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Standardizing the Wastewater Composition in Order to Minimize the Eutrophication Risk for the Reservoir

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ABSTRACT

The article strives to determine the allowable content of nutrients in the wastewater that is being discharged into a reservoir, with the end goal of minimizing the risk of eutrophication. It was noted that the methodology currently used in Ukraine and most European countries to control pollutant discharge in wastewater is designed to simply not exceed the permissible pollution level in natural water based on sanitary indicators, which does not guarantee the absence of the eutrophication risk to the water bodies. The article describes a developed method for determining the allowable composition of wastewater based on biogenic indicators. The proposed method takes into account the consecutive transformation of nutrients, the probabilistic nature of the factors that determine the quality of water in water bodies, as well as the cost of purifying wastewater from various pollutants. The problem was considered for the case of wastewater discharge into a reservoir through a watercourse. This research is a practical scientific basis for further improving the methodology for standardization of the wastewater composition in order to protect water bodies from eutrophication.

Keywords: environmental safety, reservoir, watercourse, eutrophication, wastewater, pollutants, nutrients, limited concentrations.

INTRODUCTION

The problem of anthropogenic pollution of water bodies is relevant for all economically developed countries. This problem is especially significant for the water bodies that are used as sources of drinking water. One of the possible consequences of water pollution is eutrophication: saturation with biogenic elements that leads to an increase in biological productivity (Prepas et al., 2003, Malovanyy et al., 2021). Eutrophication causes an increase in the growth of blue-green algae, which makes natural water unsuitable for drinking, as well as other recreational needs (Melekhin et al., 2019, Malovanyy et al., 2016a).

One of the main anthropogenic factors of eutrophication is the entry of biogenic elements (nutrients), primarily phosphorus and nitrogen-containing substances, into water bodies with the wastewater from enterprises. The main threat of eutrophication comes from municipal wastewater, the wastewater from livestock complexes, and the wastewater from some chemical industries. Quite often, biological (Malovanyy et al., 2016b, Malovanyy et al., 2021) or adsorption (Ptashnyk et al., 2020, Malovanyy et al., 2020) methods are used for the final treatment of such waters before discharge into water bodies. However, in the case of biological treatment, there is a problem with the disposal of the resulting activated sludge (Tymchuk et al., 2020, Tymchuk et al., 2021 According to both European and Ukrainian legislation, water disposal standards are developed and approved for water-user-enterprises. The legislation defines the permissible discharge of pollutants entering the reservoir with wastewater. The purpose of establishing these standards is to preserve and restore water resources by preventing pollution of natural water above the established permissible level. However, the conclusion about the permissible pollution of water is made based on the chemical composition of water according to sanitary indicators. The existing methodology for establishing the allowable discharge of substances does not provide a water eutrophication risk analysis. In addition, the existing methodology for standardizing wastewater discharge does not take into account the consecutive transformation of nutrients in natural water or the probabilistic nature of pollution factors (Boulard et al., 2017). Interconversion transformation can occur during the biochemical decomposition of organic compounds that are directly or indirectly fed with nitrogen-containing substances. However, this is a very specific situation, therefore, in this work only consecutive transformation is considered, as the most typical case. The task becomes more complicated if the discharge of wastewater into the reservoir is carried out through a watercourse, since in this case the water quality in the reservoir is also affected by the background pollution of the watercourse, which is also of a random nature. Because of this, it is relevant to develop the proposals for improving the system of standardizing wastewater discharge that will be aimed at minimizing the risk of water eutrophication. The purpose of this article was to present the developed method for calculating the allowable concentration of nutrients in wastewater, ensuring the minimal eutrophication risk for the water bodies. The authors considered the case of wastewater discharge from one outlet into a reservoir through a natural watercourse.

