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Ecological consequences of the catastrophic destruction of the Kakhovka reservoir dam

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ABSTRACT

Formulation of the problem. The relevance is due to the need detail physical and mathematical modeling to the ecological consequences of the destruction of the Kakhovka Reservoir dam (Kherson region, Ukraine) on June 6, 2023.

Purpose. Determination of the ecological consequences by numerical modeling of the parameters of unregulated release of super-strong water flow that occurred as a result of the destruction of the Kakhovka Reservoir dam.

Methods. Multi-factor analysis, mathematical simulation, analytical and numerical calculations.

Results. For the first time, mathematical 1D, 2D and 3D models dynamics of water flow from the Kakhovka Reservoir have been developed, which make it possible to assess the ecological consequences of flooding large territorials of the country. Relationships were obtained to estimate the potential energy of the water mass in the reservoir, the kinetic energy of the water flow, the height of the level and mass of water in the reservoir, flow speed, and water outflow rate. These relationships were used to assess the consequences of the disaster. The developed methodology can be used to predict the consequences of dam damage on other rivers and reservoirs. Numerical modeling of the dynamics of the main parameters of the water flow from the destroyed Kakhovka Reservoir was carried out. It was established that in about ten days the height of the water column in the reservoir decreased by more than an order of magnitude, the flow speed by about 4 times, the volume by 45 times, water flow by almost two orders of magnitude, the flow power and potential energy of water in the reservoir by almost three orders of magnitude. The reservoir lost approximately 18 Gt of water. A territory of 650 km^2 was flooded. The height of the water column in the vicinity of the dam reached 10 m, and at a distance of ~80 km it reached 5 m. The initial speed of water flow below the dam was close to 10 m/s. This speed remained at a distance of ~80 km from the dam, which contributed to the rapid onset and inevitability of the disaster, which took place late at night (about 03 h). The environmental consequences of the world's largest man-made disaster in decades were very significant. Some consequences will be observed for ~10 years or more. It can be argued that the ecosystems of Ukraine have suffered irreparable damage that qualifies as ecocide.

Conclusions. The results obtained indicate that the consequences of the destruction of the Kakhovka dam were catastrophic for the ecological situation of the region, hydropower, water supply, fisheries and agriculture, etc.

Keywords: *Kakhovske reservoir, dam destruction, water flow, mathematical model, water outflow, outflow rate, energy characteristics.*

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Introduction. The Kakhovka hydroelectric power station (HPP) was built in 1956 in the Dnieper riverbed [1]. Its electrical power was 335 MW. The operation of the HPP was ensured by a reservoir stretching from Zaporizhzhia to Kherson regions. In addition to its energy function, the reservoir was of great household importance. It contained 40% of the fresh water of Ukraine. The reservoir was used for irrigation of arid lands, water supply to Kryvyi Rih, Marhanets and other populated areas, cooling of equipment of the Zaporizhzhia Nuclear Power Plant (NPP), fisheries, and water transport.

On June 6, 2023, as a result of the actions of the aggressor, the Kakhovka reservoir dam was destroyed, which was preceded by two powerful explosions at 02:35 and 02:54 Kyiv time. These explosions were recorded by technical means of the Main Center of Special Monitoring of the State Space Agency of Ukraine [https://gcsk.gov.ua]. According to the authors' estimates, the energy release of the second, more powerful explosion was 0.5–15 t of standard explosive (TNT, trinitrotoluene).

The explosions led to the instant destruction of the dam, rapid water flow, flooding of large areas that were located along the Dnieper below the reservoir and a terrifying ecological disaster [2–28].

The paper [2] is devoted to a qualitative analysis of the consequences of the Kakhovka dam destruction. The ecological problems that arose after the Kakhovske reservoir depletion is partially described in the papers [3-5, 7, 8, 23, 24, 26, 27].

The results of multi-temporal Interferometric Synthetic Aperture Radar monitoring of the Kakhovka dam are presented in [21].

The authors of [23] have estimated 35962 m^3/s of peak discharge from the 300-meter dam breach scenario and the flood extent (823 km^2) from this scenario also matched with the actual situation as observed by remote sensing data. These estimations help in understanding and managing the risks associated with structural failures. The findings in paper [22] highlight safety and risk-reduction measures pivotal in avoiding such scenarios.

The study [24] aims to address knowledge gaps related to the event by employing multi-temporal change detection of pre- and post-event Sentinel-1 synthetic aperture radar imagery, analyzed using the Google Earth Engine platform, to map flood extent and impacts.

The results of the studies devoted to the consequences of the Kakhovka dam destruction and the emptying of the Kakhovske reservoir are presented in [3-5]. The water regime of the lower reaches of the Dnipro River was studied, in particular, the water temperature. The remote sensing data on spatial features of water temperature are given. Significant changes in water temperature are shown in the lower reaches of the Dnipro River and in the former Kakhovske reservoir.

In study [25], a unique operational system for estimating irrigation water using data from satellite soil moisture, reanalysis precipitation, and potential evaporation, have been created. As a proof of concept, the authors implemented the method at a 1 km resolution during the period of 2015–2023 over the area south of the Kakhovka Dam in Ukraine, which collapsed on 6 June 2023.

