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Mathematical model of mudflow breakthrough, taking into account the decrease in the volume of water in the reservoir

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Abstract

Over the past 15 years, Kazakhstan has experienced numerous devastating floods and mudflows, which have resulted in human casualties and significant economic damage. In particular, events in the Almaty region (2010), the Karaganda region (2014), and the northern and western regions (2024) highlighted the need to create effective monitoring systems for hydraulic structures. The purpose of this work is to determine the parameters of the mathematical model describing the breakthroughs of debris flows through hydraulic structures such as dams and weirs. Achieving this goal will allow us to correlate the developed model with real observations and data. This paper presents a forecasting system capable of assessing the consequences of mudflows. The developed system is based on mathematical modeling methods. Unlike analogues, the proposed model takes into account both the parameters of the reservoir and the features of the river bed. To implement the system in practice, software was created in Python. The experiments showed that the model reliably reflects real conditions and can be successfully applied in various scenarios.

Keywords: Forecasting, Mathematical model, Mudflow, Pool, Weir.

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1. Introduction

Relevance Over the last century, the world has experienced numerous disasters related to the destruction of hydraulic structures, which have resulted in human casualties and significant economic losses. One of the most tragic was the St. Francis Dam disaster in California in March 1928, when more than 600 people died. In 1963, the collapse of a mountain range in the Vajont reservoir (Italy) caused giant waves up to 70 meters high, destroying four settlements and leading to the deaths of 4,400 people. The flood in Krasnodar Krai in July 2002, which led to the destruction of a hydroelectric complex, caused the deaths of 114,000 people and resulted in economic damages estimated at 15 billion rubles [1, 2].

On August 17, 2009, a major accident occurred at the Sayano-Shushenskaya hydroelectric power station, resulting in the loss of 75 lives. Consequently, the station's equipment and infrastructure were severely damaged. The accident led to negative changes in the environmental condition of the adjacent water area and significantly impacted the socio-economic situation of the region and the country as a whole [3].

Modern monitoring systems must ensure continuous observation of natural and man-made processes in order to identify potential threats to human life and the environment in advance. The main task of monitoring is to provide accurate information necessary for predicting emergency situations. To do this, it is necessary to combine the intellectual, informational, and technological resources of various organizations and departments responsible for monitoring specific hazards.

Designing monitoring systems requires the development and analysis of mathematical models capable of determining in real time the volume of water that a reservoir can hold, as well as predicting the time until it is filled (to the level of the dam crest). This data is critical for timely warning of the population and authorities, which allows for prompt action to ensure environmental safety.

Thus, research aimed at developing mathematical models for assessing dam failures and creating reliable means of information protection remains highly relevant.

There are 1,665 hydraulic structures in Kazakhstan, including 319 reservoirs with a capacity of over 1.0 million m^3. Of these, 83 facilities are in republican ownership, 200 are municipal, 34 are private, and 60 reservoirs are ownerless. Among the 443 dams, 32 are in republican ownership, 346 are municipal, 45 are private, and 20 remain ownerless. Additionally, there are 125 dams and 778 other hydraulic structures in operation.

Among the large reservoirs, the following stand out: Astana (1970, volume 410.9 million m^3), Seletin (1965, 230 million m^3), Kargalinskoye (1975, 280 million m^3), Bartogay (1982, 320 million m^3), Kapshagay (1970, 18,560 million m^3), Ters-Ashibulak (1963, 158.6 million m^3), Tasotkel (1974, 620 million m^3), Samarkand (1939, 253.7 million m^3), Verkhne-Tobolsk (1972, 816.6 million m^3), Karatomar (1965, 586 million m^3), Bugunskoe (1967, 370 million m^3), and others.

Most reservoirs and hydroelectric facilities (about 60%) are in municipal ownership, including on the balance sheet of Kazvodkhoz, and about 20% of the facilities belong to the agricultural departments of akimats. This situation indicates that the issue of the final ownership of these facilities has not been resolved. Over the past 10-15 years, about 20% of reservoirs have been leased to private individuals, primarily for the needs of agriculture, fish farming, and recreation. However, only in isolated cases does leasing bring positive results, since private lessees often lack funds to repair key structures [4].

