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INTEGRATED MATHEMATICAL MODELS AND THEIR APPLICATIONS

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Abstract. This study examines the joint impact of random water consumption and emergency failures on water supply systems. Traditional reliability indicators are inadequate, as they overlook consumer-specific supply characteristics. The research develops integrated mathematical models to optimize system performance and proposes a method to calculate the probability of uninterrupted water supply to each consumer by considering all consumption and failure scenarios. The model enables reliability assessment for both individual consumers and the entire system, offering more realistic and operationally adequate evaluation and optimization tools.

Keywords: water supply, water supply and distribution system, unplanned water withdrawal, integrated model, probabilistic nature of water consumption and the occurrence of emergency situations, the possibility of uninterrupted water supply to consumers, the coefficient of readiness for water supply to consumers.

Integrallashgan matematik modellar va ularning qo‘llanilishi

Annotatsiya. Ushbu tadqiqotda tasodifiy suv iste'moli va avariya holatlarining suv ta'minoti tizimlariga birgalikdagi ta'siri o‘rganiladi. An’anaviy ishonchlilik ko‘rsatkichlari yetarli emas, chunki ular har bir iste’molchining ta’minot xususiyatlarini hisobga olmaydi. Tadqiqotda tizim ishini optimallashtirish uchun integrallashgan matematik modellar ishlab chiqilgan va barcha ehtimoliy iste’mol hamda nosozlik ssenariylarini hisobga olgan holda har bir iste’molchiga suv uzluksiz yetkazib berish ehtimolini aniqlash usuli taklif etilgan. Model tizimning umumiy va individual ishonchliligini baholash imkonini beradi hamda amaldagi jarayonlarga mos, realistik optimallashtirish vositasi hisoblanadi.

Kalit so‘zlar: suv ta’minoti, suv ta’minoti va taqsimot tizimi, rejasiz suv iste’moli, integrallashgan model, suv iste’molining ehtimollik xususiyati va avariya holatlarining yuzaga kelishi, iste’molchilarga suvni uzluksiz yetkazib berish imkoniyati, iste’molchilarni suv bilan ta’minlashga tayyorlik koeffitsienti.

Интегрированные математические модели и их применение

Аннотация. В данном исследовании рассматривается совместное влияние случайного водопотребления и аварийных отказов на системы водоснабжения. Традиционные показатели надёжности недостаточны, так как не учитывают особенности водоснабжения отдельных потребителей. В работе разработаны интегрированные математические модели для оптимизации работы системы и предложен метод расчёта вероятности бесперебойного водоснабжения каждого

потребителя с учётом всех возможных сценариев потребления и отказов. Разработанная модель позволяет оценить надежность, как для отдельных потребителей, так и для всей системы в целом, обеспечивая более реалистичную и адекватную оценку и оптимизацию работы водоснабжения.

Ключевые слова: водоснабжение, система водоснабжения и распределения, незапланированный водоотбор, интегрированная модель, вероятностный характер водопотребления и возникновения аварийных ситуаций, возможность бесперебойного водоснабжения потребителей, коэффициент готовности водоснабжения потребителей.

Introduction. The water distribution and supply system (WDSS) is one of the most critical elements of modern urban infrastructure. The health and well-being of the population depend on its condition, efficiency, and operational reliability. Therefore, studying its operating modes, identifying the patterns of emergency situations, their occurrence, escalation, and resolution, as well as establishing the stochastic and cyclical nature of water consumption, are of great importance. In water supply systems, the time required to replace pipelines is a random process. When justifying the structure and parameters of the network, possible scenarios of such modes and their probabilities must be taken into account. In the absence of such considerations, a significant discrepancy may arise between the actual water demand during a specific time interval and the system's ability to meet these demands, even in the absence of failures or random events. All of this confirms that the reliability requirements for water supply systems must be determined based on consumer needs. The system must be designed in such a way that no random events disrupt the continuous water supply [7].

Methods. Currently, in almost every district of Nurobod, a large volume of statistical data has been collected on water consumption patterns for individual residential buildings, as well as for the district and the city as a whole [6, 8]. This statistical data provides an opportunity to characterize the probabilistic nature of the water consumption process. A histogram and mathematical expectation of water consumption over *t* hours for a group of residential buildings have been determined [3, 4].

$$\overline{M}_t = \sum_{\int 1}^{k} M_{t,\int} \quad \rho_{t,\int} \ ,$$

Here, ***k*** represents the number of intervals for possible water consumption scenarios; is the volume of water corresponding to the interval over $-t$ hours $\frac{m^3}{soat}$; $\rho_{t,\int}$ - is the probability of the given water volume occurring within the $-t$ hour interval.