REVIEW OF EXISTING STUDIES

In the existing studies on the subject, the problem of eutrophication is covered mainly in these four aspects:

1. Study of the current state of water bodies and analysis of the problem with an end goal of preserving water resources. One can single out the work (Mustafa Al Kuisi et al., 2023), in which, using the studies on the state of ponds in the Jordan River Valley, it was concluded that the generally accepted measures to counteract eutrophication were not enough and that there is a need for a nationwide program for water preservation. In another article (Kupczyk et al., 2019), the entire spectrum of factors leading to eutrophication was considered, using the example of the Baltic Sea.
2. The study of biochemical processes occurring in the aquatic ecosystem that lead to the eutrophication of water bodies. In this work (Mohamed M. Khalil et al., 2022), the nutrient pollution and eutrophication problems were integrated into a nature-based solution that incorporates microalgae-based nutrient removal from wastewater and collecting the residues in an anaerobic digestion plant to produce biogas that is directly exported to an existing gas-fired power plant, which closes the bioresource loop (Studies were conducted using El Burullus Lake in Egypt as an example.) The article (Kostenko et al., 2023) studied the effect that changes in the chemical composition of artificial aquatic biotopes have on the vital activity of cyanobacteria. The aim of the work (Agatha Sih Piranti et al., 2021) was to assess the concentration of nutrients (macro and micronutrients) and chlorophyll as well as examine the connection between nutrient concentration and algal biomass to identify the determinants of algal development in tropical lakes.
3. Developing proposals for improving the state of water bodies. An example is an article (Minggat et al., 2021) that describes a method for removing nutrients from a water body using the marine diatom Chaetoceros muelleri. The article (Tavrel et al., 2022) aimed to ensure the efficient operation of aeration equipment in shallow water bodies with an average depth of only a few meters.
4. Modeling the state of the water body. In (Kotsiuba et al., 2022), statistical modeling for the development processes of blue-green and green algae as well as and diatoms in the waters of the river Uzh Korosten district was conducted, it included monitoring the average values of their content for less than three years.

At the same time, the search for methods to calculate a permissible composition of wastewater discharge into a water body with the minimal risk of eutrophication has not yielded any results as of yet. It only solidifies the relevance of the research presented in the article.

RESEARCH METHODOLOGY

Problem statement

The problem of determining the admissible composition of wastewater according to biogenic indicators (taking into account its probabilistic nature) can be formulated as follows. Let $\{X_j\}$ be the set of the desired allowable concentrations of nutrients in the wastewater after treatment, which will have to be indicated in the documents for special water use; $\{x_j\}$ is the set of concentrations of the substance in the wastewater, including the chance factor:

$$x_j = X_j + \varepsilon_j \,, \quad (1)$$

where: j – substance index; ε – random variable with zero mathematical expectation.

Due to this, the environmental risk assessment mechanism can be used to solve the given task (Rybalova et al., 2022). Accounting for the transformation of substances and probabilistic factors, the desired set of concentrations $\{X_j\}$ should ensure that the following condition is met at the control point (CP) of the reservoir:

$$\mathrm{P}\left(y_N\left(\{x_j\}\right) \le y_{N,cr} \wedge y_P\left(\{x_j\}\right) \le y_{P,cr}\right) \ge 1 - \alpha \,, \quad (2)$$

where: P – probability designation; Λ – designation of logical multiplication (conjunction); $y_N(\{x_j\})$ and $y_P(\{x_j\})$ – calculated concentrations of total nitrogen and phosphorus at the CP; α – accepted risk limit; $y_{N,cr}$, $y_{N,cr}$ – critical concentration values.

It is assumed that the values $y_{N,cr}$ and $y_{N,cr}$ are initially specified. Their determination, taking into account uncontrolled factors influencing eutrophication (adverse weather conditions, solar radiation, morphometric characteristics of a water body, etc.), is a particular task that is beyond the scope of this article.

The procedure for solving the problem

The random nature of the value x for a given treatment facilities mode of operation is a consequence of a large number of random natural and technical factors. This circumstance, according to the central limit theorem (Elassassi Zahra et al., 2022), allows assuming that the value of x with a high degree of probability is distributed according to the normal law.

