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Assessment of the stability and reliability of the water treatment plant in Nowy Sącz using control cards

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Abstract: The subject of the study was to evaluate the stability and reliability of the sewage treatment plant in Nowy Sącz. The scope of the analysed indicators included the main indicators of wastewater contamination: BOD_5 (biochemical oxygen demand), COD_{Cr} (chemical oxygen demand), total suspended solids (*TSS*), total nitrogen (N_{tot}), and total phosphorus (P_{tot}). The operation stability of the sewage treatment plant in Nowy Sącz was determined on the basis of control cards x for 24 observations made in the period 2018–2019 (2 years). Moreover, the technological reliability of the tested sewage treatment plant (*WN*) was determined based on the values of the analysed pollution indicators in treated sewage and their permissible values. On the basis of the conducted analyses, full stability of the removal process of most of the analysed contaminants was found. In no case was there any crossing of the control lines, only a single grouping of samples above the help line in the case of total nitrogen, which could indicate a periodical disturbance in the stability of the removal process of this compound. On the basis of the obtained values of the reliability coefficient, which were below WN = 1.00, reliable operation of the analysed facility was found, with a high degree of reduction (η) of the analysed pollutants. The method of determining the technological reliability and stability of the treatment plant with the use of control cards is an effective and easy tool for detecting any disturbances and instabilities in the processes taking place in the tested facility. It enables the operator to take quick action to remove them, thus ensuring a safe wastewater treatment process for the environment and human health.

Keywords: control cards, pollution reduction efficiency, stability of wastewater treatment, technological reliability, water treatment plant

INTRODUCTION

Contemporary challenges in the management of technological processes of operated wastewater treatment plants are largely related to the need to achieve a constant, high-quality treated wastewater and ensure efficient and reliable operation of a given facility. According to Śliz [2018b], each city and municipality that has and manages sewage management facilities, such as sewage treatment plants, should strive to use them as fully as possible while minimizing their negative impact on the natural environment. Untreated or insufficiently treated sewage contains numerous toxic substances, including heavy metals, parasites, bacteria, pathogens, and eutrophic compounds (compounds of phosphorus and nitrogen) that disturb the natural balance of the surface water environment [Bohdziewicz *et al.* 2015; Krzanowski, Wałęga 2009; Miksch, Sikora 2010]. In the light of the legal regulations in force, maintaining high efficiency of wastewater treatment requires the operators of wastewater treatment plants to constantly monitor the processes taking place in wastewater treatment plants. Meeting the requirements for the proper efficiency, stability and reliability of the operation of a given facility is particularly important for ensuring the proper protection of the quality of the receiving waters, and thus for the protection of the entire water ecosystem of a given region. According to Wagner and Breil [2013], the problem of water pollution in urban areas is particularly important and current, due to the process of progressive urbanisation, aging of ecological infrastructure and high population density. Moreover, Poland as a member of the European Union is obliged, in accordance with the Water Framework Directive (WFD), to rationally use and protect its water resources [MŁYŃSKI *et al.* 2016].

In the case of any failure of the treatment plant, it is necessary to determine its cause as soon as possible and take immediate action to remove the problem [BUDKOWSKA *et al.* 2012]. In this situation, control cards can be an easy and effective tool for the operator, allowing to detect any disturbances and irregularities in the course of the process in the analysed facility, and thus allow for taking appropriate action to remove them [BUGAJSKI *et al.* 2019; BUGAJSKI, WAŁĘGA 2012; WAŁĘGA 2009]. Moreover, according to KRZANOWSKI and WAŁĘGA [2006], the analysis of control cards allows to detect irregularities that may be eliminated in the future in newly designed or existing facilities.

The aim of this study was to analyse the reliability and stability of wastewater treatment processes taking place in one of the largest wastewater management facilities in the Sądecczyzna region that is the sewage treatment plant in Nowy Sącz. The evaluation of the operation of the analysed facility was also extended to include the analysis of the effectiveness of the reduction of the analysed pollution indicators in treated sewage. Determination of changes in the values of the analysed pollution indicators in treated wastewater against the limit values contained in the water use permit [Pozwolenie... 2015], made it possible to determine the technological reliability index of the said wastewater treatment plant in the analysed period of two years (2018–2019). On the other hand, the use of statistical quality control, in the form of control cards x for 24 observations, made it possible to verify the stability of the processes of removing individual wastewater pollutants in the said treatment plant in Nowy Sącz.

