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CHOICE OF THE EFFICIENT FLOW DIAGRAM OF BIOLOGICAL WASTEWATER TREATMENT AT MUNICIPAL WASTEWATER TREATMENT PLANTS

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Abstract. The possibility of increasing the efficiency of municipal wastewater treatment plant (WWTP) operation by changing the flow diagram of biological wastewater treatment in aeration tanks at minimum expenses for their reconstruction is shown in the paper on the example of one of the regional centres of Ukraine. The technology of nitri-denitrification of wastewater according to the flow diagram of the two-stage modified Ludzak-Ettinger process is offered for the considered conditions. The distribution of wastewater flows and internal nitrate recycling between the individual stages of this flow diagram has been optimized in order to minimize the residual content of total nitrogen in the treated effluents. Computer dynamic modelling of biochemical processes has proved the high efficiency and reliability of the flow diagram proposed by the authors.

Keywords: wastewater, biological treatment, aeration tanks, nitri-denitrification, flow diagram, Ludzak-Ettinger process.

1. Introduction

One of the most important problems of water supply and sewerage in Ukraine is the low efficiency of the majority of municipal wastewater treatment plants (National report, 2019, National report, 2020). Almost all of them were built in the 60s and 80s of the last century with the expected operational life of about 25–30 years but continue to operate today.

For many years of operation, such facilities have been maintained in operation due to the repair of building structures and basic technological equipment without significant changes in wastewater treatment technology. At the same time, since the commissioning of these treatment facilities, there have been significant changes in the quantitative and qualitative characteristics of wastewater, technologies and requirements for their treatment. Mostly, the costs of wastewater have decreased, their capacity has significantly decreased, and they have acquired the characteristic of typical municipal wastewater, which is characterized by the predominance of the domestic component and relatively low content of industrial pollution.

The requirements for the effluent quality, in particular, for the residual content of nutrients - nitrogen and phosphorus – have become stricter. New effective flow diagrams of biological wastewater treatment from these elements, which are now widely used in foreign practice, have been developed and studied (Henze et al., 2008; Grady et al., 2011; Haandel; Lubbe, 2012; WEF Manual, 2010).

It should be noted that currently, the design capacity of most municipal wastewater treatment plants in Ukraine is only partially loaded. Therefore, there is significant potential to increase their efficiency by changing the technology of biological wastewater treatment with minimal reconstruction costs. At the same time, when choosing the flow diagram for each treatment plant, the individual approach should be applied - specific local conditions must be taken into account: costs, composition and properties of wastewater, available treatment technologies, the capacity of treatment plants and equipment, etc. Let’s consider this question on the example of municipal wastewater treatment plants of one of the regional centres of Ukraine.

2. Methods and Materials

The considered treatment plants were put into operation in the mid-1970s, had a design capacity of

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70.000 m^3/day and provided for complete biological treatment of municipal wastewater. In the 1980s, reconstruction and expansion of treatment plants were carried out, bringing their design capacity to 150.000 m^3/day, which also included the construction of complexes for the treatment of biologically effluent and for mechanical sludge dewatering. However, due to the collapse of the USSR and the termination of funding, these works were not completed. Currently, unfinished buildings are partially or completely destroyed and are not subject to restoration and further use.

In the last decade, two mechanized screens with 5 mm of bar spaces have been installed at existing treatment plants, new two-section horizontal aerated grit chambers of the design capacity of 100.000 m^3/day and sand landfills have been constructed, primary and partially secondary radial clarifiers had major repairs, replacing of aeration systems, and other construction works were implemented.

Today, biological wastewater treatment plants are represented by four sections of four-corridor continuous-flow aeration tanks with a total capacity of 46,000 m^3 and three radial secondary clarifiers (D = 28 m each). The aeration tanks operate according to the flow diagram with preliminary regeneration of the return activated sludge. Two of four corridors of each aeration tank, 50 % of the construction volume, are allocated for regenerators. Excess activated sludge from secondary clarifiers flows to pre-aerators for preliminary bio-coagulation of wastewater pollutants before their clarification in two primary radial clarifiers (D = 40 m).

This flow diagram of mechanical and biological wastewater treatment fully complied with the building standards and regulations for the design and construction of the treatment plant. When developing flow diagrams and designing treatment plants, the main attention was paid to wastewater treatment from mechanical and organic pollutants, while deep removal of nutrients from effluents was not provided. Today, such technological solutions are obsolete and do not meet the current level of development of science and technology and regulatory requirements for the required degree of wastewater treatment from nitrogen and phosphorus compounds.

