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Assessing the Feasibility of Recovering Water from Treated Municipal Wastewater

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ABSTRACT

The problem of recovering water from treated wastewater may concern an increasing number of countries, especially those with low water resources. After costly treatment processes, water taken from surface and underground intakes is used and then largely discharged to receivers in the form of treated wastewater. Advanced wastewater treatment methods ensure that the treated wastewater is characterized by very low physical and chemical pollution, sometimes better than the water quality in the receiving basin. The research was conducted under a cooperation agreement between Bialystok University of Technology and Bialystok Waterworks Ltd. The recovery of water from wastewater was one of the topics pursued.This paper analyzes the parameters of treated wastewater from the largest municipal wastewater treatment plant in the Podlaskie Province. The analysis of the treated wastewater composition was based on monitoring studies conducted by the company Bialystok Waterworks Ltd. between 2020 and 2023. The analysis concerned the basic parameters of wastewater, namely the content of organic matter and total suspended solids.This was due to the requirements for the recyclability of treated wastewater. Linear modeling was performed to determine if a sufficiently strong correlation was detected;otherwise output distribution characteristics were provided.In all cases, the output concentrations were far below the class A limits for irrigation in the whole research period.

Keywords: water recovery, municipal wastewater, parameter variation analysis, linear modeling.

INTRODUCTION

Industrial and agricultural development, climate change and better living standards of a population are connected with the problem of lack of water resources [Myka-Raduj, Jóźwiakowski 2022]. Water scarcity is one of the most important global threats, as are extreme weather events [Voulvoulis 2018, Dolganova et al. 2019, Tzanakakis, Capodaglio 2023].

According to the literature, half of the European countries experience water shortage problems [Ungureanu et al. 2020]. Despite increasing water shortages, European countries have a low percentage of reclaimed water usage in comparison to Asia and America. The total reuse capacity of water in the EU is 1 billion m^3/yr. The most common uses are in agriculture (36%), industry (15%), and recreation (11%) [Tzanakakis, Capodaglio 2023].

Poland is considered a country poor in water resources.The largest share of water consumption for the needs of national economy and population belongs to industry (72%) [GUS 2022].

In response to emerging water scarcity challenges, one alternative is to implement wastewater reclamation. The situation is similar in the case of, for example, rainwater [Smith et al. 2018, Ramm, Smol 2023, Carbajal-Morán et al. 2021]. Rainwater recovery, which is not only a pro-ecological initiative but also an investment that reduces the cost of tap water charges, is gaining popularity [Bator, Piechurski 2019]. It is increasingly common to use grey water from households for purposes such as cleaning certain areas in homes, watering gardens and evacuating toilets [Carbajal-Morán el al. 2021]. Recycling and treated water reuse are important elements in the circular economy [Voulvoulis 2018]. Treated wastewater can be an alternative water source for agricultural irrigation during rainless periods. In addition, it also serves as fertilizer, which reduces the need for applied mineral fertilizers. Recovering water from wastewater for field irrigation can help reincorporate plant nutrients (nitrogen, phosphorus and potassium). One of the important factors determining the possibility of recovering water from wastewater is, in addition to its physical and chemical composition, the content of microbiological contaminants.

In most countries, various methods of wastewater disinfection are commonly used (chlorination, ozonation, performic acid, peracetic acid, pasteurization, UV radiation, membrane methods and ultrasounds) [Hawrylik 2020].

Practical aim of presented results was to determine existence of main factors affecting the quality of treated wastewater, that will be used for water recovery. The scientific aim wasto analyze what parameters in the treated wastewater can be modeled using, for example, wastewater temperature or raw wastewater parameters.

LEGAL AND TECHNICAL ASPECTS OF WATER RECOVERY FROM WASTEWATER

Guidelines on how to treat wastewater for reuse were first issued by the World Health Organization (WHO) in 1973. In countries such as Australia, Cyprus, India, Israel, Japan, South Africa, Singapore and the United States, initiatives have been developed to reuse wastewater for agricultural irrigation and drinking purposes [Kanchanapiya, Tantisattayakul 2022]. In 2020, legal requirements for water reuse for agricultural purposes in the EU were set by the European Commission (EC). The European Parliament and the Council Regulation EU 2020/741 on minimum requirements for water reuse aim to mobilize member states to take action on water recovery from wastewater.The most advanced are southern countries (e.g. Portugal, Italy, France, Spain, Greece), which are prone to droughts due to their location in warm climate zones. In Poland, water recovery from wastewater is practically not practiced. Table 1 presents selected parameters of reclaimed water in the chosen European countries.

Poland, as an EU member state, is obliged to implement the European water policy based on transparent, effective and coherent legal provisions contained in the Water Framework Directive 2000/60/EC (WFD), which establishes guidelines for community activities in the field of water policy, and in Directive 91/271/EEC of 1991 concerning urban wastewater treatment. The common European water policy obliges countries to rationally use and protect water resources, in accordance with the principle of sustainable development [Myka-Raduj et al. 2022].

As of mid-June 2023, all EU countries including Poland are bound by the EU Regulation 2020/741 on minimum requirements for reusing recycled water from wastewater. The specific reclaimed water quality requirements for agricultural irrigation are presented in Table 2.