The root mean square deviation of the water amount for t hours:

$$\sigma_{M,t} = \sqrt{\sum_{\int 1}^{k}}$$

For each t-hour period, water distribution is considered within the range of the root mean square deviation according to the "3σ" rule:

$\overline{M}_t^{[min]} - 3 \cdot \sigma_{Q,t}^{[min]}$- lower bound, $\overline{M}_t^{[max]} + 3 \cdot \sigma_{M,t}^{[max]}$- upper bound. Figure 1 presents the probability density distribution in graphical form.

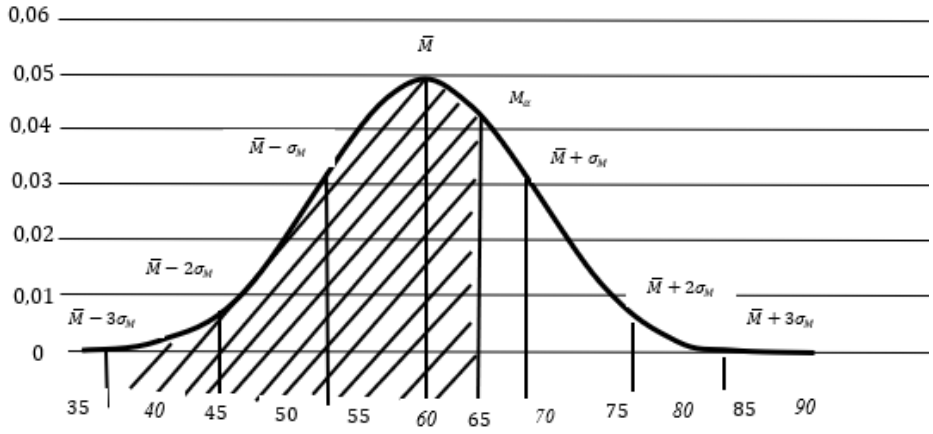

Figure 1. Probability Density Distribution of Hourly Water Consumption

Considering the probabilistic functional relationship of an arbitrary consumer (Figure 1), we examine a method for assessing the reliability of water supply to consumers. The probability distribution function of water consumption for each hour of the studied time period (24 hours) is divided into several intervals.

Each interval consists of $\frac{\sigma_{j,t}}{3}$ Based on this, there are 18 intervals, making the total number of divisions $\alpha = 19$. The amount of water consumed in each division is equal to:

$$M_{j,\alpha,t} = \overline{M}_{j,t} - 3\sigma_{j,t} + \frac{k\sigma_{j,t}}{3}$$

here, k represents the interval index.

The probability of fully supplying a consumer with water within the studied interval is equal to the area of the shape located on the left side of the given consumption amount (Figure 1).

Considering the segmentation process, we analyze the probability of supplying consumers with water and the water consumption for each examined hour.

Starting from the lowest consumption, the issue of consumption distribution in undefined network branches is considered for each section and each hour of the studied time period [8]. In this case, calculations are performed for both the normal operation of the water distribution system and all possible failure scenarios. After each calculation, water consumption at the node is evaluated. If all consumers receive the specified amount of water, the system is considered reliable.

If, at any stage of the calculations, a consumer starts receiving less water than specified, the consumption and its probability are determined based on the previous state. Thus, using probability functions of water consumption and a series of hydraulic calculations, the probability distribution of consumer water supply is determined.

The main parameters for assessing the reliability of the Water Distribution and Supply System (WDSS) are, the probability of continuous operation, and K_T, the readiness coefficient [1, 2].

$$P = e^{-\lambda(d)\mu t}; K_T = \frac{\mu}{\mu + \lambda} = \frac{T_0}{T_0 + T_v},$$

here λ - failure rate of the pipeline,$\frac{1}{kmyear}$; K_{od} - simplicity coefficient; l - length of the pipeline, km; μ – repair rate of the pipeline, $\frac{1}{yil}$; t - Operating time, including one additional year from the start of the study period, i.e., $t = t_{foy} + 1$; T_0 - mean time between failures, $T_0 = \frac{1}{\lambda \cdot l}$; T_v - mean repair time, $T_v = \frac{1}{\mu}$ da. Figure 2 illustrates a water supply scheme consisting of 6 nodes and 7 sections.