All of the above papers [6-20] are of a descriptive and informative nature. In order to be able to fully assess the ecological consequences of the disaster, it is necessary to quantitatively model the situation and provide a mathematical justification and description for it. Scientific research of this kind has not been carried out and, subsequently, there are still no models of the parameters of an unregulated super-powerful water flow from a huge reservoir. To date, this disaster is considered the largest in Europe in recent times. The modeling results are intended not only to explain the horrific consequences of the disaster, but also to assess the possible consequences of other catastrophic dam failures on large rivers.

The state of the Kakhovske reservoir before and after destruction is shown in Fig. 1.

The purpose of the study is to determine the ecological consequences by numerical modeling of the parameters of unregulated release of super-powerful water flow that occurred as a result of the Kakhovka reservoir dam destruction. For this purpose, two-dimensional and three-dimensional modeling of water flow parameters was carried out and its main parameters were calculated.

Information on the Kakhovske reservoir. According to the project, the length of the Kakhovske reservoir was $L \approx 230$ km, and the width l varied from ~5 to ~30 km [2]. The total area of the reservoir was $S_0 = 2155$ km^2. The initial height of water column was $h_0 \approx 16–17$ m. With an initial volume of water $V_0 \approx 18.1$ km^3 the mass of water was $m_0 \approx 1.8 \cdot 10^{13}$ kg. According to the authors' estimates, the initial potential energy of water in the reservoir, calculated by the formula:

$$E_{p0} \approx \frac{1}{2} m_0 g h_0,$$

reached $E_{p0} \approx 1.4$ PJ ≈ 337 kt of TNT. Here g is gravitational acceleration. Initial water flow speed

$$v_0 \approx \sqrt{g h_0}$$

at $h_0 \approx 16.5$ m was 12.7 m/s.

After the destruction of the dam, which had a length of 447 m and a maximum height of 29 m, the water level in the reservoir initially was decreasing by $\Delta h \approx 0.15$ m every hour. This makes it possible using the known values of $\Delta h/\Delta t$ and v_0 to estimate the cross-sectional area S_{10} of the water flow from the following relation:

$$\frac{dm}{dt} = \rho S_0 \frac{dh}{dt} = -\rho S_{10} v_0$$

or

$$\rho S_0 \frac{\Delta h}{\Delta t} \approx -\rho S_{10} v_0.$$

Hence, with $\Delta h/\Delta t \approx -4.17 \cdot 10^{-5}$ m/s and $v_0 = 12.7$ m/s we have $S_{10} = 7.1 \cdot 10^3$ m^2.

The main indicator for assessing catastrophic consequences and the impact on the ecological situation of the region should be considered the power of the water flow. The initial power of the water flow was calculated according to the formula:

$$P_{k0} = \frac{1}{2} v_0^2 \left|\frac{dm}{dt}\right| \approx \frac{1}{2} v_0^2 \rho S_0 \left|\frac{\Delta h}{\Delta t}\right| \approx \frac{1}{2} \rho S_{10} v_0^3 \approx 7.3 \text{ GW}.$$

To compare and evaluate the strength and power of a certain water flow, we point out that such power corresponds to the power of 7–8 power units of a typical NPP.

The initial water outflow rate can be estimated as follows:

Fig. 1. Kakhovske reservoir before (above) and after the disaster (according to [https://grivna.ua/publikatsii/kahovska-ges:-yak-use-pochinalosya-velike-budivnictvo-stalinskoyi-epohi-%28foto%29])

$$\left(\frac{dm}{dt}\right)_0 \approx \left(\frac{\Delta m}{\Delta t}\right)_0 = -\rho S_{10} v_0.$$

Calculations showed that it was –90 kt/s, and the volumetric water outflow rate $\Delta V/\Delta t$ was $9\cdot 10^4$ m^3/s. At the same time, reference data on average water flow rate of the largest rivers of Ukraine are known: for Dniester it is $3.1\cdot 10^2$ m^3/s, for Dnieper it is $1.67\cdot 10^3$ m^3/s, and for Danube it is $6.43\cdot 10^3$ m^3/s. A comparison of these characteristics indicates that the parameters of the water flow from the destroyed Kakhovske reservoir were practically catastrophic and environmentally dangerous for the entire region, both land and other hydrographic objects, including the Dnieper-Bug estuary, the Black Sea coast and the Black Sea itself (the quality of its water, Black Sea flora and fauna). The water level in the flooded areas increased until June 09, 2023, on this day it reached its maximum, and then gradually decreased. The width of the Dnieper has increased in some places to 10 km. For example, the water level in the Dnieper in the city of Kherson, which is located at a distance of approximately 80 km from the Kakhovka dam, increased by 5.37 m. The Inhulets River overflowed its banks.

Results of modeling. The initial equations describing the water flow from the destroyed Kakhovske reservoir are the equations for the flow speed $v(h)$, the current mass m or the current volume of water $V(h)$ in the reservoir and the water outflow rate $dm(h)/dt$ as a result of a leakage:

$$v = \sqrt{gh}, \tag{1}$$

$$m = \int_V \rho dV = \rho \int_0^L dL \int_0^l dl \int_0^{h_0} dh,$$

$$\frac{dm}{dt} = -\rho S_1 v, \tag{2}$$

where $L = L(h)$, $l = l(h)$, $m = m(h)$, $S_1 = S_1(h)$.

