JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2022, 23(11), 139–146
https://doi.org/10.12911/22998993/153602
ISSN 2299–8993, License CC-BY 4.0

Received: 2022.08.09
Accepted: 2022.09.15
Published: 2022.10.01

Establishing Environmental Standardization of Wastewater Composition Based on Environmental Risk Assessment

Oleg Proskurnin[1], Myroslav Malovanyy[2*], Karina Belokon[3], Olha Rybalova[4], Taras Ivashchenko[5], Nataliia Tsapko[1], Olena Stepova[6]

[1] Ukrainian Research Institute of Environmental Problems, Bakulina str., 6, Kharkiv, 61165, Ukraine

[2] Viacheslav Chornovil Institute of Sustainable Development, Lviv Polytechnic National University, S. Bandera Str. 12, Lviv, 79013, Ukraine

[3] Zaporizhzhia National University, Zhukovsky str., 66, Zaporizhzhia, 69600, Ukraine

[4] National University of Civil Defence of Ukraine, Chernyshevska str., 94, Kharkiv, 61023, Ukraine

[5] State Ecological Academy of Postgraduate Education and Management, Metropolitan Vasyl Lypkivsky str., 35, bldg. 2, Kyiv, Ukraine, 03035

[6] Yuri Kondratyuk Poltava Polytechnic National University, ave. Pershotravnevuj, 24, Poltava, Ukraine, 36000

* Corresponding author's e-mail: mmal@lp.edu.ua

ABSTRACT

The article considers the problem of rationing wastewater discharge in terms of environmental risk management, caused by the pollution of waterbodies. The cases of using a simple indicator of water quality in the form of concentration of a substance, as well as a complex indicator of water quality were considered. The relevance of using a complex indicator is caused by the similar effect of various substances on the ecosystem and man. For both cases, the algorithms for determining the permissible composition of wastewater, ensuring compliance with the established standards of natural water quality in the control points of the water body with a given probability, were developed. In the case of using complex indicators in order to unambiguously solve the problem of rationing wastewater composition, permissible concentrations of substances were finally determined by solving the optimization problem. The optimization criterion is the minimum cost of water treatment. The method of ecological standardization of wastewater composition suggested in the article is applicable for the case of normal probability distribution of a substance in wastewater according to data of field measurements.

Keywords: wastewater, pollutant, waterbody, environmental risk, limited concentrations, comprehensive quality indicator, optimization, water quality standards.

INTRODUCTION

One of the most extensive environmental problems of economically developed countries is the pollution of waterbodies by wastewater (Odnorih et al. 2020, Belokon et al. 2018), diverted from industrial, agricultural and municipal enterprises (EU Water Framework Directive 2000, Zhelnovach et al. 2022, Popovych et al. 2020). In a series of post-Soviet countries, in particular, in Ukraine, in order to prevent the level of waterbodies pollution above the safe level, regulations for discharges of pollutants are developed and approved. These regulations represent the mass of a substance permitted to be discharged into waterbodies per unit of time (Water Code of Ukraine 2004, Methodic Recommendations 2021).

Since the volume of wastewater is determined by the technological parameters of the enterprises-water users (Bobylev et al. 2014, Matukhno et al. 2019), the calculation of discharge regulations is reduced to the determination of the permissible composition of wastewater. The disadvantage of the existing approach to the solution of this problem is the failure to take into account the probabilistic nature of the content of substances in wastewater after purification at treatment plants. In the methodical literature, the instability of wastewater composition is specified only by the requirement to consider the arithmetic average values as the actual concentrations of substances in wastewater (Methodic Recommendations 2021). However, in general, the calculation has a deterministic character: permissible concentrations of substances in wastewater are calculated, which do not lead to the violation of water quality standards in the control points (CP) of the waterbody. Thus, it is relevant to improve the methodology for calculating the permissible composition of wastewater discharged into waterbody by taking into account the probabilistic nature of waste water composition and, consequently, the probabilistic nature of wastewater pollution in the zone of influence of the discharge. The solution of this problem will make it possible to increase the level of ecological safety of wastewater discharges into waterbody. The most perspective direction in this plan is considered to be the use of the mechanism of ecological risk assessment (Proskurnin 2013, Lisichenko et al. 2011). According to the classical definition, risk is a measure of uncertainty which can be estimated by the probability method (Lisichenko et al. 2011). At the same time, in practice, various criteria for the quantitative assessment of this uncertainty are used. In most cases, environmental risk is understood as either the probability of occurrence of negative changes in the environment, or the mathematical expectation of the amount of the damage as a result of such changes (Rybalova et al. 2018, Rybalova et al. 2022). Since in the tasks of rationing of water disposal, only the possible fact of exceeding the maximum permissible concentration (MPC) in waterbody water is considered without analyzing its consequences for the ecosystem and man, it is advisable to use the first definition of environmental risk – to consider the risk as the probability of violation of the established standards of waterbody quality due to the discharge of wastewater.