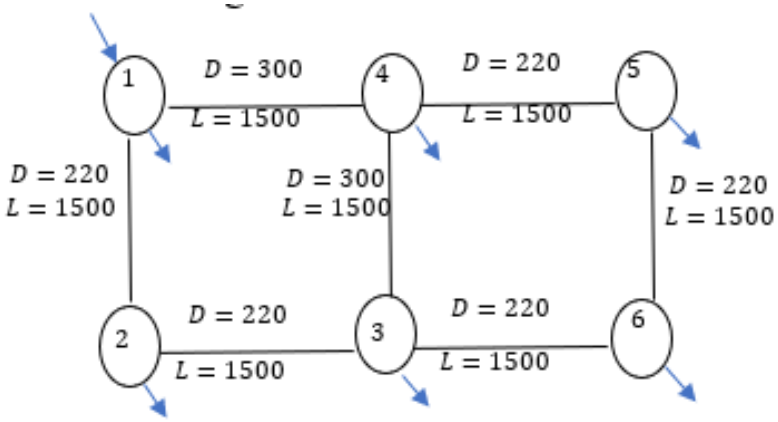

Figure 2. Loop Diagram of the Water Supply System

We introduce the following notation: pipeline restoration time.

$T_{qs} = 24soat; \mu_{vs} = \frac{8760}{24} = 365; \lambda = 0{,}064 * D^{-0{,}8}$, here D - pipeline diameter, m.

The results of calculating the stationary probability of the operational state of the Water Distribution and Supply System (WDSS) network are presented in **Table 1**.

Taking into account the occurrence of emergency situations and the probabilistic characteristics of water consumption, we develop a mathematical model for the operation of pipeline systems.

i along the networks $\alpha_s = 0, \dots, 18$for each *t*-hour period, across the network sections, the X consumption distribution can be expressed by two systems of equations: system 1 – unchanged mode: this system represents the normal operating condition, where the network structure remains unaltered, system 2 – failure mode: this system accounts for the altered operating condition, in which the network configuration is modified by sequentially shutting down the faulty sections. $(i = 1,2, \dots, n)$ [9]:

$$\begin{cases} AX = M \\ A^T P = SX^2 - H \end{cases} \qquad \begin{cases} A_{Fv} X_{Fv} = M \\ A_{Fv}^T P = S X_{Fv}^2 - H \end{cases},$$

Here,$A - (m-1)xn$ is a matrix of dimensions composed of elements a_{ij}that represents the interconnection of nodes and networks; in the calculation scheme,i denotes a node and j denotes a network; A_{Fv} - i - as a result of shutting down the section n_i by sequentially outputting the elements A network routing matrices obtained from the matrix, i.e.,$A_{Fv} - (m-1)x(n-1)$; X– The consumption vector along the networks of the calculation scheme, composed of$n$ -dimensional elements x_i; X_{Fv}– the consumption vector along the networks of the calculation scheme,

Table 1

Calculation of the probability of the network state when sections are turned off.

Locations that need to be shut down.	L	D	λ	$\lambda * L$	μ	$\gamma = \frac{\lambda * L}{\mu}$	$1+\gamma$	$\rho_{av} = \frac{\gamma}{\prod(1+\gamma)}$
1-2	1500	220	0,0341	0,0511	365	0,00014	1,00014	0,00014
2-3	1500	220	0,0341	0,0511	365	0,00014	1,00014	0,00014
3-4	1500	300	0,0266	0,0399	365	0,00011	1,00011	0,00010
1-4	1500	300	0,0266	0,0399	365	0,00011	1,00011	0,00010
4-5	1500	220	0,0341	0,0511	365	0,00014	1,00014	0,00014
3-6	1500	220	0,0341	0,0511	365	0,00014	1,00014	0,00014
5-6	1500	220	0,0341	0,0511	365	0,00014	1,00014	0,00014
$\prod(1+\gamma)$							1,00092	

$= \frac{p_0}{\frac{1}{\prod(1+\gamma)}}$							0,99908	0,00089

which is $(n-1)$-dimensional and composed of $x_i$elements; H - an n -dimensional vector that influences the pressure in the network.