In the spring of 2010, a devastating flood occurred in the Almaty region, caused by a dam break, resulting in human casualties and large-scale destruction. A similar tragic event was repeated in 2014 in the Karaganda region. These disasters served as a serious warning for the country and underscored the importance of preventing such situations in the future [5].

Before delving into the details of mathematical models and protection measures, it is important to understand what exactly causes dam failures. Dam failure can be caused by many factors. These include natural phenomena such as heavy rainfall or earthquakes, as well as human error, design flaws, or operational deficiencies. Research shows that about 30% of dam failures are due to design flaws, while natural factors can influence the operation of hydraulic structures.

The consequences of a dam failure can be catastrophic. Millions of liters of water can fall on populated areas, destroying everything in their path. According to the World Health Organization, on average, more than 10,000 people lose their lives as a result of such incidents every year. In addition, the damage to infrastructure and ecosystems can take decades to recover. Research aimed at developing mathematical models for assessing dam failures, as well as creating reliable protection measures, plays a key role in preventing potential disasters. Complex interactions between various factors affecting dam stability require careful analysis and continuous monitoring. Using statistical, hydrodynamic, and structural modeling methods, the accuracy of forecasts and, accordingly, the level of safety can be significantly improved.

2. Literature Review

In recent years, reservoir operation has changed due to the effects of climate change and the instability of hydrological data, moving towards an adaptive model using inflow forecasts. The article [6] discusses the importance of long-term inflow forecasts for effective dam management, as well as the impact of forecast lead times on the reliability of reservoir operation, especially in multi-reservoir systems where both water quantity and quality are considered. In the review, the authors [7] analyze dam failure and landslide dam failure cases, with an emphasis on documented failure incidents, as well as laboratory and field experiments. Empirical and physically based models are discussed, along with the current state of the art in physical and mathematical modeling of the main mechanisms and processes associated with failures.

The safety of reservoirs and dams is one of the most pressing issues in hydraulic engineering and the operation of water bodies. The accuracy of forecasting the filling of a reservoir to the level of the dam crest, as well as the ability to determine the volume of water in real time, are critical to preventing emergency situations and providing timely warnings to the population and authorities. The development and analysis of mathematical models, their integration into monitoring systems, and ensuring the information security of these processes are key areas of modern research. Thus, the article [8] presents a model that combines autoregressive and moving average components, which allows for considering the dynamics of time series with an explanation of variables. To improve the accuracy of the forecast, the model includes two moving sub models. The results of the Monte Carlo study and the application of the model to forecasting water flow at hydroelectric power plants increase its practical value.

The study [9] developed nine nonlinear mathematical models based on data from 40 historical dam failures. The first eight models, created using various regression analysis methods, are purely empirical. At the same time, the last model is a semi-analytical approach obtained on the basis of an analytical solution to problems related to floods during a dam failure in a trapezoidal channel. An analysis of the mathematical models used demonstrates that hydrodynamic models based on one-dimensional and two-dimensional Boussinesq-Saint-Venant equations are used to calculate the movement of the breakthrough wave in each case. The main objective of the work [10] is to create a methodology for calculating the flooding of the lower pool due to the failure of an earth dam.

The authors of Peramuna, et al. [11] reviewed existing methods with an emphasis on their advantages and disadvantages, which will allow modelers to select the most appropriate approach for assessing wave processes during dam failures.

The paper Sreekumar, et al. [12] summarizes and critically analyzes the latest advances in the field of modeling processes associated with tailings dam failures and the downstream propagation of flood waves. Various approaches to mudflow modeling are considered, including single-phase, quasi-two-phase, and two-phase models; methods for calculating runoff during dam failure; rheological properties of tailings materials; and the use of geographic information systems (GIS) and remote sensing technologies to analyze the consequences of tailings dam failures.

The studies by Tsakiris and Spiliotis [13] are devoted to modeling the formation of a dam break and calculating the corresponding outflow hydrograph using a semi-analytical method. They pay special attention to modeling the destruction of an embankment dam as a result of overflow. The method is based on the assumptions of a constant rate of vertical erosion during the development of a break and the parabolic geometry of the resulting cross-section. Two solution options are proposed depending on whether the shape of the reservoir is considered prismatic or the reservoir volume is described by a power dependence on the water depth.