According to the regulation, reclaimed water can be used to irrigate the following types of crops: crops for raw consumption, crops for consumption after processing and non-food crops. Member states may also reuse the reclaimed water in industrial, municipal and environmental services. The regulation outlines the quality classes of reclaimed water (A, B, C, D), and the permitted

Table 1. Selected parameters of reclaimed water used in individual countries [Ramm, Smol 2023]

Parameter	Quality requirements [UE 2020/741]	Cyprus	France	Italy	Portugal	Spain
Escherichia coli (cfu/100 mL)	$10–10^4$	$10–10^3$ [1]	$250–10^5$	10 or 100	$10–10^4$	$10^3–10^5$
TSS (mg/L)	10–35	10–45	< 15 or 2	10	10–60	5–35
Turbidity (NTU)	≤ 5 and no limit	n/a	n/a	n/a	≤ 5 and no limit	1–15 and no limit
BOD_5 (mg/L)	10–25	10–70	n/a	20	10–40	n/a
COD (mg/L)	n/a	70 or n/a	<60	100	n/a	n/a

Note: * n/a—not applicable; [1] Cyprus law applies to coliforms; [2] In accordance with regulations for discharges of treated wastewater to the receiver outside the irrigation period.

Table 2. Reclaimed water quality requirements for agricultural irrigation [based on UE 2020/741]

Reclaimed water quality class	Indicative technology target	*E. coli* (number/100 ml)	BOD5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Other
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	*Legionella* spp.: < 1 000 cfu/l where there is a risk of aerosolization Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment and disinfection	≤ 100	In accordance with Directive 91/271/EEC (Annex I, Table 1)	In accordance with Directive 91/271/EEC (Annex I, Table 1)	-	
C	Secondary treatment and disinfection	≤ 1 000			-	
D	Secondary treatment and disinfection	≤ 10 000			-	

agricultural uses and irrigation methods for each class. Indicative purposes for applying the technology (secondary treatment, filtration and disinfection) are also included. In municipal and industrial wastewater, treatment methods (mainly disinfection) may be necessary due to potential pathogenic contamination. In Poland, there are currently no legislation on the use of any specific disinfection process for wastewater discharged into the aquatic or soil environment. The application of the disinfection process can significantly affects the recovery of water from wastewater [Ramm, Smol 2023, UE 2020/741]. The search for economically viable and technologically simple wastewater treatment solutions is also very important [Félix-López et al. 2023]. Water recovered from sewage can be used not only for irrigation, it is possible to use for different municipal or industrial purposes. Using it for irrigation is simple and applied in many countries, probably there is no way to avoid it in Poland.

METHODS

The research aimed to determine the relationship between raw and treated wastewater parameters. The study objective was to show whether the treated municipal wastewater displays parameters that allow it to be recycled and reused after treatment.

Characteristic of municipal WWTP in Bialystok

The study was conducted based on the results of analyzing wastewater from the municipal WWTP in Bialystok. Table 3 shows the basic parameters of the facility, while Figure 1 shows a schematic representation and an aerial view of the treatment plant.

Municipal sewage discharged to Bialystok WWTP includes domestic sewage and some industrial mainly from food industry. Due to the legal regulation of the requirements for the quality of treated wastewater, disinfection of treated wastewater is not used.

This wastewater treatment plant uses mechanical processes (screening, sedimentation, removal of mineral suspended solids) and biological processes (defosfatation and nitrogen removal processes based on predenitrification, denitrification and nitrification). The treatment plant does not use chemical phosphorus removal. The sludge line incorporates thickeners, digesters, dewatering presses and a sludge-drying plant. Biogas is used to produce heat and electricity for the facility's own needs.

Table 3. Basic parameters of the Bialystokmunicipal WWTP

Parameter	Unit	Value
Sewage PE- permission	-	740000
Sewage PE-2022	-	515804
Sewage quantity-permission (average)	m^3 d^{-1}	80000
Sewage quantity-2022 (average)	m^3 d^{-1}	58951
Sewage sludge quantity-2022	tons of dry mass d^{-1}	6309

Source: Bialystok Waterworks Ltd.2009.