The purpose of this article was to develop a mechanism for calculating the permissible concentrations of substances in wastewater using an assessment of the environmental risk caused by wastewater discharge into the waterbody. The paper considers the simplest case: one discharge of waste water into a waterway in the absence of self-purification of water.

STATEMENT OF THE PROBLEM

The problem of ecological standardization of wastewater composition considering its probabilistic nature can be formally stated as follows. Let C_w – the desired permissible concentration of a pollutant in the wastewater after treatment, which eventually must be specified in the documents on special water use. In order to simplify mathematical calculations in this article consider not the concentration itself, but its multiple of exceeding MPC:

$$X = \frac{C_w}{C_{iim}} \tag{1}$$

where: C_{lim} – MPC of a substance.

Let x to be a random variable representing the multiple of exceeding MPC of a substance in wastewater at an random point in time:

$$x = X + \varepsilon \tag{2}$$

where: ε – is a random value with zero mathematical expectation.

Then the required value X in the simplest case is defined as the maximum possible value ensuring, in consideration of (2), observance of the following condition (Proskurnin 2013):

$$\mathrm{P}\big(y(x) \le 1\big) \ge 1 - \alpha \tag{3}$$

where: P – designation of probability, $y(x)$ – multiplicity of MPC exceedance in wastewater watercourse CP below wastewater discharge (according to the Ukrainian legislation, 500 m below the outlet (Methodic Recommendations 2021)), α – is the accepted maximum permissible risk.

In case of using complex indicators of water quality of waterbody condition (3) is replaced by the following:

$$\mathrm{P}(Y(\{x_j\}) \le Y_{cr}) \ge 1 - \alpha \tag{4}$$

where: Y – a complex index of water quality, defined by a set of values of concentrations of substances $\{x_j\}$; Y_{cr} – critical value of complex index of quality.

In the second case, the solution of the problem will be ambiguous. Therefore, the necessary conditions for determining the allowable concentrations must be supplemented by the requirement of the minimum cost of wastewater treatment, ensuring their acceptable composition.

The problem solution procedure when using a simple indicator of water quality (in the form of concentration of a pollutant)

Random character of x-value at a given mode of operation of wastewater treatment plants is a consequence of a large number of random natural and technical factors. This circumstance, according to the central limiting theorem (Jose et al. 2018), allows assuming that the value of x is distributed with high probability under the normal law. The first parameter of distribution – mathematical expectation – is obvious: $X = \langle x \rangle$ (Hereinafter, angle brackets indicate mathematical expectation of a random value). The way to estimate the second parameter of the distribution – the standard deviation σ_x – depends on the availability of information about the operation of wastewater treatment plant in different modes. If such information is available, the parameter σ_x is taken on the basis of retrospective data processing. In the absence of retrospective information, an assumption about the constancy of the coefficient of variation of x-value can be made:

$$v = \frac{\sigma_x}{\langle x \rangle} = const \tag{5}$$

In this case, the coefficient of variation can be determined by measuring the output concentrations in any mode of the wastewater treatment plant, and then for an arbitrary value of X, the standard deviation will be:

$$\sigma_x = X \cdot v \tag{6}$$

Thus, the density of the frequency distribution of exceeding of MPC in wastewater is the following:

$$f_x = \frac{1}{\sqrt{2\pi} \cdot \sigma_x} \cdot exp\left(-\frac{(x - X)^2}{2\sigma_x{}^2} \right) = \frac{1}{\sqrt{2\pi} \cdot X \cdot v} \cdot exp\left(-\frac{(x - X)^2}{2X^2 v^2} \right) \tag{7}$$