The paper [14] proposes a new model using the point method to analyze the interaction between soil and water, as well as to predict the parameters characterizing the failure rate. It is assumed that the dam is a homogeneous embankment formed from cohesive soil. The water inflow is specified as a hydrograph obtained using third-party flow routing software.

In recent decades, a number of works have been published on the modeling of hydrological processes in reservoirs. The paper [15] proposes analytical solutions to the equations of the kinematic wave

A number of studies pay special attention to numerical modeling. The paper [16] considers the use of numerical modeling through the computational fluid dynamics (CFD) method to analyze the processes of wave generation and propagation that occur when landslide masses enter a reservoir. The scenario is modeled as a multiphase flow, including the interaction of compressed air, water, and moving alluvial material. The landslide is represented as a rigid body sliding along an inclined slope until it contacts the water surface. A hybrid approach is used for the calculation. The CFD model solves the Navier-Stokes equations using the RNG k-ε turbulence model and the volume of fluid (VOF) method, which allows for accurate tracking of the phase boundary in the form of a clear front.

The article [17] presents the results of experimental studies on the speed of the breakthrough wave front downstream of a hydroelectric unit, which occurred as a result of an emergency partial instantaneous breach of the dam along its width. It also discusses the use of a parameter based on the speed of the front to determine the moment of the beginning of the formation of a steep breakthrough wave containing periodic waves in its body after the destruction of the dam.

In Ivanov et al. [18], the characteristics of each hydroelectric complex were calculated, including the depth and width of the flooded area. this enabled macroanalysis using a triangulation model of the surface. the calculations considered parameters such as wave collapse and barriers (intersections) in the event of a dam break at a hydroelectric power station or a rise in water level. a mathematical model and a three-dimensional model were developed, and a flood zone forecast was produced as a result of an emergency using satellite imagery data.

Different machine learning models are also considered for water flow forecasting and improving flood forecasts, for example, using multi-objective optimized learning models and hybrid approaches. The authors in Jia, et al. [18] presented a new hybrid machine learning model, multi-objective conservative extreme learning machine (MCEELM), which appears promising for reservoir storage forecasting. Traditional models may not be sufficiently reliable to predict extreme events; this approach, with comprehensive error minimization, especially for floods, can significantly improve outcomes. The results presented in the paper are impressive: a 5.27% reduction in mean square error for flood events and the potential to increase hydroelectric power generation by 130 million kWh are notable achievements. These models assist in more accurately estimating peak outflows during dam failures and managing water resources.

In Eghbali et al. [20], a new hybrid clustering model based on artificial neural networks and genetic algorithms (ANN-GA) is proposed to improve the accuracy of peak outflow prediction from failed embankment dams. The results of the study demonstrate that this model can more accurately estimate peak outflows, especially under major flood conditions.

3. Materials and Methods

It is important to note that studies show the high importance of considering various factors, such as the height and volume of water behind the break, in the forecasting and modeling of flooding in the event of accidents at hydraulic structures. The article [19] conducted a study on forecasting the peak value of a broken dam, which is important for flood risk analysis. The authors used support vector machine and extreme kernel learning machine as methods for this task. In the analysis, they found that the height of the dam is a key factor in predicting the peak outflow, while the strength parameters did not have a significant effect. The developed methods can be useful for flood modeling and other hydrological forecasts in regions at risk of flooding.

Thus, the analysis of modern scientific publications shows high dynamics and demand for research aimed at developing mathematical modeling, monitoring, and protection of hydraulic structures. In the future, promising areas include the implementation of intelligent decision support systems, the integration of AI, and the development of cybersecurity procedures, which will improve both safety and the efficiency of responses to emergency situations.

4. Results

The mathematical model considers a trapezoidal type of reservoir, the view of which from the dam side is shown in Figure 1.

