Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 313–322
https://doi.org/10.2478/rtuect-2025-0022
https://content.sciendo.com

Mitigating Environmental Impacts of Small Hydropower Plants Through Advanced Hydraulic Modelling

Oksana HALYCH[1]*, Petr NOWAK[2], Eva BILKOVA[3], Oleksandr RIABENKO[4]

[1,4]*Department of Hydropower Engineering, Thermal Power Engineering and Hydraulic Machines, National University of Water and Environmental Engineering, Rivne, Ukraine*

[2,3]*Department of Hydraulic Structures, Faculty of Civil Engineering, CTU in Prague, Czech Republic*

Received 19.03.2025; accepted 05.06.2025

Abstract **– This study investigates the hydraulic conditions of the tailrace channel at the Perehonivka mini hydropower plant (HPP) in Ukraine using 2D computer modelling with HEC-RAS 6.6. Hydropower facilities, while essential for renewable energy generation and water regulation, can experience negative hydraulic effects that compromise equipment performance, structural integrity, and environmental stability. The Perehonivka HPP, initially constructed in the 1950s and reconstructed in 2014, was analyzed under two flow scenarios: regular turbine operation (4.6 m³/s) and combined turbine and spillway operation during a 5% probability flood event (397 m³/s). The simulation results revealed subcritical flow under normal operation, but excessive velocity values that may cause erosion in the inlet canal. During flood events, water overflowed the canals and exceeded the designed hydraulic capacity, highlighting risks of structural damage and flooding. These results emphasize the importance of modern hydraulic modelling in the design and reconstruction of HPPs to ensure operational efficiency and minimize environmental and structural risks. The study supports the need for updated infrastructure designs aligned with current flood probability standards.**

Keywords **– Environmental impact; hydraulic regime; mini hydropower plant; modelling.**

Nomenclature		
α_1, α_2	velocity weighting coefficients at the first and second cross-sections respectively	–
Z_1, Z_2	elevation of the main channel at the first and second cross-sections respectively	m
Y_1, Y_2	depth of water at the first and second cross-sections respectively	m
h_e	energy head loss	m
g	gravitational acceleration	ms^{-2}
u, v	the velocities in the Cartesian directions	ms^{-1}
v_t	the horizontal eddy viscosity coefficient	$kgsm^{-2}$
c_f	the bottom friction coefficient	–
R	the hydraulic radius	m
f	Coriolis parameter	$Rads^{-1}$
Q	flow rate	m^3s^{-1}

* Corresponding author.
E-mail address: o.o.halych@nuwm.edu.ua

1. INTRODUCTION

Hydropower engineering is one of the most widespread sources of renewable energy in the world, which not only generates clean electricity but also plays an important role in the regulation and reliable operation of the country's energy system. Today, a large number of hydroelectric power plants are being designed, built, and operated around the globe, varying in capacity, head, composition, and layout of structures and equipment, etc. [1]. Moreover, such plants are being hybridised with solar or wind power plants in different countries [2], and Ukraine is not an exception.

Regardless of whether the HPP is hybridised or not, the construction, operation, and reconstruction of hydropower plants are accompanied by the formation of various hydraulic processes and regimes in the head race and tailrace, which can have a negative impact on the operation of hydropower equipment, the condition of structures, their elements, and the environment [3]–[5]. Under typical operating conditions of the HPP, the flow in the tailrace is largely calm. Provided the tailrace bed is flat, no notable hydraulic disturbances are observed downstream of the HPP structure, except for the potential development of a surface roller (Fig 1a). However, if the depth of the tailrace is close to the critical depth, a wave-like free-surface occurs there (Fig. 1b), which can cause overflows through the canal top, destruction of bank anchorage, erosion of the channel bottom, etc. [6]. Such unstable hydraulic processes can occur during the synchronous and asynchronous emergency shutdowns of the plants [7] and can cause displacements and deformations of hydraulic structures, mechanical stress, and potential damage to penstocks and turbines. For example, at the Myhiyivska small hydropower plant, it was necessary to reduce the operating capacity due to the increased vibration of hydro turbines caused by the formation of vortices in the forebay [8].