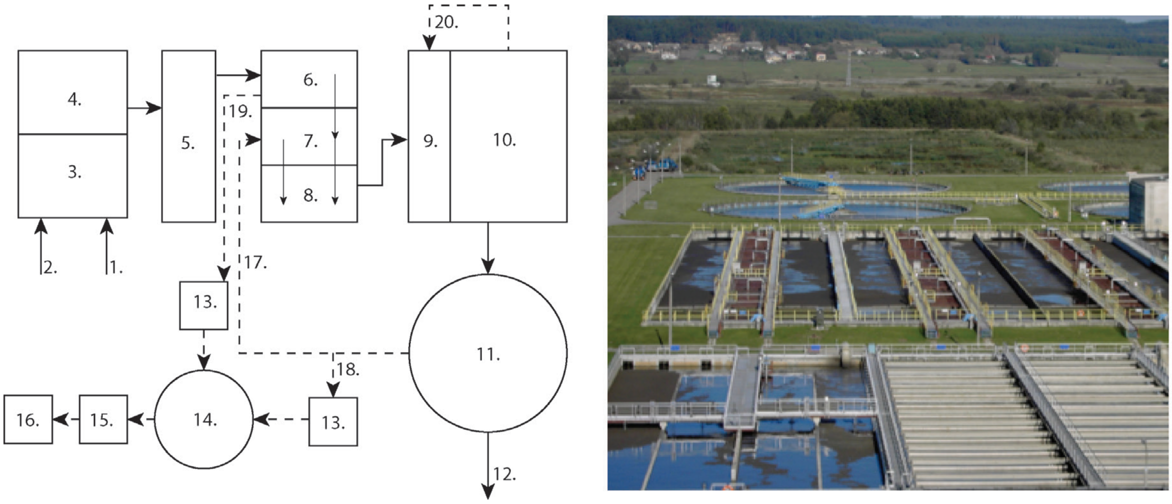

Figure 1. Scheme and view of Bialystok municipal WWTP. (1. raw sewage, 2. reject water, 3. Screen, 4. Pumping station, 5. Sand trap, 6. Sedimentation tank, 7. Pre-denitrification chamber, 8. Defosfatation chamber, 9. Denitrification chamber, 10. Nitrification chamber, 11. Sedimentation tank, 12. Treated sewage discharge, 13. Sludge thickening, 14. Digestor,15. Sludge dewatering press, 16. Sludge drying station, 17. Sludge recirculation, 18. Excess sludge, 19. Sludge from sedimentation tank, 20. Internal recirculation)

Scope and methodology of wastewater testing

The analysis of the treated wastewater composition was based on monitoring studies conducted by Bialystok Waterworks Ltd. carried out in 2020–2023. Data were collected at a frequency of 2 to 5 samples per month (raw and treated wastewater using automatic samplers for sample averaging). A total of 162 measurements were collected. Each measurement covered basic parameters of raw and treated wastewater such as wastewater temperature, BOD_5 and COD values, and total suspended solids concentrations. Wastewater was collected using automatic samplers;the sampling lasted 24 hours. The tests were conducted in an accredited laboratory.

Statistical analysis

In order to determine which variables can be described in terms of influent parameters, correlation analysis was performed. The Henze-Zirkler multivariate normal distribution test [Henze, Zirkler 1990] was performed in order to assess the validity of applying the Pearson correlation coefficient [Bravais, 1844] to each group. When the p-value was significant, the Spearman correlation coefficient [Spearman 1904] was calculated instead of the Pearson one. The obtained correlations were presented graphically with their values and circles proportional to their magnitude. Since not all correlations yield the possibility of a useful relation,the important ones were marked with a black frame.

Pairs of variables with the absolute correlation coefficient greater than 0.5 (plotted with an additional green frame) were selected for modeling. All models include influent sewage temperature as an independent variable. Due to the heteroskedasticity logarithm the transformation was performed on concentration values.The final models were presented in the form:

$$\begin{aligned} \ln\left(c_{out}\right) &= aT + b + \varepsilon \\ c_{out} &= e^{aT} e^{b} e^{\varepsilon} \end{aligned} \quad \varepsilon \sim N\left(0, \sigma^2\right) \tag{1}$$

where: c_{out} – output concentration;
T – temperature;
a, b – linear coefficients;
ε – residual dispersion.

In order to validate the obtained models, their residuals (on logarithmic scale) were tested against:
- Symmetry of distribution test with Rothman-Woodroofe statistics [Gaigall 2020];
- Normality of distribution Shapiro-Wilk test [Shapiro, Wilk 1965];
- Breush-Pagan test for heteroskedasticity [Breusch, Pagan 1979];
- Model curves with background scatter plots were further presented.

The parameters not selected for modeling were described by their distribution parameters in the following pattern:

$$\frac{mean \pm sd\left(med \pm mad\right)}{min, q1, q3, max} \qquad (2)$$
$$p_{RW}, p_{SW}$$

where: *mean* – arithmetical mean;
sd – standard deviation;
med – median;
mad – scaled median deviation from the median - the so-called MAD (median absolute deviation) measure;
min, *max* – extreme values;
$q1$, $q3$ – 1'st and 3'rd quartile;
p_{RW}, p_{SW} – p-values for tests: Rothman-Woodroofe (symmetry of distribution) and Shapiro-Wilk (normality).

The interpretation of the above notation may suggest a certain symmetry with respect to the mean or median. Therefore, a symmetry test of the distribution with Rothman-Woodroofe statistics was performed to validate this interpretation.

The mean value has the correct interpretation when the selected distribution is symmetrical. The standard deviation has a proper interpretation only when the distribution of the measured quantity is normal. The normal distribution is symmetrical. Therefore, the Shapiro-Wilk normality test was performed [Shapiro, Wilk 1965], but only when the symmetry test gave a statistically insignificant result. Irrespective of the test results, all aggregate statistical parameters are included due to a similar approach used in literature. Appropriate p-values of the tests allow the selection of the most appropriate ones.

The following value was used as a scale factor for MAD:

$$k_{MAD} = \frac{1}{cdf^{-1}_{N(0,1)}\left(0.75\right)} \qquad (3)$$

where: k_{MAD} – scale factor;
$cdf^{-1}_{N(0,1)}$ – inverse of cumulative standard normal distribution function.

