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COMPUTER MODELING OF TERRITORY FLOODING IN THE EVENT OF AN EMERGENCY AT SEREDNIODNIPROVSKA HYDROELECTRIC POWER PLANT

Purpose. Computer modeling of territory flooding in the event of an emergency at Seredniodniprovska Hydroelectric Power Plant (HPP).

Methodology. The computer model of possible territory flooding at Seredniodniprovska HPP is developed using simulation modeling methods and geometric and hydrological approaches and considers initial boundary conditions of the water-engineering system. Calculations of the wave break height and the half-divided cross-sectional area of the river bed were made and a three-dimensional model of the territory flooding was built using the Python language and ArcGIS Desktop software.

Findings. The data for each creation of the hydraulic node, namely the depth and width of the flooded territory, were calculated. This allowed analyzing the macro level considering the triangulation model of the surface. The wave break parameters and flaps (intersections) were taken into account in case of a dam break at a hydroelectric power plant or a rise in the water level. A mathematical model, and a 3D model were developed, and a forecast of the flood zone due to an emergency was made using satellite survey data.

Originality. The mathematical method received further development for calculating flood territories in the event of an emergency at Seredniodniprovska Hydroelectric Power Plant, taking into account the parameters of the breakthrough wave and the calculation of cross-sections for the cases when a hydroelectric dam breaks or the water level rises; the method uses one-dimensional and two-dimensional systems of Saint-Venant equations, and geometric and hydrological approaches. A three-dimensional model of the territory flooding is developed to predict possible consequences.

Practical value. The obtained results can be used to model the flooding of the territory located near dangerous hydro-technical objects, such as dams, dikes as well as to forecast flooded territories during the construction of drainage and protective structures.

Keywords: *simulation, 3D model, flood zone, breakthrough wave, cross-sectional area, hydraulic structure*

Introduction. For many centuries, people have been making enormous efforts to protect against floods, but have not been successful in this endeavor. Flood damage continues to mount. In the second half of the last century, the relevance of this issue increased approximately by ten times. Flooding areas in low-lying territories are dangerous when dams and hydraulic systems are destroyed [1, 2]. The immediate danger is a rapid and strong movement of water, which causes damage, flooding, and destruction of buildings [3], and structures and can lead to ecological [4], technogenic disasters [5]. Due to the high speed and the amount of moving water, various structural damages and casualties among the population may occur. The height and speed of the breakthrough wave depend on the size of the hydraulic structure destruction, the difference in height between the head and tail water. For flat areas, the speed of the breakthrough wave varies from 3 to 25 km/h, in mountainous areas it reaches 100 km/h. Usually, after 15–30 minutes a significant locality is found submerged by a layer of water with a thickness of 0.5 to 10 m or more [6].

Military actions on the territory of Ukraine by the Russian military have led to the emergence of many social and humanitarian problems. This caused severe threats of manufactured emergencies due to high-power missiles. Thus, there was a threat of flooding the banks of the Dnipro due to the dam breach. The destruction of the dam of Seredniodniprovska Hydroelectric Power Plant (HPP) is dangerous due to the sudden and uncontrolled release of a large amount of water from the reservoir, the rapid spread of the breach wave from the destroyed dam, the flooding of the banks of Kamianske city, material damage to this city, harm to people's health, and their death [7].

For the effective use of forces and means of emergency and rescue formations, reliable information on the consequences of the breakthrough of the pressure front of the reservoir is required. This information is obtained as soon as possible and with maximum accuracy. Therefore, it is necessary to jointly use the forecasting of the parameters of the flooding territories and to carry out measures for the flooding areas calculations. For complex solving of these tasks, human casualties can be reduced to minimum values due to more effective, more targeted, and timely actions of emergency and rescue formations [8].