A special period of HPP operation is the period of flood or high water when a flow carrying a significant amount of excess energy is discharged into the tailrace of the HPP, which can cause damage to structural elements, bottom erosion and shoreline of the tailrace canal and natural channel [9].

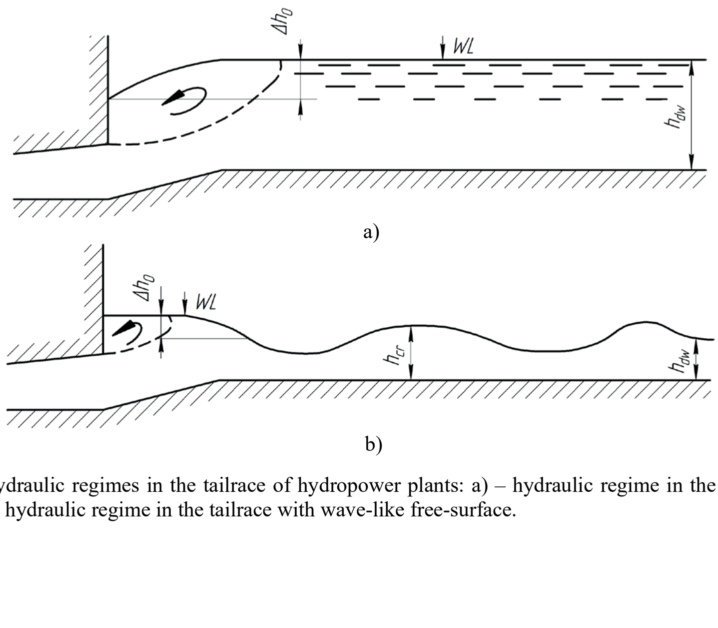

Fig. 1. Possible hydraulic regimes in the tailrace of hydropower plants: a) – hydraulic regime in the tailrace with free-surface roller, b) – hydraulic regime in the tailrace with wave-like free-surface.

Thus, the correct design of the inlet and outlet canals of hydropower plants, spillways, hydraulic constructions, or other elements of hydropower plants can have a positive impact not only on the operation of hydropower plants, electricity generation, and the condition of structures but also have a minimal impact on the environment.

To increase the efficiency of hydropower plants, it is important to apply rational layouts of hydropower plant buildings, which are often either adopted in accordance with analogies of existing structures or by means of hydraulic calculations and modelling. Although hydraulic calculations are kept to a minimum in the first case compared to the second or third, modelling can help to understand hydraulic processes and their impact on the structure, plant operation, and the environment much better.

The most commonly used hydraulic modelling for the construction and operation of hydropower plants is either physical modelling or computer modelling. Despite all the advantages of physical modelling, computer modelling is now widely used to solve many problems related to the design, construction, operation, and reconstruction of hydropower plants and hydraulic structures. The article focuses on the computer simulation of the hydraulic conditions in the tailrace channel of the Perehonivka mini hydropower plant during turbine operation and during flood passage. In this study, hydraulic 2D flow modelling was performed by means of Hydrologic Engineering Center's River Analysis System (HEC-RAS) [10]. The streamlines, velocity values and possible flood areas were determined and analyzed.

Given the complexity of hydraulic phenomena around hydropower structures – especially during high-flow events – modern modelling techniques are increasingly essential for diagnosing and mitigating design limitations. This study offers a novel application of 2D hydraulic modelling using HEC-RAS to evaluate the hydraulic performance of the reconstructed Perehonivka mini hydropower plant during both normal turbine operation and extreme flood scenarios. Unlike many conventional designs based on outdated assumptions or minimal hydraulic analysis, this approach provides detailed spatial insights into flow velocity, depth distribution, and critical overflow zones. The results not only illustrate the hydraulic vulnerabilities of the historical design but also validate the effectiveness of recent structural upgrades aimed at increasing flood resilience. The methodology and findings contribute new practical knowledge applicable to the assessment and modernization of similar small hydropower facilities, particularly in regions with aging infrastructure and evolving hydrological risks.