Concentration of a substance in CP (in the form of a multiple of exceeding of MPC) is calculated from the balance equation in the absence of self-purification:

$$y(x) = \frac{C_{fon} \cdot Q_{fon} + q \cdot x}{Q \cdot C_{lim}} = \frac{C_{fon} \cdot Q_{fon}}{Q \cdot C_{lim}} + \frac{q}{Q \cdot C_{lim}} \cdot x = A + B \cdot x \tag{8}$$

where: C_{fon} – substance concentration in background alignment (BA) above wastewater discharge; Q_{fon} – flow rate of watercourse in BA; $Q = Q_{fon+q}$ – water flow rate in CP; C_{lim} – MPC of the substance; $A = C_{fon}Q_{fon}/(QC_{lim})$, $B = q/(QC_{lim})$.

Distribution density of y-value is determined based on the rule (Jose et al. 2018), according to which if a random variable η depends linearly on a random variable μ:

$$\eta = A + B\mu \tag{9}$$

then the distribution densities of both quantities are related by the following relationship:

$$f_\eta = \frac{1}{B} \cdot f_\mu \left(\frac{\eta - A}{B} \right) \tag{10}$$

Thus, the density of distribution of substance in CP is as follows:

$$f_y = \frac{1}{B} \cdot f_x \left(\frac{y - A}{B} \right) = \frac{1}{B\sqrt{2\pi} \cdot X \cdot v} \cdot exp\left(-\frac{\left(\frac{y - A}{B} - X \right)^2}{2X^2 v^2} \right) = \frac{1}{B\sqrt{2\pi} \cdot X \cdot v} \cdot exp\left(-\frac{(y - A - B \cdot X)^2}{2B^2 X^2 v^2} \right). \tag{11}$$

In the traditional form, the distribution density of the quantity y is as follows:

$$f_y = \frac{1}{\sqrt{2\pi} \cdot \sigma_y} \cdot exp\left(-\frac{(y - \langle y \rangle)^2}{2 \cdot \sigma_y^2} \right) \tag{12}$$

where: $\sigma_y = B \cdot X \cdot v$, $\langle y \rangle = A + B \cdot X$.

As according to the laws of probability theory (Jose et al. 2018):

$$P(y \le 1) = \int_{-\infty}^{1} f_y \, dy \tag{13}$$

then, taking into account (1), the required concentration C_w is found numerically from equation:

$$\frac{C_{lim}}{B\sqrt{2\pi} \cdot C_W \cdot v} \cdot \int_{-\infty}^{1} exp\left(-\frac{\left(y - A - \frac{B \cdot C_W}{C_{lim}} \right)^2}{2B^2 C_W{}^2 v^2} \right) dy = 1 - \alpha \tag{14}$$

This equation can also be written through the Laplace function:

$$\frac{1}{2}+\Phi\left(\frac{1-A-\frac{B\cdot C_W}{C_{lim}}}{B\cdot\frac{C_W}{C_{lim}}\cdot v}\right)=\frac{1}{2}+\Phi\left(\frac{1-\langle y\rangle}{\sigma_y}\right)=1-\alpha \tag{15}$$

where: F – is a Laplace function:

$$\Phi(t)=\frac{1}{\sqrt{2\pi}}\cdot\int_0^t exp\left(-\frac{t^2}{2}\right)dt \tag{16}$$

Problem solution procedure when using a complex indicator of water quality

In ecological wastewater quality standardization, the sum of MPC exceedance multiplicity, which should not exceed 1, is considered as a complex indicator of water quality (Rybalova 2011, Vasenko et al. 2015). At the same time, substances are divided into groups on the basis of limiting signs of harmfulness (LSH): toxicological, sanitary-toxicological, fishery and others (Florica Brasoveanu et al. 2012, Dieter Prinz et al. 2015, Rybalova et al. 2017). Thus, the complex indicator is also a dimensionless value:

$$Y(\{x_j\})=\sum_{j=1}^{N_L} y_j\le 1 \tag{17}$$

where: N_L – the amount of substances contained in wastewater under consideration and having the L-th LSH.