Literature review. The Saint-Venant model based on a system of two-dimensional shallow water equations was presented in the works by Michal Szydlowski, et al. [9]. This model is widely used to simulate flood propagation over wide and flat floodplains. The modeling object was Bielkowo HPP and the territory around the reservoir banks. Calculation of Bielkowo HPP parameters is used to estimate flood wave parameters. This allows for identifying and mapping inundation areas and inundation risk analysis. It is proposed to use a mathematical model of a free-surface two-dimensional time-dependent water flow for the numerical simulation of the flood. The inundation hazard maps present the calculated results in inundation zones. The maps have been used by local authorities and the dam owner to manage the flood risk associated with the operation of hydroelectric plants on the Radunia River. Sulaiman S. proposed an HEC-Res Sim simulation model based on monthly observed inflow data with tributaries to the reservoir [10]. It uses two statistical metrics to evaluate the effectiveness of the model: the correlation coefficient and the effectiveness of the Nash-Sutcliffe coefficient. Testing was carried out at the Dokan dam to study the operational reservoir behavior and simulate the system in real-time. The authors of work [11] describe a combined approach of hydrologic and hydraulic modeling to assess flood-prone areas. This method was tested for the Po River (Northern Italy). A new precipitation dataset for Italy is based on a hydrological model driven by GRIPHO. It helps to calculate the discharge of the river and runoff. This made it possible to calculate the flood hazard map with a resolution of 90 m. The proposed approach provides good potential for subsequent uses, such as accurate flood hazard analysis under future climate conditions.

The disadvantage of the above-mentioned studies is that they do not use the following to obtain an accurate simulation model of the flooding of territories: a geometric approach, a hydrological approach, and one-dimensional and two-dimensional systems of Saint-Venant equations.

Purpose. The aim is territory flooding modeling of Kamianske city in the event of an emergency at Seredniodniprovska Hydroelectric Power Plant. The scientific novelty is the method development for calculating the zones of territory flooding in the event of emergencies at Seredniodniprovska HPP caused by hostilities. The parameters of the breakthrough wave and the calculation of the beams in the event of a breakthrough of the hydroelectric power plant or an increase in the water level are taken into account.

In this work, to achieve the set goal, the following tasks were formed and solved:

- to explain the principles of simulation modeling of the flooding process;
- to develop a method for detecting areas of territory flooding;
- to design and develop a software part for simulation modeling of flooding zones in the event of emergencies at Seredniodniprovska HPP;
- to develop a three-dimensional model of the territory's flooding zones to predict possible consequences.

Methods. The paper proposes a model of the territory flooding in the event of an emergency at Seredniodniprovska HPP caused by hostilities. Implementing the model is based on the following methods and tools:

- the method for modeling territories, based on the solution of one-, two-dimensional systems of Saint-Venant equations;
- a geometric approach based on the analysis of the triangulation model of the surface;
- the hydrological approach is used for macro-level analysis, that is, for territories with an area of tens and hundreds of square kilometers.

The structural diagram of the model of territory flooding in the event of an emergency at Seredniodniprovska HPP caused by hostilities is shown in Fig. 1. Let us describe the terms, definitions, and formulas used in the work.

Data. Output data for calculations and visualization of results:

