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SUBSTANTIATION OF ENVIRONMENTALLY SAFE MODES AND PARAMETERS OF OPERATION OF MINERAL PROCESSING WASTE STORAGE FACILITIES

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Abstract. The subject of the paper is the modes and parameters of operation of mineral processing waste storage facilities. Liquid waste storage facilities that accumulate processing products and mine water from several mining enterprises are considered, taking into account climatic factors of influence, technological limitations on the volume of waste. The analysis of the main results shows that environmental safety in the operation of waste storage facilities is based on two principles: to prevent waste overflow over the edges of the embankment dam and to provide a protective layer of liquid over the bottom, which is formed from particles of dusty and clay fractions. The purpose of the study is to scientifically substantiate the possible modes of operation of liquid waste storage of mineral raw materials processing and mining, as well as the creation of methods for calculating their maximum possible volumes entering the storage during the year, taking into account environmental safety. The study used the methodology of logistic systems, in the framework of which storage facilities are considered as a node of accumulation, and its model includes a system of equations describing the height of the water mirror and the bottom level depending on the volume of placers from the water volumes that entered and withdrawn from it during the period of operation, which is analyzed, taking into account the geometric features of the storage bowl. As a result, a mathematical model of liquid waste storage, which accumulates processing products and mine water from several mining enterprises, has been developed, taking into account climatic factors of influence, technological limitations on waste volumes. This model allows to determine the level of the free surface mirror in any month of the year, as well as to calculate changes in the current height of the free surface mirror in the storage for any period of time. On the basis of these formulas and ecological safety requirements at operation of artificial storages of wastes from processing of mineral raw materials the restrictions on volumes of wastes which enter the storage during a year, or during spring months have been received. The use of these restrictions allowed to determine and justify the rational values of capacities on salable concentrates of mining enterprises, duration of their downtime for a certain period of the year.

Keywords: storage of mineral processing waste, height of the water mirror, environmental safety of operation.

1. Introduction

The volume of mine waters to be stored on the day surface and the volume of liquid enrichment waste (EW) depend on mining and geological conditions of the deposit and features of mining and processing technology and they are directly proportional to the amount of primary minerals extracted [1–3]. Thus, the increase in the depth of mining and increase of production capacity of mining enterprises in the Kryvbas region led to joint storage of mine waters, which are characterized by high alkalinity and must be pre-treated before discharging into rivers. The possibilities of storing the EW are limited by the existing storage facilities volume, as it is impossible to build new ones because they are located within cities; and the construction of dams is already environmentally dangerous, as it threatens to pollute the environment in case of destruction. The only way to restore the accumulation capacity of such storage facilities [1, 3] is to discharge part of the EW into rivers every year during floods in three spring months. Today there is a situation when the capacity of mining enterprises and their stable operation is limited by the ability of the waste storage facility to accept liquid man-made deposits.

This situation was not foreseen and arose as a result of the current circumstances, so the management of liquid waste for each enterprise in the region is carried out without appropriate scientific justification. In other words, there are currently no models for existence of the EW storage facilities and no scientifically based methods for determining their parameters that would ensure environmentally safe operation and functioning of mining enterprises in the region.

The results of the analysis of mining enterprises of the Kryvyi Rih iron ore basin indicate the need to solve the following problems to ensure environmental safety and sustainable development of the region [1, 2]:

– to formulate scientifically grounded conditions for environmentally safe operation of the liquid man-made waste storage facility;

– to define restrictions on the regulated reduction of the water mirror height in the storage facility during the year;

– to calculate the maximum possible amount of the EW received at the storage facility during the spring months and throughout the year taking into account environmental safety reasons;

– to estimate the possible volume of liquid man-made waste that can be removed from the storage facility during the spring months, depending on the EW volume received in the storage facility during the year;

– to create a methodology for determining the reduction of capacity for sellable concentrates of each of the mining enterprises that store liquid man-made waste in the storage facility, or the corresponding duration of downtime;

– to substantiate the possibility of storing a part of liquid man-made waste within the industrial area of the enterprise with subsequent discharge to the storage facility after or during the spring months.