If the area of the mirror water surface $S(h) = S_0$, then we have a one-dimensional model (1D model):

$$V_0 = V_0 \frac{h}{h_0}, \qquad m = m_0 \frac{h}{h_0},$$

where the index «0» refers to the initial volume, initial mass and height of the water column, and without the index to the current values of these parameters.

The simplest (1D) model of a reservoir is a rectangular parallelepiped of length L, width l and height h. In fact, when water leaks, the length L and width l of the mirror water surface also decrease with decreasing height of the water column h. Since L >> l, one can first assume that L(h) ≈ L0, and l = l(h). Such a model is two-dimensional (2D model). In a three-dimensional (3D) model L = L(h), l = l(h). Knowing these dependencies, it is possible to calculate the dependence of the volume of water on the height of the water column, that is, V = V(h), and then other parameters of the water flow.

Let us obtain the relation for $l(h)$. To do this, consider a cross section of the reservoir (Fig. 2).

Let the bottom profile be described by the relationship

$$h = h_0 \left(\frac{l}{l_0}\right)^{\alpha},$$

where $l_0 = l(h_0)$, α is the flatness index of the reservoir bottom to be determined. At the same time

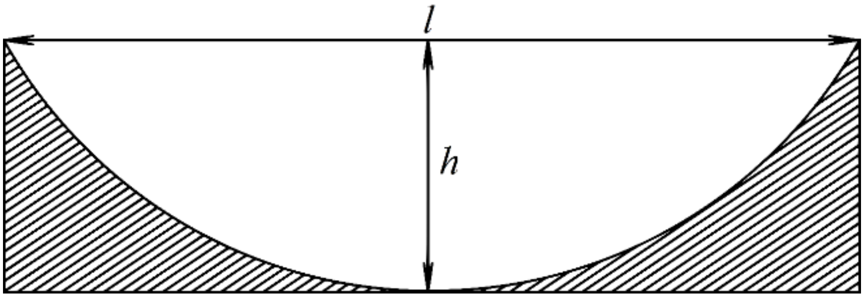

Fig. 2. Cross-section model of the reservoir

$$l = l_0\left(\frac{h}{h_0}\right)^{1/\alpha} = l_0 H^{1/\alpha}, \qquad (3)$$

$$H = \frac{h}{h_0}.$$

The area of the shaded figure shown in the Appendix under the $h(l)$ curve is given by the relation

$$S_{l1} = 2\int_0^h h\,dl = \frac{2}{\alpha} l_0 h_0 \int_0^H H^{1/\alpha} dH = \frac{2}{1+\alpha} l_0 h_0 H^{1+1/\alpha}.$$

The area of a rectangle of width l and height h is equal to $S_{l2} = lh$. Then the cross-sectional area of the reservoir:

$$S_l = S_{l2} - S_{l1} = \frac{\alpha-1}{\alpha+1} l_0 h_0 H^{1+1/\alpha}. \qquad (4)$$

Hence

$$S_{l0} = S_l(h_0) = \frac{\alpha-1}{\alpha+1} l_0 h_0, \qquad (5)$$

and the initial volume of water in the reservoir is determined by the formula

$$V_0 = S_l(h_0) L_0 = \frac{\alpha-1}{\alpha+1} L_0 l_0 h_0 = \frac{\alpha-1}{\alpha+1} S_0 h_0, \qquad (6)$$

where $L_0 l_0 = S_0$. From (6) we find that $\alpha \approx 3.21$.

It should be taken into account that in this approximation it follows from (4) and (5) that

$$\frac{V(h)}{V_0} = \frac{S_l(h)}{S_{l0}} = H^{1+1/\alpha}, \qquad (7)$$

From equation (2) taking into account the fact that $S_1(h) = S_{10}H$, (1) and (7) we have:

$$\rho V_0\left(1 + \frac{1}{\alpha}\right) H^{1/\alpha} \frac{dH}{dt} = -\rho S_{10} v_0 H^{3/2}, \quad H(0) = 1. \qquad (8)$$

The solution to (8) is given by the following relation:

$$H = \left(1 + \frac{t}{\tau}\right)^{-2\alpha/(\alpha-2)}, \qquad (9)$$

$$\tau = \frac{2V_0}{S_{10} v_0} \frac{\alpha+1}{\alpha-2},$$

here τ is the characteristic time of the reservoir depletion.