As a result, treatment plants do not operate efficiently enough, as demonstrated by the excess of permissible concentration of effluent pollutants for almost all main indicators, except for COD.

2.1. Wastewater characteristics

Currently, the treatment plant receives a mixture of domestic, industrial and partially storm and melt wastewater of the city (the latter is from the combined sewer of the central, "historic" part), as well as the filtrate from the municipal landfill and liquid waste from cesspools and septic tanks of the city districts without sewage facilities. The daily wastewater flow rate is about 35.000–45.000 m^3/day in dry weather and up to 80.000 m^3/day during heavy rains. The average daily wastewater flow rates of influential in 2017–2019 are shown in Fig. 1.

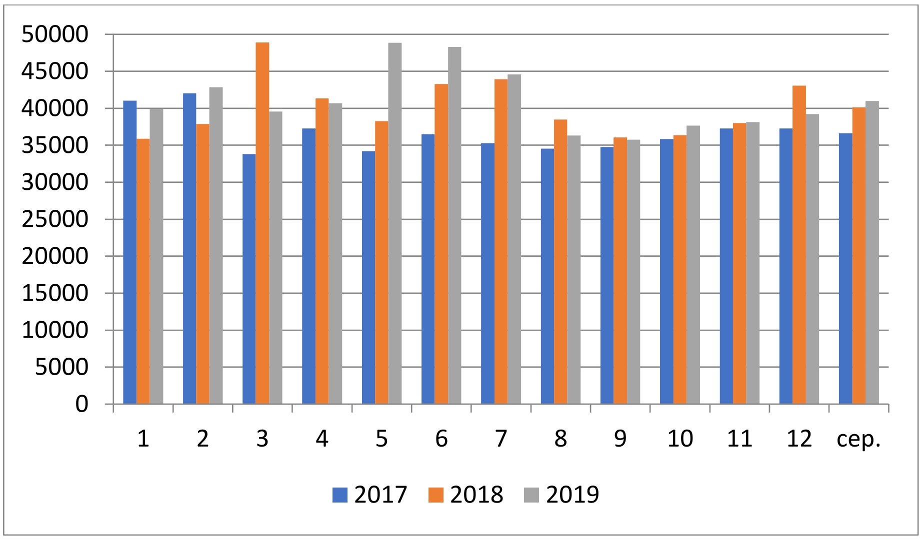


Fig. 1. Average monthly daily influent flow rates, m^3 / day in 2017–2019

The average monthly influent temperatures during this period varied from 7.0 to 20.2° C (Fig. 2). The coldest wastewater was usually in January-February, the warmest – in August. Relatively low values of sewage temperature in winter (about 7–9° C) should be noted. This is due to the peculiarities of the structure of the municipal sewerage system, in particular, the presence of a combined sewer in its central part. This fact indicates the possibility of a significant negative impact of low wastewater temperatures in the cold period of the year on the processes of biological wastewater treatment in aeration tanks, in particular, from nitrogen compounds. The effluent temperature was on average 0.8° C higher than the influent temperature.