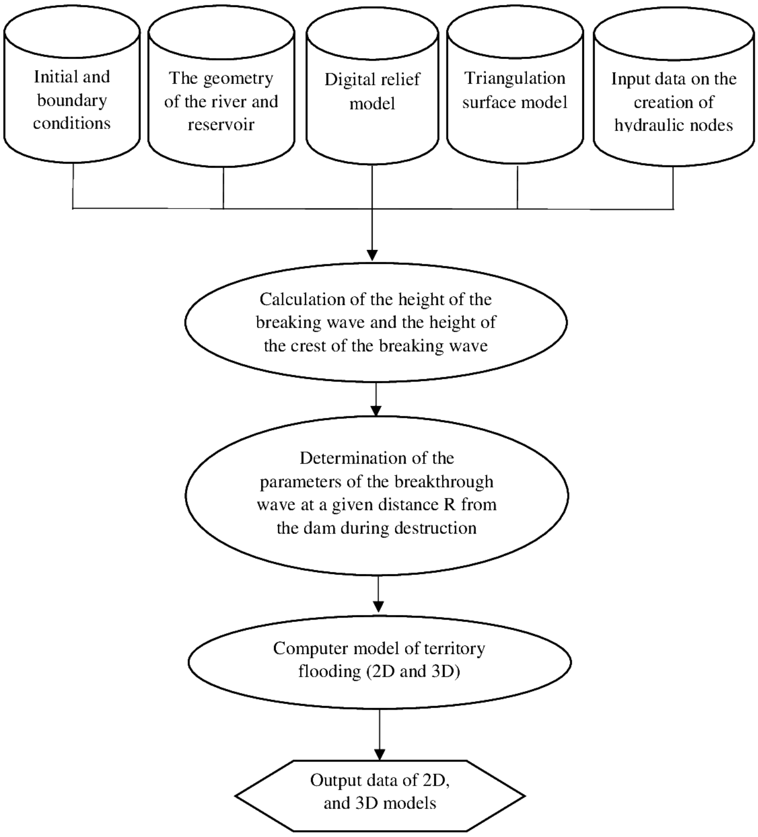

Fig. 1. Structural scheme of the territory flooding model in the event of an emergency at Seredniodniprovska HPP

- HERE Maps API [12];
- reservoir volume – W, m^3;
- depth of water in front of the dam (closure channel) – H, m;
- the width of the closure channel or the area of water overflowing through the crest of the dam – B, m;
- average speed of movement of the breakthrough (recession) wave – V, m/s;
- the distance from the dam (reservoir) to the foundation – R, km.

Computer modeling. Solving the given task requires data on the hydraulic node and the area located above (reservoir) and downstream of the river. For this purpose, the area downstream of the river is divided into so-called flaps, sections perpendicular to the river flow with a step of 5 km. The necessary parameters are determined in the corresponding cross-sections. The most important is the distance from the hydraulic node, the marks of the terrain horizons, and the distance between them. Data on the volume of the reservoir, and the width and depth of the reservoir in the dam and the tail-water are important for the hydraulic unit and the reservoir.

The aim of the modeling in this work is the city of Kamianske located near a hydroelectric power station downstream. Since the dam height is small (12 m), the simulation considered the option of complete instantaneous destruction of the hydroelectric unit. The data on the construction of the hydraulic unit was used from the mass media. In addition, to ensure the maximum safety of the population, the worst-case event development must be considered to avoid losses. A geoinformation system is used as a forecast and assessing tool for the extent of flooding.

Fig. 2 presents the block diagram of the software algorithm proposed in the paper.

Hydrotechnical structures (HTS) are engineering constructions designed to use water resources or combat the destructive effects of water. The main hydro-technical structures, whose destruction (breakthrough) leads to a hydrodynamic accident (HA), include dams (overpasses, etc.), water intake, and water collection structures (sluices).

Dams are pressure-type hydro-technical structures (artificial dams) or natural formations (natural dams) that create a difference in water levels from the riverbed. So, a dam (sluice, overpass, etc.) blocks a river or other drain to raise the water level in front of it to create water pressure on its area and form a reservoir.

Artificial dams are hydro-technical structures created by humans for their needs and include dams of hydroelectric power plants, water intakes, irrigation systems, dams, bridges, hooks, and others. Dams are divided into low-pressure ones – up to 10 m, medium-pressure from 10 to 50 m, and high-pressure ones – over 50 m according to the dam height. And depending on the construction materials used, there are concrete, reinforced concrete, gravity, buttress, arched, stone, soil (dams, etc.), and wooden dams. Before the dam, water accumulates upstream, and artificial and natural reservoirs are formed.

The section of the river between two adjacent dams on the river or the section of the channel between two locks is called the canal pound. The hydraulic slope of the river is the excess (in meters) of the height of the river level per 1,000 m of length. The part of the river above the supporting structure (dam, sluice) is called the headwater of the dam, and the part of the river below such a structure is called the tail-water. The carcass of the dam forms a zero leaf. The height of the water level in the headwater of the dam is the water level in the reservoir.

Such natural phenomena or natural disasters as earthquakes, landslides, landslides, floods, soil erosion, hurricanes, etc., as well as technological factors – the destruction of structures, operational and technical defects or design errors, violation of the water collection regime, hostilities, and others can be the causes of the destruction of a hydro-technical structure.

The initial phase of a hydrodynamic incident is a dam breach, which is the process of closure channel formation and unregulated overflow of reservoir water from the headwater through the closure channel into the tail-water. Flow fronts are sent into the closure channel in water, and a wave break is formed.