For $\alpha \approx 3.21$ we get $\tau \approx 1.4 \cdot 10^6$ s ≈ 16 days. In this case, from (9), we have:

$$H = \left(1 + \frac{t}{16}\right)^{-5.3}.$$

In the limiting case, when $l(h) = l_0$, from (9) we obtain for the 1D model:

$$H = \left(1 + \frac{t}{\tau}\right)^{-2}, \ \tau = 4.6 \text{ days}. \qquad (10)$$

Knowing dependence (9), it is possible to calculate other main parameters of the water flow:

$$v = v_0 H^{1/2}, \qquad (11)$$

$$\frac{m}{m_0} = H^{1+1/\alpha}, \qquad (12)$$

$$\frac{dm}{dt} = -\rho S_{10} v_0 H^{3/2}, \qquad (13)$$

$$E_p = \frac{1}{2} mgh = E_{p0} H^{2+1/\alpha}, \qquad (14)$$

$$P_k = \frac{1}{2} \rho S_{10} v_0^3 H^{5/2} = P_{k0} H^{5/2}. \qquad (15)$$

Here E_p is the potential energy of water in the reservoir, P_k is the power of water flow. The water deficit in the reservoir can be determined from the equation

$$\Delta m = m_0 - m = m_0\left(1 - H^{1+1/\alpha}\right). \qquad (16)$$

Results of calculations of the dependence of the water flow main parameters (relative water level (H), water level (h), water flow speed (v), relative mass of water in the reservoir (m/m_0), water deficit in the reservoir (Δm), water outflow rate (dm/dt), water flow power (P_k) and potential energy of water mass (E_p)) versus time, counted from the moment of the Kakhovka dam destruction, are shown in Figs. 3–10.

Next, we take into account the approximate dependence of the reservoir length L on its depth, that is $L(h)$. Such a model is a three-dimensional one (3D model). By analogy with expression (3), we will assume that

$$L = L_0\left(\frac{h}{h_0}\right)^{1/\beta} = L_0 H^{1/\beta}. \qquad (17)$$

According to our estimates, the exponent characterizing the flatness of the reservoir bottom in the longitudinal direction is $\beta \approx 10$. Then the equation for the relative height of the water column $H(t)$ taking into account the water outflow rate (2), the bottom profile in two directions (3) and (17) has the form:

$$\rho V_0 (1 + \gamma) H^{\gamma} \frac{dH}{dt} = -\rho S_{10} v_0 H^{3/2}, \qquad H(0) = 1. \qquad (18)$$

It is taken into account here that the dependence of the volume of water on the height of the water column has the form:

$$V = V_0 H^{1+\gamma},$$

where a dimensionless parameter that describes the bottom profile in two directions

$$\gamma = \frac{1}{\alpha} + \frac{1}{\beta}.$$

The solution to equation (18) is given by the following relation:

$$H = (1 + \frac{t}{\tau})^{1/(\gamma - 0.5)}, \quad (19)$$

$$\tau = \frac{V_0}{S_{10} v_0} \frac{1+\gamma}{0.5-\gamma}. \quad (20)$$

Dependence (19) is the basic one. It is used to determine the temporal dependencies of all other parameters of the water flow. Temporal variations in the relative height of the water column in the reservoir $H(t)$ depend on the dimensionless parameter γ, which characterizes the profile of the reservoir bottom. Thus, for $\gamma < 0.5$ we have

$$H = \frac{1}{(1+t/\tau)^{1/(0.5-\gamma)}}.$$

In particular, for $\alpha = 3.21$, $\beta = 10$ we have $\gamma \approx 0.41$, characteristic time $\tau \approx 3.15 \cdot 10^6$ s ≈ 36 days, describing the water flow dynamics.

If $\gamma > 0.5$, then

$$H = (1 - \frac{t}{\tau})^{1/(\gamma - 0.5)},$$

where

$$\tau = \frac{V_0}{S_{10} v_0} \frac{1+\gamma}{\gamma - 0.5}.$$

For example, for $\gamma = 0.6$ we obtain practically the same characteristic time $\tau \approx 36.8$ days.

In the case where $\gamma = 0.5$ the temporal dependence has the simplest form:

$$H(t) = e^{-2t/3\tau},$$

where

$$\tau = \frac{V_0}{S_{10} v_0} \approx 2 \cdot 10^5 \approx 2.3 \text{ days}. \quad (21)$$

From the given estimates of the characteristic time it is clear that it significantly depends on the bottom profile. The characteristic time of reservoir depletion is given by the relation (21). It is determined by the initial values of the reservoir volume, speed and cross-sectional area of the water flow.

Having relation (19), characteristic time τ and parameter γ, it is possible to calculate the main parameters of the water flow (height of the water column in the reservoir h, flow speed v, relative mass of water in the reservoir m/m_0, water deficit in the reservoir Δm, water mass outflow dm/dt, power of water flow P_k, and potential energy of water mass E_p) according to equations (9), (11)–(16).

Let us compare the values of $H = h/h_0$ for three (1D, 2D, and 3D) models of water flow parameters given by relations (10), (9) and (19) (H_1, H_2, and H_3, respectively) (Table 1). As can be seen from the results presented in Table 1, the difference in the relative height (H) values given by different models usually does not exceed 10–20%. This means that all three models satisfactorily describe the dynamics of water flow.