Results and discussion. Evaluating the water supply system solely based on its operating time and readiness indicators is not always sufficient, because these are only related to the network structure and parameters and do not account for the unique characteristics of supplying each consumer.

It is proposed to evaluate the reliability of water supply to consumers based on key indicators by adapting the methodology for assessing the reliability of heating networks [9] to water supply networks.

The reliability of the accounted water supply state is determined for each consumer node and is evaluated using the readiness coefficient K_j, which represents the probability that the *j*-th node is supplied with the specified amount of water at any arbitrary time during the study period.

The readiness coefficient for supplying the *j*-th consumer with the specified amount of water. (The calculation scheme is determined for each *j*-th consumer.)

$$K_j = p_0 + \sum_{f \in F_i} p_f, K_j = \prod_{i=1}^{n} (1+\gamma_i)^{-1} \cdot \left(1 + \sum_{i=1}^{n} {}_{f \in F_i}\gamma_i\right)$$

Here,F_i -is the set of water supply elements whose failure does not affect the specified level of water supply for the$j$ -th consumer.$p_f -$ the probability of the network state corresponding to the failure of element$f$

P_j– the probability of uninterrupted water supply for the j -th consumer. The probability that the water supply for the j -th consumer does not fall below the minimum allowable level is determined as follows (a target schedule is set for each consumer).

$$P_j = exp\left(-\left[p_0 \sum_{d \in D_j} \left(\lambda_d l_d \tau_{j,d}\right)\right]\right)$$

Here, $D_j$is the set of water supply elements whose failure affects the unforeseen (emergency) water supply condition of the *j*-th consumer. $\tau_{j,d} = T \cdot \frac{1}{24} \cdot \sum_{t=1}^{24}\left(1-\rho_{j,t}\right)$ - The duration of supplying the j -th consumer with water below the minimum allowable level; T - the duration of the study period, in years; $\rho_{j,t}$– j- the probability of the consumer's hourly water supply, $\overline{m}_{j,k} \geq \varphi_k^{av} \quad k \in F_j^k$ here, $\overline{m}_{j,k}$represents the hourly water consumption of the j -th consumer when the - j element of the network's loop section fails (relative to the calculated demand); F_j^k– the set of sections of the looped part of the water supply network that are hydraulically connected to the j -th consumer; φ_k^{av},– the water supply standard for consumers in emergency situations. In this case, the consumer is supplied with no more than 30% of the normal amount.

The probability of uninterrupted water supply for the j -th consumer.

$$P_j = exp\left(-\left[\prod_{i=1}^{n}(1+\gamma_i)^{-1} \cdot \left(1 + \sum_{i=1}^{n} {}_{d \in D_j}\lambda_i l_i\right) \cdot \left(T \cdot \frac{1}{24} \cdot \sum_{t=1}^{24}\left(1-\rho_{j,t}\right)\right)\right]\right)$$

According to SNiP 2.04.02-84, the standardized value of operational reliability probability and the readiness coefficient are as follows:P_j(norm)= 0,99998; K_j(norm) = 0,99178.

To mathematically express the probability of consumer supply, the normal distribution law (Laplace transformation) is used.

$$K_j \geq K_t(norm), K_t(norm) = 99178, P_j \geq P_j(norm), P_j(norm) = 99998$$

The result is presented in Table 2.

Table 2

Comparison of the calculated reliability indicators of consumer water supply with normalized values

Indicator		Probability of Supplying Consumers by Nodes					
		1	**2**	**3**	**4**	**5**	**6**
K_j	0,99178	0,999984	0,999506	0,998812	0,999318	0,998066	0,997767
P_j	0,99998	1,000000	0,999970	0,999836	0,999573	0,999543	0,999563

According to the calculation results, the probability of continuously supplying water to consumers in nodes 3–6 is below the normalized values; accordingly, the operation of the system is considered unreliable.

Conclusion. In the presented calculations and the example given for the probability of supplying consumers with water, a 100% supply was considered, with a 30% reduction under failure conditions. The method under consideration allows for the formation of complex indicators to assess the reliability of consumer supply. By taking into account the probability of water consumption and the occurrence of failure states, it provides a comprehensive approach for evaluating the operational reliability of water supply systems, determining the probability of supplying water to each consumer, and, if applicable, assessing it.

This method can be useful both in practical applications and in developing promising diagrams for the advancement of water supply systems.

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