Thus, using known models of the EW storage facility that serves several mining enterprises, it is necessary to determine the possible operating modes of such a hydraulic facility from the point of view of environmental safety and to develop scientifically sound methods for calculating the relevant parameters and waste volumes.

2. Methods

The purpose of the paper is to scientifically determine the possible modes of operation of the EW storage facility from the point of view of environmental safety and to develop methods for calculating the maximum possible volume of the EW entering the storage facility during the year.

A storage facility for mineral processing waste that serves several mining enterprises is considered as an accumulation site [3–5]. Its model includes a system of equations that describe the height of the water mirror and the bottom level depending on the volumes of placers and water fed into and withdrawn from the storage facility during the analyzed period of operation, taking into account the geometric features of the storage bowl. In this case, the consumption of the EW entering the storage facility is calculated according to the capacity of all mining enterprises that send liquid waste to the storage facility, as follows:

$$Q_{OF}(t) = \sum_{i=1}^{N} Q_{OF}^{(i)}(t); \quad Q_{OF}^{(i)}(t) = \mu_i G_{OF}^{(i)}(t), \tag{1}$$

where Q_{OF} – the EW consumption entering the storage facility, m³/h; $Q_{OF}^{(i)}(t)$ – the EW consumption, entering the storage facility from the i-th mining enterprise, m³/h; i – serial number of the i-th mining enterprise, that directs liquid waste to the storage facility; μ_i – processability coefficient of the i-th mining enterprise, that directs liquid waste to the storage facility; $G_{OF}^{(i)}$ – capacity of the i-th mining enterprise for sellable concentrates, m³/h; t – time, h; N – number of mining enterprises, that directs liquid waste to the storage facility.

Considering the formulas of the mathematical model of the accumulation node [1–4], taking into account (1), with a frequency of one month, the following recurrent formulas can be used to calculate the current height of the water mirror:

$$\int_{H_W^{(i-1)}}^{H_W^{(i)}} F_w(z)dz = \left(1 - \frac{C_0'}{m}\right) Q_{OF}^{(i)} t_i - k_{AT}^{(i)} \int_{T_{i-1}}^{T_i} F_w(H_W)dt - W_E \frac{i}{3} \delta(i,1,3); \quad (2)$$

$$\delta(k,i,j) = \begin{cases} 1, & i \le k \le j \\ 0, & k < i, \quad k > j \end{cases}; \quad T_i = \sum_{j=1}^{i} t_j; \quad k_{AT}^{(i)} = 0{,}007\Sigma_+ \left(1 - \frac{\alpha_i}{\Sigma_+}\right); \quad (3)$$

$$W_E = \left(1 - \frac{1-m}{m} C_P\right) W_0^W; \qquad C_P = \frac{1 - 0{,}5 P_{0,1}}{P_{0,1} - 0{,}335}, \quad (4)$$

where $k_{AT}^{(i)}$ – parameter that takes into account the precipitation impact (table 1); δ – function that determines the flood interval on the rivers of the region; T_i – time interval, h; t_j – working time fund in the month with the number j; C_0' – volume concentration of the hydraulic mixture coming from the processing plant; Σ_+ – the sum of air temperature norms for the months of the warm season [7–10]; C_P – maximum permissible volume concentration of solid particles in the liquid extracted from mining waste; W_E – volume of liquid man-made waste removed from the storage facility during the spring months, m³; W_0^W – volume of clarified water taken from the accumulation node, m³; m – porosity of beneficiation waste after back fill; H_W – current height of the water mirror, m; $F_w(z)$ – function describing the dependence of the current cross-sectional area of the accumulation node occupied by the liquid fraction on the height of the water mirror, m²; $P_{0,1}$ – the share of particles with a diameter of less than 0.1 mm in the solid fraction of the EW; z – current height of the water mirror, m.