In order to simplify the presentation, only one LPV is considered further in the article, and the index L is omitted.

According to the laws of probability theory (Jose et al. 2018), the sum of random variables that have a normal distribution is also subordinated to the normal distribution law. In this case, mathematical expectations and dispersions of random variables are added. Therefore, the distribution density of the complex index will be as follows:

$$f_Y(\{x_j\})=\frac{1}{\sqrt{2\pi}\cdot\sigma_Y}\cdot exp\left(-\frac{(Y-\langle Y\rangle)^2}{2\cdot\sigma_Y^2}\right) \tag{18}$$

where: $\sigma_Y=\sqrt{\sum_j^N\sigma_j^2}$, $\langle Y\rangle=\sum_j^N\langle y_j\rangle$ (19)

The final composition of wastewater is proposed to be determined by solving the optimization problem (Bajčetić Marko et al. 2016). The set of optimized variables will be the required permissible concentrations $\{C_{w,j}\}$. The following expression can be used as a target function:

$$Z=\sum_{j=1}^N d_j\cdot(F_j-C_{W,j})\rightarrow min \tag{20}$$

where: F_j – the actual concentration of pollutant j according to the data of field measurements, mg/dm^3; d_j – the cost of purification of a unit volume of wastewater from substance j, \$/(m^3·mg/dm^3).

Limitations of the optimizing problem are dictated by the requirement not to exceed the value of acceptable environmental risk, the principle of non-deterioration of the existing water quality of waterbody, as well as the technical capabilities of the water treatment facilities:

$$\begin{cases}\frac{1}{2}+\Phi\left(\frac{1-\left\langle Y\left(C_{W,j}/C_{lim,j}\right)\right\rangle}{\sigma_Y}\right)\le 1-\alpha,\ j=1\div N;\\ C_{W,j}\ge P_{W,j};\\ C_{W,j}\le F_j,\end{cases} \tag{21}$$

where: $P_{W,j}$ is the minimum concentration determined by the technological capabilities of the wastewater treatment plant.

Calculation example of permissible concentrations of substances

The demonstration example presented in the article is based on the developed and approved standards for wastewater discharge from the drinking water treatment system of Kharkov (Ukraine). The discharge is carried out into the Siverskyi Donets River (the right tributary of the Don River; according to the classification of the Water Code of Ukraine [Report on the research 2016], this waterbody refers to the large rivers) through the small Tetleha River. In the example, the substances with toxicological sign of harmfulness are considered: nitrites, ammonium nitrogen, phosphates, iron.

The low-water flow of the Tetleha River is practically equal to zero. This allows the calculation of permissible concentrations to consider the discharge of wastewater directly into the Siverskyi Donets River, where BA and CP are installed (Report on the research 2016), (Fig. 1).

