Analysis of the probabilistic-temporal characteristics of wastewater of mechanical engineering enterprises

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Abstract. In the paper, the results of studies on simulating wastewater pollutant fluxes using averaged integral functional characteristics of the pollution occurrence time are given. The main elements of the effect of the probabilistic and temporal characteristics of the industrial wastewater pollutant fluxes on the average integral functional characteristics of the analytical wastewater control have been considered. The below parameters have been determined: mean no-pollution time, mean pollution occurrence time, the pollution inflow rate, and the average amount of pollution load over the monitoring period. The dynamics of detecting pollutants using express analysis of liquid fluxes when monitoring some specific wastewater pollutants in the enterprise water treatment systems have been analyzed. The technique for estimating the average wastewater pollution load proposed by the authors has been described, which is based on evaluating the average integral characteristics of various pollutant fluxes. The calculation equations are given to determine the average pollution load imposed by certain pollutants detected by the control system over the forecasted monitoring period. The calculation equations are given to estimate the mean total no-pollution time for certain pollutants over the monitoring period.

1. Introduction

Modern industrial facilities comprise industrial wastewater treatment and filtration systems. Wastewater from such enterprises contains a whole range of different components. Wastewater is a complex heterogeneous system contaminated with various dissolved and undissolved substances, as well as those in a colloidal state. Therefore, the problem of a reliable real-time water pollution analysis arises to further decide on implementing certain protective measures [1-3]. To determine the wastewater composition, a lot of different chemical and sanitary and bacteriological analyzes are required, including measurements, tests, checking several parameters, and determining their compliance with the rates prescribed [4-7].

The available wastewater analysis techniques, as a rule, require complex technique, high-precision equipment with advanced functionality that provides measurement results with guaranteed accuracy according to the method adopted, which is not always possible in industrial conditions.

But even if all the harmful substances and pollutants are determined, and the amount of each of them is below the maximum permissible concentration (MPC), it is rather difficult to ensure high water quality by express analysis. This is due to the integral impact of chemical substances and
elements contained in the industrial wastewater on a living organism. The complex wastewater composition and high workload of determining each pollutant in practice lead to the need for choosing indicators that would characterize certain water properties without identifying individual substances.

From the standpoint of the water pollutant concept, the household and technical use of water may also be considered. From a practical point of view, the main and decisive factor is the use of pure water for practical purposes and the discharge of wastewater containing harmful substances.

These substances significantly affect the aquatic ecosystem self-purification and renovation, which can be represented as a complex of interconnected hydrodynamic, physicochemical, microbiological, and hydrobiological processes leading to the restoration of the initial state of a water body. However, such processes are developing extremely slowly.

After the water treatment, express analysis of water from surface or deep layers of natural reservoirs is performed for the presence and concentration of harmful substances. In the case of positive test results, when the pollutant concentration does not exceed the maximum permissible concentration, water is supplied to consumers. As a result of dynamic changes in the water composition using an express analysis system, control actions are developed, leading to a change in the water treatment process. These actions ensure the restoration of the required water purification level.

The wastewater treatment quality by not only the structural composition but also the integral functional characteristic should be determined. This approach can be used as an express analysis technique, which is very important for an eco-monitoring system.

2. Materials and methods

The analysis technique and equipment are chosen based on the presence or absence of certain pollutants in wastewater. Once harmful discharges are eliminated, it is difficult to determine a specific contamination source that may lead to recurrent pollutions. In real wastewater filtration systems, as a rule, active experiments are irrelevant, therefore, data are usually obtained by monitoring the process over a long time.

Due to the modernization of filtration systems and changes in the pollution source number and nature and the treatment facility users, the data obtained are approximate. This does not allow identifying the pollution source and forecasting the exceedance of permissible indicators and unauthorized wastewater discharge, as well as the filtration system behavior with the required detail degree based on the forecasted set of key parameters [8].

In this regard, the most promising and relevant problem is building a mathematical model of the water pollution occurrence [9,10] and performing a series of experiments based on this model, aimed at understanding the system operation specifics and developing a control strategy meeting the criteria chosen. According to physical principles and constraints imposed, an algorithm has been developed for simulating the flow of random events of the pollution occurrence and elimination.

The research objective is studying the effect of the probabilistic and temporal characteristics of the wastewater pollutant flux and the industrial wastewater treatment quality on the average integral functional characteristics of the environmental and analytical control over the machine builder wastewater conditions.

To improve the wastewater analysis reliability, a technique has been developed based on the probability theory, mathematical statistics, and queueing theory. The treatment plant operation has been mathematically presented in the form of a system, studying the characteristics of which allows optimizing the environmental control methods and techniques, improving the accuracy of measuring the pollution degree, and obtaining objective real-time information on the wastewater control quality.