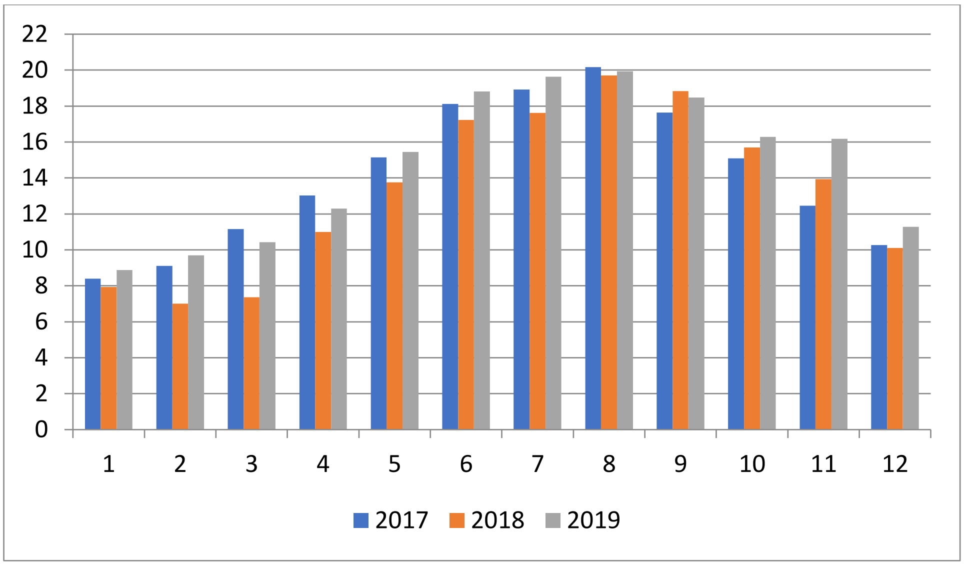


Fig. 2. Average monthly influent temperatures, ° C, in 2017–2019

The average monthly values of the main indicators of wastewater pollution for the period 2017–2019 are given in Table 1. The values of wastewater indicators of 85 % load availability given in this table are calculated according to the method described by the authors (Protsenko et al., 2020).

Table 1

Average monthly values of costs and main indicators of influent in 2017–2019

Indicators	Values of indicators			
	min.	max.	average	85 % of availability
Wastewater flow rate, m^3/day	33790	48896	39248	43475
Wastewater indicators, mg/dm^3:				
Suspended solids	221	347	264	270
BOD_5	203	344	243	250
COD	367	703	463	473
Ammonium nitrogen	32.8	60.4	44.9	46.2
Phosphates	5.71	9.25	7.10	7.27

The average ratio of COD and BOD_5 of wastewater is 1.9, which indicates a relatively high content in water organic compounds suitable for biodegradation and low content of industrial pollutants. Concentrations of ammonium nitrogen in influent are quite high (about 45 mg/dm^3), while the phosphate content can be considered quite low (about 7.1 mg/dm^3).

2.2. The recommended flow diagram of biological wastewater treatment

The most obvious and simple solution to the problem of improving the efficiency of biological wastewater treatment, including nutrients, is to transform at the considered operating treatment plants the aeration tanks from full biological treatment technology with activated sludge regeneration into nitri-denitrification technology (BIO -N) according to the modified Ludzak-Ettinger process (MLE) (Meshengisser, 2012), shown in Fig. 3.

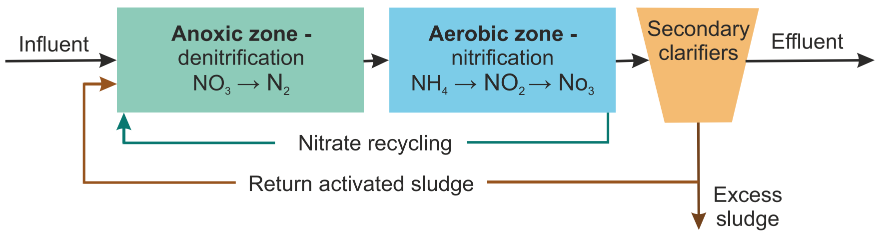


Fig. 3. Flow diagram of the modified Ludzak-Ettinger process (MLE)

The BIO-N process involves the installation of a separate anoxic zone in the aeration tank with nitrification for nitrate nitrogen denitrification. In order to prevent the activated sludge settling, the submersible mechanical mixers are installed in the anoxic zone, or pneumatic mixing is provided with minimization of water saturation with oxygen. Therefore, the concentration of dissolved oxygen in the sludge mixture is close to zero in the anoxic zone, and nitrates and nitrites are the source of oxygen for the activity of numerous heterotrophic bacteria.

The BIO-N process can be implemented using various flow diagrams. In the MLE flow diagram (see Fig. 3), the anoxic zone precedes the aerobic one. In the anoxic zone, heterotrophic activated sludge bacteria reduce nitrates and nitrites formed in the aerobic zone to nitrogen gas, using organic compounds of influent as a substrate for their nutrition. Nitrification occurs in the aerobic zone simultaneously with the removal of almost all residual organic wastewater. Nitrates enter the anoxic zone partly with return activated sludge and mainly by pumping nitrate-enriched sludge mixture from the end of the aerobic to the beginning of the anoxic zone (nitrate recycling, or so-called "internal" recirculation).

The computation of the wastewater treatment process for the considered conditions according to the international standard method of the ATV-DVWK-A 131E (2000) shows that the share of an anoxic zone in the total volume of nitri- denitrifier should be 50 %, and the ratio of total (internal and external) recirculation is quite high and equal to 3.