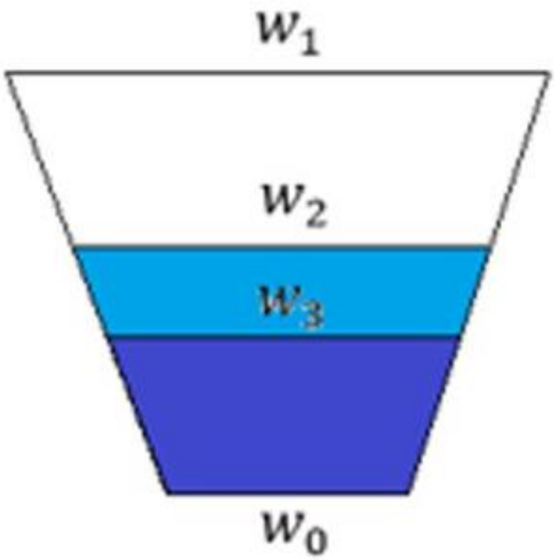

Figure 1.
View of the reservoir from the dam side.

Let us introduce the following notations: Mazakov, et al. [20], Mazakov, et al. [21] and Jomartova, et al. [22]

ΔT- time step of the count (in hours);

l- length of the reservoir (in meters)

ω_0, S_0- the width and area of the reservoir at the base;

ω_1, S_1- the width and area of the reservoir at the level of the dam crest;

ω_2, S_2- the width and area of the reservoir along the water surface;

ω_3, S_3- the width and area of the reservoir at the highest point of the gap in the dam;

V_0– total volume of the reservoir;

V_1– unfilled volume of the reservoir;

V_2– the volume of the reservoir from the water surface to the top point of the gap in the dam; dam; time ΔT;

V_3– the volume of the reservoir from the lower to the upper point of the gap in the

ΔV_1- the volume of water entering the reservoir during time ΔT;

ΔV_2- the volume of water flowing out of a reservoir during time ΔT;

ΔV- the difference between the volumes of water flowing out and entering during the

h_0- dam height;

h_1- the distance from the dam crest to the water surface;

h_2- the distance from the water surface to the top point of the gap in the dam;

h_{pr}- the height of the gap in the dam;
ω_{pr}- the width of the gap in the dam.

Since the parameter is h_0, $h_{pr}$are constant $h_1$and $h_2$change over time, then we introduce the notations $h_{1,k}$and $h_{2,k}$, where the index k denotes the value of the corresponding parameter at the time T_k.
Then the formulas are valid.

$$h_0 - h_{pr} = h_{1,k} + h_{2,k}, \qquad V_0 - V_3 = V_{1,k} + V_{2,k} \qquad (1)$$

Length of the reservoir l, width of the reservoir at the base ω_0 and crest of the dam ω_1, height h_0, the width and height of the gap h_{pr} are ω_{pr}known and are constant. The volume of water entering the reservoir during time is also ΔV_1assumed to be constant ΔT.
Then the width of the reservoir at the top point of the gap in the dam can be calculated using the formulas

$$\omega_3 = (\omega_1 * h_0 + (\omega_0 - \omega_1) * (h_0 - h_{pr}))/h_0 \qquad (2)$$

Surface S_0 areas,S_1 и S_3 are also immutable and can be calculated:

$$S_i = l * \omega_i, \quad i = 0,1,3 \qquad (3)$$

Therefore, some volumes can be calculated

$$V_0 = (1/3) * h_0 * (S_1 + \sqrt{S_1 * S_0} + S_0)$$

$$V_3 = (1/3) * h_{pr} * (S_0 + \sqrt{S_0 * S_3} + S_3) \qquad (4)$$

Since the distance to the water surface changes over time, the width and area of the reservoir, as well as some changing volumes at the water surface level at a given moment in time, $T_k$can be calculated using the formulas.

$$\omega_{2,k} = (\omega_1 * h_0 + (\omega_0 - \omega_1) * h_{1,k})/h_0,$$

$$S_{2,k} = l * \omega_{2,k}.$$

$$V_{1,k} = (1/3) * h_{1,k} * (S_1 + \sqrt{S_1 * S_{2,k}} + S_{2,k}),$$

$$V_{2,k} = (1/3) * h_{2,k} * (S_{2,k} + \sqrt{S_{2,k} * S_3} + S_3) \qquad (5)$$