When calculating using formulas (1)–(4), the initial value of the current water surface height $H_W^{(0)}$ is assumed to be equal to the value at the end of February. The use of these formulas involves determining the type of function that describes the dependence of the current cross-sectional area of the accumulation node occupied by the liquid fraction on the height of the water mirror. The analysis of scientific works by Ukrainian researchers [1–3, 5–10] clearly indicates the possibility of introducing the following approximation for the tasks considered in the conditions of liquid man-made waste storage facilities of Kryvbas mining enterprises:

$$F_w(z) = kR^2, \tag{5}$$

where k – geometric shape factor of the repository perimeter, equal to 1 for a square and 3.14 for a circle; R – conditional radius of the repository bottom, m (Figs. 1, 2)

Table 1 – Formulas for calculating the parameter α_i during the year for the conditions of the Dnipro region [1–3, 5–11]

The month of the year	The month number	The value
January	1	0,013
February	2	0,015
March	3	0,018
April	4	0,024
May	5	0,021
June	6	0,015
July	7	0,015
August	8	0,013
September	9	0,017
October	10	0,018
November	11	0,017
December	12	0,014

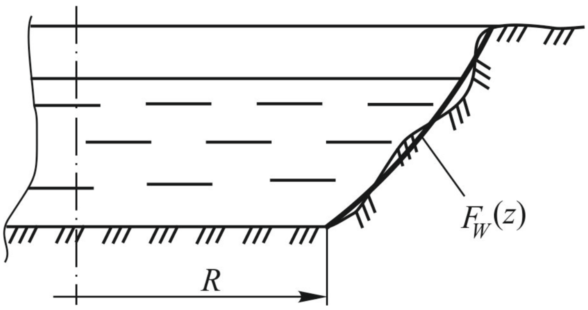

Figure 1 – Structure of the internal slope of the storage facility [1-4].

Formulas (1)–(5), after the transformations, allow us to obtain a dependence for calculating the change in the current height of the water mirror in the storage facility relative to the previous value:

$$H_W^{(i)} = H_W^{(i-1)} + \left(1 - \frac{C_0(t)}{m}\right)\frac{Q_{OF}^{(i)}}{1{,}1R^2}t_i - \frac{k_{AT}^{(i)}}{1{,}1}t_i - \frac{W_E}{1{,}1R^2}\frac{i}{3}\delta(i{,}1{,}3). \tag{6}$$

According to the study by experts of the Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine [1–3], environmental safety in the operation of waste storage facilities is based on two principles: to prevent waste overflow over the edges of the embankment dam and to provide a protective layer of liquid over the bottom, which is formed from particles of dusty and clay fractions. In case of waste overflow over the edges of the embankment dam, the contaminated liquid enters the public water supply, poisons the bio- and noosphere, and in large volumes threatens to flood the land around the storage facility. The reduction of the protective layer of liquid above the bottom, which is formed from particles of dusty and clay fractions, leads to the suspension of these particles under the influence of the current caused by the wind impact on the day surface, which makes the liquid unclarified. And when the liquid layer completely disappears, it causes dusting of the air around the storage facility, which threatens animals, people and plants.