2. METHODS AND METHODOLOGY

2.1. Study Area

There are many small hydropower plants in Ukraine that need to be reconstructed [11]. The study area is the Perehonivka mini-hydropower plant on river Yatran as seen in Fig. 2. It was built in the 1950s but was closed for almost 40 years. In 2014 it was reconstructed and put again into operation [12]. Reconstruction of Perehonivka mini hydropower plant included upgrading the hydraulic structures that make up the hydroelectric complex (earthen dam, concrete spillway dam, inlet and outlet canals, and powerhouse) (Fig. 2 and Fig. 3), selection of modern hydropower equipment, minimization of harmful effects on the river fish fauna, protection of the adjacent territory and the Perehonivka village from flooding by the Yatran River.

Fig. 2. Photo from the air of Perehonivka mini hydropower plant.

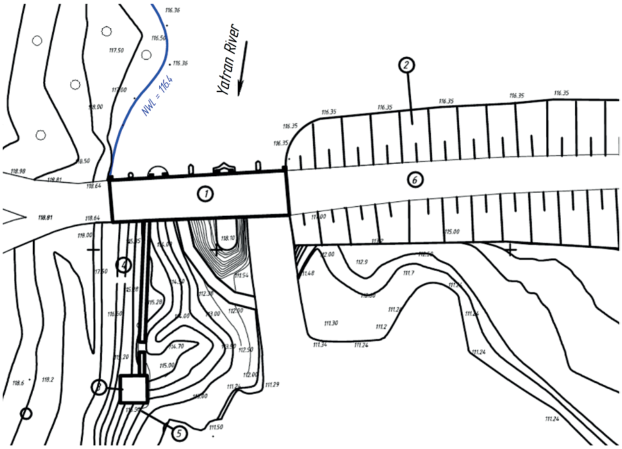

Fig. 3. Scheme of Perehonivka mini hydropower plant: 1 – water spillway, 2 – earth dam, 3 – power house, 4 – inlet canal, 5 – outlet canal, 6 – road.

2.2. Hydrological Data

The Yatran River is a right tributary of the Syniukha River (Southern Buh River basin) [13]–[14]. It flows into the Syniukha River at a distance of 67 km from the mouth, at an altitude of 87.2 meters above sea level. The length of the Yatran River basin reaches 70 km, its average width is 31 km, and it stretches from northwest to southeast (Fig. 4). The catchment area at the mouth is 2170 square kilometers and 107 km long, while the catchment area in the location of the mini hydropower plant to be reconstructed is 1615 square kilometers. The average long-term flow rate is 3.07 m^3/s. It needs to be mentioned that the river basin is subject to high storm activity: the average annual rainfall is 633 mm [13]. The maximum values of flow rates have reached 840 m^3/c as depicted in Fig. 5.

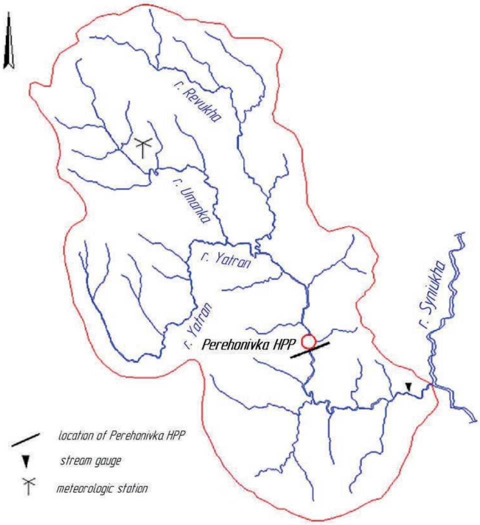

Fig. 4. Yatran River basin with its tributaries.

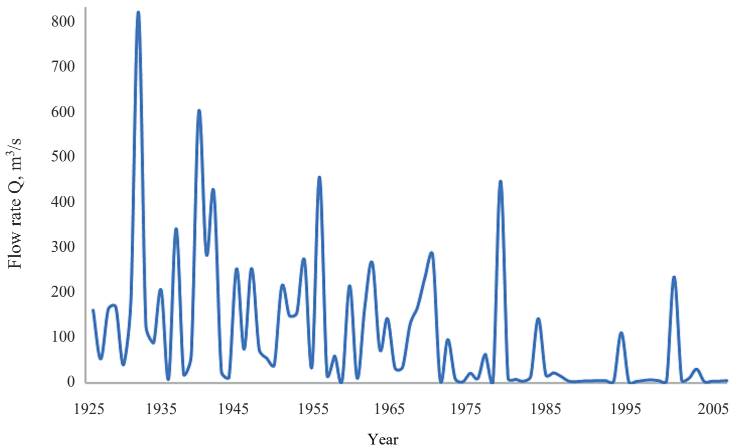

Fig. 5. Flow rate of floods in the location of Perehonivka HPP.