In order to reduce energy costs for nitrate recirculation, it is recommended to use a two-stage flow diagram in existing aeration tanks, each stage of which is similar to a separate MLE process (Fig. 4). According to this solution, part of the nitrates and nitrites formed in the first aerobic zone will flow to the beginning of the second anoxic zone by gravity, which will slightly reduce the amount of internal nitrate recycling. It is also recommended to supply the inffluent gradually at two points - at the beginning of the first and second anoxic zones. This will create a certain gradient of activated sludge concentration in the system, as the return sludge will be diluted with wastewater in the "head" of the bioreactor only partially, and the sludge mixture will be more concentrated at the first stage of the aeration tank. As a result, the total sludge mass in the system and its age will be increased, which will have a positive effect on the nitri-denitrification processes.

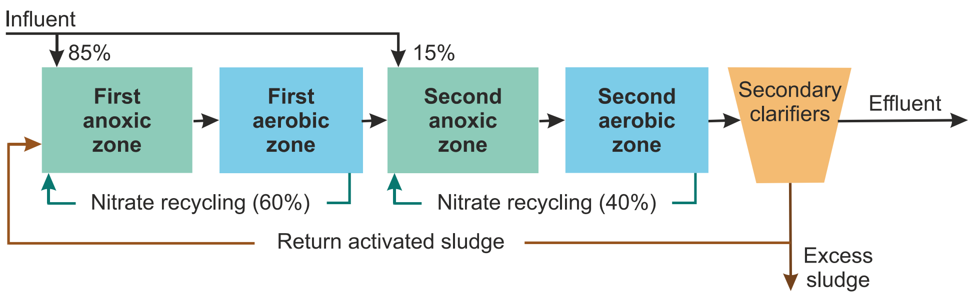


Fig. 4. Recommended flow diagram of two-stage MLE process

The proposed flow diagram is quite simple to be implemented in practice in the existing four-corridor aeration tanks of the treatment plant. To do this, the first corridor of each aeration tank must be converted into the first anoxic zone, the second corridor - into the first aerobic zone, the third - into the second anoxic zone and, finally, the fourth - into the second aerobic zone. Therefore, the volume of the denitrifier will be 50 % of the total volume of the bioreactor. In the first and third corridors, instead of the existing aeration system, submersible mechanical mixers should be installed. It is also necessary to organize internal recycling of the sludge mixture from the end of the second corridor to the beginning of the first and from the end of the fourth corridor to the beginning of the third one. This can be done by arranging holes in the partitions separating the respective corridors and installing low-pressure submersible axial pumps in them. Additional pipelines are not required as the sludge recirculation will take the shortest route. Such reconstruction of existing aeration tanks will require a minimum of capital expenditures.

3. Results and Discussions

In order to determine the efficient distribution of influent flows and internal nitrate recycling between the stages of the bioreactor, the proposed flow diagram was optimized using the computer program Hydromantis GPS-X. The optimization aimed to determine the distribution of these flows between two stages of the bioreactor, at which the total nitrogen content in the effluent (the objective function) is the lowest.

As the result of the optimization, it was found that the lowest total nitrogen content in effluent corresponds to the distribution at the first stage of the bioreactor of about 85 % of influent and 60 % of internal nitrate recycling. The remaining wastewaters and internal sludge recycling should be directed to the second stage of the bioreactor (see Fig. 4).

The dynamic modelling of aeration tanks according to different flow diagrams for flow rates, temperatures and quality indicators of wastewater according to their actual average monthly values during 2017-2019 was performed to assess the efficiency of the proposed flow diagram of biological wastewater treatment.

Three flow diagrams of aeration tanks operation were investigated:

1) complete biological wastewater treatment with regeneration of activated sludge (existing regime of aeration tanks operation);

2) nitri-denitrification according to the traditional single-stage flow diagram of the MLE process;

3) nitri-denitrification according to the recommended two-stage flow diagram of the MLE process.

Dynamic modelling of wastewater treatment processes was performed on computer models of treatment plants in the program Hydromantis GPS-X (Fig. 5) using the standard model of biochemical processes mantis2 (GPS-X Guide, 2019).