The first distribution parameter, the mathematical expectation, is obvious: $X = \langle x \rangle$. (Hereinafter, the angle brackets denote the mathematical expectation of a random variable.) The method for estimating the standard deviation σ_x depends on the availability of information about the operation of the treatment facility in various modes. In the absence of retrospective information, an assumption can be made about the constancy of the coefficient of variation v of x:

$$v = \frac{\sigma_x}{\langle x \rangle} = const \,. \quad (3)$$

In this case, according to the output concentrations data in any mode of operation of the treatment facilities, it is possible to determine the coefficient of variation. Then, for an arbitrary value of X, the standard deviation will be

$$\sigma_x = X \cdot v \,. \quad (4)$$

Thus, the probable pollutant density in wastewater is as follows:

$$f_x = \frac{1}{\sqrt{2\pi} \cdot \sigma_x} \cdot \exp\left(-\frac{(x-X)^2}{2\sigma_x^2}\right) = \frac{1}{\sqrt{2\pi} \cdot X \cdot v} \cdot \exp\left(-\frac{(x-X)^2}{2X^2 v^2}\right) \quad (5)$$

If the discharge of wastewater into a reservoir through a watercourse is considered, the concentration of each considered nutrient at the CP is determined by the formula:

$$y_j = \frac{(c_j - g_j)}{n} + g_j = \frac{c_j}{n} + \frac{n-1}{n} \cdot g_j \quad (6)$$

where: c – concentration of a substance in a mixture of wastewater and stream water; g – background pollution of the reservoir.

The initial concentration of each substance in the mixture is easily calculated using the balance Equation

$$c_j^0 = \frac{q \cdot x_j + Q_f \cdot w_j}{Q} \,, \quad (7)$$

where: q, Q_f, and Q – wastewater, watercourse water, and their amount; v – concentration of a substance in a watercourse prior to wastewater discharge.

Figure 1 shows a scheme of the discharge of wastewater into a reservoir through a water stream and designations of the concentrations of

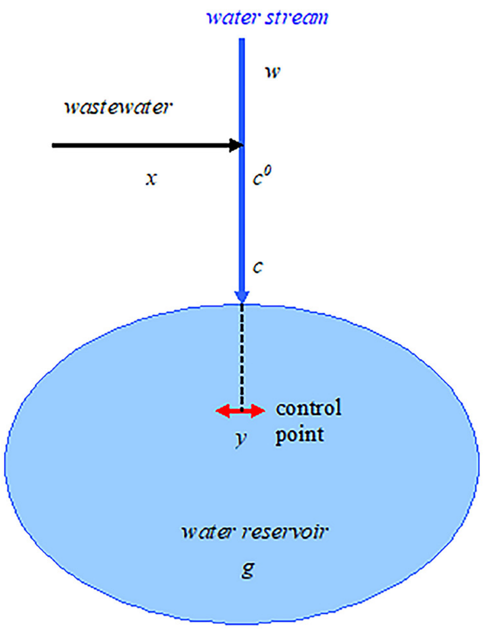

Figure 1. Scheme of the discharge of wastewater into a reservoir through a water stream and designations of the concentrations of substances at various points

substances at various points.The values w, g, c^0 are considered random with the corresponding expectation values being W, G, C^0. The dynamic model is described by the matrix Equation

$$\vec{C}(t) = A(t)\cdot\vec{C}^0 \tag{8}$$

where: $\vec{C}^0, \vec{C}(t)$ – vectors of substance concentrations at the initial moment and at a transformation coefficients.

The non-zero elements of the transformation matrix are as follows:

$$\begin{cases} a_{jj} = \exp(k_j \cdot t),\ j = 1 \div 4; \\ a_{31} = g(1,1,2)\cdot f(3,1,3); a_{31} = g(1,1,2)\cdot f(3,1,3); a_{32} = f(2,2,3); \\ a_{41} = r(1,1,2)\cdot\{r(2,1,3)\cdot[w(3,1,3)-w(3,3,4)] - r(2,2,3)\cdot[w(3,2,4)-w(3,3,4)]\}; \\ a_{42} = r(2,2,3)\cdot[w(3,2,4)-w(3,3,4)]; a_{43} = w(3,3,4) \end{cases} \tag{9}$$

Phosphorus is not transformed into other biogenic pollutants, so only a self-purification process is considered for it. However, to simplify mathematical calculations, it is advisable to include phosphorus in the matrix model with index 5. The fifth row of the transformation matrix will be zero, except for the diagonal element that equals to $a_5 = exp(k_5 \cdot t)$.