Results of calculations of the main parameters of water flow for the 3D model (19) using relationships

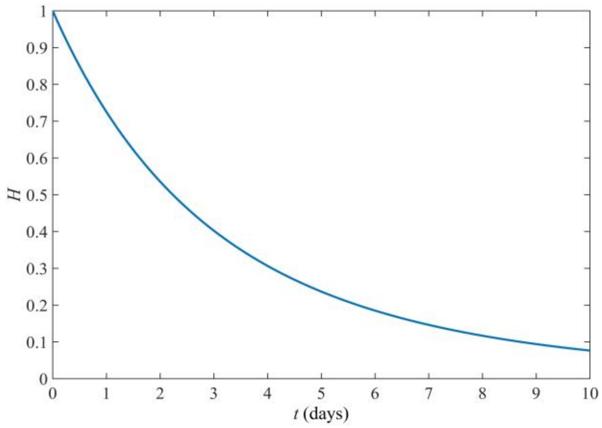

Fig. 3. Temporal dependence of the relative water level in the Kakhovske reservoir

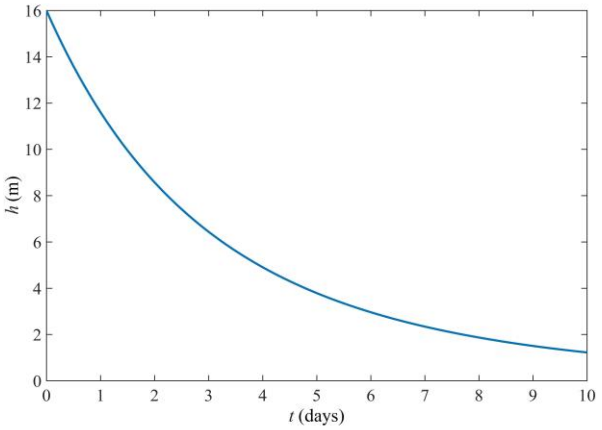

Fig. 4. Temporal dependence of the water level in the Kakhovske reservoir

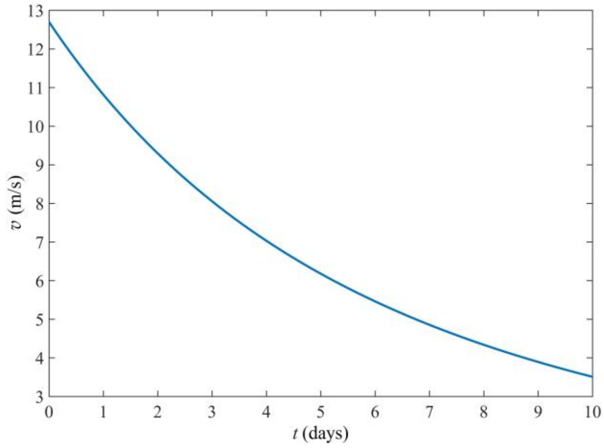

Fig. 5. Time dependence of the water flow speed from the Kakhovske reservoir

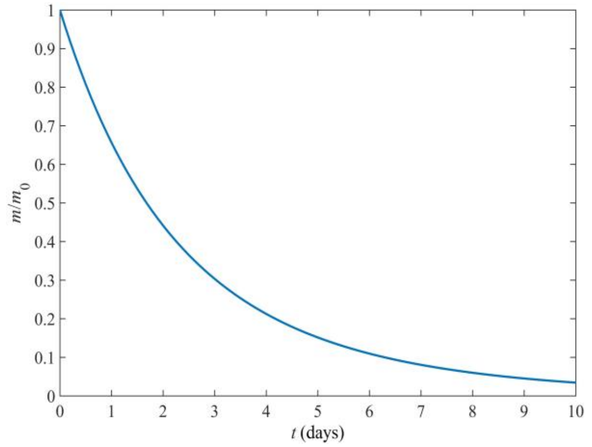

Fig. 6. Temporal dependence of the relative mass of water in the Kakhovske reservoir