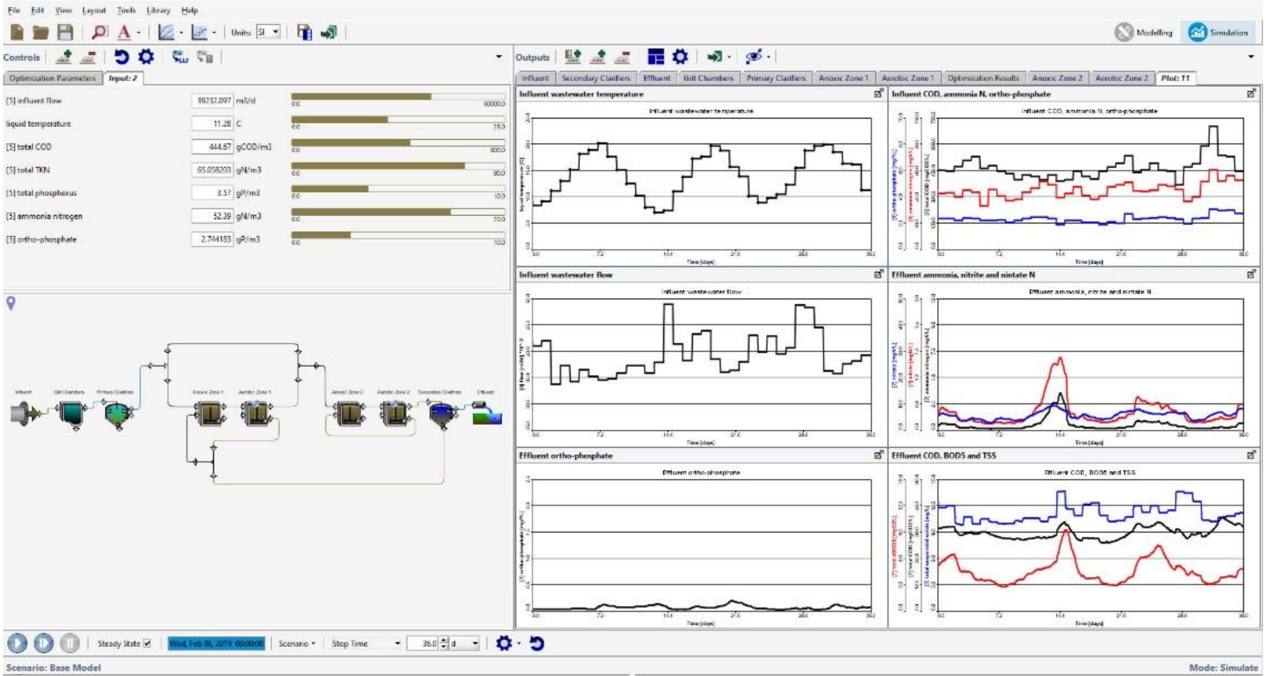


Fig. 5. Dynamic modelling of operation of biological wastewater treatment facilities in the computer program Hydromantis GPS-X

To perform dynamic modelling of technological processes of biological wastewater treatment at the actual flow rate, temperature and quality of wastewater in the models of treatment plants were provided with appropriate input control parameters - flow rate, temperature, COD, total nitrogen concentration by the Kjeldahl method, ammonium nitrogen, total phosphorus and phosphorus phosphates in wastewater. The appropriate pattern was created using a file with the actual data. In the dynamic modelling of wastewater treatment plants, one conditional day corresponded to one set of average monthly indicators of flow rate, temperature and wastewater pollution.

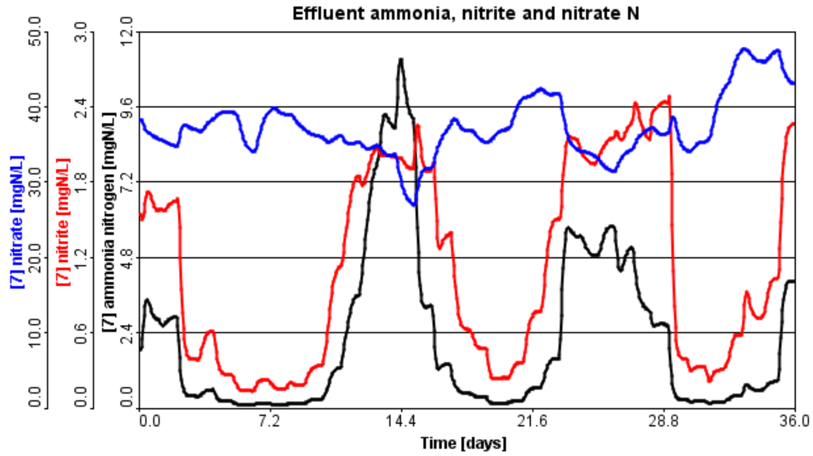
The generalized results of dynamic modelling of the biological wastewater treatment process according to different variants of flow diagrams are presented in Table 2.