In this case, the concentrations of nutrients at CP will equal to:

$$y_j = \frac{\sum_{u=1}^{j} a_{ju} c_u^0}{n} + g_j \cdot \frac{n-1}{n},\ j = 1 \div 5. \tag{10}$$

The total concentration of all nitrogenous substances at the CP can be written as follows

$$y_N = \sum_{j=1}^{4} y_j = \frac{q\cdot\sum_{j=1}^{4} x_j \cdot \sum_{u=1}^{j} a_{uj}}{Q\cdot n} + \frac{Q_f \cdot \sum_{j=1}^{4} w_j \cdot \sum_{u=1}^{j} a_{uj}}{Q\cdot n} + \frac{n-1}{n}\cdot\sum_{j=1}^{4} g_j \tag{11}$$

It is easy to see that the right side of (11) is a linear combination of random variables x, w and g.

According to the laws of probability theory, the sum of random variables that have a normal distribution is also subject to the normal distribution law. In this case, the mathematical expectations and variances of random variables are added. Because of this, the distribution density of total nitrogen at the CP will be as follows:

$$f_{y_N}(\{X_j\}) = \frac{1}{\sqrt{2\pi}\cdot\sigma_{y_N}}\cdot\exp\left(-\frac{(y_N - \langle y_N\rangle)^2}{2\cdot\sigma_{y_N}^2}\right), \tag{12}$$

where:

$$\langle y_N\rangle = \frac{q\cdot\sum_{j=1}^{4} X_j \cdot \sum_{u=1}^{j} a_{uj}}{Q\cdot n} + \frac{Q_f \cdot \sum_{j=1}^{4} W_j \cdot \sum_{u=1}^{j} a_{uj}}{Q\cdot n} + \frac{n-1}{n}\cdot\sum_{j=1}^{4} G_j \tag{13}$$

$$\sigma_{y_N} = \sqrt{\frac{q^2\sum_{j=1}^{4} X_j^2\cdot\nu_j^2\cdot\left(\sum_{u=1}^{j} a_{uj}\right)^2}{Q^2\cdot n^2} + \frac{Q_f^2\sum_{j=1}^{4}\sigma_{w_j}^2\cdot\left(\sum_{u=1}^{j} a_{uj}\right)^2}{Q^2\cdot n^2} + \left(\frac{n-1}{n}\right)^2\sum_{j=1}^{4}\sigma_{g_j}^2} \tag{14}$$

Similarly

$$f_{y_P}(\{X_5\}) = \frac{1}{\sqrt{2\pi}\cdot\sigma_{y_P}}\cdot\exp\left(-\frac{(y_N - \langle y_P\rangle)^2}{2\cdot\sigma_{y_P}^2}\right) \tag{15}$$

where:

$$\langle y_P\rangle \quad \frac{q\cdot X_5\cdot a_5}{Q\cdot n} \quad \frac{Q_f\cdot W_5\cdot a_5}{Q\cdot n} \quad \frac{n \quad 1}{n}\cdot G_5 \tag{16}$$

$$\sigma_{y_P} = \sqrt{\frac{q^2\cdot X_5^2\cdot\nu_5^2\cdot a_5^2}{Q^2\cdot n^2} + \frac{q^2\cdot\sigma_{w_5}^2\cdot a_5^2}{Q^2\cdot n^2} + \left(\frac{n-1}{n}\right)^2\cdot\sigma_{g_5}^2} \tag{17}$$