Fig. 4 shows the decreasing flood flow rate value after building the Perehonivka mini HPP. However, floods with large values of flow rate continue to occur. According to many studies [15]–[17], there is still a risk of overflowing in the event of floods of 20, 50, 100, and 200-year frequency in the rivers, which can lead to the formation of different negative hydraulic processes, damage to the hydraulic structure, and overflooding adjacent area. As an example of studying the possible hydraulic regimes during the flood period, the old structure composition of Perehonivka HPP was considered and used for hydraulic modelling in HEC-RAS.

2.3. Method of Hydraulic Processes Modelling

Simulation of hydraulic processes and regimes that can occur during the operation of mini hydropower plants, including flood periods, was performed by using open software HEC-RAS 6.6. This software is basically used for hydraulic and hydrologic analysis, such as simulating river flow, floodplain management, and designing flood protection infrastructure. Moreover, HEC-RAS has recommended itself well for determining hydraulic regimes during hydraulic structure operation. It performs flow analysis using different equations, the main of which are [18]:

– Energy equation, Eq. (1):

$$Z_2 + Y_2 + \frac{\alpha_2}{2g} = Z_1 + Y_1 + \frac{\alpha_1}{2g} + h_e , \quad (1)$$

where

Z_1, Z_2 elevation of the main channel at the first and second cross-sections respectively;
Y_1, Y_2 the depth of water at the first and second cross-sections respectively;
V_1, V_2 average velocities at the first and second cross-sections respectively;
α_1, α_2 at the first and second cross-sections respectively;
g gravitational acceleration;
h_e energy head loss.

– Shallow water equations, Eq. (2) and Eq. (3):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - c_f u + fv , \quad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial H}{\partial x} + v_t\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - c_f v + fu , \quad (3)$$

where

u and v the velocities in the Cartesian directions;
v_t the horizontal eddy viscosity coefficient;
c_f the bottom friction coefficient;
R the hydraulic radius;
f the Coriolis parameter.

To perform a 2D analysis of hydraulic processes in HEC-RAS, the information on topography with hydraulic structures and on water flow rates through the turbine and water spillway was used.

3. RESULTS AND DISCUSSION

To reach the purpose of this article, two variants of hydraulic regimes simulation during Perehonivka hydropower plant operation were carried out: during turbine operation with a flow rate – 4.6 m^3/s and during spillway and turbine operation with a total flood flow rate of 5 % probability – 397 m^3/s.

As a result of modeling the data, the main parameters as velocities and depths in the head race in the tailrace were received (Figs. 6–9).

The results and figures of modelling show that during turbine operation in head race and tailrace the subcritical flow occurs that is common for such operation and corresponds to the designed hydraulic regime. However, the velocity values in the inlet canal exceed the allowable values [19]. Such values can cause erosion of the canal and lead to hydropower plant inoperability.