Table 2

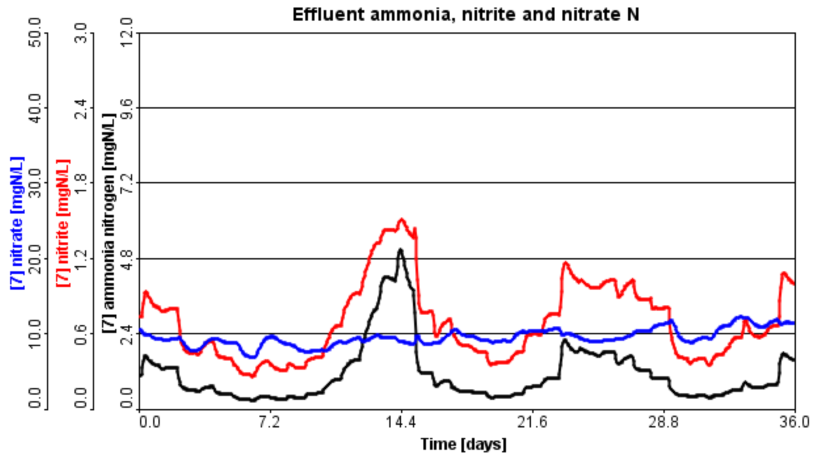
Generalized results of dynamic modelling of the process of biological wastewater treatment according to the compared flow diagrams

Indicators	**Values of indicators, average (min.-max.), for comparable flow diagrams**		
	complete biological treatment (existing regime)	**single-stage MLE process**	**two-stage MLE process (recommended flow diagram)**
Effluent indicators, mg/dm^3:			
Suspended Solids	11.0 (9.8-13.5)	11.2 (9.9-13.7)	11.1 (9.9-13.6)
BOD_5	5.3 (2.9-11.9)	5.8 (3.8-10.8)	4.6 (2.8-9.2)
COD	37.2 (32.0-45.0)	37.4 (32.2-44.7)	35.7 (31.0-42.6)
Ammonium nitrogen	2.19 (0.10-11.1)	1.11 (0.28-5.07)	0.48 (0.13-3.35)
Nitrite nitrogen	1.11 (0.13-2.48)	0.69 (0.26-1.51)	0.40 (0.14-1.65)
Nitrate nitrogen	37.2 (27.0-47.6)	9.52 (6.82-12.2)	5.62 (2.75-9.18)
Phosphorus phosphates	1.48 (0.49-2.23)	0.06 (0.03-0.08)	0.07 (0.02-0.19)

As the research results show, the proposed flow diagram of the two-stage MLE process, in comparison with other flow diagrams, provides a higher and more sustainable efficiency of wastewater treatment, especially from nitrogen compounds (Fig. 6).



a



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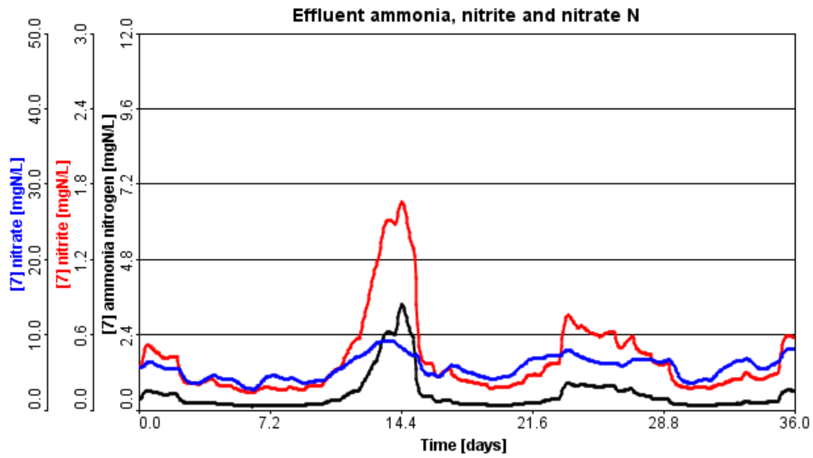

c

Fig. 6. Concentrations of ammonium, nitrite and nitrate nitrogen in effluent based on the results of dynamic modelling of the biological treatment process in the computer program Hydromantis GPS-X for comparable flow diagrams of aeration tanks: *a* – the existing regime; *b* – traditional single-stage MLE process; *c* – the recommended two-stage MLE process