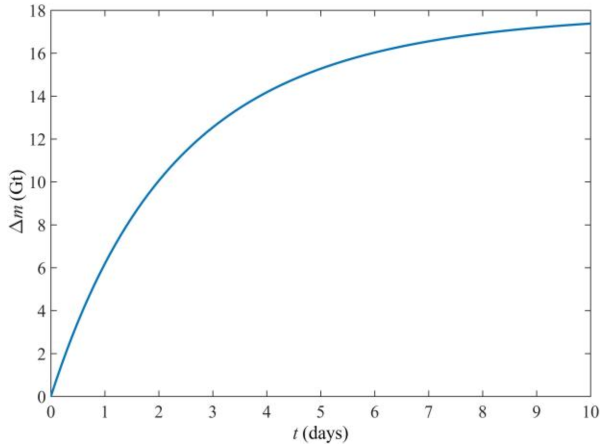

Fig. 7. Temporal dependence of water deficit in the Kakhovske reservoir

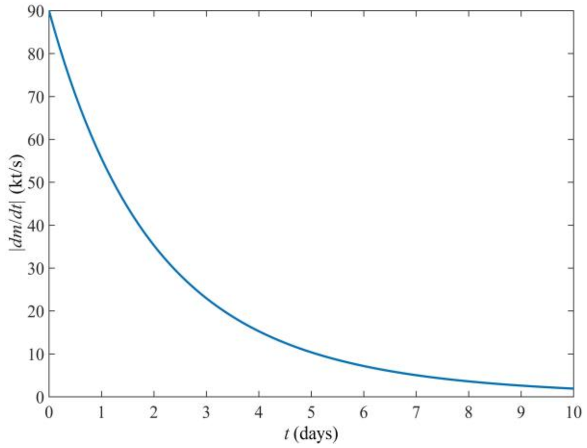

Fig. 8. Temporal dependence of the water flow modulus in the Kakhovske reservoir

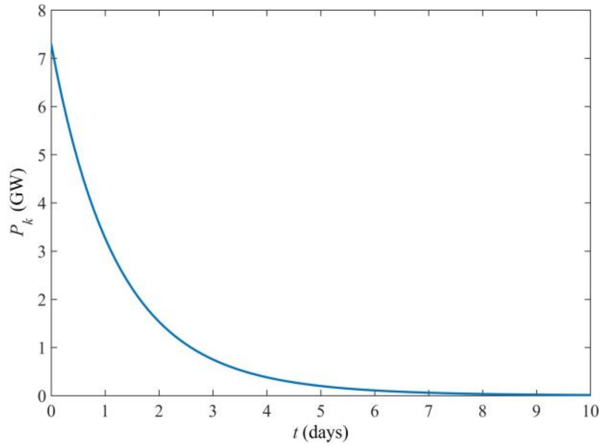

Fig. 9. Temporal dependence of the power of water flow from the Kakhovske reservoir

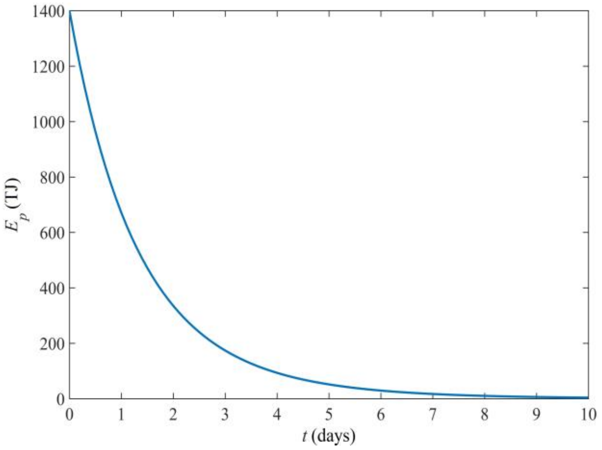

Fig. 10. Temporal dependence of the potential energy of water mass in the Kakhovske reservoir

for water flow speed (11), water outflow rate (13), water flow power (15) and relative mass of water in the reservoir

$$\frac{m}{m_0} = H^{1+\gamma} = (1 + \frac{t}{\tau})^{\frac{\gamma+1}{\gamma-0.5}},$$

water deficit in the reservoir

$$\Delta m = m_0(1 - H^{1+\gamma}) = m_0[1 - (1 + \frac{t}{\tau})^{\frac{\gamma+1}{\gamma-0.5}}]$$

and potential energy of the water mass in the reservoir

$$E_p = E_{p_0} H^{\gamma+2} = E_{p_0}(1 + \frac{t}{\tau})^{\frac{\gamma+2}{\gamma-0.5}}$$

are given in Table 2. The data in Table 2 show that over 10 days, the height of the water column in the reservoir decreased from 16 to ~1 m, the water outflow speed from 12.7 to 3.4 m/s, the mass of water from 18 to ~0.4 Gt, water outflow rate from 90 to 1.7 kt/s, water flow power from 7.3 to 0.01 GW, and energy E_p decreased from 1400 to ~2 TJ. Thus, the re-

Table 1

Temporal dependence of the relative height of the water column in the Kakhovske reservoir for three models (1D, 2D and 3D)

Number of days	Relative height of the water column		
	H_1	H_2	H_3
1	0.67	0.73	0.74
2	0.49	0.53	0.55
3	0.39	0.40	0.42
4	0.29	0.31	0.31
5	0.23	0.24	0.24
6	0.19	0.18	0.18
7	0.16	0.15	0.14
8	0.13	0.12	0.11
9	0.11	0.09	0.09
10	0.10	0.08	0.07

Table 2

Main parameters of water flow from the destroyed Kakhovka dam

Number of days	Main parameters of water flow						
	Height h, m	Speed v, m/s	Relative mass m/m_0	Mass deficit Δm, Gt	Outflow rate $\lvert dm/dt \rvert$, kt/s	Flow power P_k, GW	Potential energy E_p, TJ
0	16	12.7	1	0	90	7.30	1400
1	11.8	10.9	0.65	6.3	57.3	3.44	678
2	8.8	9.4	0.43	10.3	36.7	1.64	331
3	6.7	8.2	0.29	12.8	24.5	0.84	173
4	5.0	7.1	0.19	14.6	15.5	0.39	83
5	3.7	6.2	0.13	15.7	10.6	0.21	45
6	2.9	5.4	0.09	16.4	6.9	0.10	22.5
7	2.2	4.8	0.06	16.9	4.7	0.055	12.3
8	1.8	4.2	0.04	17.3	3.3	0.03	6.9
9	1.4	3.8	0.03	17.5	2.4	0.02	4.2
10	1.1	3.4	0.02	17.6	1.7	0.01	2.3

sults of mathematical modeling and calculations show that in approximately 18 days, that is, on June 24, 2023, the unregulated water flow from the reservoir stopped. By the end of June 2023, the Kakhovske reservoir ceased to exist [2].