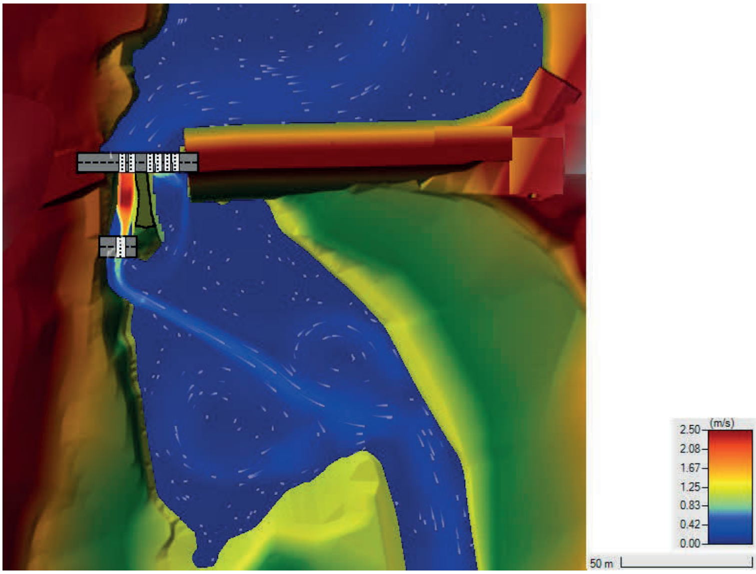

Fig. 6. Velocities values of modelling during turbine operation with $Q = 4.6$ m^3/s.

Fig. 7 and Fig. 9 show that during flood flow rate passage, the values of velocities and depth increased in both head and tailraces. Moreover, the water overflows the inlet and outlet canals, and the water spillway can barely cope with the passage of flood water. That means that the hydraulic regimes which occurred did not correspond to the design regimes. Moreover, taking into account the hydrograph of the flood flow rate of floods (Fig. 5), such unpredictable hydraulic regimes that caused different damages to hydraulic structures and their elements during floods might have been one of the reasons for closing Perehonivka HPP in the past.

According to standards and normative documentation, the old HPP was designed to pass the maximum flow rate with a 5 % probability, which is 397 m^3/s. However, in accordance with the current legislation, the structures must be designed to pass the maximum flow rate with a 3 % probability [20], when the flow rate is 420 m^3/s. Therefore, in the project of Perehonivka HPP reconstruction to increase the capacity of the hydroelectric facility during floods, an overflow wall of the flume with an elevation of +116.80 m was designed, which would increase the flow capacity. When the water level in the water reservoir exceeds the elevation of +117.60 m, water flows to the floodplains, with the water level in front of the hydraulic structures being +118.00 m.

Modelling the hydraulic regimes during turbine operation and spillway and turbine operation, the streamlines and velocity directions are also shown. It helps to predict the places of geomorphological changes in the river bottom and banks. Sometimes, places of bottom erosion can occur near the dam or spillways, which may lead to a loss of structure stability.

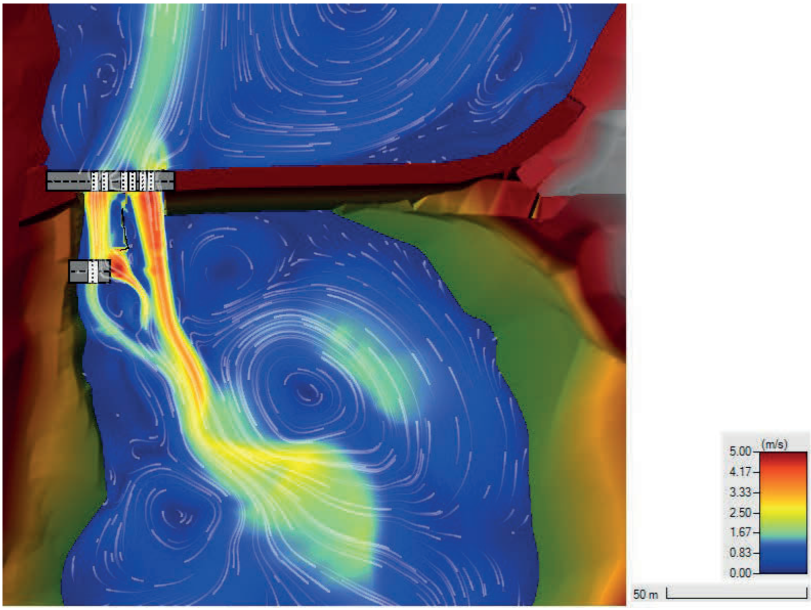

Fig. 7. Velocities values of modelling during turbine and spillway operation with $Q = 397$ m^3/s.