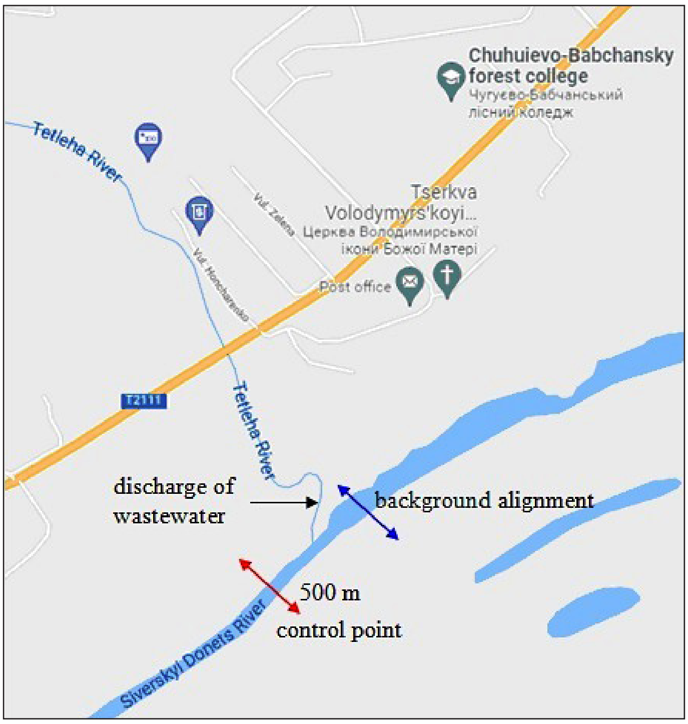

Figure 1. Scheme of discharge of wastewater

Normative discharge of wastewater and low-water discharge of river water in the BA of the river Siverskyi Donets are equal to 0.12 m^3/s and 3.74 m^3/s, respectively. Table 1 shows the data on the background pollution of the river. Seversky Donets is higher than the discharge of wastewater, as well as the values of the MPC of substances. Table 1 shows the data on the background pollution of the Siverskyi Donets River above the wastewater outlet, as well as the values of MPC substances.

Table 2 shows the data of 2019 on the content of the mentioned substances in wastewater (as a multiple of exceeding MPC) after their treatment at water treatment facilities, as well as technical and economic parameters of the treatment (Zaitseva et al. 2021).

On the basis of the data in Table 2, the optimizing problem was solved using the "Solution Search" function in the Excel software system. Moreover, for comparison, on the basis of the same initial data, the problem of finding permissible concentrations without taking into account environmental risk (i.e., without taking into account the probabilistic nature of the composition of wastewater) was solved. In this case, the first condition in the restriction system (4) is replaced by the condition (Proskurnin 2010):

$$Y(\{C_{W,j}\}) = 1 \tag{22}$$

The result of the solution is given in Table 3. As we can see, taking into account the environmental risk leads to lower permissible concentrations of substances in the wastewater. Figure 2 shows graphs of the density distribution of the complex index Y at the found permissible average concentrations of substances in the wastewater.

As it can be seen from the graph, the calculation of the permissible composition of the wastewater, including environmental risk, ensures compliance with the required quality of river water according to the composite indicator, i.e. condition $Y \leq 1$, with a probability of 95%. When calculating without taking into account the allowable risk, the probability of meeting this condition is only 50%.

Table 1. Background concentrations and MPC of substances in the water of the Siverskyi Donets River

Indicator	Nitrites	Ammonium nitrogen	Phosphates	Iron
Concentration, mg/dm^3	0.033	0.2	1.05	0.078
MPC, mg/dm^3	3.3	2	3.5	0.3
The frequency of exceeding the MPC	0.01	0.1	0.3	0.26

Table 2. Composition of wastewater (as a multiple of exceeding MPC) over 2019, discharged into the Siverskyi Donets River, as well as technical and economic parameters of treatment

Month of the year	Nitrites	Ammonium nitrogen	Phosphates	Iron
1	3.833	1.143	3.591	2.677
2	3.833	2.851	4.224	2.736
3	3.982	3.769	3.424	5.324
4	3.833	2.013	1.714	3.672
5	4.017	2.301	1.948	3.646
6	3.833	1.935	1.730	2.381
7	3.833	2.322	2.384	3.237
8	9.108	2.511	2.954	3.866
9	3.833	2.408	4.039	4.703
10	3.833	2.357	3.175	2.529
11	3.833	2.308	2.350	2.552
12	3.833	4.081	2.067	3.477
Average, <*F*>.	4.302	2.502	2.802	3.402
Standard deviation, □$_x$	1.515	0.784	0.889	0.916
Coefficient of variation, □	0.352	0.313	0.317	0.269
Minimum possible concentration after treatment, *P*, mg/dm^3	0.03	0.5	0.05	0.01
Notional cost of treatment, *d*, \$/ (m^3·mg/dm^3)	1	2.5	1.6	2.8