MATERIALS AND METHODS

DESCRIPTION OF THE STUDY OBJECT

The analysed facility, located in Nowy Sącz (49°66' N, 20°69' E), is a mechanical-biological sewage treatment plant that neutralises municipal sewage from the city of Nowy Sącz and its vicinity. The sewage treatment plant was launched in 1996, the main purpose of its construction was to protect the waters of Lake Rożnowskie and to collect household and industrial sewage from the area of Nowy Sącz. The technological process of the wastewater treatment plant includes mechanical, biological and chemical treatment of wastewater, treatment of sludge in order to stabilise and dehydrate it, as well as proper waste management from wastewater treatment. In the sewage treatment plant in Nowy Sącz, there are two biological reactors of the MUCT type, in which the process of sewage treatment with the use of activated sludge takes place. Each biological reactor consists of three technological zones: anaerobic zone, where dephosphatation takes place, an oxygen-free zone with a denitrification process, and an oxygen zone, where the nitrification process takes place. Polyaluminium chloride (PAX) coagulant is sometimes added to the hypoxic zone. After the stage of biological reactors, the wastewater is directed to secondary settling tanks, from where, as treated wastewater, it goes to the measuring channel, and then to the receiver. After the modernisation of the sewage treatment plant in 2005, the equivalent number of inhabitants increased from 150,000 to 180,000. The planned average daily flow is 30,000 $m^3 \cdot d^{-1}$, and the actual capacity ranges from 23,000 to 25,000 $m^3 \cdot d^{-1}$. As a result of the modernisation, the treatment plant was expanded, among others a second fermentation chamber with a capacity of 3000 m^3 with a heat exchanger, a new biogas tank with a capacity of 1040 m^3 and a biogas desulphurisation plant. The Dunajec River (km 103 + 600) [SWNS undated] is the receiver of the sewage treated from the sewage treatment plant in Nowy Sącz. Pursuant to the valid water use permit [Pozwolenie… 2015], the values of pollution indicators for sewage discharged into the Dunajec River may not exceed the following values: BOD_5 – 15.0 mg $O_2 \cdot dm^{-3}$, COD_{Cr} – 125.0 mg $O_2 \cdot dm^{-3}$, TSS – 35.0 mg$\cdot dm^{-3}$, N_{tot} – 10.0 mg $N \cdot dm^{-3}$, P_{tot} – 1.0 mg $P \cdot dm^{-3}$.

METHODS

In order to analyse the reliability and stability of the wastewater treatment processes in the wastewater treatment plant in Nowy Sącz, the results of physical and chemical tests of treated wastewater from 2018 to 2019 were used. The scope of the analysed indicators included the main indicators of wastewater pollution, ie: BOD_5 (biochemical oxygen demand), COD_{Cr} (chemical oxygen demand), TSS (total suspended solids), N_{tot} (total nitrogen), and P_{tot} (total phosphorus).

To determine the reliability of the processes taking place in the tested sewage treatment plant, the technological reliability coefficient was used, calculated from the following dependence:

$$WN = \frac{x_{\mathrm{avg}}}{x_{\mathrm{per}}} \tag{1}$$

where: WN = plant reliability factor (–), x_{avg} = average value of the analysed pollution index in treated sewage ($mg \cdot dm^{-3}$), x_{per} = permissible value of the analysed pollution index in treated sewage ($mg \cdot dm^{-3}$).

In order to determine the effectiveness of wastewater treatment in the facility, the percentage reduction of the analysed pollution indicators in treated wastewater was calculated according to the following formula:

$$\eta = \frac{S_s - S_o}{S_s} 100\% \tag{2}$$

where: η = reduction of a particular pollutant index in treated sewage (%), S_s = value of the pollution index in raw sewage ($mg \cdot dm^{-3}$), S_o = value of the pollution index in treated sewage ($mg \cdot dm^{-3}$).