$\Delta V_{2,k}$- the volume of water flowing out of a reservoir during time ΔTcan be calculated in accordance with Torricelli's hydraulic law using the formula

$$\Delta V_{2,k} = Q * \Delta T = h_{pr} * \omega_{pr} * \sqrt{2 * g * h_{2,k}} \qquad (6)$$

Let us denote by $\Delta V = \Delta V_{2,k} - \Delta V_1$– the difference between the water that has flowed out and arrived in the reservoir. Then the following relations are valid

$$V_{1,k+1} = V_{1,k} + \Delta V, V_{2,k+1} = V_{2,k} - \Delta V \qquad (7)$$

In addition, the calculated parameter is informative Δh_k- the height to which the water level is expected to drop over the next period of time.

Let's introduce the following notations:

$$x = \Delta h_k$$

Then the width of the reservoir at the surface level at a subsequent moment in time $T_{k+1} = T_k + \Delta T$can be calculated

$$\omega_x = (\omega_1 * h_0 + (\omega_0 - \omega_1) * (h_1 + x))/h_0, \qquad (8)$$

$$S_x = l * \omega_x.$$

Then the expected water consumption x for the subsequent period of time is found from the solution of the following nonlinear equation

$$x * (S_2 + \sqrt{S_2 * S_x} + S_x) = 3 * \Delta V. \qquad (9)$$

Due to the complexity of equation (9), an analytical expression for cannot be found. In this connection, $x$the numerical q dichotomy method is used to calculate the expected water rise x [106].

Let's introduce the functions:

$$s(x) = (\omega_1 * h_0 + (\omega_0 - \omega_1) * (h_1 + x)) * l/h_0, \quad (10)$$

$$g(x) = S_2 + \sqrt{S_2 * s(x)} + s(x), \quad (11)$$

$$f(x, y) = x * g(y) - 3 * \Delta V \quad (12)$$

Then, to determine the expected lowering of the water surface, a “dichotomy” method for finding the parameter is proposedx_k:

Step 1. Let$x_0 = 0$.

$\varepsilon = 0.01$– the specified calculation accuracy.

Let's assign $x^l = h^0$, $x^p = h_\text{п}$.

Step 2. Let$x_k = (x^l + x^p) * 0.5$.

Calculate the value of the function

$f(x_k, x_k)$ according to formula (12). If the function value $f(x_k, x_k)$ is less than 0, then we move on to step 3.

Let's define a new left boundary $x^l = x_k$. Proceed to step 4.

Step 3. Let's define a new right boundary $x^p = x_k$.

Step 4. Find the accuracy of the calculation

$r = abs(x^l - x^p)$.

If $r \leq \varepsilon$then go to step 5, otherwise, go to step 2.

Step 5. The calculation result is inx_k.

As a result of the algorithm's operation, the value of the height to which the water surface in the reservoir has dropped is calculated.

The maximum wave height $h_{max}$is sought in the form

$$h_{max} = \alpha_0 * ((h_{pr} * \omega_{pr})^{\alpha_1} h_2^{\alpha_2} V_2^{\alpha_3} \cos\theta)/L^{\alpha_4}, \quad (13)$$

Where θ - the slope angle of the terrain over a distance of L.

In formula (13) all coefficients $\alpha_i > 0$, i = $\overline{0,4}$. Based on the available information about the breakthroughs that occurred, 30 variants of parametric data were prepared. Based on this information, the following formula is obtained:

$$h_{max} = 0.00134 * ((h_{pr} * \omega_{pr})^{0.32} h_2^{0.55} V_2^{0.4} \cos(\theta))/L^{0.4} \quad (14)$$

In formula (14) the volume of the reservoir (V_2) and the height to the water surfaceh_2 change over time; the distance from the dam site to the observation point (L) depends on the coordinates of the observed point.

Note. The formula obtained in work (14) has the following limits of applicability (related to the methodology of its justification): reservoir capacity (V_2) – from 3 million m^3 and higher; dam height (h_0) – from 3 m and higher; distance from the dam site to the observation site (L) – from 3 m and higher. The above restrictions do not interfere with practical interests.

5. Discussion

The countdown is every half hour:

ΔT = 0.5 hours = 30 minutes.