Thus, based on the laws of probability theory, the following can be written:

$$P(y_N(\{x_j\}) \le y_{N,cr} \wedge y_P(\{x_j\}) \le y_{P,cr}) =$$

$$\left[\Phi\left(\frac{y_{N,cr} - \langle y_N\rangle}{2\cdot\sigma_{y_N}}\right)\right]\cdot\left[\Phi\left(\frac{y_{P,cr} - \langle y_P\rangle}{2\cdot\sigma_{y_P}}\right)\right] \tag{18}$$

where: Φ – Laplace function:

$$\Phi(t) = \frac{2}{\sqrt{2\pi}}\cdot\int_0^t \exp\left(-\frac{t^2}{2}\right)dt. \tag{19}$$

The authors propose determining the final composition of wastewater by solving an optimization problem, similar to the regulation of wastewater discharges, accounting for complex indicators of water quality (Proskurnin et al., 2022). The set of variables to be optimized are the required admissible concentrations $\{X_j\}$. The following equation can be taken as the goal function:

$$Z = \sum_{j=1}^{N} d_j \cdot (B_j - X_j) \rightarrow \min , \quad (20)$$

where: B_j – actual concentration of the pollutant j according to the field measurements, mg/dm^3; d_j – is the cost of cleaning a unit volume of wastewater from substance j, conventional units / (m^3·mg/dm^3).

The limitations of the optimization problem as follows:

$$\begin{cases} \Phi\left(\dfrac{y_{N,cr} - \langle y_N \rangle}{2 \cdot \sigma_{y_N}}\right) \cdot \Phi\left(\dfrac{y_{P,cr} - \langle y_P \rangle}{2 \cdot \sigma_{y_P}}\right) \le 1 - \alpha, \ j = 1 \div N; \\ X_j \ge P_j; X_j \le B_j, \end{cases} \quad (21)$$

where: P_j – minimum concentration determined by the technological capabilities of the treatment facilities.

An example of calculating the allowable concentrations of substances.

The demonstrated calculation was created using the reservoir near the "Krasnopavlivske" reservoir as an example. This reservoir is used for running a drinking water supply in Kharkiv City (Ukraine) and is also a water intake facility for household wastewater as a part of the Water Treatment Complex "Dnipro". The layout of the enterprise is shown in Figure 2.

In 2020, the standards for permissible discharges of pollutants were calculated for the enterprise. The calculation was made in accordance with the current methodological base in Ukraine, which does not take into account the risk of eutrophication. The critical content of nutrients in a reservoir, at which the threat of eutrophication is real, is unique for every reservoir. To determine it, various mathematical models have been developed, in particular, (Fadel et al., 2019). However, such models include a large number of parameters, the identification of which is a complex science-intensive process (Fadel et al., 2019). As a simplification, one can use the environmental standards contained in the methodology for the environmental assessment of water bodies according to the relevant criteria. According to it, water is considered eutrophic at the following critical concentrations of nutrients C_{cr}: for nitrogen-containing substances – 2.62 mg/dm^3, for phosphorus – 0.16 mg/dm^3. Since the analysis did not show the content of organic phosphorus in water, in this problem only phosphates are considered as phosphorus-containing substances. The corresponding values for transformation ratios for organic nitrogen, ammonium nitrogen, nitrites, and nitrates, are 0.23, 0.21, 4.32, and 0.17. For phosphates – 0.03. Since Environmental Quality Standards (EQS) have not been established for organic nitrogen, it is not standardized according to the existing methodology. This is why for this demonstration, the concentration of organic

Figure 2. The layout of the "Dnipro" water treatment complex

nitrogen in both reservoir and wastewater is taken approximately in accordance with (Ayoub Ait Bella et al., 2023).

The layout of the wastewater discharge is shown in Figure 3. The initial data for the calculation is presented in Table 1. The calculation of the optimal composition of wastewater was carried out using the Excel software. The allowable composition of wastewater was calculated according to the current methodology. The result of the calculation is given in Table 2. The result of the calculation is presented in Table 2. As it can be seen from Table 2, the permissible composition of wastewater obtained as a result of solving the optimization problem is more stringent. To eliminate the risk of eutrophication of a reservoir with minimal costs, it is necessary to reduce the content of organic nitrogen, ammonium nitrogen, and phosphates in wastewater. This result ensures the environmental safety of wastewater disposal from the standpoint of minimizing the risk of eutrophication.