Table 3. Permissible concentrations of substances in the wastewater

Indicator	Considering environmental risk				Excluding environmental risk			
	Nitrites	Ammonium nitrogen	Phosphates	Iron	Nitrites	Ammonium nitrogen	Phosphates	Iron
Permissible concentration, mg/dm^3	0.030	3.498	4.362	0.972	8.511	5.004	9.807	1.021
Permissible frequency of exceeding MPC	0.009	1.749	1.246	3.240	2.579	2.502	2.802	3.402

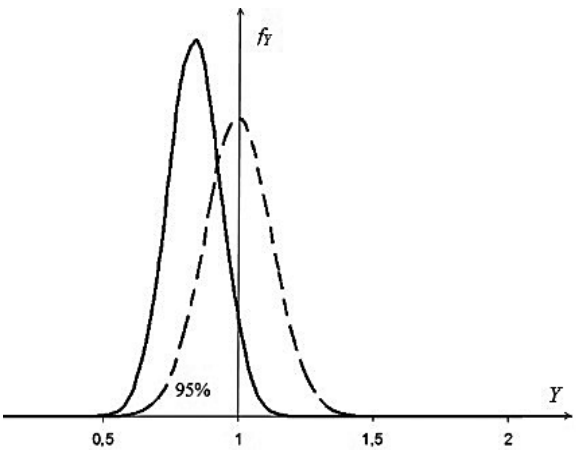

Figure 2. Probability distribution of the complex indicator *Y* (the continuous line – including environmental risk, the dotted line – excluding environmental risk)

CONCLUSIONS

The mechanism proposed in the article for calculating the permissible concentrations of pollutants in wastewater ensures that the permissible value of the ecological risk caused by wastewater infiltrating into the waterbody, with a certain probability, which increases the level of environmental safety of the wastewater discharge. Thus it is necessary to notice that at consideration of probabilistic character of concentration of the substance in wastewater at discharge from water treatment facilities, the following legislative problem arises (Yurchenko et al. 2013).

The permissible concentration of a substance indicated in the documents for special water use has two functions:

1) it determines the amount of tax for discharge of wastewater;
2) it is included when controlling compliance with the approved norms of wastewater discharge.

It seems reasonable to leave only the first function according to the concentration calculated by the proposed methods, and to make the conclusion about compliance with the established water disposal regime taking into account possible fluctuations in concentration.

The direction for further research in this area is to consider the stochastic dependence of concentrations of substances at the discharge from the water treatment system, as well as to solve a similar problem for the river basin area.