For normally distributed data, the selected scale factor makes MAD measure asymptotically approximate standard deviation. Quartiles and MAD are non-parametric and their interpretation is appropriate for any distribution.

Distributions of the selected variables were presented graphically. Due to the finite number of measurements, the most appropriate graphical representation is a histogram and box-whisker plot. The number of histogram bars was determined using the Sturges algorithm [Sturges 1926].

The histogram approximates the true density function of the represented variable. Another possible approximation is the curve graphresulting from the 'density' algorithm. This algorithm approximates the true density function by convoluting the original data with a certain window function using the Fourier transform, from which the values of the density function approximation are computed [Silverman 2018]. The calculated histogram and the curve have a similar shape but on a different scale. The natural interpretation of the histogram is the frequency, which is responsible for the height of each bar. This interpretation was left unchanged, but the density curve was rescaled. Its values have been scaled by a factor:

$$k_{density} = n \cdot d_{glob} \qquad (4)$$

where: $k_{density}$ – scale factor;
n – total number of samples

The box-whisker plots show the distribution of the selected variable. The box represents the median (horizontal box line) and the 1st and 3rd quartiles (box edges). The whiskers extend at most 1.5 times the difference between the 1st and 3rd quartiles but do not go beyond the extreme values. All observations outside the whiskers are marked as points.

As previously mentioned,the algorithms are implemented in the R statistical environment [R Core Team 2023]. The 'symmetry_test' function of the symmetry package [Ivanović et al. 2020] implements the symmetry test. The number of bootstrap repetitions was specified as 10000. This was a reasonable compromise between the stability of the test results and the operation time. The 'shapiro_test' function of the stats package implements the Shapiro-Wilk normality test. The 'bptest' function of the lmtest package [Zeileis, Hothorn 2002] implements the Breusch-Pagan test. The 'corrplot.mixed' function of the corrplot package [Wei, Simko 2021] allows for a graphical display of correlation coefficients. The 'mvn' function of the MVN package [Korkmaz et al. 2014] implements the Henze-Zirkler multivariate normal distribution test.

RESULTS AND DISCUSSION

The authors of the study adopted the goal of assessing the feasibility of determining relationships between raw and treated wastewater parameters, one of the relevant parameters being wastewater temperature. The aim of the statistical analysis was to find adequately justified models. On the one hand, this is a new approach to the evaluation of wastewater treatment plants based on very advanced monitoring (this is about the scope and frequency of testing). On the other hand, the scope of the analysis and its discussion is difficult due to the lack of available literature.Such studies are challenging to carry out in smaller facilities using similar technology because of very limited monitoring resulting from the regulation regarding the quality of wastewater discharged to a receiver [Journal of Laws 2019 item 1311].

The Henze-Zirkler multivariate normal distribution test has a significant result (test statistics 2.07, p<0.001). The Spearman correlation coefficient was used in further calculations. Figure 2 presents the obtained coefficients in a graphical form.

Out of every pair of useful correlations, only one between BOD_5 and input sewage temperature had a magnitude (absolute value) greater than 0.5. There were strong correlations between the selected input parameters themselves, or the selected output parameters, but they carried no predictive usefulness. The following model was obtained:

$$\ln\left(c_{out,BOD_5}\right) = -0.053 \times T + 1.657$$
$$c_{out,BOD_5} = 5.244 \times 0.948^{T} \quad (5)$$

For every 1 degree,the predicted concentration of BOD_5 is less by 5%. This effect is cumulative.

Table 4. Tests of residual distribution

Residual Test	Statistics	p-value	Significant
Shapiro-Wilk (normality)	W = 0.98735	0.1514	NO
Breusch-Pagan (equal variance)	BP = 0.53752, 1 df	0.4635	NO
Symmetry (RW)	RW = 0.044601	0.902	NO