The use of average integral functional characteristics of the wastewater inflow and condition significantly improves the clarity and understandability of the specifics of functioning the water pollution occurrence and contributes to the development of an optimal control strategy [9,11].
For a formalized representation of the wastewater pollution inflow to the treatment plant for each \( i \)-th pollutant type with an integral impact on a living organism, with \( i \) varying within 1 to \( m \), where \( m \) is the maximum load by the \( i \)-th pollutant type, we adopt:

- \( T_{n_i} \) is the mean no-pollution time for the \( i \)-th pollutant type,
- \( T_{p_i} \) is the mean pollution occurrence time for the \( i \)-th pollutant type,
- \( \lambda_i \) is the \( i \)-th pollutant type inflow rate,
- \( \beta_i \) is the \( i \)-th pollutant type flow rate,
- \( o_T \) is the monitoring period,
- \( M_{p_i}(T_o) \) is the average pollution load by the \( i \)-th pollutant type over the monitoring period,
- \( M_{n_i}(T_o) \) is the total mean no-pollution time for the \( i \)-th pollutant type over the monitoring period,
- \( M_{p_i}(T_o) \) is the total mean pollution occurrence time for the \( i \)-th pollutant type over the monitoring period.

The monitoring period \( o_T \) is set based on practical requirements (the reporting period duration: day, week, month, quarter, and year). The \( i \)-th pollutant type inflow rate \( \lambda_i \) is the average amount of the pollution inflow per unit of time, the reciprocal of the \( T_{n_i} \) value. The \( i \)-th pollutant type flow rate \( \beta_i \) is the average amount of the pollution flow per unit of time, the reciprocal of the \( T_{p_i} \) value.

Various pollution sources are characterized by an obvious lack of representative statistical data on the process failures, errors, technical malfunctions, accidents at similar facilities, and the uniqueness of production cycles, as well as comprehensive source data on the production and the equipment arrangement and operation conditions [12-15].

The use of the mathematical apparatus of the theories of probability, queueing, and random flows allows optimizing the probabilistic and temporal characteristics of wastewater treatment plants [16-18]. This is realized through the use of Erlang flow for the formal representation of the wastewater inflow to the treatment plant.

The order of this flow is determined by the number of restrictions imposed on the use of modular coordination and unified equipment. Analytical equations have been obtained, not contradicting the mathematical simulation and pilot operation results. The consistency of the theoretical and statistical distribution has been checked using Pearson's chi-squared test.

3. Results and discussion

At the first stage, we adopt the pollutant elimination time to be zero and only fix the pollutant occurrence moment. This allows representing the flow of random events of the pollutant occurrence and elimination as ordinary (the probability of the simultaneous occurrence of two or more events is zero), stationary (the event occurrence frequency is constant) and consequential (the random event probability does not depend on the previous event occurrence instant) one. On the basis thereof, the Poisson flow of events is used for mathematical formalization.

For the simplest flow of events, the probability of occurrence of exactly \( k \) events over a time interval \( \tau \) (\( k \) varies from 0 to \( \infty \)) has a Poisson distribution with the parameter \( \lambda = \lambda \tau \), where \( \lambda \) is the event flow rate:

\[
P\{X(t, \tau = k)\} = \frac{\lambda^k e^{-\lambda \tau}}{k!}.
\]  

(1)

The physical meaning of \( \lambda \) is the average number of events per unit of time; the dimensionality is 1/time.
Let us adopt the $i$-th pollutant type inflow and flow rates to be equal. This allows considering the odd intervals between even (and the start of the monitoring period) and odd events in the Poisson flow as the no-pollution time for the $i$-th pollutant type, and even intervals between odd and even (and the end of the monitoring period) events as the pollution occurrence time for the $i$-th pollutant type.

For such a situation, the average pollution load by the $i$-th pollutant type over the monitoring period can be obtained by summing the amounts of pollutants with weights equal to the probabilities of occurrence of such pollution load. Considering the equation (1), we obtain:

$$M_{\rho_i}(T_o) = \frac{1}{2} \cdot \lambda_i T_o + \frac{1}{4} \left[1 - \exp(-2\lambda_i T_o)\right].$$

Introducing the concepts:

$$\mu_i = \frac{T_o}{T_o + T_{a_i}} \quad \text{and} \quad V_i = \frac{T_{a_i}}{T_o + T_{a_i}},$$

for the general case, we obtain:

$$M_{\rho_i}(T_o) = \lambda_i V_i T_o + \mu_i^2 \left[1 - \exp(-\frac{\lambda_i}{\mu_i} T_o)\right]. \quad (2)$$

The pollution load over the monitoring period has been calculated for $\mu = 0.1, 0.5, \text{and} 0.9$.

Similarly, we calculate the total mean no-pollution time for the $i$-th pollutant type over the monitoring period:

$$M_{a_i}(T_o) = \frac{1}{2} T_o + \frac{1}{4\lambda_i} \left[1 - \exp(-2\lambda_i T_o)\right].$$

For the general case, we obtain:

$$M_{a_i}(T_o) = V_i T_o + \mu_i^2 \frac{\lambda_i}{\mu_i} \left[1 - \exp(-\frac{\lambda_i}{\mu_i} T_o)\right]. \quad (3)$$

Using equation (3), the ratio of the total mean no-pollution time for the $i$-th pollutant type to the monitoring period has been calculated for $\mu = 0.1, 0.5, \text{and} 0.9$.