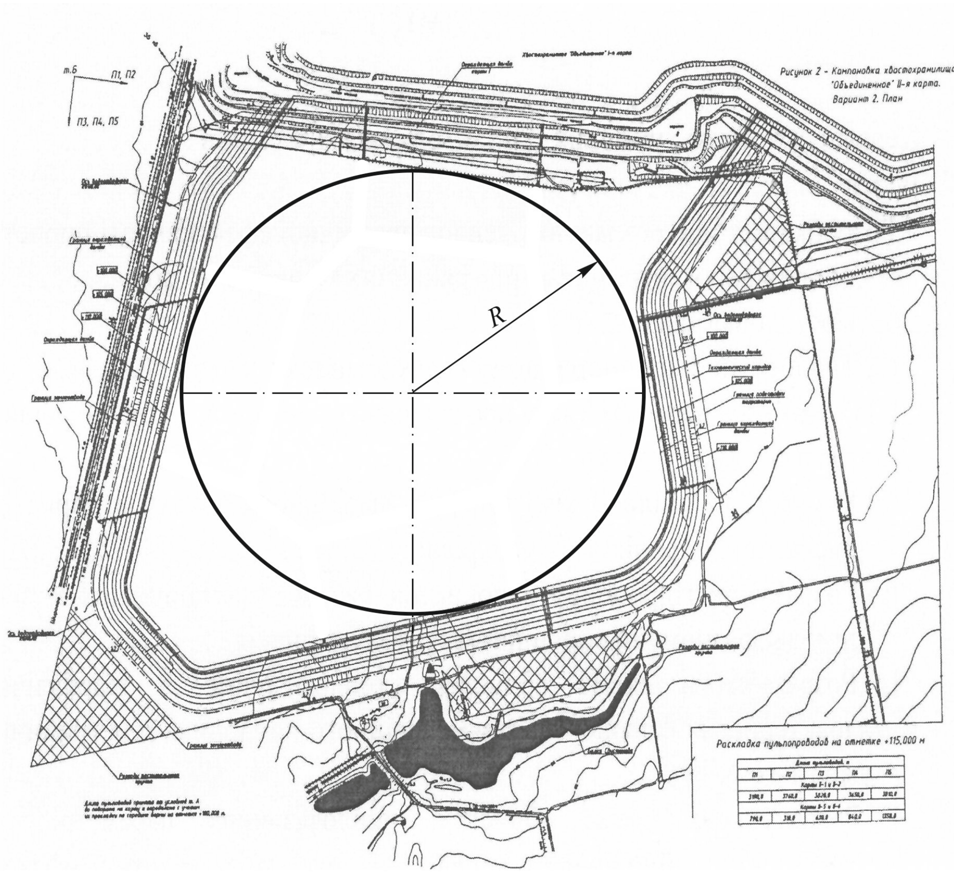

Figure 2 – Explanation of the parameter essence R [1-3]

The water surface vibrations in the storage facility occurs throughout the year and depend on many factors. The basis of this annual cycle is due to the possibility of discharging some of the contaminated liquid into local rivers during floods, which is the only way to reduce the volume of liquid accumulated in the storage facility. That is, from March to early June, all the liquid that has been accumulated over the entire year must be discharged from the storage facility, but in such a way that a protective layer of liquid remains above the bottom. Formula (6) is focused on calculating the change in the current height of the water mirror in the storage facility for one month, but it can be used to obtain dependencies for calculating the change in the current height of the water mirror for any period of the year, for example, during the spring months or for the entire year:

$$H_W^{(4)} = H_W^{(0)} + \frac{cQ_{1,4}}{1{,}1R^2} - \frac{k_{1,4}}{1{,}1} - \frac{W_E}{1{,}1R^2};\ H_W^{(12)} = H_W^{(0)} + \frac{cQ_{1,12}}{1{,}1R^2} - \frac{k_{1,12}}{1{,}1} - \frac{W_E}{1{,}1R^2};\ (7)$$

$$c = 1 - \frac{C_0'}{m};\quad Q_{i,j} = \sum_{k=i}^{j} Q_{OF}^{(k)} t_k;\quad k_{i,j} = \sum_{k=i}^{j} k_{AT}^{(k)} t_k, \qquad (8)$$

where $H_W^{(4)}$ – height of the water mirror in the storage facility after the spring months, m; $H_W^{(12)}$ – the height of the water mirror in the storage facility in early March of the current year, m; $H_W^{(0)}$ – the height of the water mirror in the storage facility in early March last year, m; $Q_{i,j}$ – volume of the EW received in the storage facility for the period between the month with the number i to the month with the number j, m^3/h; $k_{i,j}$ – the integral value of the parameter that takes into account the influence of precipitation for the period between the month with the number i to the month with the number j.

Since it is only during the spring months that liquid is discharged from the storage facility to the rivers, the height of the water mirror in the storage facility should decrease from March to early June:

$$H_W^{(3)} < H_W^{(2)} < H_W^{(1)} < H_W^{(0)}, \qquad (9)$$

and during all other months this value only increases:

$$H_W^{(3)} < H_W^{(4)} < H_W^{(5)} < H_W^{(6)} < H_W^{(7)} < H_W^{(8)} < H_W^{(9)} < H_W^{(10)} < H_W^{(11)} < H_W^{(12)}, \qquad (10)$$

where $H_W^{(i)}$ – the height of the water mirror in the storage facility at the beginning of the month with the number i according to Table 1, m.