Control cards x, which were determined for selected pollution indicators in treated sewage, were used to analyse the stability of sewage treatment in the tested facility. The normal distribution of the examined random variables was verified using the Shapiro–Wilk test for the significance level $\alpha = 0.05$ [SHAPIRO, WILK 1965]. Due to the fact that the analysed random variables did not have a normal distribution, the random variables were normalised by their logarithm. The boundaries of the help lines, control lines and the centre line were determined taking into account the three-sigma rule for the normal distribution N (μ, σ) [KRZANOWSKI *et al.* 2008; KRZANOWSKI, WAŁĘGA 2006]:

Lower control line (LCL):

$$LCL = \mu - 3\sigma \tag{3}$$

Lower warning line (LWL):

$$LWL = \mu - 2\sigma \tag{4}$$

Lower help line (LHL):

$$LHL = \mu - 1\sigma \tag{5}$$

Central line (CL):

$$CL = \mu \tag{6}$$

Upper control line (UCL):

$$UCL = \mu + 3\sigma \tag{7}$$

Upper warning line (UWL):

$$UWL = \mu + 2\sigma \tag{8}$$

Upper help line (UHL):

$$UHL = \mu + 1\sigma \tag{9}$$

where: μ = mean value of the analysed variable (mg $O_2 \cdot dm^{-3}$, $mg \cdot dm^{-3}$), σ = standard deviation of the analysed variable (mg $O_2 \cdot dm^{-3}$, $mg \cdot dm^{-3}$).

According to ANDRAKA [2005], disruption or instability of the wastewater treatment process occurs when the following observations occur: eight consecutive points on one side of the centre line, one point outside the control limits, two of the three points outside the warning lines $\pm 2\sigma$ and four out of five consecutive points beyond the extension lines $\pm 1\sigma$.

RESULTS AND DISCUSSION

Table 1 presents the calculated values of the technological reliability coefficient (WN) for the removal of specific wastewater pollutants together with a summary of the average reduction efficiency (η) of the analysed pollution indicators in the tested wastewater treatment plant.

Table 1. Summary of the value of the technological reliability coefficient against the average efficiency of the analysed pollutants removal in the Sewage Treatment Plant in Nowy Sącz

Indicator	BOD_5	COD_{Cr}	TSS	N_{tot}	P_{tot}
Reliability coefficient WN (–)	0.34	0.36	0.41	0.74	0.49
Reduction efficiency η (%)	98.7	95.8	97.0	89.8	95.0

Explanations: BOD_5 = biochemical oxygen demand, COD_{Cr} = chemical oxygen demand, TSS = total suspended solids, N_{tot} = total nitrogen, P_{tot} = total phosphorus.
Source: own study.

The highest technological reliability, and thus the lowest WN values, were obtained for the removal of BOD_5 (0.34) and COD_{Cr} (0.36). Then, a slightly worse reliability was obtained for TSS (0.41) and P_{tot} (0.49). However, according to the study of CHMIELOWSKI *et al.* [2015], the reliability coefficient – already at the level of WN_{BOD5} = 0.44 and WN_{CODCr} = 0.57 – proves the satisfactory operational reliability of the tested sewage treatment plant. Total nitrogen (WN = 0.74) showed the lowest removal reliability among the analysed pollutants, which is often found also in other facilities of this type. In the ŚLIZ study [2018a], the reliability coefficient for total nitrogen was 0.81, with WN_{BOD5} = 0.25 and WN_{CODCr} = 0.17. Lowering the reliability of total nitrogen removal in the wastewater treatment process could be associated with significant fluctuations in total nitrogen concentrations in raw sewage, the phenomenon of wastewater cooling in winter, or with disturbances in the nitrification and denitrification process in a biological reactor where nitrogen compounds are removed. According to BUGAJSKI *et al.* [2015], the above factors may adversely affect the metabolism of activated sludge microorganisms and contribute to an increase in the value of total nitrogen in treated sewage, and thus contribute to disrupting the reliability of its removal. In the case of sewage treatment plants with activated sludge technology, the temperature of the sewage is one of the main factors influencing the processes related to the removal of nitrogen compounds in treated sewage. The temperature below which the nitrification process can significantly deteriorate (decrease) is 12°C [BUGAJSKI 2011].