The next stage of the research was the assessment of flooding parameters. In approximately 200 s, the water flow traveled a distance from the nearest village (Kozats'ke village) $R \approx 2$ km. This means that its speed was $w \approx 10$ m/s. Since

$$\frac{dV}{dt} \approx S_w w \approx l_w h_w w,$$

where S_w is the cross-sectional area, l_w is the width, and height h_w of the water flow in the vicinity below the Kakhovka dam, then with a volumetric water outflow rate $dV/dt \approx 9 \cdot 10^4$ m^3/s, a flow width $l_w \approx 1$ km, we have a flow height $h_w \approx 9$ m.

It is known that the water flow from the reservoir reached the city of Kherson ($R \approx 80$ km) in about 2 hours [2]. In this case, the water flow speed $w \approx 10$ m/s. The initial flooding rate was 0.2–0.3 m/h. The average flooding rate was close to 0.1 m/h. Over the course of two days, the height of the water column in the city reached $\Delta h \approx 5$ m. During this time, the water flow rate decreased almost three times and the value of Δh was gradually decreasing almost exponentially:

$$\Delta h = \Delta h_0 e^{-t/t_1},$$

where $\Delta h_0 \approx 5$ m at the beginning of June 08, 2023, $t_1 \approx 7$–8 days. These estimates are in good agreement with the observational data [2, 3].

Mathematical modeling and numerical calculations showed that the potential energy of the water mass in the reservoir was 28 times higher than the energy release during the explosion of a nuclear bomb over Hiroshima. The power of the water flow reached the power of 7–8 NPP units. The initial speed of the water flow was close to 13 m/s, the water outflow rate was many times higher than the water outflow rate in the most powerful rivers and the strongest waterfalls. All this could not help leading to catastrophic consequences in the ecosystems located below the Kakhovske reservoir. There were also catastrophic consequences for what remained of the reservoir.

Ecological consequences of the Kakhovka reservoir dam catastrophic destruction. The results of mathematical modeling of water flow parameters from the reservoir showed that they were catastrophic. The destruction of the Kakhovka reservoir dam simply could not help causing very serious consequences and environmental hazards (and not only environmental).

The research and mathematical modeling carried out made it possible to substantiate the classification of the ecological consequences of the disaster by time. The following three categories are proposed: short-term, medium-term and long-term consequences.

The short-term consequences of the ecological situation lasted from the beginning of the disaster to ~10 days, that is, until the reservoir was empty. At the same time, nearby areas continued to be flooded. Infrastructure facilities in the territory were flooded, such as residential buildings, gas stations, landfills, sewers, cattle burial grounds, cemeteries and burial grounds, etc. 650 tons of petroleum products spilled into the water. More than 75 people and a large number of domestic and wild animals died. The flooding was accompanied by pollution of the Dnieper-Bug estuary and, finally, the Black Sea. The area of pollution was 7300 km^2 [2], dirt propagation speed was ~1 m/s. Flooding significantly affected the biodiversity in the Dnieper floodplain. The salinity of sea water in the northern part of the Black Sea decreased by 3–3.5 times (from 12–14 g/l to 4 g/l) [2]. The concentration of toxic substances (Cu, Zn, As, organochlorines, petroleum products) increased significantly [2].

Medium-term ecological consequences lasted from ~1 month to many months. They began with the complete depletion of the Kakhovske reservoir, the destruction of the water supply system of the cities of Kryvyi Rih, Marhanets, Berislav, Enerhodar and other settlements, where about 1 million inhabitants live, and the destruction of 31 irrigation systems in three regions (Dnipropetrovsk, Zaporizhzhia and Kherson). Problems arose with cooling the equipment of the Zaporizhzhia NPP. On an area of 584 km^2 arable land has been significantly damaged as a result of the washout of the top fertile soil layer, therefore, there will be a noticeable decrease in the area of productive soils, which means that the parameters of land productivity in the region will decrease significantly. There have been significant losses to the fisheries industry. A threat has arisen to the existence and preservation of especially valuable ecosystems. These include the Nyzhn′odniprovs′kyy National Park, the Black Sea Biosphere Reserve, the Kinburn Spit, etc. Certain consequences are caused by active processes of eutrophication in water bodies. Other biohazardous consequences are caused by the decomposition of the remains of shellfish weighing 500 thousand tons remaining at the bottom of the former Kakhovske reservoir [28].

Long-term consequences (from ~0.5 to 10 years or more) are associated with the exposure and drying of the bottom of the former reservoir, which contained large amounts of pollutants, heavy metals, radioactive elements, etc. These substances can enter the atmosphere, be transported by wind currents over significant distances, and finally appear in the food chain [29]. Irrigation systems have been destroyed over an area of 5840 km^2 [27], which will most likely ultimately lead to desertification, and this in turn will affect the intensity of dust storms. Eventually this will lead to significant climate change. Flooding can lead to the activation of dangerous geological processes. Flooding and emptying of the reservoir had a negative impact on land use in certain regions of the Dnipropetrovsk, Zaporizhzhia, Kherson and Mykolaiv regions.

Discussion. The modeling carried out in the paper showed that the destruction of the Kakhovka dam led to the release of an unregulated water flow with an initial power of about 7.3 GW, an initial water flow rate of $9\cdot10^4$ m^3/s, while the water flow of the Dnieper River was on average $1.7\cdot10^3$ m^3/s, that is, they were 53 times less. A powerful water flow about 10 m high led to flooding of large areas. The area of the mirror water surface was about 650 km^2. In approximately 1 day, the flow reached the Dnieper-Bug estuary, and in 2 days it reached the Odessa seaport. The flooding situation more or less stabilized in ~10–15 days. During this time, the reservoir lost most of its water volume. Its area decreased from 2155 to 261 km^2, that is, by 88%.