All further calculations model the events that occurred in the village of Kyzylagash in the Almaty region on March 11 and 12, 2010. The 45-meter-high dam was designed to store 42 million cubic meters of water.

Based on the developed automated system, a model of the events that occurred on March 11-12, 2010, in the village of Kyzylagash was created. According to the Almaty Department of Emergency Situations, the accident occurred as a result of heavy rain and increased air temperature. These conditions led to the movement of ice and provoked the formation of mudflows.

The situation that developed in the village of Kyzylagash was modeled using formula (14) and is presented in Figure 2-5.

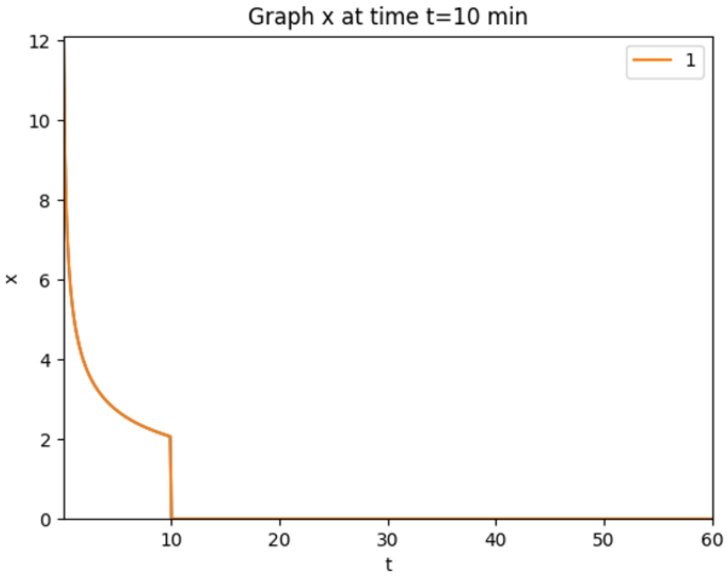

Figure 2.
Chart of the maximum breakout wave in the first 10 minutes.

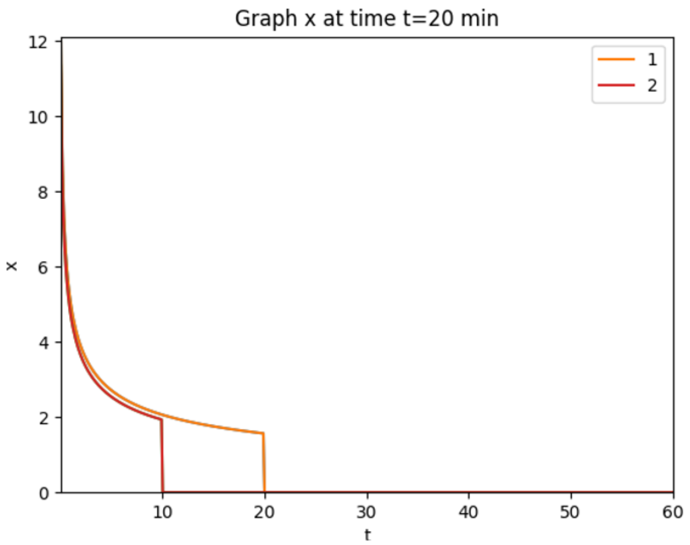

Figure 3.
Chart of the maximum breakout wave in the first 20 minutes.

