N_t} = 86.6% and η_{P_t} = 93.9%. Comparing the obtained data set with the requirements for the efficiency of removing pollutants from sewage in municipal sewage treatment plants, it can be concluded that only in the case of total nitrogen for wastewater treatment facilities serving more than 100,000 inhabitants was this value lower than the required value. The average real efficiency of the remaining four pollution indicators is several per-centage points higher than that specified in the applicable regulations.

The obtained results of analyses concerning the quality of treated wastewater and the efficiency of the operation of municipal treatment plants provide the basis for undertaking detailed research aimed at further sewage treatment, allowing for its preparation for use for various purposes. The findings contained in the article are the initial phase of the implementation of the issue of water recovery from sewage.

The literature data (Tchobanoglous, Burton, Stensel, 2003) shows that expanding the conventional treatment system with other processes, such as microfiltration, filtration, and reverse osmosis, will significantly reduce the concentration of pollutants to a level that allows for the reuse of recovered water. Laboratory tests of municipal sewage planned soon will identify the most favourable technological layout of the part of the sewage treatment plant, determining the optimal system for the quality of recovered water and issues related to economy and operation. The critical aspects of designing a water recovery plant are the quality of the incoming sewage and the quality requirements of the end product. Therefore, the scheme of sewage treatment should be considered individually for each wastewater treatment facility (Voulvoulis, 2018).

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