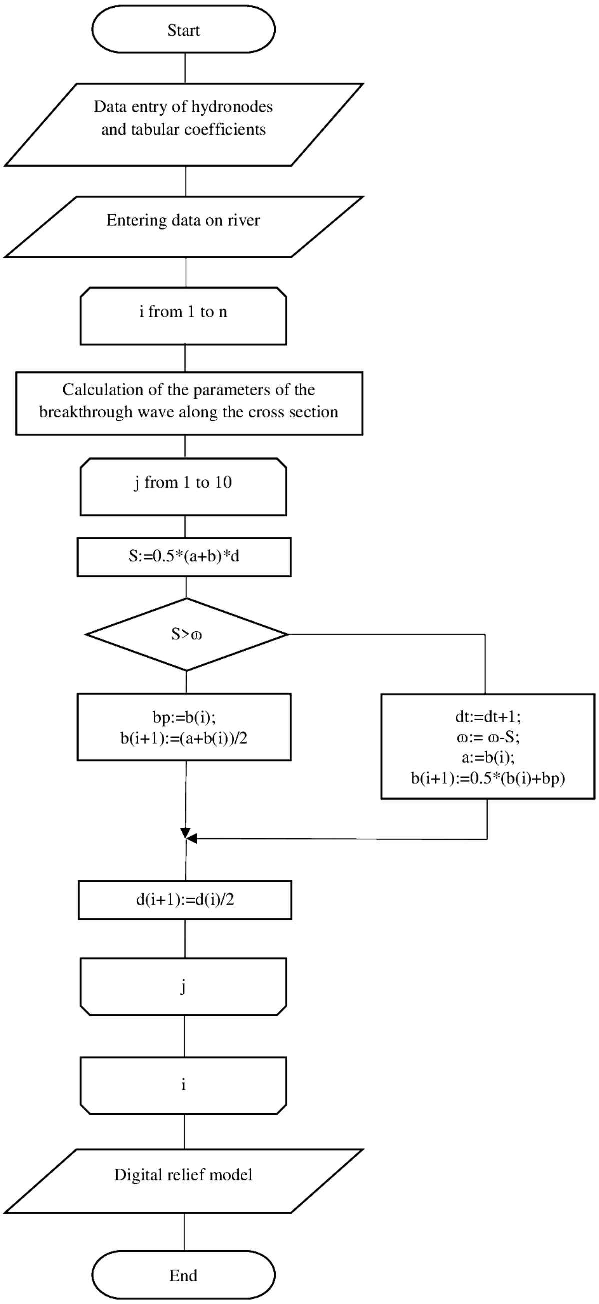

Fig. 2. A calculation algorithm of the flooding zone

A closure channel is narrow in the dam construction, a spit, a shoal, in a river delta, or a straightened section of a river formed as a result of the erosion of a twist in a flood. A breakthrough wave is a wave formed at the front of a water flow passing through a closure channel, which has a significant speed of movement and possesses great destructive power.

Thus, the HA breakthrough wave occurs due to the high-water velocity, which creates a threat of an emergency. The impressive factor of the HA is the breakthrough wave of the hydro-technical structure. The main parameters of its action are the speed, height, and depth of the breakthrough wave, water temperature, and the time of existence of the breakthrough wave.

In its physical nature, a wave break is the movement of a water stream in which the breadth, profundity, surface of the ceiling, and current speed vary in time (Fig. 3). Wave break

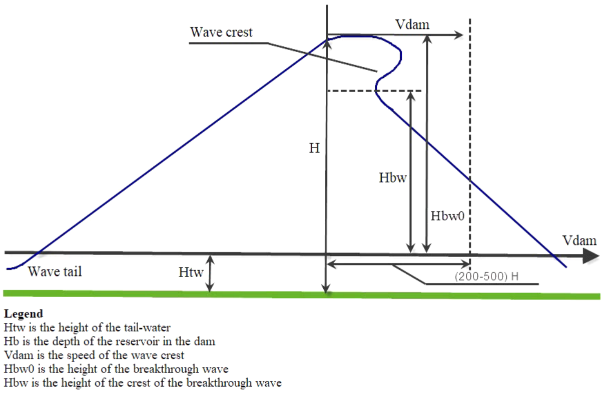

Fig. 3. Breakthrough wave and its essence

height and the movement velocity rely on the scope and depth of the reservoir; area surface of the water basin; the size of the closure channel; the difference in the head-, and tail-waters; hydrological and topographic conditions of the riverbed, and flood-plain. In the area of the zero alignments (dam construction), the size of the wave break (H_{bw0}) is determined by the formula [13]