However, the obtained results did not exceed the limit value WN = 1.00 in any case, proving the basic technological reliability of the facility. Moreover, the reduction levels (η) presented in Table 1 prove the high efficiency of removal of the analysed indicators of pollutants in the treated sewage of the analysed sewage treatment plant (η_{BOD5} – 98.7%, η_{CODCr} – 95.8%, η_{TSS} – 97.0%, η_{Ntot} – 89.8%, η_{Ptot} – 95.0%). The obtained values indicated the fulfilment of the requirements contained in the applicable legal acts for a given study period, in which the minimum reduction of the discussed indicators in the wastewater discharged into the receiving waters should be: 90.0% for BOD_5, 75.0% for COD_{Cr}, 90.0% for TSS, 70.0–80.0% for N_{tot} and 80.0% for P_{tot} [Rozporządzenie... 2014; 2019].

Figure 1a shows the control chart x developed for the BOD_5 indicator in treated sewage. Its analysis shows that during the study period, the analysed values fluctuated around the centre line, not exceeding the upper or lower control line. This fact proved that the process of BOD_5 removal in the tested sewage treatment plant was fully stable. Similar results confirming the stability of the BOD_5 removal process were also presented in the studies by MŁYŃSKI *et al.* [2016].

The analysis of Figure 1b shows that there are no disturbances in the COD_{Cr} removal process in the sewage treatment plant in Nowy Sącz. There are no crossings of the control lines and there are no disturbing grouping of samples, which proves a stable process of COD_{Cr} removal in the treated sewage of the analysed object. During the research period there was two cases of exceeding the lower warning line (LWL) and this occurred for the samples 17 and 18. Nevertheless, this situation is not worrying because it is related to the low value of the COD_{Cr} index in sewage flowing into the treatment plant, which also resulted in its low value in treated sewage (19.0 mg $O_2 \cdot dm^{-3}$ and 23.05 mg $O_2 \cdot dm^{-3}$).

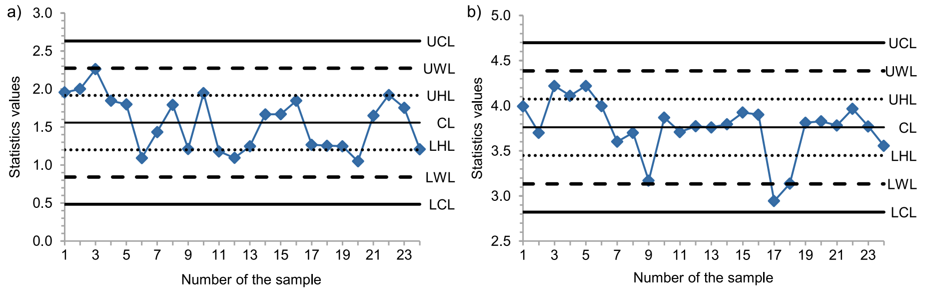

Fig. 1. Control chart x for indicators of oxygen demand in treated sewage: a) biological (BOD_5), b) chemical (COD_{Cr}); *UCL*, *UWL*, *UHL*, *CL*, *LHL*, *LWL*, *LCL* as in Eqs. (3)–(9); source: own study

Figure 2a also shows the full stability of the processes of removing the next analysed pollutant, which is the total suspension. The values of the tested indicator oscillate around the central line, not grouping excessively and not exceeding the upper or lower control line. A similar distribution of samples was presented in the work of BUGAJSKI *et al.* [2019], which proves the stability of the discussed process.