The graphs of the probability distribution functions of the content of total nitrogen and phosphates in CP at the optimal composition of wastewater are presented in Figures 4–5. The probability of exceeding critical concentrations when using the proposed method to make calculations is as follows:

$$P\left(y_N(\{x_j\}) \le y_{N,cr} \wedge y_P(\{x_j\}) \le y_{P,cr}\right) = 0.996 \cdot 0.959 = 0.955 \quad (22)$$

The result of calculations using the proposed method ensures environmentally safe wastewater discharge, while the indicator for non-optimized calculation (i.e. calculation made using the existing method) is 0.00001, which means a high risk of eutrophication of the reservoir near the “Krasnopavlivske” reservoir.

RESULTS AND DISCUSSION

The calculation of allowable concentrations of nutrients entering the reservoir near the “Krasnopavlivske” reservoir with wastewater from the Water Treatment Complex “Dnipro” through the Popelna River that was carried out using both the existing and newly developed methods, showed

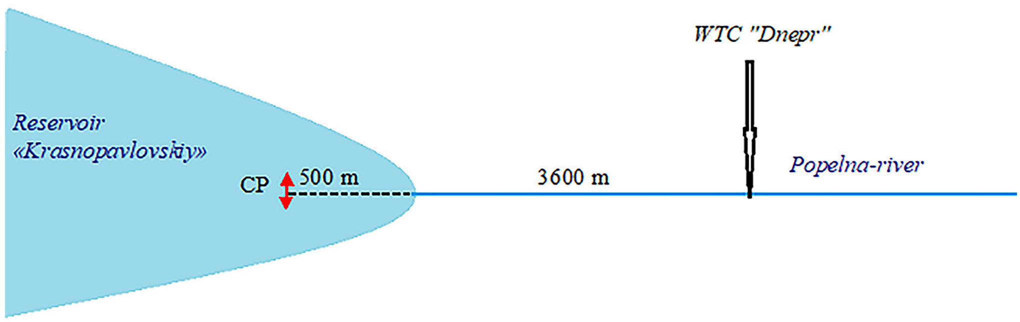

Figure 3. Wastewater discharge scheme

Table 1. The initial date for calculating the allowable concentrations of nutrients

Indicator	Desig-nation	Organic N	Ammo-nium N	Nitrite N	Nitrate N	Phosphate
Wastewater from the Water Treatment Complex “Dnipro”						
Average concentration	*B*	5	4.38	0.11	1.58	2.8
Variation coefficient	ν	0.28	0.32	0.7	0.52	0.61
The lowest possible concentration after water treatment, mg/dm^3	*P*	0.01	0.5	0,03	0.02	0.05
Conditional cost of water treatment, conditional units/ (m^3×g/dm^3)	*d*	2.1	2.5	1	0,7	1.6
Popelna river						
Average	*V*	0.16	0.66	0.12	2.24	0.61
RMS	σ_v	0.12	0.13	0.03	2.24	0.13
Reservoir "Krasnopavlivske"						
Average	*G*	0.1	0.62	0.015	0.7	0.01
RMS	σ_g	0.05	0.06	0.03	0.32	0.06

Table 2. The result of calculating the permissible composition of wastewater

Indicator	Organic N	Ammonium N	Nitrite N	Nitrate N	Phosphate
Calculation according to the current methodology					
Concentration in wastewater	5	4.38	0.11	1.58	2.8
Concentration at CP	0.62	1.06	0.04	0.62	0.37
Optimized calculation					
Concentration in wastewater	1.00	1.00	0.03	1.58	0.07
Concentration at CP	0.20	0.66	0.02	0.90	0.06
EQS	–	2	3.3	45	3.5