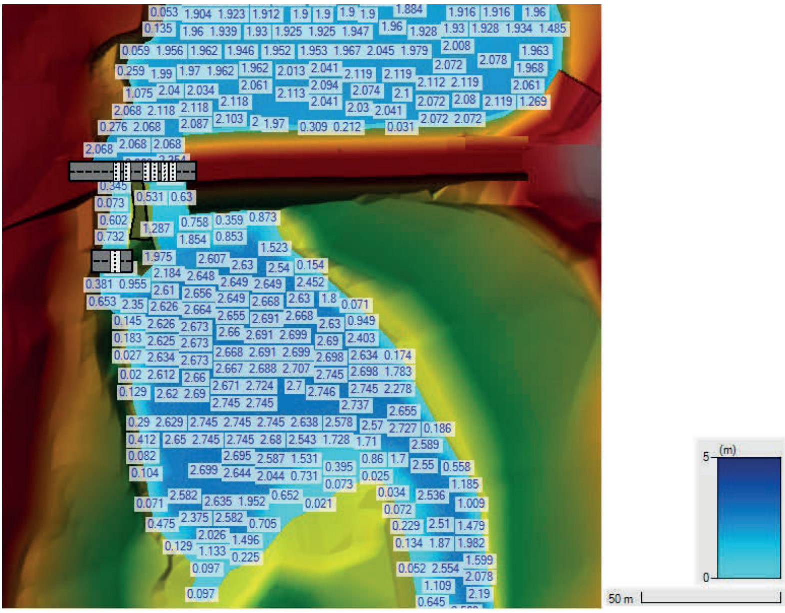

Fig. 8. Depth values of modelling during turbine operation with $Q = 4.6$ m^3/s.

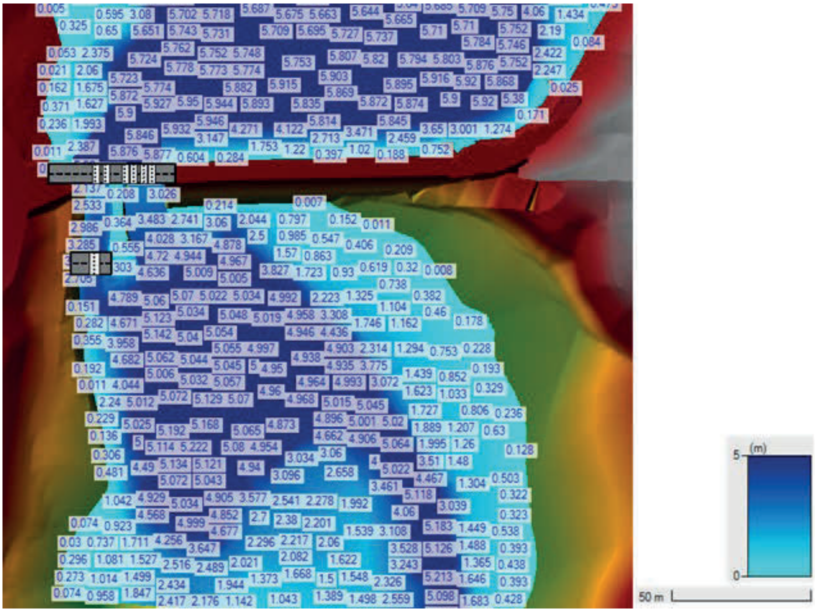

Fig. 9. Depth values of modelling during turbine and spillway operation with $Q = 397$ m^3/s.

4. Conclusion

During the operation of hydropower plants and hydraulic constructions, different hydraulic regimes can occur that can cause unstable operation of hydraulic equipment and damage to hydraulic constructions. Therefore, it is important to predict possible hydraulic regimes and processes in the head and tailraces by conducting hydraulic calculations and hydraulic or computer modelling.

The study highlights the importance of detailed hydraulic modelling in evaluating and improving small hydropower plants' operational safety and efficiency. Using HEC-RAS 2D simulations, two key operational scenarios at the Perehonivka mini hydropower plant were analyzed – normal turbine operation and flood flow conditions. The results demonstrated that while the current system handles turbine operation under normal flow rates effectively, it becomes highly stressed during flood events, with water levels exceeding the canal banks and potential overflow beyond the design limits.