Only one case of exceeding the allowable content in the effluent of ammonium and nitrite nitrogen was observed at peak hydraulic load on treatment plants (48.900 m³/day) and abnormally low wastewater temperature (7.0–7.4 °C) during February-March 2018 when modelling the operation of treatment plants according to this flow diagram for the entire research period. At the same time, the same high hydraulic load at a higher effluent temperature (15.5 °C) in May 2019 had no longer a similar negative impact on the efficiency of wastewater treatment plants.

High efficiency of biological wastewater treatment from phosphorus phosphates was also observed both according to the traditional flow diagram of the MLE process and according to its two-stage variant (Table 2).

4. Conclusions

Thus, the studies confirm the possibility and feasibility of the reconstruction of the considered treatment plants according to the recommended two-stage flow diagram of the MLE process. This will provide high and sustainable efficiency of their operation at the minimum cost of construction and installation work.

• The example of municipal sewage treatment plants in one of the regional centers of Ukraine shows the possibility of efficiency of increasing their operation by changing the flow diagram of biological wastewater treatment in aeration tanks with minimal costs on reconstruction.

• The technology of wastewater nitri-denitrification according to the flow diagram of the two-stage modified Ludzak-Ettinger process is offered for the considered treatment facilities.

• Optimization of the wastewater flows distribution and internal nitrate recycling between the individual stages of the recommended two-stage flow diagram of the MLE process has been performed in order to minimize the total residual nitrogen content in the effluent.

• The high efficiency and reliability of the two-stage flow diagram of the MLE process proposed by the authors are proved for different variants of flow diagrams by comparing the results of dynamic modelling of biological wastewater treatment processes under the considered conditions.

References

National report on the quality of drinking water and the state of drinking water supply in Ukraine in 2019. (2020). Kyiv: Ministry of Development of Communities and Territories of Ukraine. Retrieved from https://www.minregion.gov.ua/wp-content/uploads/2020/12/naczionalna-dopovid-za-2019-rik.pdf

National report on the state of the environment in Ukraine in 2018. (2019). Kyiv: Ministry of Environmental Protection and Natural Resources of Ukraine. Retrieved from https://mepr.gov.ua/timeline/Nacionalni-dopovidi-pro-stan-navkolishnogo-prirodnogo-seredovishcha-v-Ukraini.html

Henze, M., van Loosdrecht, M. C., Ekama, G. A., & Brdjanovic, D. (2008). *Biological Wastewater Treatment. Principles, Modelling and Design*. London, UK: IWA Publishing. doi: https://doi.org/10.2166/9781780401867

Grady, C. P., Daigger, Jr., Love, N. G., & Filipe, C. D. (2011). *Biological Wastewater Treatment*. London, UK: IWA Publishing. doi: https://doi.org/10.1201/b13775

van Haandel, A. C., & van der Lubbe, J. G. (2012). *Handbook of Biological Wastewater Treatment. Design and Optimisation of Activated Sludge Systems*. London: IWA Publishing. doi: https://doi.org/10.2166/9781780400808

Nutrient Removal. (2010). WEF Manual of Practice No. 34. Alexandria, VA, USA: WEF Press. Retrieved from https://www.accessengineeringlibrary.com/content/book/9780071737098

Mešenhysser, U. (2012). *Retechnology of wastewater treatment plants*. Moscow: Vokruh cveta.

Protsenko, S., Kizyeyev, M., & Novytska, O. (2020). *Selection of initial data for calculation and design of reconstruction of sewage treatment plants*. Sustainable Development: Environment Protection. Energy Saving. Sustainable Environmental Management. Collective monograph. Lviv. doi: https://doi.org/10.23939/book.ecocongress.2020

Standard ATV-DVWK-A 131E. (2000, May). *Dimensioning of Single-Stage Activated Sludge Plants*. ATV-DVWK Water, Wastewater and Waste. Retrieved from https://dlscrib.com/download/atv-dvwk-a-131e_58ff62c7dc0d60307d959e98_pdf

GPS-X User's Guide: GPS-X Version 8.0. (2019). Hydromantis Environmental Software Solutions. Retrieved from https://www.hydromantis.com/