$$H_{bw0} = (8.42 \cdot \ln H)^{1/2.126} \cdot \sqrt{H_{tw}}, \qquad (1)$$

where H is the depth of the reservoir in the dam, m; $\gamma = 0.5772$ is Euler's constant; H_{tw} is the height of the tail-water, m.

Accordingly, the height of the crest of the breakthrough wave (H_{bw}) (Fig. 2) is [13]

$$H_{bw} = (8.42 \cdot \ln H)^{1/2.126} \cdot (1 + \gamma / 2.126 \cdot \ln H) \cdot \sqrt{H_{tw}}. \qquad (2)$$

Usually, the size of the wave break is in the range of 2–12 m and can reach 10–30 m. The propagation velocity of the motion breakthrough wave is 3–25 km/h, and for mountain and foothill areas – up to 100 km/h. The speed of the motion breakthrough wave is V = 2.5–5 m/s and taken for areas of catastrophic flooding and dangerous flooding, and areas of possible flooding V = 1.5–2.5 m/s. At the same time, the static pressure of the water flow is at least 20 kPa with duration of action of at least 0.25 hours.

The nature of the impact on the object is determined by such factors as the hydrodynamic pressure of the water flow; the height, depth, and speed of the water flow; the level and time of flooding; the river bed deformation; the pollution of the hydrosphere, erosion, and transfer of soils. The main consequence of a hydrodynamic accident is the catastrophic flooding of the area.

Catastrophic flooding is a disaster due to a hydrodynamic accident, which is the result of dam destruction and consists of the rapid inundation of a breach wave below the located area and the occurrence of a flood. The following parameters of catastrophic flooding are:

- the maximum possible height and speed of the breakthrough wave;
- the estimated arrival time of the breakthrough wave in the corresponding locality);
- the maximum depth of flooding of the area;
- duration of flooding of the territory;
- within the boundaries of the zone of possible flooding.

A catastrophic flooding moves at the speed of a breach wave and leads (after some time after a dam breach) to the flooding of large areas with a layer of water of 0.5–10 m. In this case, flood zones are formed. The flood zone of the destroyed HTS is a part of the river (or lake, reservoir) adjacent to the territory, which keeps the water. The consequences of the HTS destruction near the possible water flooding can lead to the emergence of a zone of catastrophic flooding. Part of the flooding zone, within which the breakthrough wave spreads, causes mass loss of people, destruction of buildings and structures, and destruction of other material values. It is called a catastrophic flooding zone. At its outer limits, the height of the crest of the breakthrough wave (H_{bw}) exceeds 1 m (Fig. 3), and the speed of its movement is more than 10 m/s. The time during which flooded areas can be below the surface varies from 4 hours to several days. The parameters of the inundation zone depend on the size of the reservoir, water pressure, and other parameters of a particular hydraulic unit, and the hydrological and topographic features of the area.

The main factors of catastrophic flooding are the destructive wave of the breach, the water flow, and the calm waters that have flooded the territory of the land and the object. The impact of a breakthrough wave on people is similar to the impact of the shock wave of a nuclear explosion. The significant differences between these factors are the much lower velocity and higher density of matter in the breakthrough wave. Therefore, we determine the wave break parameters (recession) at a given distance R from the dam (Fig. 3) in the event of its destruction.

Mathematical models. Below is the sequence of calculations performed for the mathematical model of the method.

The time of approach of the breakthrough (release) wave at a given distance R (to the target) is, hour,

$$t_{bw} = \frac{R}{3600 \cdot V}. \qquad (3)$$

For extremely dangerous flooding zones, the values of V = = 2.5–5 m/s are accepted; for areas of possible flooding the values are V = 15–24 m/s.