The total area of flooded lands is given in Table 3. The data presented in Table 3 shows that grassy wetlands, forests, meadows and pastures were most affected.

Table 3

Territorial distribution of lands in the flood zone as a result of the destruction of the Kakhovka HPP dam [27]

Land distribution	Area, ha	Relative area, %
Total	65004	100
Grassy wetlands	32473	50
Forests	13577	20.9
Meadows, pastures	12177	18.7
Buildings	4088	6.3
Arable land	3606	4
Other	82	0.1

The flooding led to a number of catastrophic ecological consequences: more than 75 people and a large number of wild and domestic animals died, buildings, industrial facilities, roads, arable land, etc. were damaged. Landfills, sewers, cattle burial grounds, and cemeteries were flooded, which became a biohazardous phenomenon in the region. The remains ended up in the Dnieper, Dnieper-Bug estuary and the Black Sea. The sanitary and epidemiological condition of the adjacent territories has significantly deteriorated.

The destruction of the Kakhovka dam led to short-term, medium-term and long-term socio-ecological, biohazardous, negative sanitary and hygienic consequences, the significance of which remains to be determined. Now we can already state that they are catastrophic. There was a real ecocide. Nothing like this has happened in the world for decades.

Main results. 1. For the first time, a methodology has been developed for quantitative analysis of dynamic processes during the unregulated release of large masses of water from damaged dams. Simple analytical two- and three-dimensional models of water flow parameters from the destroyed Kakhovske reservoir have been proposed. Relationships were obtained to estimate the potential energy of the water mass in the reservoir, the kinetic energy of the water flow, the height of the level and mass of water in the reservoir, flow speed, and water outflow. These relationships were used to assess the consequences of the disaster. The developed methodology can be used to predict the consequences of dam damage on other rivers and reservoirs.

2. Numerical modeling of the dynamics of the main parameters of water flow from the destroyed Kakhovske reservoir was carried out. It was established that in about ten days the height of the water column in the reservoir decreased by more than an order of magnitude, the flow speed by about 4 times, the volume by 45 times, water outflow rate by almost two orders of magnitude, the flow power and potential energy of water in the reservoir by almost by three orders of magnitude.

3. The reservoir lost approximately 18 Gt of water. An area of 650 km^2 was flooded. The height of the water column in the vicinity of the dam reached 10 m, and at a distance of ~80 km it was 5 m. The initial speed of the water flow below the dam was close to 10 m/s. This speed was maintained at a distance of ~80 km from the dam, which contributed to the rapid onset and inevitability of the disaster that took place in the dead of night (about 03:00).

4. The ecological consequences of the worst man-made disaster in decades were very significant. Certain consequences will be observed for ~10 years or more. It can be argued that irreparable damage has been caused to ecosystems, which is classified as ecocide.

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Екологічні наслідки катастрофічного руйнування греблі Каховського водосховища

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Актуальність обумовлена необхідністю детального фізико-математичного моделювання для кількісної оцінки жахливих екологічних наслідків катастрофічного руйнування греблі Каховського водосховища (Херсонська область, Україна) 06 червня 2023 р. Метою роботи є визначення екологічних наслідків шляхом числового моделювання параметрів нерегульованого скиду надпотужного водного потоку, що стався внаслідок руйнування греблі Каховського водосховища. Для досягнення мети використовувалися багатофакторний аналіз, математичне моделювання, аналітичні та числові розрахунки. Головні результати полягають у наступному. Вперше розроблено математичні 1D, 2D- та 3D-моделі динаміки водного потоку з Каховського водосховища, що дозволяють оцінити екологічні наслідки затоплення значних територій країни. Проведено обчислення часових залежностей основних параметрів водного потоку зі зруйнованого Каховського водосховища. Встановлено, що приблизно за десять діб висота стовпа води у водосховищі зменшилася більше, ніж на порядок, швидкість потоку – приблизно у 4 рази, об'єм – у 45 разів, витрати води – майже на два порядки, потужність потоку та потенціальна енергія води у водосховищі – майже на три порядки. Водосховище втратило близько 18 Гт води. Була затоплена територія площею у 650 км^2. Висота стовпа води в околицях греблі сягала 10 м, а на відстані ~80 км – 5 м. Початкова швидкість потоку води нижче греблі була близькою до 10 м/с. Така швидкість зберігалася на відстані ~80 км від греблі, що сприяло швидкому настанню та неминучості катастрофи, яка мала місце глибокої ночі (близько 03 годин). Екологічні наслідки найбільшої в світі техногенної катастрофи за десятиліття були дуже значними. Певні наслідки будуть спостерігатися ~10 років і більше. Можна стверджувати, що екосистемам України нанесено непоправну шкоду, яка кваліфікується як екоцид.

Ключові слова*: Каховське водосховище, руйнування греблі, математичні моделі, водний потік, витрата води, швидкість витікання, енергетичні характеристики.*

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