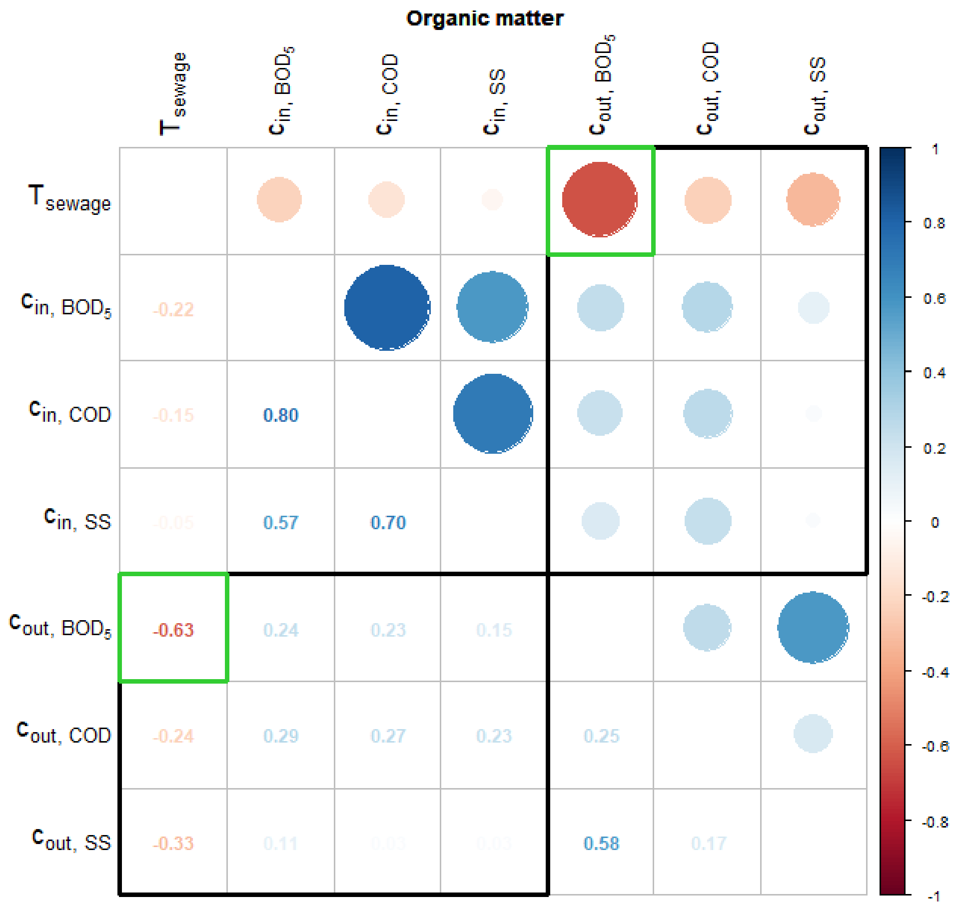

Figure 2. Calculated correlation coefficients

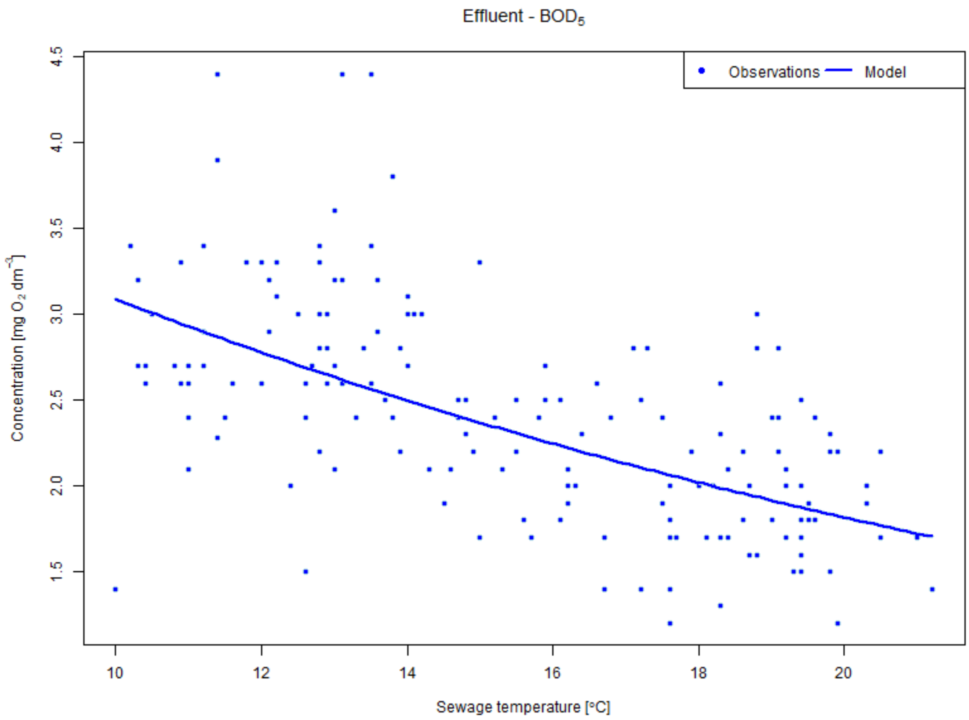

Figure 3. Graphical representation of model (5)

The reported values of BOD_5 concentration in total do not exceed 4.5 gO_2 m^{-3}.

Table 4 presents residual tests of model (5). The insignificant results give no reason to reject the hypotheses regarding proper residual distribution and good model specification. Model (5) is illustrated in Figure 3.

Table 5 presents distribution characteristics forall influent and other effluent concentrations with limits for treated sewage and a limit for reuse [EU 2020/741].

In all cases the hypothesis about parameter distribution symmetry had to be rejected. The median, along with the other quartiles, has a valid interpretation regardless of the symmetry or normality. Due to the asymmetry, it is expected that one of the distribution tails will reach further than the other one. The influent parameters tend to be heavily right-sided, with the maximum value much further from the median in terms of MAD than the minimum ones. For BOD_5 and COD the maximum value is about 10 times MAD from the median, and the minimum only about 1.5 times. For SS the differences are 7.5 and 3.2 times MAD respectively. The BOD_5 concentration limit for class A is 2 times greater than the obtained maximum value. The COD output concentration is much more symmetrical, but the appropriate test result is still significant.The SS output concentration was limited by the measuring protocol