The height of the breaking (falling) wave h at a distance R from the object is, meters,

$$h = m \cdot H, \qquad (4)$$

where m is the coefficient that depends on the distance of the HTS to the object.

The time of emptying the reservoir is according to the formula, hour,

$$T = \frac{W}{3600 \cdot N \cdot B}, \qquad (5)$$

where N is the maximum water consumption per 1 m of the closure channel width

The time of passage of the breakthrough (release) wave t at a given distance to the object R is, hour,

$$t = m_1 \cdot T, \qquad (6)$$

where m_1 is the coefficient depending on the distance to the dam (reservoir).

Water will flow from the reservoir until the entire volume of water is drained. Let the volume of water in the normal state of the channel be unchanged since the water in the river flows constantly and cannot completely drain out. Thus, the calculation will be carried out only for the volume of the reservoir. The water from the storage reservoir, directed into the closure channel in the breakthrough waveform, will pass through the plane in the calculated time t (6). To determine water consumption (volume per unit of time [m^3/s]), we use the formula

$$Q = \frac{W}{t}. \qquad (7)$$

On the other part

$$Q = \omega \cdot V, \qquad (8)$$

where ω is the cross-sectional area of the channel.

We determine the cross-sectional area of the channel in this creation as

$$\omega = \frac{W}{t \cdot V}. \qquad (9)$$

For channels with a trapezoidal cross-section (Fig. 4), the geometric elements are determined by the following formulas:

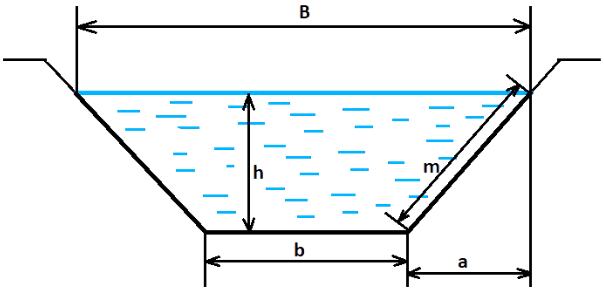

Fig. 4. Parameters of a trapezoidal channel

- cross-sectional area (trapezoidal area)

$$\omega = (b + m \cdot h) \cdot h, \tag{10}$$

where m is the slope coefficient, equal to the ratio of the laying of the slope to the height (Fig. 4)

$$m = \frac{a}{h}; \tag{11}$$

- wetted perimeter

$$\chi = b + 2h\sqrt{1 + m^2}. \tag{12}$$

We approximate the channel crossing to a trapezoid, whose lower base is the natural water level in the river. We calculate it as the sum of the distances from the axis of the river to the riverside horizon. Knowing the mark of the horizontal height and the water cut under normal conditions, we calculate the area of the trapezoid, which is formed by a breakthrough wave, then compare it with the analytically calculated one. If it is less than the flow obtained from the equation, then we calculate the area relative to the next horizontal mark. Next, using the method of half-division (we limit the number of iterations to 10), find the cross-sectional area equal to the analytically calculated one. We calculate the level of water rise from the cross-sectional area (Fig. 5).

Results. The computer modeling method of the territory flooding at Serednioprovska Hydroelectric Power Plant is proposed in the work [14]. This is achieved based on the methods for calculating the height of the breaking wave and dividing the cross-sectional area of the river by half. The obtained data made it possible to build a 3D model (Fig. 6) and forecast the flooding zone on a satellite image (Fig. 7).

The computer model was created based on the Python language and ArcGIS Desktop software. The created functionality was implemented as an extension.

Conclusions. The result of the conducted research was developed for calculating territory flood zones. A complex algorithm for calculating the depth and width of the flooded areas for Serednioprovska HPP and nearby areas is also proposed. In this work, the flooding level territory is calculated based on the hydrodynamic data of the breakthrough wave, the flow equation, the equations for the calculations of open channels, and the method of half-division of the inundation depth of the structure. We created program software for calculating flooding parameters for visual modeling. Terrain-model 3D designed for a flooded zone.

The proposed computer modeling can simulate territory flooding near dangerous hydraulic facilities, such as dams, lanes, etc. Prediction of flooded areas is the main stage in the construction of drainage and protective structures.