Using inequalities (9) and (10), we can formulate a condition for environmentally safe operation of a liquid industrial waste storage facility based on a comparison of the heights of the water mirror in the storage facility in early March of the previous and current years (Table 2).

Using formulas (7) and Table 2, we can obtain the condition for environmentally safe operation of a liquid industrial waste storage facility with restored accumulation capacity:

$$Q_{1,12} \le Q_L; \qquad Q_L = \left(1 + \frac{k_{1,12}}{k_a}\right)\frac{W_E}{c}; \qquad k_a = \frac{W_E}{kR^2}, \tag{11}$$

where Q_L – the maximum possible amount of the EW received at the storage facility during the year for environmental safety reasons, m^3/h; k_a – the volume of liquid man-made waste removed from the storage facility during the spring months per unit area of its bottom, m^3.

Table 2 – Characteristics of the storage operation mode

Characteristics of the storage operation mode		Definition condition
by environmental threat	by storage capacity	
Safe	Without recovery	$H_W^{(12)} = H_W^{(0)}$
	With recovery	$H_W^{(12)} < H_W^{(0)}$
Unsafe	–	$H_W^{(12)} > H_W^{(0)}$

3. Results and discussion

To ensure environmentally safe operation of a liquid man-made waste storage facility with recovery of a certain amount of accumulation capacity, the following condition should be used:

$$H_W^{(0)} - H_W^{(12)} = \Delta H_W, \tag{12}$$

which, after the transformations, allows us to propose the following instead of formula (11):

$$Q_{1,12} = Q_L - 1{,}1\frac{kR^2}{c}\Delta H_W, \tag{13}$$

where ΔH_W – regulated the decrease in the height of the water mirror in the storage facility over the year, m.

Since the left side of formula (13) must be positive, we obtain a restriction on the regulated decrease in the water surface elevation in the storage facility per year

$$\Delta H_W \le 0{,}91(k_a + k_{1,12}). \tag{14}$$

Constraint (14) is essentially of a technological nature. Environmental safety during the annual decrease in the height of the water mirror in the storage facility is to prevent the influence of the free surface of the liquid on the solid particles that formed the bottom of the storage facility, for which the following condition is usually put forward [4, 5, 6, 10]:

$$H_W^{(4)} - H_S^{(4)} \geq \Delta H_S; \tag{15}$$

$$H_S^{(4)} = H_S^{(0)} + \frac{C_0}{m}\frac{Q_{1,4}}{1{,}1kR^2}, \tag{16}$$

where $H_S^{(4)}$ – height of current storage bottom at the end of May, m; ΔH_S – minimum permissible thickness of liquid layer, which prevents the influence of perturbations of the liquid free surface on solid particles that form interface between the solid and liquid phases, m; $H_S^{(0)}$ – height of the current storage bottom at the end of February last yea, mr.

Substituting formulas (6) and (16) into inequality (15) and performing the necessary transformations, taking into account (11), we obtain the following inequality:

$$Q_{1,4} \geq Q_L' + 1{,}1kR^2\frac{k_H - 1}{1 - 2\frac{C_0'}{m}}\Delta H_S;\ Q_L' = \frac{1 + \frac{k_{1,4}}{k_a}}{1 - 2\frac{C_0}{m}}W_E;\ k_H = \frac{H_W^{(0)} - H_S^{(0)}}{\Delta H_S}, \tag{17}$$

where Q_L' – minimum possible amount of the EW received at the storage facility during the spring months for environmental safety reasons, m^3/h; k_H – safety parameter of the storage operation to prevent the free surface impact on solid particles that formed the storage bottom, the value of which should exceed 1.