Table 5. Distribution characteristics of selected parameters

Parameter	Distribution measures for influent	Distribution measures for effluent	Limits water legal permit]	Limit for class A water reuse
BOD_5 $\left[mg\,O_2 \times dm^{-3}\right]$	$\frac{460 \pm 160\ (430 \pm 100)}{260; 360; 510; 1\,430}$ $p_{RW} < 0.01$	Temperature dependent	15	10
COD $\left[mg\,O_2 \times dm^{-3}\right]$	$\frac{1\,230 \pm 400\ (1\,130 \pm 280)}{690; 980; 1\,350; 4\,000}$ $p_{RW} < 0.01$	$\frac{29.7 \pm 5.4\ (29.5 \pm 5.2)}{16.0, 26.0, 33.0, 44.0}$ $p_{RW} = 0.04$	125	–
SS $\left[mg \times dm^{-3}\right]$	$\frac{630 \pm 230\ (610 \pm 170)}{60; 490; 720; 1\,870}$ $p_{RW} < 0.01$	$\frac{2.28 \pm 0.48\ (2.00 \pm 0.00)}{2.00, 2.00, 2.40, 5.00}$ $p_{RW} < 0.01$	35	10

and accuracy. More than half of the results were reported as 2.00. For such a result, the calculated MAD measure was equal to 0, i.e. no nonparametric deviation at all. The maximum reported output concentration of SS is again 2 times smaller than the limit for class A water reuse.

Distributions of those variables were plotted in Figures 4-8. Plots of influent and effluent concentration distributions confirm the results obtained from the analysis in Table 5. The shapes of approximate distributions were visibly different among influent and effluent.