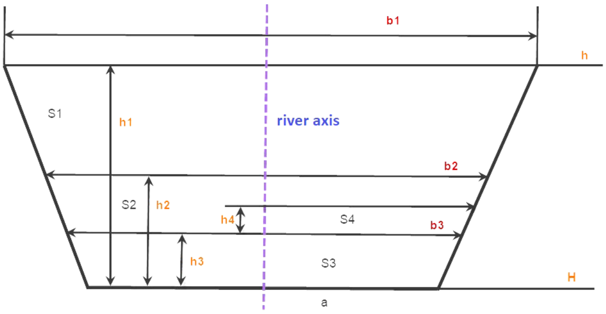

Fig. 5. Parameters of a trapezoidal channel

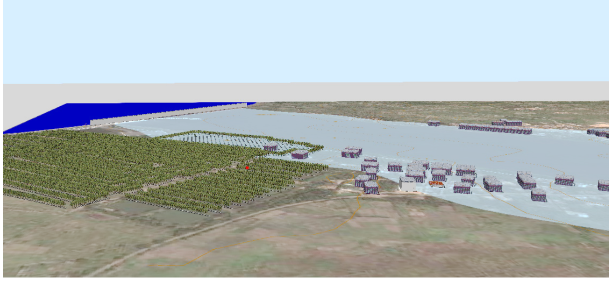

Fig. 6. Result of the three-dimensional model of the flood zone

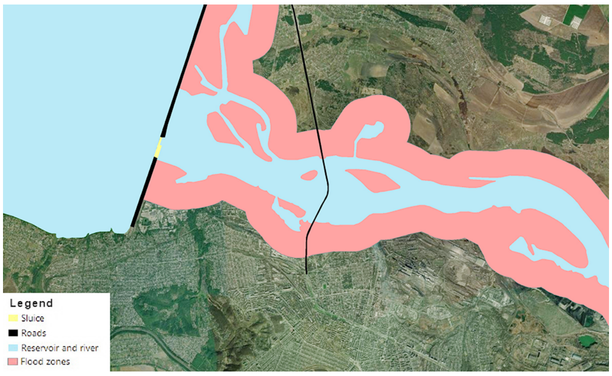

Fig. 7. Forecasting a flood zone on a satellite image

References.

1. Thapa, B., Watanabe, T., & Regmi, D. (2022). Flood Assessment and Identification of Emergency Evacuation Routes in Seti River Basin, Nepal. *Land, 11*, 82. https://doi.org/10.3390/land11010082.

2. Mozgovoy, D., & Hnatushenko, V. (2020). Information Technology of Satellite Image Processing for Monitoring of Floods and Drought. In Shakhovska, N., & Medykovskyy, M. (Eds.). Advances in Intelligent Systems and Computing IV. CCSIT 2019. *Advances in Intelligent Systems and Computing, 1080*. Springer, Cham. https://doi.org/10.1007/978-3-030-33695-0_32.

3. Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J. E., ..., & Wisotzky, C. (2022). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe. *Natural Hazards and Earth System Sciences*. https://doi.org/10.5194/nhess-2022-137.

4. Hapich, H., Andrieiev, V., Kovalenko, V., Hrytsan, Yu., & Pavlychenko, A. (2022). Study of fragmentation impact of small riverbeds by artificial waters on the quality of water resources. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (3), 185-189. https://doi.org/10.33271/nvngu/2022-3/185.

5. Wang, Z., Sun, Y., Li, C., Jin, L., Sun, X., Liu, X., & Wang, T. (2022). Analysis of Small and Medium–Scale River Flood Risk in Case of Exceeding Control Standard Floods Using Hydraulic Model. *Water, 14*, 57. https://doi.org/10.3390/w14010057.

6. Urzică, A., Mihu-Pintilie, A., Stoleriu, C., Cîmpianu, C. I., Hutanu, E., Pricop, C. I., & Grozavu, A. (2020). Using 2D HEC-RAS Modeling and Embankment Dam Break Scenario for Assessing the Flood Control Capacity of a Multi-Reservoir System (NE Romania). *Water, 13*(1). https://doi.org/10.3390/w13010057.