The analysis revealed that the previous infrastructure could not safely accommodate extreme flood discharges, which may have contributed to historical operational shutdowns. The modelling also showed that critical flow velocities in the inlet canal during normal operation could lead to erosion risks, emphasizing the need for reinforcement or redesign of certain hydraulic structures.

To mitigate these risks and improve resilience, the reconstruction project incorporated an overflow wall and floodplain usage to increase discharge capacity. These findings underscore the critical role of hydraulic modelling not only for design validation but also for anticipating failure modes and informing future upgrades. Ultimately, incorporating modern modelling tools in the design and rehabilitation of hydropower plants ensures both environmental safety and energy system reliability.

ACKNOWLEDGEMENT

This work was supported by the program of the Ministry of Foreign Affairs of the Czech Republic "Strengthening professional capacities of public universities in Ukraine in 2025" [grant number 25-PKVV-UM-006].

REFERENCES

[1] Renewable energy statistics 2024, International Renewable Energy Agency, Abu Dhabi, 2024.

[2] Brence K., Kudurs E., Valters K., Blumberga D. Twinned Renewable Energy Accumulation: Case of Wind and Hydro Energy. *Environmental and Climate Technologies* 2023:27(1):696–710. https://doi.org/10.2478/rtuect-2023-0051

[3] Chow V. T. Open Channel Hydraulics. New York: McGraw-Hill, 1959.

[4] Walter H. Graf. Fluvial hydraulics: flow and transport processes in channels of simple, 2001.

[5] Majewski W. Hydrauliczne badania modelowe w inżynierii wodnej. Instytut Meteorologii i Gospodarki Wodnej Państwowy Instytut Badawczy, Warszawa 2019.

[6] Geiger C, Riedelbauch S. Power Plant Transients including Hydraulic Short Circuit Operation Mode. *Energies* 2023:16(11):4492. https://doi.org/10.3390/en16114492

[7] Riabenko O. A., Sunichuk S. V., Filipovych Y. Y. Optimisation of the hydraulic mode of operation of the water intake of the Myhiyivska HPP. Bulletin of the National University of Water and Environmental Engineering 2018:2(82).

[8] Riabenko O., Nowak P., Bilkova E., Halych O. Modelling of Undular Jump Characteristics. *Environmental and Climate Technologies* 2024:28(1):221–229. https://doi.org/10.2478/rtuect-2024-0018

[9] Slissky S. M. Hydraulics of hydroelectric power plant buildings, Energia, 1970.

[10] Introduction to HEC-RAS [Online]. [Accessed 18.03.2025]. Available: https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/introduction-to-hec-ras

[11] Halych O., Nowak P., Bilkova E., Riabenko O. Analysis of Hydropotential and Prospects for Small Hydropower Development in Ukraine. *Environmental and Climate Technologies* 2023:27(1):763–774. https://doi.org/10.2478/rtuect-2023-0056

[12] Renewable energy sources [Online]. [Accessed 18.03.2025]. Available: https://www.energo.ua/en/assets/small_hppperehonivka

[13] Yatsyk A.V. (ed). Small rivers of Ukraine: Handbook. Kyiv. Urozhay, 1991.

[14] Vyshnevsky V. I., Kosovets O. O. Hydrological characteristics of rivers of Ukraine. Kyiv. Nika-Center. 2003.

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

[16] Manopiniwes W., Irohara T. Optimization model for temporary depot problem in flood disaster response. *Nat Hazards* 2021:105:1743–1763. https://doi.org/10.1007/s11069-020-04374-1

[17] Aerts J. P. M., Uhlemann-Elmer S., Eilander D., Ward P. J. Comparison of estimates of global flood models for flood hazard and exposed gross domestic product: a China case study. *Nat. Hazards Earth Syst. Sci*. 2020:3245–3260.

[18] HEC-RAS User's Manual [Online]. [Accessed 18.03.2025]. Available: https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest

[19] Khlapuk M. M., Shynkaruk L. A., Demianiuk A. V., Dmytrieva O. A. Hydrotechnical structures: a textbook. Rivne, NUWEE, 2013.

[20] SBN B.2.4-3:2010 Hydraulic, power and reclamation systems and structures, underground mine workings. Hydraulic structures. Main provisions, 2010.