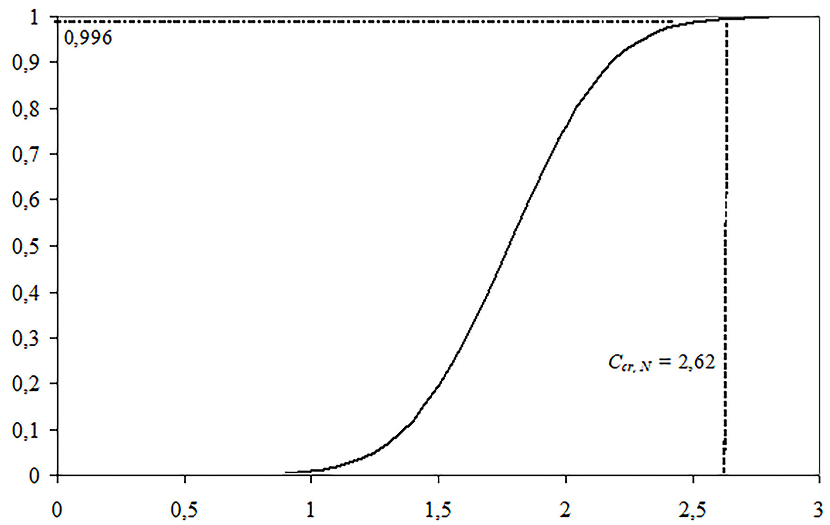

Figure 4. Probabilistic distribution of the content of total nitrogen in CP with optimal composition

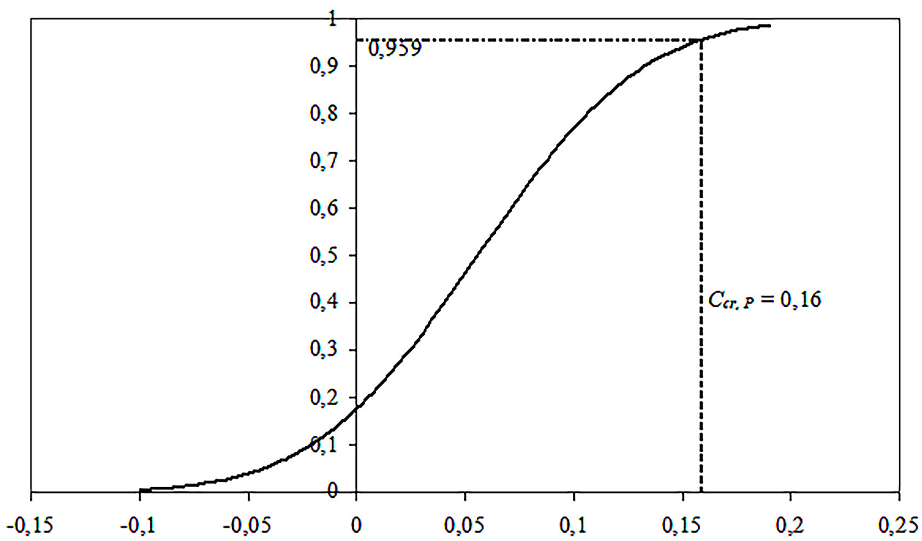

Figure 5. Probabilistic distribution of the content of phosphates in CP with optimal composition

the advantage of the latter in terms of ensuring the environmental safety of wastewater disposal. Thus, the developed method for standardizing the composition of wastewater is more conducive to maintaining the environmental state of the reservoir at a satisfactory level.

CONCLUSIONS

The article substantiated that the existing methodology for standardizing the composition of wastewater based on biogenic indicators does not ensure the environmental safety of its discharge into a water body in terms of the risk of its eutrophication. A method for determining the permissible concentrations of pollutants in wastewater was developed to minimize the risk of eutrophication of natural water. The developed method takes into account the transformation of nutrients, as well as probabilistic factors in the formation of water quality. These studies can be used as a scientific basis for improving the methodology for standardizing the composition of wastewater in terms of biogenic indicators in order to minimize the risk of eutrophication of water bodies. Methodology correction for standardizing the composition of wastewater should first and foremost affect municipal enterprises, livestock complexes, and chemical enterprises, which cause significant pollution of water bodies with phosphorus and nitrogen-containing substances.

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