7. *The war increases the risks of emergency situations at hydroelectric power plants*. Retrieved from http://epl.org.ua/wp-content/uploads/2022/04/Novyna-GES-10504.pdf.

8. Tschiedel, A., Paiva, R., & Fan, F. (2020). Use of large-scale hydrological models to predict dam break-related impacts. *Scientific/Technical Article,* RBRH 25. https://doi.org/10.1590/2318-0331.252020190128.

9. Szydłowski, M., Szpakowski, W., & Zima, P. (2013). Numerical simulation of catastrophic flood: The case study of hypothetical failure of the Bielkowo hydro-power plant reservoir. *Acta Geophysica, 61*(5). https://doi.org/10.2478/s11600-013-0104-6.

10. Sulaiman, S., Abdullah, H., Al-Ansari, N., Laue, J., & Yaseen, Z. M. (2021). Simulation Model for Optimal Operation of Dokan Dam Reservoir Northern of Iraq. *International Journal of Design & Nature and Ecodynamics, 16*(3), 301-306. https://doi.org/10.18280/ijdne.160308.

11. Nogherotto, R., Fantini, A., Raffaele, F., Di Sante, F., Dottori, F., Coppola, E., & Giorgi, F. (2022). A combined hydrologicaland hydraulic modelling approach for the floodhazard mapping of the Po river basin. *Journal of Flood Risk Management, 15*(1). https://doi.org/10.1111/jfr3.12755.

12. *HERE Maps API.* Retrieved from https://developer.here.com/documentation#services.

13. George Z. Forristall (2017). Wave and Crest Height Distributions. *Encyclopedia of Maritime and Offshore Engineering.* https://doi.org/10.1002/9781118476406.emoe080.

14. Kashtan, V., Hnatushenko, V., Hnatushenko, Vik., Reuta, O., & Udovyk, I. (2021). Voxel Approach to the Shadow Formation Process in Image Analysis. *The 11th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAASC),* Cracow, Poland, (pp. 33-37). https://doi.org/10.1109/IDAACS53288.2021.9660909.

Комп’ютерне моделювання затоплення території при виникненні надзвичайної ситуації на Середньодніпровській ГЕС

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Мета. Комп’ютерне моделювання зони затоплення прилеглої території при виникненні надзвичайної ситуації на Середньодніпровській гідроелектростанції (ГЕС).

Методика. Комп’ютерна модель можливого затоплення прилеглої території на Середньодніпровській ГЕС побудована на основі методів імітаційного моделювання, геометричного й гідрологічного підходів і враховує початкові граничні умови гідровузла. Здійснено розрахунок висоти хвилі прориву й половинного ділення площі перерізу русла ріки та побудована тривимірна модель затоплення території з використанням мови Python і програмного забезпечення ArcGIS Desktop.

Результати. Розраховані дані по кожному створу гідровузла, а саме глибина й ширина території, що затоплюється. Це дозволило провести аналіз на макрорівні з урахуванням тріангуляційної моделі поверхні. Були враховані параметри хвилі прориву та стулок (перетинів) у разі прориву дамби гідроелектростанції або підвищення рівня води. Розроблена математична модель, побудована 3D-модель і здійснене прогнозування зони затоплення внаслідок надзвичайної ситуації з використанням даних супутникової зйомки.

Наукова новизна. Отримав подальший розвиток математичний метод розрахунку зон затоплення територій при виникненні надзвичайних ситуацій на Середньодніпровській ГЕС з урахуванням параметрів хвилі прориву й розрахунку створів (перетинів) у разі прориву дамби гідроелектростанції або підвищення рівня води на основі одновимірних і двовимірних систем рівнянь Сен-Венана, геометричного й гідрологічного підходів. Розроблена тривимірна модель затоплення території для прогнозування можливих наслідків.

Практична значимість. Отримані результати можуть бути використані для моделювання затоплення територій, що знаходяться в безпосередній близькості до небезпечних гідротехнічних об’єктів, таких як дамби, греблі, та ін., а також прогнозування територій, що затоплюються при будівництві дренажних і захисних споруд.

Ключові слова: *імітаційне моделювання, 3D-модель, зона затоплення, хвиля прориву, площа перерізу, гідротехнічна споруда*

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