Similarly, the total mean pollution occurrence time for the $i$-th pollutant type over the monitoring period can be calculated:

$$M_{\nu_i}(T_o) = T_o - V_i T_o + \mu_i^2 \frac{\lambda_i}{\mu_i} \left[1 - \exp(-\frac{\lambda_i}{\mu_i} T_o)\right] = (1 - V_i) T_o + \mu_i^2 \frac{\lambda_i}{\mu_i} \left[1 - \exp(-\frac{\lambda_i}{\mu_i} T_o)\right]. \quad (4)$$

In extreme cases, when the pollution occurrence time tends to zero and can be neglected or tends to infinity, and pollution cannot be eliminated until the end of the monitoring period, equations (2), (3), and (4) are transformed to the obvious form.

To calculate the average integral functional characteristics of the first main type of wastewater pollution with an integral impact on a living organism, equations (2) and (3) are used with $i = 1$ and the substitution of real values of the 1$^{st}$ pollutant type inflow and flow rates, and the monitoring period. The obtained values determine the average pollution load and the total mean no-pollution time for the 1$^{st}$ pollutant type over the monitoring period.

To calculate the average integral functional characteristics of the second pollutant type, equations (2) and (3) are used with $i = 2$ and the substitution of real values of the 2$^{nd}$ pollutant type inflow and flow rates. Instead of the monitoring period $T_o$, the total mean no-pollution time for the 1$^{st}$ pollutant type over the monitoring period $M_{a_1}(T_o)$ is used.
Equations (2) and (3) are used to calculate the average integral functional characteristics of the subsequent pollutant types with the substitution of real values of the corresponding pollutant type inflow and flow rates, and instead of the monitoring period $T_m$, the total mean no-pollution time for the $(i-1)$-th pollutant type over the monitoring period is used.

After summing up the average pollution load by the $i$-th pollutant type over the monitoring period with $i$ varying within 1 to $m$, we obtain the average load by all the wastewater pollutant types with an integral impact on a living organism.

The average amount of coinciding pollutants can be calculated by substituting the total mean no-pollution time for the $i$-th pollutant type instead of the total mean pollution occurrence time for the $i$-th pollutant type over the monitoring period and performing similar mathematical operations.

To check the correctness of the technique developed using the Pearson's criterion, the divergence between the results obtained by mathematical simulation using a random number generator and those obtained by calculation using the mathematical equations proposed has been estimated. For the confidence probability $\alpha = 0.90$ or the significance level $q = 0.10$, the lower $\chi^2_{\alpha}$ and upper $\chi^2_{1-q}$ confidence limits were set determining an interval, in which the measure of deviation could fall for purely random reasons. The calculations have shown that the measure of deviation $\chi^2$ is within the interval specified, which allows arguing that the hypothesis of the convergence of the results obtained by mathematical simulation and calculations using the mathematical equations proposed is consistent with the experimental data.

4. Conclusion

There is a wide range of instruments to monitor the industrial wastewater pollution, some of which are used in control systems. Their operation is based on various physical and chemical techniques (conductometric, dielectric, potentiometric, optical, etc.). Among them, optical techniques operating in the ultraviolet, X-ray, near-infrared, and infrared bands have great capabilities [19-23].

To implement the technique considered, a measuring complex has been developed to record and identify individual pollutant discharges into the industrial wastewater system [24]. In this case, a certain list of pollutants is assumed that may unexpectedly occur in the industrial wastewater as a result of an emergency. This list is formed a priori when assessing probable beyond-design-basis accidents.

To record and identify coagulates of such substances, a device is used to monitor changes in the optical density of the wastewater flow. Changes in the optical density are measured at several wavelengths of probing laser radiation that are determined a priori.

Identifying substances is based on the analysis of changes in optical density at several laser radiation wavelengths. To do this, a table of optical density values at different wavelengths is pre-compiled. For real cases, data obtained at three to five probing laser radiation wavelengths are enough.

Data obtained by the measuring complex allow accumulating statistical data on coagulates forming as a result of emergency discharges, which can be used to forecast the occurrence of some pollutant types. Therefore, these data may be considered in the algorithm for identifying discharges. This allows controlling the wastewater filtration or discharge of pollutants into settling tanks.

The proposed approach and technique improve the wastewater treatment quality by redistributing flows to various filters and settling tanks in the industrial wastewater treatment systems.

Thus, the studies have shown that to identify and eliminate harmful discharges during environmental and analytical monitoring of the wastewater conditions at treatment plants of large-scale machine builders, the average integral functional characteristics and the probability of pollution should be considered.

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