REFERENCES

1. Bajčetić M., Brnjas Z., Drašković B. 2016. Economic efficiency of water protection within environmentally friendly and integrated water resources management. International Review, (1–2), 82–90.
2. Belokon K., Belokon Y. 2018. The study of catalysts based on intermetallic NiAl alloys. Ceramic Transactions, 262, 219–225.
3. Bobylev V.P., Matukhno Y.V., Turishchev V.V., Belokon K.V. 2014. Methodical approach for selection of design parameters of electrodialisys diaphragmless apparatus for regeneration of electrolytecontaining solution. Metallurgical and Mining Industry, 5(2), 77–80.
4. Dieter P., Any J., Widodo B. 2015. Future water management problems in asian megacities. Jurnal Sains & Teknologi Lingkungan, 1(1), 1–16. DOI: 10.20885/jstl.vol1.iss1.art1
5. EU Water Framework Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. 2000. Official Journal of the European Communities, 43 (22.12), 72.
6. Brasoveanu F., Petru A., Brezeanu L. 2012. European policy concerning the protection of the quality of the environmental factor - water. Challenges of the Knowledge Society, 2, 1058–1063.
7. Jose S., Thomas S. 2018. Interval estimation of the overlap coefficient of two normal distributions / Discussiones Mathematicae Probability and Statistics, 38(1–2), 5–15.
8. Lisichenko G.V., Khmel G.A., Barbashev S.V. 2011. Methodology of Environmental Risk Assessment. Odessa: Astroprint, 368.
9. Matukhno E., Belokon K., Shatokha V., Baranova T. 2019. Ecological aspects of sustainable development of metallurgical complex in Ukraine. Procedia Environmental Science, Engineering and Management, 6(4), 671–679.
10. Methodic Recommendations on Development of Norms of Maximum Permissible Discharge of Pollutants into Waterbodies with Circulation Waters (Approved by the Decree № 173 of Ministry of Environment of Ukraine 05.03.2021) // https://mepr.gov.ua/documents/3331.html.
11. Odnorih Z., Manko R., Malovanyy M., Soloviy K. 2020. Results of surface water quality monitoring of the western bug river Basin in Lviv Region. Journal of Ecological Engineering, 21(3), 18–26. https://doi.org/10.12911/22998993/118303
12. Popovych V., Telak J., Telak O., Malovanyy M., Yakovchuk R., Popovych N. 2020. Migration of Hazardous Components of Municipal Landfill Leachates into the Environment. Journal of Ecological Engineering, 21(1), 52–62. DOI: 10.12911/22998993/113246
13. Proskurnin O.A. 2010. Optimization approach to limiting the content of substances in wastewater taking into account the limiting signs of harmfulness. Problems of Natural Environment Protection and Ecological Safety, 32, 162–173.
14. Proskurnin O.A. 2013. Normalization of wastewater composition by assessing the environmental risk. Water and Ecology: Problems and Solutions, 4, 65–73.
15. Report on the research «Development of the project of maximum permissible discharge (MPD) of pollutants with return water of the communal enterprise «Kharkovvodokanal» in the Krasnopavlovskoye reservoir and the Tetlegu River». 2016. UkrNIIEP, Kharkiv, 63.
16. Rybalova O.V. 2011. An integrated approach to determining the ecological state of small rivers. Problems of environmental protection of the natural environment and ecological safety, 33, 88–98.
17. Rybalova O., Artemiev S. 2017. Development of a procedure for assessing the environmental risk of the surface water status deterioration. EasternEuropean Journal of Enterprise Technologies, 5(10–89), 67–76. DOI: 10.15587/1729-4061.2017.112211
18. Rybalova O., Artemiev S., Sarapina M., Tsymbal B., Bakhareva A., Shestopalov O., Filenko O. 2018. Development of methods for estimating the environmental risk of degradation of the surface water state. Eastern-European Journal of Enterprise Technologies, 2, 10(92), 4–17. DOI: 10.15587/1729-4061.2018.127829
19. Rybalova O., Malovanyy M., Bondarenko O., Proskurnin O., Belokon K., Korobkova H. 2022. Method of assessing the potential risk to the health of the population during recreational water withdrawal. Journal of Ecological Engineering, 23(5), 81–91.

20. Vasenko O.G., Rybalova O.V., Artem'ev S.R. 2015. Integral and complex assessments of the state of the environment. Kharkiv: NUGZU, 419.
21. Water Code of Ukraine. 2004. K., Publishing House " In Yure", 138.
22. Zhelnovach G., Belokon K., Barabash O., Dychko A. 2022. Airport runoff management: Engineering solutions. Ecological Engineering and Environmental Technology, 23(1), 230–240.
23. Yurchenko A.I., Proskurnin O.A. 2013. Problems of calculating the maximum permissible discharge of complex substances into a water body with wastewater. Environmental safety: Problems and solutions: Proc. of the 9th Interdepartmental Scientific and Practical Conference, Alushta 2013. Kharkov, 296–298.
24. Zaitseva V.G., Nesterenko O.V., Chernishenko G.O., Samokhvalova A.I. 2021. The influence of enterprises of residential and communal services (RCS) on the environmental condition and the health of the people. Scientific Journal of Building, 1, 289–294.