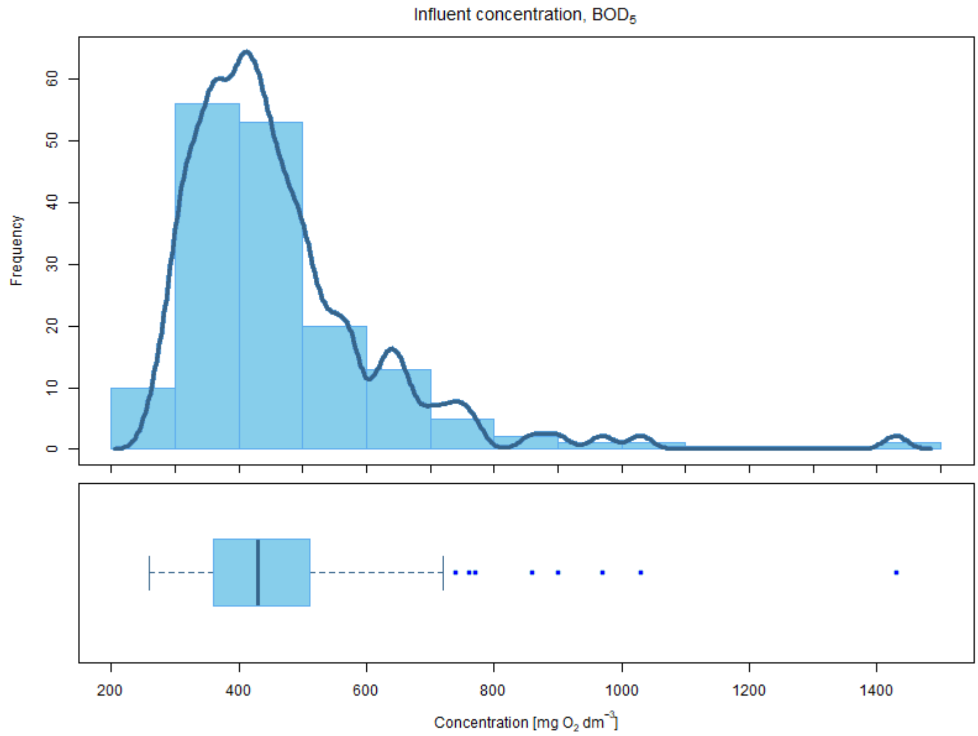

Figure 4. Influent value of BOD_5

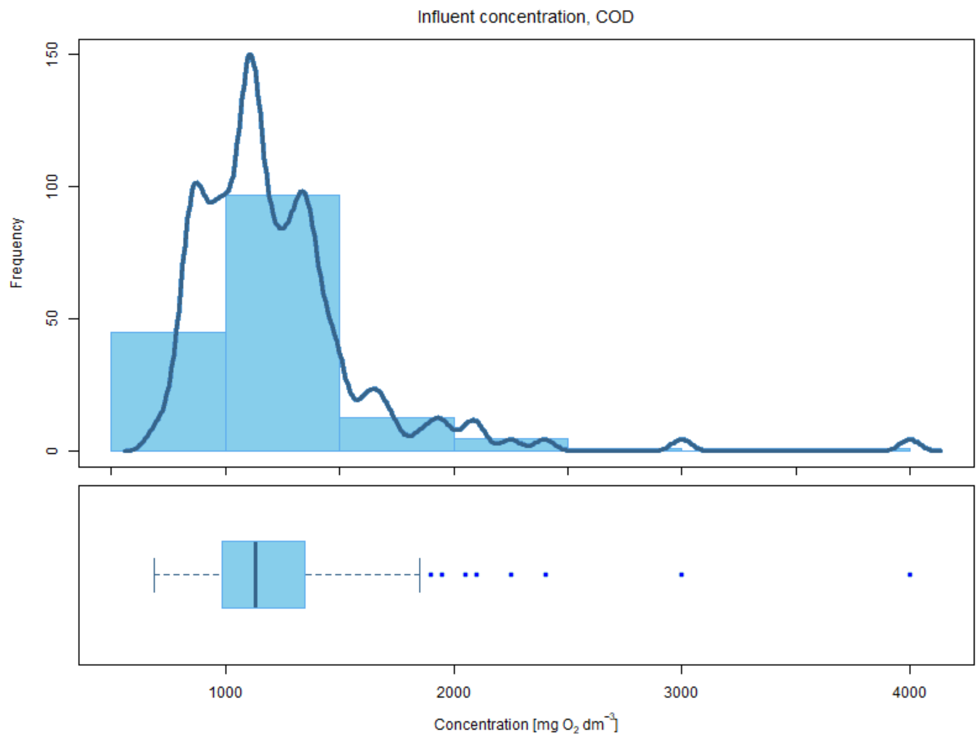

Figure 5. Influent value of COD

This observation further reinforces the recognized low correlation coefficients. Outliers were clearly visible among all influent and effluent SS concentrations, most of them on the right side. A greater symmetry of COD output was also visible.

From the results analysis of tests on raw sewage flowing into the treatment plant, it can be concluded that the raw sewage parameters fluctuate significantly. The results were slightly higher than those reported by Ignatowicz, who studied COD fractions in municipal wastewater at the treatment