Inequality (17) limits from below the volume of the EW that entered the storage facility during the spring months, while from above this value is limited by inequality:

$$H_W^{(0)} - H_W^{(4)} \geq 0, \tag{18}$$

which can be rewritten in the following form:

$$Q_{1,4} \leq Q_L''; \qquad Q_L'' = \left(1 + \frac{k_{1,4}}{k_a}\right)\frac{W_E}{c}, \tag{19}$$

where Q_L'' – maximum possible amount of the EW received at the storage facility during the spring months for environmental safety reasons, m^3/h.

If the reliability factor is introduced, formula (11) helps to move from the inequality to the equation and obtain a dependence for calculating the possible volume of liquid man-made waste that can be removed from the storage facility during the spring months, depending on the volume of the EW received at the storage facility during the year:

$$W_E = \frac{ck_Q Q_{1,12}}{1 + \dfrac{k_{1,12}}{k_a}}, \qquad (20)$$

where k_Q – reliability factor, must exceed one.

Note that, taking into account formulas (1), inequality (11) limits not only the volume of the EW received by the storage facility during the year, but also the capacity of each mining enterprise for sellable concentrates. Based on the properties of algebraic linear combinations and taking into account formulas (1), dependence (8) can be reduced to the following form:

$$Q_{i,j} = \sum_{l=1}^{N} \mu_l \overline{G}_{i,j}^{(l)}; \qquad \overline{G}_{i,j}^{(l)} = \sum_{k=i}^{j} t_k G_l^{(k)}, \qquad (21)$$

where $\overline{G}_{i,j}^{(l)}$ – capacity of the l-th mining enterprise for sellable concentrates for the period between the month with the number i to the month with the number j, m^3/h.

Thus, if condition (11) is not satisfied, i.e., there is an inequality

$$Q_{1,12} > Q_L, \qquad (22)$$

then, taking into account (20) and (21), the equation for determining the reduction of capacities for sellable concentrates of each of mining enterprises that store liquid man-made waste in this storage facility is:

$$\sum_{l=1}^{N} \mu_l \sigma_l \overline{G}_{1,12}^{(l)} = \frac{Q_L}{k_Q}, \qquad (23)$$

where σ_l – capacity reduction factor for sellable concentrates of the l-th mining enterprise.

In case of a reduction in the capacity of sellable concentrates of the mining enterprise, the duration of downtime for the year is:

$$T_l = (1 - \sigma_l) T_*; \qquad T_* = \sum_{k=1}^{12} t_k, \qquad (24)$$

and the corresponding amount of social payments to employees in accordance with current legislation is

$$Z = \frac{2}{3} T_* \sum_{l=1}^{N} (1 - \sigma_l) Z_l M_l, \qquad (25)$$

where T_l – duration of downtime at the l-th mining enterprise per year, h; T_* – annual working time fund, h; Z – total losses from social payments to employees during downtime, m; Z_l – salary of employees of the l-th mining enterprise, m; M_l – is the number of employees of the l-th mining enterprise who do not work in case of downtime.

To determine the optimal σ_l values, equation (23) is considered in conjunction with the minimum requirement (25), which takes into account the social aspect of managing mining enterprises.

An alternative to reducing capacity is also the possibility of storing part of liquid man-made waste within the enterprise industrial area with subsequent discharge to storage facility after or during the spring months. In this case, the volume of liquid man-made waste to be temporarily accumulated within the l-th mining enterprise is determined in proportion to its capacity:

$$\delta Q_l = \mu_l \overline{G}_{1,12}^{(l)} \frac{Q_{1,12} - Q_L}{Q_{1,12}}, \tag{26}$$

where δQ_l – volume of liquid man-made waste to be temporarily accumulated within the boundaries of the l-th mining enterprise, m^3/h.

In a situation where inequality (22) is present, it is possible to take into account not only the capacity of mining enterprises and the number of workers involved in production. One of the most promising methods is to release additional storage capacity for other enterprises for the period of repairs, modernization or installation of new equipment at one of the enterprises.