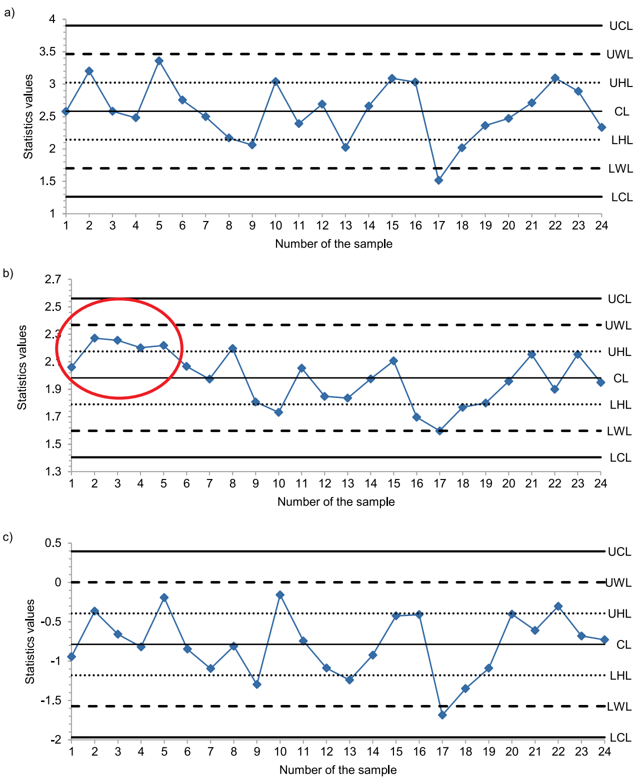

Fig. 2. Control chart x for wastewater contamination in treated sewage: a) total suspended solids, b) total nitrogen, c) total phosphorus; *UCL*, *UWL*, *UHL*, *CL*, *LHL*, *LWL*, *LCL* as in Eqs. (3)–(9); source: own study

The analysis of Figure 2b shows that there were no crossings of the control lines in the case of total nitrogen, however, a one-time grouping of the samples (four observations) above the upper help line was noted. This fact could indicate a periodical disturbance of the stated stability, slightly affecting the deterioration of the effects of removing this compound in the tested sewage treatment plant, but not exceeding the permissible value for total nitrogen in treated sewage. The grouping of the samples in question took place in the winter-spring period and could be related to the negative impact of the reduced sewage temperature on the process of nitrogen compounds removal. In the studies by KRZANOWSKI and WAŁĘGA [2006] the occurrence of a similar instability in total nitrogen removal was associated with a temporary disturbance in the nitrification and denitrification process.

Based on the analysis of the results presented in Figure 2c, full stability of the total phosphorus removal process in the tested sewage treatment plant in Nowy Sącz was found. The concentrations of the indicator in question oscillated around the central line, did not show any crossing of the control lines or grouping of samples below or above the characteristic lines.

CONCLUSIONS

The operation of key wastewater management facilities, such as sewage treatment plants, requires constant control and verification of the proper operation of these facilities. It is particularly important in terms of the proper protection of the natural environment, and thus human and animal health against the toxic effects of municipal sewage. This work was concerned with the assessment of the functioning of the Sewage Treatment Plant in Nowy Sącz using, among others, modern control tools, such as control cards x. The subject of the analysis was to assess the reliability and stability of wastewater treatment processes as well as to analyse the effectiveness of removing the most important wastewater pollutants against the background of applicable legal requirements and regulations. On the basis of the obtained results, the following conclusions and statements were made.

1. The obtained values of the technological reliability index (*WN*) proved the high efficiency of the tested facility. In the case of BOD_5, COD_{Cr}, total suspended solids and total phosphorus, the reliability coefficient was low: $WN_{BOD5} = 0.34$; $WN_{CODCr} = 0.36$; $WN_{TSS} = 0.41$; $WN_{Ptotal} = 0.49$. The lowest technological reliability was noted in the case of total nitrogen ($WN_{Ntotal} = 0.74$), which could indicate some problems occurring at the stage of the nitrification and denitrification process. However, it should be emphasised that in each of the analysed cases the minimum degree of reduction of the analysed pollutants was achieved ($\eta_{BOD5} = 98.7\%$; $\eta_{CODCr} = 95.8\%$; $\eta_{TSS} = 97.0\%$, $\eta_{Ntotal} = 89.8\%$; $\eta_{Ptotal} = 95.0\%$), referred to in applicable legal regulations.
2. The analysis of control cards showed full stability of the process of removing BOD_5, COD_{Cr}, total suspended solids and total phosphorus in the tested facility. In the case of total nitrogen, a single grouping of samples above the help line was noted. This could prove a periodical disturbance in the stability of the process of removing this compound in the investigated

sewage treatment plant, but it did not exceed the limit value in treated sewage and did not significantly deteriorate the average efficiency of total nitrogen reduction in treated sewage.
3. The conducted analyses showed that one of the main sewage management facilities in the Nowy Sącz region, which is the sewage treatment plant in Nowy Sącz, fulfils its basic function in terms of sewage management, i.e. it effectively protects the natural environment against the negative impact of municipal sewage generated in a given region.
4. Control cards can be an effective tool for assessing the operation of a sewage treatment plant, allowing to detect any disturbances in the course of the sewage treatment process in the tested facility. Thus, they enable the operators to take appropriate action to remove them quickly, and thus to ensure the protection of the water quality of the natural reservoir.

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