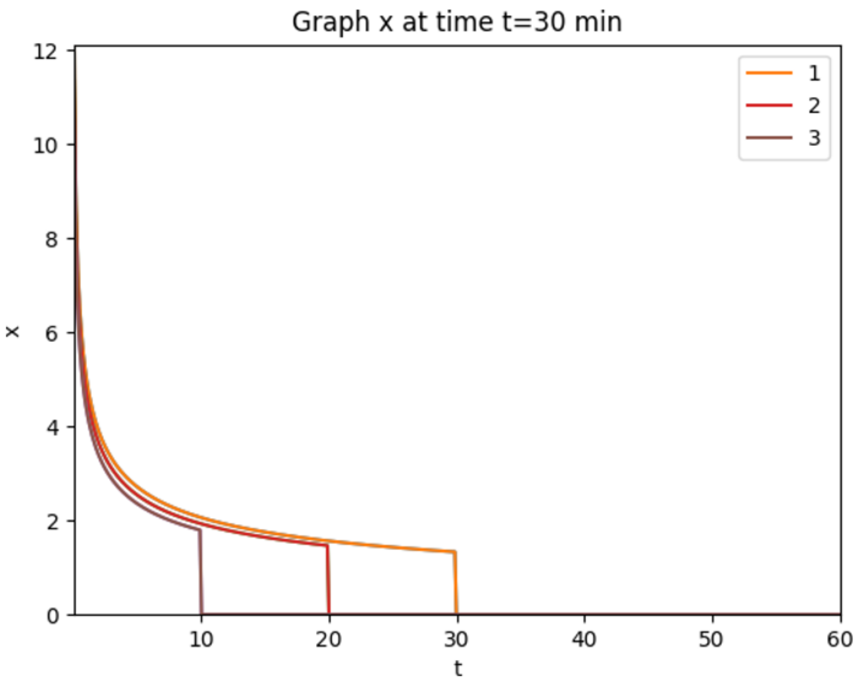

Figure 4.
Chart of the maximum breakout wave in the first 20 minutes.

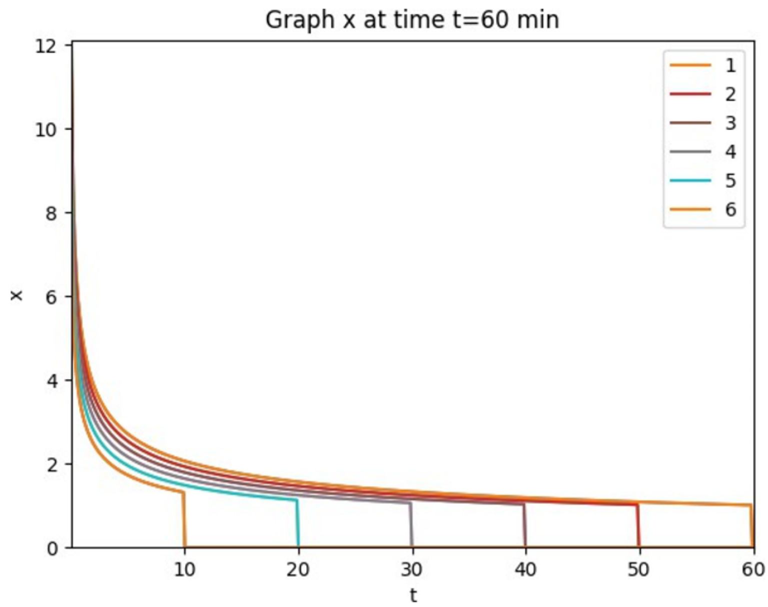

Figure 5.
Chart of the maximum breakout wave in the first 60 minutes.

As can be seen from Figures 2-5, the volume of water and the heights of subsequent breakthrough waves decrease over time. This fact aligns well with reality.

According to the data in the figure, the breakthrough wave that reached the village of Kyzylagash within one hour had a height of 1.5 meters. During the same period, the height of the wave coming out of the reservoir decreased from 12 meters to 7 meters. Thus, the results of numerical modeling are confirmed by actual data recorded during the event.

6. Conclusion

The following results were achieved within the framework of the conducted study:

A mathematical model has been developed to predict the consequences of a dam break. An algorithm has been created to calculate the maximum level of a break wave, taking into account various parameters of the hydraulic structure. The proposed approach is highly practical in comparison with existing methods.

A hardware and software complex (HSC) for monitoring and predicting the consequences of a dam break has been created in Python.

Based on the solution of the model problem, the effectiveness of the developed PAC was confirmed. The situation that occurred in the village of Kyzylagash in the Almaty region of the Republic of Kazakhstan was used as a practical basis.

The obtained results can be used to support decision-making by the water management authorities of Kazakhstan. The proposed methodology and technologies offer a qualitatively new approach to water resources monitoring, identifying phenomena that contribute to emergency situations, and assessing their consequences.

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