4. Conclusions

Based on dependencies (1)–(6) and the data in Table 1, taking into account Fig. 1 and Fig. 2, a mathematical model of a liquid waste storage facility that accumulates processing products and mine water from several mining enterprises was obtained, taking into account climatic factors of influence and technological limitations on waste volumes. This model makes it possible to determine the level of the free surface mirror in any month of the year (formula (6)), as well as calculate the change in the current height of the water mirror in the storage facility for any period of the year, for example, during the spring months or for the entire year (formulas (7) and (8)). Based on these formulas and environmental safety requirements for the operation of artificial storage facilities for mineral processing waste, Table 2 and formulas (11), (13), (17) and (19), we obtained restrictions on the amount of waste received by the storage facility during the year or during the spring months. The use of these restrictions makes it possible to determine and justify the rational values of capacities for sellable concentrates of mining enterprises, the duration of their downtime for a certain period of the year (formulas (23)–(26)).

Thus, we formulated scientifically based conditions for environmentally safe operation of the liquid man-made waste storage facility; restrictions on the regulated decrease in the water mirror height in the storage facility during the year were determined, and the maximum possible volume of EW received in the storage facility during the spring months and during the year was calculated for environmental safety reasons; the possible volume of liquid man-made waste that is removed from storage during the spring months depending on the volume of EW received in storage during the year was estimated; methodological foundations for determining the amount of reduction in capacity for sellable concentrates of each of the mining enterprises that store liquid man-made waste in this storage facility or the corresponding duration of downtime were created; the possibility of storing part of the liquid man-made waste within the industrial area of the enterprise with subsequent discharge to the storage facility after or during the spring months was substantiated.

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ОБҐРУНТУВАННЯ ЕКОЛОГІЧНО БЕЗПЕЧНИХ РЕЖИМІВ ТА ПАРАМЕТРІВ ЕКСПЛУАТАЦІЇ СХОВИЩ ВІДХОДІВ ПЕРЕРОБКИ МІНЕРАЛЬНОЇ СИРОВИНИ

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Анотація. Предметом дослідження є режими та параметри експлуатації сховищ відходів переробки мінеральної сировини. Розглядаються сховище рідких відходів, яке акумулює продукти переробки та шахтні води з декількох гірничих підприємств, з врахуванням кліматичних факторів впливу, технологічних обмежень на обсяги відходів. Аналіз основних результатів досліджень доводить, що екологічна безпека при експлуатації сховищ відходів базується на двох принципах: запобігання переливу відходів через краї дамб обвалування та забезпечення захисного шару рідини над дном, який утворено з частинок пилуватих та глинистих фракції. Мета роботи полягає в науковому обґрунтованому визначені можливих з точки зору екологічної безпеки режимів експлуатації сховища рідких відходів збагачення та видобутку мінеральної сировини та створенню методів розрахунку їх максимально можливих обсяг, що надходять до сховища протягом року. При дослідженні використовуються методологія логістичних систем, в межах якої сховище розглядається як вузол акумуляції, а його модель включає в себе систему рівнянь, що описують висоту дзеркала води і рівня дна в залежності від обсягів розсипів і води, що потрапило до нього і відібрані з нього за аналізований період експлуатації, з урахуванням геометричних особливостей чаші сховища. В результаті створено математичну модель сховища рідких відходів, яке акумулює продукти переробки та шахтні води з декількох гірничих підприємств, з врахуванням кліматичних факторів впливу, технологічних обмежень на обсяги відходів. Ця модель дозволяє визначати рівень дзеркала вільної поверхні в будь-який місяць року, а також розраховувати змінення поточної висоти дзеркала води у сховищі за будь-який проміжок часу. На основі цих формул, та вимог екологічної безпеки при експлуатації штучних сховищ відходів переробки мінеральної сировини отримано обмеження на обсяг відходів, що надійшов до сховища, протягом року, або протягом весняних місяців. Використання цих обмежень дозволило визначати та обґрунтовувати раціональні значення потужностей по товарним концентратам гірничих підприємств, тривалості їх простоїв за певний період року.

Ключові слова: сховища відходів переробки мінеральної сировини, висота дзеркала води, екологічна безпека експлуатації.