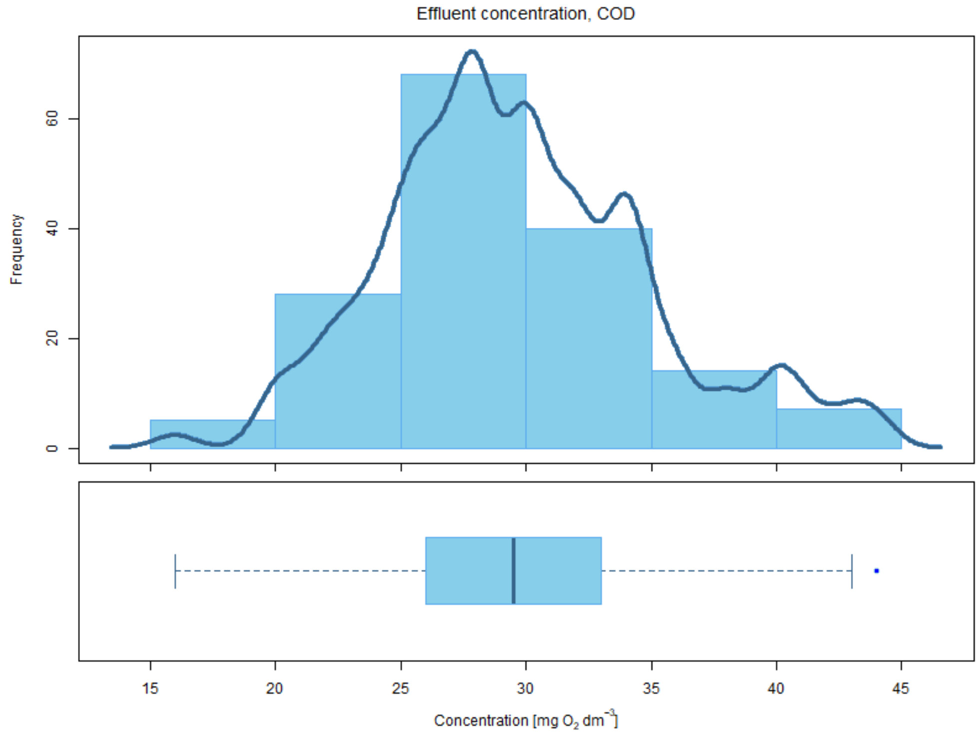

Figure 6. Effluent value of COD

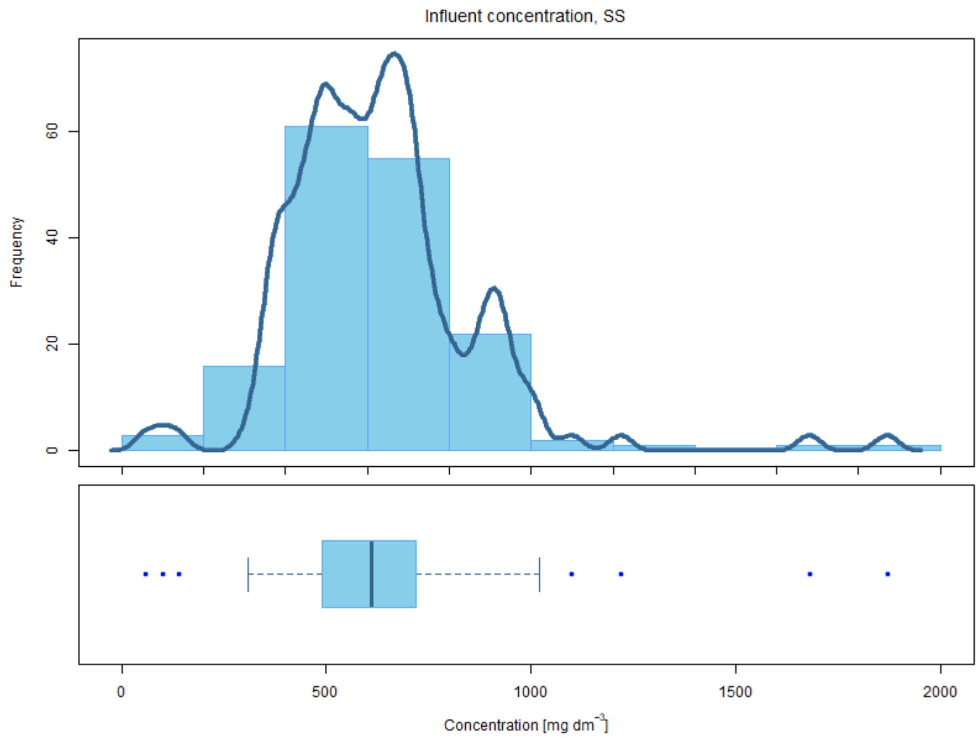

Figure 7. Influent concentration of SS

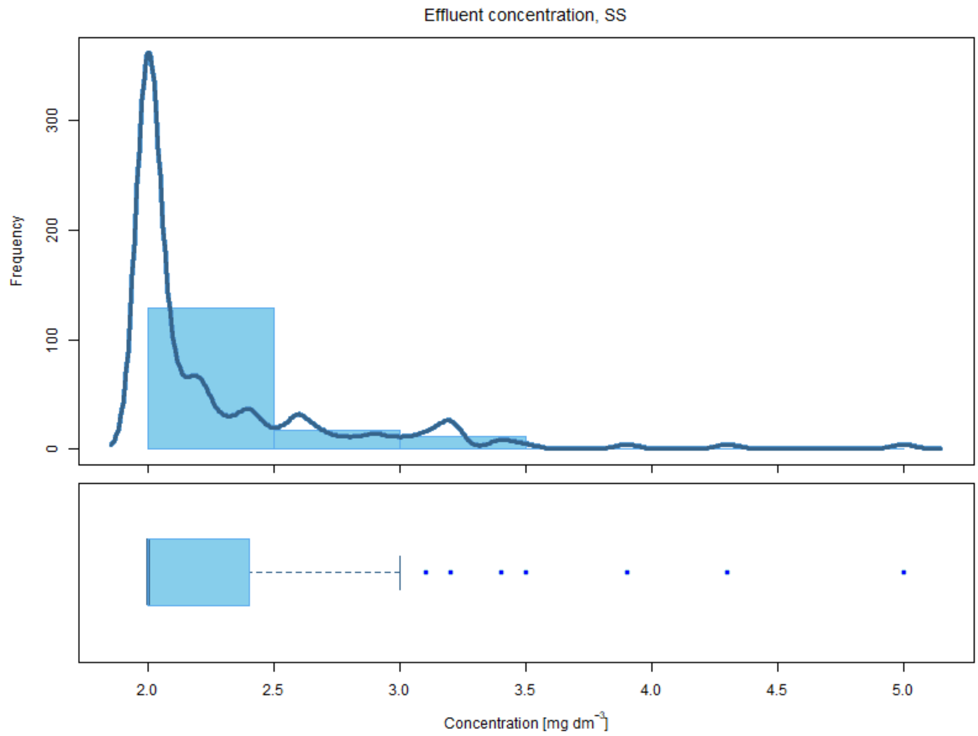

Figure 8. Effluent concentration of SS

plant in Bialystok [Ignatowicz, 2019]. This was associated with a decrease in water consumption and a change in the method of supplying the wastewater treatment plant with incoming sewage from septage tanks.

CONCLUSIONS

Stable and predictable treated sewage parameters are basic for future feasibility of recovering water. Chosen technologies for further treatment will be tested depending on the intended end use of the wastewater.

The parameters of the treated wastewater at the analyzed municipal wastewater treatment plant predispose it to recycling and reuse for irrigation or other municipal uses. Regardless of the parameters of the wastewater flowing into the WWTP, its efficiency was high and stable over time. Activated sludge technology commonly used in municipal and industrial treatment systems, combined with a high level of operation and monitoring, makes it possible to ultimately recover water from wastewater.

In all cases, the output concentrations were far below the class A limits for irrigation in the whole research period. Such a wide margin was preserved throughout the duration of the study.Besides BOD_5, one can expect random output concentration values for COD and SS, regardless of the input parameters. Due to the asymmetry, there is no easy interpretation of the distribution dispersion, as most distributions are visibly skewed to the right side. The median values represent the location of distributions better than the mean.

There was a sufficiently strong correlation between the input sewage temperature and BOD_5 concentration. The obtained linear model on the logarithmic scale predictsa cumulative 5% reduction of the mean BOD_5 concentration per every degree of the sewage input temperature. This temperature clearly depends on seasonality, therefore the BOD_5 concentration has a consistent temporal characteristic.Further studies will evaluate selected industrial wastewater for recyclability with an indication of what processes should be additionally applied to make it a stable and safe process for consumers and the environment. In the future research authors are planning to apply water recovery from industrial sewage (food production).

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